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RESEARCH

Evaluation of the Technological Performance of Soft Wheat Flours for Fresh-Pasta Production as Affected by Industrial Refining Degree

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Abstract

Nowadays, whole grain and less refined flours deriving from higher extraction rate milling processes have received much attention due to the presence of the external parts of the grain constituting the bran, with well-known health benefits. The use of these flours can represent a rational option for the valorization of native bran with minimal by-product generation while improving the nutritional and functional profile of the end products. This work aims to evaluate the techno-functional characteristics of commercial soft wheat flours with different refining degrees (proximate composition, functional, rheological, and starch-related properties) and their relation to the produced fresh-pasta quality (cooking behavior, mechanical and optical properties, and sensory assessment). Specifically, water holding capacity, fat absorption capacity, and swelling ability of flours gradually decreased with the refining degree (up to 25%, 16%, and 36%, respectively). Regarding the starch properties, the overall gelatinization process resulted to be negatively influenced by higher extraction rates, leading to a lower consistency of the whole grain starch gels (~17% in the maximum force during heating and ~12.39% peak viscosity). Cooked pasta was darker and redder when increasing the extraction rate. In addition, whole grain-based pasta had 42% higher cooking loss, and it was 86% harder and 101% firmer, leading to the production of a less elastic fresh-pasta with lower swelling ability. However, a good quality end product with naturally high nutritional value can be produced with flours with low refining degree. Results are useful to assess the best productive destination of flours basing on their technological properties.

Keywords Functional properties · Starch pasting properties · Fiber · Fresh-pasta · Bran

Introduction

Wheat is one of the most important crops in terms of global production (over 781 million metric tons in 2022/2023, as reported by FAOSTAT—www.fao.org/faostat) for its versatile high-quality flour, largely utilized for the production of bread, pasta, cereal, pastries, cookies, crackers, muffins, or pitas. In modern society, whole grain and less refined flours with higher extraction rate have become more and more

Highlights

- Technological aptitude of flours at diverse refining degree is mainly influenced by fiber content.
- Less refined flours have higher hydration capacity and lower gelatinization ability.
- Starch stability and viscosity respectively increased and decreased with flour extraction rate.
- Fresh-pasta labelling as a "source of fiber" claim can be made with flour with 85% extraction rate.

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attractive thanks to their bran content offering various nutritional benefits (Shewry and Hey, 2015). In fact, both soluble and insoluble dietary fiber mainly present in the pericarp have been associated to a lower risk of some common chronic diseases such as cardiovascular disease, metabolic syndrome, and type 2 diabetes and to a lower incidence of certain cancers (Stevenson et al., 2012). This motivates that many countries have adopted specific recommendations for the selection of whole grain-based foods rather than refined grain-based ones (van der Kamp et al., 2021). However, the utilization of bran in wheat-based processes is still a challenge for the industry. Most of the studies regarding the technological repercussions of wheat bran on flours' characteristics are focused on the enrichment of refined flours with increasing amounts of wheat bran. Nevertheless, the use of unrefined or less refined wheat flours directly from the milling industry could be a rational option for the valorization of native bran. Those less refined flours include milling by-products at the same, or with a little different, relative proportion compared to that of the intact caryopsis, with important repercussions in terms of by-product management, sustainability, and nutrient intake. With this background, since few researches, mainly assessing the rheological properties, have been focused on the evaluation of the characteristics of flours as affected by the extraction rate (Moradi et al., 2016; Ramírez-Wong et al., 2007), it is of great interest to gather information on the technological and functional properties of wheat flours in relation to the extraction rate in order to efficiently use them for the production of high-quality products.

In general, the inclusion of the outer parts of the wheat kernel may cause important changes in the appearance and textural properties of cereal-based products (Ktenioudaki & Gallagher, 2012). Nonetheless, it is not easy to predict the effects of wheat bran on the characteristics of foods since they depend also on the type of product. For example, it has been demonstrated that the addition of 10% of wheat bran in pasta and biscuits did not reduce their sensory quality (Aravind et al., 2012), while the same addition level showed a strong effect on the physical characteristics of bread and cupcakes (Schmiele et al., 2012).

Considering that the main component of flours is starch (~70–80% of the wheat kernel), whose functionality is determinant for the development of cereal-based products, it is important to pay attention to the changes in the pasting and gelatinization properties of flours with the extraction rate (Barrera et al., 2013). Specifically, because starch granules' integrity can be dramatically compromised by the mechanical action of wheat milling that is higher at lower extraction rates. In particular, it has been reported that damaged starch granules have higher swelling ability and water absorption than native granules, aspects that significantly affect the viscosity of starch suspensions (Barrera et al., 2013).

Incorporating wheat flour with a higher extraction rate is advised from both nutritional and industrial perspectives, owing to its elevated fiber content and enhanced milling yield, respectively. However, it has been noted that this may impact the quality of pasta. The objective of this research was to conduct a comprehensive analysis covering from the characteristics of the flours to the properties of the fresh-pasta. The study assessed the technological suitability of various wheat flours, which varied in their degree of refinement. This comprised examinations of proximate composition, pasta production, and cooking, as well as technological and sensory evaluations, aiming to elucidate the effects of flour refinement. The holistic approach provided fundamental information about the impact of flour composition on fresh product quality, giving recommendations in terms of by-product management, sustainability, and nutrient intake.

Materials and Methods

Materials

Commercial soft wheat flours with different refining degrees (flour types: 00, 0, 1, and 2, whole grain (WG); classification based on the Italian Legislation D.P.R. 187/2001) were purchased from the same supplier of a local store (Campobasso, Italy), stored at 4 °C, and rested at room temperature (about 20 °C) before use. The Italian Legislation describes the extraction rate, as well as the maximum ash, protein, and moisture content. For reference, types 00, 0, 1, and 2 correspond to extraction rates of 70%, 75%, 80%, and 85%, respectively.

Chemicals, including lactic acid, glacial acetic acid, hydrochloric acid, sulfuric acid, boric acid, sucrose, sodium bicarbonate, sodium hydroxide, calcium chloride dihydrate, ethanol, copper catalyst, diethyl ether, and petroleum ether sulfuric acid, were obtained from Sigma-Aldrich (Madrid, Spain).

Flour Proximate Composition and Functional Properties

Proximate composition of flours was evaluated using AACC Official Methods (AACC, 2010). The obtained data were moisture (44–40.01), ash (08–01.01), fat (30–25.01), protein (46–12.01), and soluble/insoluble fiber (32–07.01). Total starch (TS) and damaged starch (DS) were determined using enzymatic assay kits K-TSTA and K-SDAM (Megazyme, Ireland), respectively. Measurements were carried out in duplicate, and all the results were reported as dry basis (db).

The water holding capacity (WHC) was determined as follows: 1.5 g of sample was mixed with 28.5 mL of deionized water through a vortex (10 s, 24,000 rpm) and then centrifuged (Eppendorf, Centrifuge 5804 R) for 30 min at 3000 rpm. Supernatant was carefully removed and the sediment was weighed. WHC was expressed as gram of retained water/gram of flour.

The fat adsorption capacity (FAC) was determined according to Ahn et al. (2005): 1 g of flour was mixed with 10 mL of commercial sunflower vegetable oil through a vortex (10 s, 24,000 rpm). Then, the flour–oil mixture was centrifuged (4000 rpm for 5 min) and weighed after removing the supernatant. FAC was calculated as gram of retained oil/gram of flour.

The solvent retention capacity (SRC) was determined according to the AACC method 56-11.01 (AACC, 2010) to quantify the solvent retention capacity by flour components (Guzmán et al., 2015). Particularly, the used solvents were sucrose (50% w/v), sodium bicarbonate (5% w/v), and lactic acid (5% v/v), allowing respectively the estimation of the contributions of pentosans (SRC-S, saccharose absorption), damaged starch (SRC-B, sodium bicarbonate absorption), and glutenins (SRC-LA, lactic acid absorption). SRC (%, standardized for a constant moisture content of 14%) was calculated by means of Eq. 1 (Haynes et al., 2009):

$$\mathrm{SRC}\ (\%) = \left(\frac{\text{gel weight (g)}}{\text{flour weight (g)}} - 1\right) \times \left(\frac{86}{100 - \text{ flour moisture } (\%)}\right) \times 100 \tag{1}$$

The swelling capacity (SC) was determined according to Chandra and co-workers (Chandra et al., 2015) and recorded as milliliters of suspension/gram of flour.

All the determinations related to the functional properties were carried out in triplicate.

Flour Starch-Related Properties

A Chopin Amylab (Chopin Technologies, Villeneuve-la-Garenne, Cedex, France) was utilized as a rapid force analyzer (RFA) to record the force changes of flours due to the starch evolution. The setting parameters followed the default option called “testogram” that lasted 90 s, consisting of heating a flour-water slurry up to 100 °C under continuous up and down stirring (Garzon & Rosell, 2021). A precision test tube was first filled with 7 g (14% mb) of flour and 25 mL of double-distilled water; the slurry was manually stirred for 30 s, before inserting the plunger to cap the tube, which was then placed into the holder of the RFA, ready for the analysis. Plots recorded show the force, expressed in Newtons, of the slurry/gel under continuous heating/shearing. Parameters defined include the following: falling number related to the enzymatic activity, maximum force, final force, slope-α (slope of the curve until maximum force), gel stability (elapsed time in which force was kept ±10% of the maximum force), and breakdown (force difference between maximum and final force) (Garzon & Rosell, 2021).

The pasting and apparent viscosity properties of flours were determined by Rapid Visco Analyzer (RVA 4500, Perten Instruments SA, Stockholm, Sweden). Specifically, 3 g of each flour was added in 25 mL of deionized water and placed on RVA cups (Espinosa-Ramírez et al., 2018). Samples were kept at 50 °C for 1 min, then heated from 50 to 95 °C at 12 °C/min and held at 95 °C for 1 min. After that, they were cooled at 12 °C/min and held at 50 °C for 2 min. The mixing speed was 80 rpm, and the viscosity was monitored in centipoise (cP). The average values for peak viscosity, trough viscosity (or minimum viscosity), final viscosity, and breakdown (difference between peak viscosity and trough viscosity) were calculated.

The starch gelatinization process was assessed by differential scanning calorimetry (DSC, Mettler Toledo, Spain) analyzing flour samples in excess water content (Martín-Esparza et al., 2018). In this respect, 5 mg of flour was placed into 40-μL stainless steel hermetic pans (Mettler Toledo, Spain), and 15 μL of water was added. The pans were placed at 4 °C for 24 h to equilibrate the water content. The heating rate in the calorimeter was 5 °C/min, and the analysis was carried out between 20 and 95 °C. Air was used as a reference, and heat flow data were taken as Watts (W = J/s), standardized with sample weight, and expressed as dry matter. Particularly, the specific heat at constant pressure represents the change of enthalpy with temperature. Thus, gelatinization enthalpy (ΔH_n) representing the area enclosed in the curve when the transition takes place was calculated from the plot reporting time vs heat flow. Moreover, onset (T_o, starch gelatinization starting point), peak (T_p, maximum starch gelatinization point), and end (T_e, ending of the process) temperatures were recorded (Santos et al., 2008). All the experiments were conducted in triplicate.

Fresh-Pasta Preparation

Dough for fresh-pasta production was prepared according to Mixolab (Chopin, Villeneuve-la-Garenne, France) dough development time (DDT) and water absorption (WA). In particular, the Chopin + protocol defined by the device supplier, utilizing 75 g of dough, was used (Rosell et al., 2010). Briefly, the test started when the mixing bowl reached 30 °C. Water previously heated at 30 °C was added to the flour and mixed at a constant mixing speed of 80 rpm to reach the fixed consistency of ~3.00 Nm. This consistency value was identified as the suitable one for fresh-pasta making in preliminary analysis (Tudorica et al., 2002). The rheological measurements were conducted twice.

Flour and water were thus mixed and kneaded in an electric cooking device (Thermomix TM-31, Vorwerk Spain M.S.L., S.C., Madrid). The obtained doughs were then kneaded by hand for 30 s and rested for 15 min inside individual plastic bags to ensure complete relaxation (Albors et al., 2016). A domestic pasta-making machine (Simplex SP150, Imperia, Italy) was used to perform a lamination process in order to obtain sheets of 1.00 ± 0.10 mm that were then cut into tagliatelle shape of 4.00 ± 0.05 mm width. Prior to cooking, the fresh-pasta samples were rested for 10 min more to prevent stickiness. Each formulation was prepared twice.

Fresh-Pasta Characterization

Proximate composition of fresh-pasta was calculated starting from the parent flour composition basing on the moisture content determined according to the AACC 44-40.01 Official Methods (AACC, 2010). All the results were expressed as wet basis (wb).

The cooking trials were conducted in duplicate according to the AACC-approved method 66–50.01 (AACC, 2010) with slight modifications. Particularly, 30 g of 7-cm-long samples of fresh-pasta was cooked in 300 mL of deionized water (ratio 1:10). Water volume was left at 90% of its initial volume by adding boiling water and covering the flasks to prevent evaporation losses. A fixed cooking time was selected to standardize the cooking process (Llavata et al., 2019). This time corresponded to 2 min (optimum cooking time for Type 00 sample, as revealed by the inner white core of fresh-pasta disappearance when squeezed between two glass plates at this time (Method 66-50.01, AACC, 2010).

Fresh-pasta was then removed from the flask, and the cooking process was quickly stopped by adding 20 mL of cold deionized water. The cooked pasta was finally drained for 2 min. This resting time for draining was respected also before performing the determination of mechanical properties and color attributes (both analyses are explained below). Cooking loss (CL), indicating the quantity of solid matter released into cooking water, was determined as described by Chillo et al. (2008) with slight modifications. Particularly, the collected cooking water was placed in an aluminum container to be evaporated to dryness in an air oven by two steps: first samples were rested at 60 °C for 24 h to reduce 2/3 volume, then at 100 °C for complete drying (about 5 h). The residue was weighed and calculated through the following Eq. 2:

$$\mathrm{CL}\ (\%) = \left(\frac{\text{weight of drained residue in cooking water}}{\text{weight of uncooked pasta}}\right) \times 100 \tag{2}$$

Volume increase (VI), water absorption index (WAI), and swelling index (SI) were also evaluated. Fresh-pasta dimensions (thickness, length, width) for volume changing evaluation were measured using a digital caliper (PCE-DCP 200N, PCE Ibérica S.L., Albacete, Spain). The water absorption index (WAI, %) was determined according to the procedure of Foschia et al. (2015) and calculated through Eq. 3:

$$\mathrm{WAI}\ (\%) = \left(\frac{\text{weight of cooked pasta} - \text{weight of uncooked pasta}}{\text{weight of uncooked pasta}}\right) \times 100 \tag{3}$$

Swelling index (SI) was determined according to the previous cited authors (Foschia et al., 2015) by weighting the samples both after cooking and after drying the cooked samples overnight at 105 °C to a constant weight. Results were expressed as gram water/gram by means of Eq. 4:

$$\mathrm{SI}\ (\text{g water/g}\ ) = \left(\frac{\text{weight of cooked pasta} - \text{weight of pasta after drying}}{\text{weight of pasta after drying}}\right) \tag{4}$$

Color measurements were taken over the surface reflectance spectra obtained by a spectro-colorimeter (Minolta CM-3600D) from 400 to 700 nm (illuminant D65, 10° standard observer) on a white background. The CIE $L^*a^*b^*$ color coordinates were measured. Particularly, L^* (lightness), a^* (redness-greenness), and b^* (yellowness-blueness) were obtained from the reflectance spectra. Moreover, the whiteness index (WI), yellowness index (YI), and the total color difference between the cooked (c) and uncooked (u) fresh-pasta (ΔE) were respectively calculated through Eqs. 5, 6, and 7 (Llavata et al., 2019):

$$\mathrm{WI}\ = 100 - \sqrt{(100 - L^*)^2 + (a^*)^2 + (b^*)^2} \tag{5}$$

$$\mathrm{YI}\ = 142.86 \times \left(\frac{b^*}{L^*}\right) \tag{6}$$

$$\Delta E = \sqrt{(L_c^* - L_u^*)^2 + (a_c^* - a_u^*)^2 + (b_c^* - b_u^*)^2} \tag{7}$$

A TA.XT2 Texture Analyzer (Stable Micro Systems, Godalming, Surrey, UK) equipped with a 5-kg load cell was used to perform the cut test on cooked fresh-pasta. Data were processed using the provided software Texture Exponent 6.1.7 (Stable Micro Systems Software).

Cut tests were run in accordance to the AACC Method 16–50 (AACC, 2010) setting the analytical conditions as follows: pre-speed 1.0 mm/s, test speed 1.0 mm/s, post-speed 1.0 mm/s, and distance 100.0%. Particularly, five 7-cm-long adjacent strands were cut using an HDP/LKBF cutting probe until total sample deformation was achieved. Cooked samples were analyzed just after the cooking procedure. Each cooking test was carried out in duplicate, and the numerical results are averages of at least five independent replicates. The obtained parameters were the following: (i) hardness, considered as the maximum cutting force (N) required to cut the cooked fresh-pasta; (ii) firmness, considered as the area under the curve expressing the cutting work (N·s); and (iii) elasticity (-), considered as the slope of the line tangent to the first part of the curve which is related to elasticity modulus, offering an idea of solid-like nature.

Sensory Analysis

Sensory analysis was conducted in individual sensory booths with 40 untrained panelists (males and females, 25–55 years old) according to standards UNE-ISO 4121:2006 and UNE 87023:1995 (Llavata et al., 2019). The cooked fresh-pasta samples (about 25 g each), coded with a random three-digit code, were served immediately after cooking in plastic dishes. All the samples were presented randomly and simultaneously to each panelist. The sensory evaluation has been approved by the Ethical Commission for Research activities at the Polytechnic University of Valencia (reference number P02, dtd 27/01/2023). Two tests were considered. Firstly, a sorting test based on attributes' intensity was conducted to appreciate significant differences between samples; the panelists had to classify samples, served all together, in a 1–5 scale, and the following attributes were considered: appearance (homogeneous/non-homogeneous), color (clear/dark), consistency (soft/hard), stickiness (not-sticky/sticky), and taste (bad/good) (Popper et al., 2004).

Secondly, a Just-About-Right scale (JAR) was conducted. Particularly, a single sample was presented to the panelists, and the same reported criteria of fresh-pasta were evaluated considering an ideal point as a reference. This test served to optimize the elements present in fresh-pasta and was combined with a 5-point hedonic scale of global acceptance (Li et al., 2014). In fact, by the means of the JAR, it is possible to determine if the single attributes of each sample were well optimized. Particularly, a penalty analysis allowing to check if an attribute is above or below its ideal point in relation to the global acceptance score was used. Then, a preference map of the studied attributes was elaborated.

Statistical Analysis

SPSS software (version 22.0, IBM Statistics, Armonk, NY, USA) was used for statistical analysis. For all the flour samples (from Type 00 to WG), each analysis was carried out in duplicate. Data were first evaluated by the analysis of variance with multiple comparisons (MANOVA) using Scheffè's post hoc test to determine differences among means. Within the tables, equal superscript letters indicate no significant differences (p-value > 0.05).

Principal component analysis (PCA) was used to transform a high number of correlated variables able to describe data variability into a smaller number of uncorrelated variables called principal components. Eigenvalues represent the amount of total observed variability on the original variables that the individuated principal components explain. They are plotted on a screen plot to show the decreasing rate at which variance is explained by additional principal components (Holland, 2008). Only eigenvalues > 1 were considered.

Within PCA, Kaiser-Meyer-Olkin (KMO) and Bartlett's sphericity tests were respectively performed to assess the factor homogeneity (-) and the significance of the outputs.

Friedman test and analogue Fisher's least significant difference (LSD) were applied to fresh-pasta sensory analysis to respectively individuate significant differences among the samples for each single attribute (Sheldon et al., 1996) and to identify the pairs of samples that significantly differed each other (Meier, 2006). Kaleidagraph software (version 4.03, Synergy Software, Reading, PA, USA) was used for graph plotting and calculations.

Results and Discussion

Flour Proximate Composition and Functional Properties

Flours, whose aspect is reported in Figure 1, were firstly characterized for their proximate composition (Table 1). As expected, the results showed that the content of protein, ash, and fat decreased with the refining degree. Furthermore, total dietary fiber (TDF), which represents around 50% (w/w dry weight) of whole wheat bran (Saini et al., 2023), increased from 1.94% ± 0.13 (Type 00) up to 9.13% ± 0.11 (WG). These percentages agreed with the available literature (Torbica et al., 2019).

As expected, the total starch content was higher in flours with higher refining. Moreover, in less refined flours, the amounts of damaged starch were lower since higher extraction rates can be related to milder milling processes, which

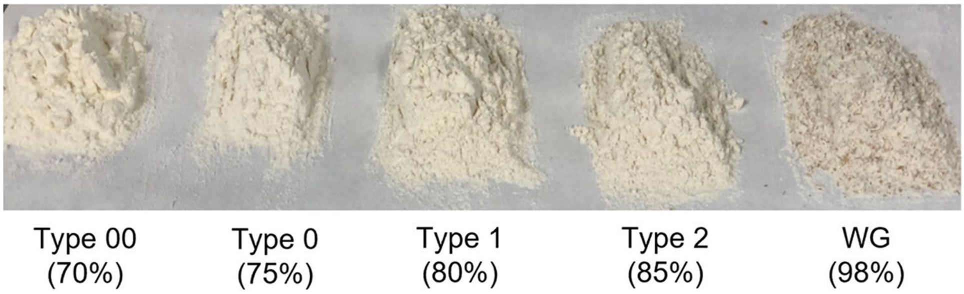

Fig. 1 Aspect of flours from different refined degrees; the extraction rates indicated within the brackets have been taken from Pagani et al. (2014)

Table 1 Proximate composition, rheological and functional properties of flours with different refining degrees (extraction rates indicated within brackets); *db* dry basis

	Type 00 (70%)	Type 0 (75%)	Type 1 (80%)	Type 2 (85%)	WG (98%)
Proximate composition					
Moisture (%)	14.90^{a} ± 0.12	14.60^{b} ± 0.12	12.30^{d} ± 0.12	12.60^{c} ± 0.12	12.50^{c} ± 0.12
Fat (% db)	0.88^{d} ± 0.02	1.21^{c} ± 0.04	2.09^{b} ± 0.03	2.13^{b} ± 0.06	2.85^{a} ± 0.02
Ash (% db)	0.43^{d} ± 0.03	0.45^{d} ± 0.02	0.81^{c} ± 0.04	0.95^{b} ± 0.02	1.74^{a} ± 0.03
TS (% db)	79.31^{a} ± 0.54	73.14^{b} ± 0.48	71.82^{c} ± 0.57	69.08^{d} ± 0.61	62.48^{e} ± 0.54
DS (% db)	6.12^{a} ± 0.05	5.48^{b} ± 0.02	5.13^{c} ± 0.04	4.89^{d} ± 0.03	4.41^{e} ± 0.04
DS (% TS)	7.71^{a} ± 0.03	7.49^{b} ± 0.04	7.12^{c} ± 0.02	7.08^{c} ± 0.03	7.06^{c} ± 0.04
Protein (N 5.7, % db)	10.68^{e} ± 0.02	10.95^{d} ± 0.03	12.01^{c} ± 0.02	12.52^{b} ± 0.02	13.94^{a} ± 0.01
Insoluble fiber (% db)	1.57^{d} ± 0.12	1.64^{d} ± 0.15	3.41^{c} ± 0.13	4.13^{b} ± 0.16	8.29^{a} ± 0.12
Soluble fiber (% db)	0.37^{d} ± 0.04	0.35^{d} ± 0.08	0.56^{c} ± 0.03	0.71^{b} ± 0.06	0.84^{a} ± 0.05
Total fiber (% db)	1.94^{d} ± 0.11	1.98^{d} ± 0.14	3.97^{c} ± 0.21	4.84^{b} ± 0.17	9.13^{a} ± 0.13
Rheological properties					
WA (%)	43.01^{e} ± 0.12	45.02^{d} ± 0.12	47.02^{c} ± 0.12	48.01^{b} ± 0.12	50.01^{a} ± 0.12
DDT (min)	0.96^{e} ± 0.02	1.04^{d} ± 0.03	1.15^{c} ± 0.03	1.27^{b} ± 0.02	1.87^{a} ± 0.04
Consistency (Nm)	3.04^{a} ± 0.03	2.98^{a} ± 0.04	2.95^{a} ± 0.03	3.02^{a} ± 0.02	3.01^{a} ± 0.02
Functional properties					
WHC (g/g flour)	0.71^{d} ± 0.02	0.72^{cd} ± 0.06	0.75^{c} ± 0.02	0.81^{b} ± 0.02	0.89^{a} ± 0.02
FAC (g/g flour)	0.74^{c} ± 0.02	0.76^{c} ± 0.02	0.82^{b} ± 0.02	0.84^{b} ± 0.02	0.86^{a} ± 0.02
SRC-S (%)	75.71^{e} ± 1.08	80.36^{d} ± 1.02	83.32^{c} ± 1.12	88.21^{b} ± 1.08	92.59^{a} ± 1.05
SRC-B (%)	77.35^{a} ± 1.02	75.43^{b} ± 1.03	72.69^{c} ± 1.13	69.54^{d} ± 1.12	65.85^{d} ± 1.17
SRC-LA (%)	80.62^{e} ± 1.08	91.95^{d} ± 1.13	95.28^{c} ± 1.23	104.54^{b} ± 1.09	109.48^{a} ± 1.15
SC (mL/g flour)	2.16^{e} ± 0.05	2.26^{d} ± 0.03	2.72^{c} ± 0.02	2.85^{b} ± 0.02	2.94^{a} ± 0.04

Values indicate mean ± standard deviation. Different superscript letters within a row indicate significant differences (p-value < 0.05). *TS* total starch, *DS* damaged starch, *WA* water absorption, *DDT* dough development time, *WHC* water holding capacity, *FAC* fat absorption capacity, *SRC-S* sucrose solvent retention capacity, *SRC-B* sodium bicarbonate solvent retention capacity, *SRC-LA* lactic acid solvent retention capacity, *SC* swelling capacity

leads to lower mechanically damaged starch (Wang et al., 2020).

All the studied functional properties increased as the extraction rate increased, except for SRC-B which presented an opposite trend. Particularly, WHC, related to the ability of a protein matrix, fibers, and damaged starch, resulted to be higher in less refined flours. The increase of FAC can be attributed to the ability of proteins to bind lipids (Ahn et al., 2005); thus, the higher amounts of fat and protein in less refined flours could be responsible for the significant differences found among flours. The increasing values of SRC-S and SRC-LA were related to the higher amounts of pentosans (which are part of the dietary fiber) and the higher protein content (Guzmán et al., 2015); the SRC-B decreasing values agree with the decrease in DS as the extraction rate increases (Table 1).

Flour Starch-Related Properties

Flour starch-related properties are reported in Table 2. The rapid force analyzer (RFA) recorded the force changes during the starch gelatinization occurring during a 90-s heating of flour slurries. The maximum force during heating and the breakdown of the starch gels decreased when increasing the extraction rate of the flours, as well as the slope-α. Presumably, the lower consistency of the starch gels and smaller slope of the force vs time curve can be mainly related to the presence of wheat bran that delayed the starch gelatinization and the lower amount of starch (Santos et al., 2008).

Conversely, the final force and stability values showed an increasing trend, in agreement with the lower breakdown mentioned above which can be related to the disintegration degree of the starch granules and to the development of a more rigid structure when fiber absorbs water (Gelencsér et al., 2008). With respect to the falling number, it increased with the extraction rate, indicating a lower α-amylase activity. These results agreed with those of Rachon and Szumilo (2009) who found a positive correlation between the falling number and the ash and the fiber content of wheat flours.

The pasting properties of flours were recorded to characterize the starch gel performance by measuring the changes in the apparent viscosity during a heating and cooling cycle.

Table 2 Starch-related properties of flours with different refining degrees (extraction rates indicated within brackets)

	Type 00 (70%)	Type 0 (75%)	Type 1 (80%)	Type 2 (85%)	WG (98%)
Testograms and α-amylase activity					
Falling number (s)	308^{e} ± 3	320^{d} ± 5	339^{c} ± 6	354^{b} ± 4	367^{a} ± 5
Maximum force (10^3 N)	19.50^{a} ± 0.04	19.20^{b} ± 0.03	18.50^{c} ± 0.02	18.50^{c} ± 0.03	16.20^{d} ± 0.02
Final force (10^3 N)	11.30^{d} ± 0.05	11.50^{d} ± 0.04	11.80^{c} ± 0.06	12.1^{b} ± 0.04	12.4^{a} ± 0.03
Slope-α (-)	107.8^{a} ± 0.3	86.71^{b} ± 0.57	74.7^{c} ± 0.2	62.4^{d} ± 0.8	43.3^{e} ± 0.8
Stability (s)	4.85^{e} ± 0.05	5.68^{d} ± 0.09	7.06^{c} ± 0.07	7.72^{b} ± 0.06	8.86^{a} ± 0.09
Breakdown (10^3 N)	8.16^{a} ± 0.09	7.67^{b} ± 0.07	6.73^{c} ± 0.07	6.32^{d} ± 0.06	3.74^{e} ± 0.02
Pasting properties					
Peak viscosity (10^3 cP)	2.42^{a} ± 0.02	2.27^{b} ± 0.02	2.16^{c} ± 0.02	2.15^{d} ± 0.02	2.12^{d} ± 0.02
Trough viscosity (10^3 cP)	1.49^{a} ± 0.02	1.31^{b} ± 0.02	1.18^{c} ± 0.02	1.13^{d} ± 0.03	1.06^{e} ± 0.02
Final viscosity (10^3 cP)	2.82^{a} ± 0.04	2.65^{b} ± 0.03	2.52^{c} ± 0.02	2.48^{d} ± 0.02	2.39^{e} ± 0.02
Breakdown (10^3 cP)	0.94^{d} ± 0.02	0.97^{c} ± 0.02	0.98^{bc} ± 0.02	1.01^{b} ± 0.02	1.05^{a} ± 0.02
Thermal properties					
T_o (°C)	52.4^{e} ± 0.2	54.25^{d} ± 0.12	55.75^{c} ± 0.08	57.85^{b} ± 0.08	60.02^{a} ± 0.13
T_p (°C)	58.99^{e} ± 0.12	60.6^{d} ± 0.2	64.5^{c} ± 0.3	65.4^{b} ± 0.3	66.6^{a} ± 0.2
T_e (°C)	67.6^{e} ± 0.2	69.3^{d} ± 0.2	70.16^{c} ± 0.09	71.49^{b} ± 0.12	72.71^{a} ± 0.08
$T_e - T_0$ (°C)	15.17^{a} ± 0.02	14.57^{b} ± 0.04	14.41^{c} ± 0.08	13.65^{d} ± 0.05	12.69^{e} ± 0.04
ΔH_n (J/g dry matter)	6.69^{a} ± 0.03	6.21^{b} ± 0.02	6.03^{c} ± 0.04	5.76^{d} ± 0.02	5.31^{e} ± 0.03

Values indicate mean ± standard deviation. Different superscript letters within a row indicate significant differences (p-value < 0.05). T_o onset temperature, T_p peak temperature, T_e end temperature, ΔH_n gelatinization enthalpy

In particular, the apparent viscosity profiles resulted to be shifted downwards when passing from Type 00 to WG, mainly because of decreasing the amount of starch due to an effective dilution associated with the higher presence of dietary fiber, proteins, and lipids that increased with the extraction rate (Schmiele et al., 2012).

In agreement with the RFA data discussed above, the maximum peak viscosity associated with the maximum swelling of the starch granules before rupture (Espinosa-Ramírez et al., 2018) also showed decreasing values. Overall, the gradual reduction of the viscosity values (including the trough viscosity and the final viscosity) was in line with the increase of the extraction rate because of starch dilution. However, it is important to note that the breakdown values from RVA are not comparable with those of the previously discussed RFA since RVA tests are based on heating-cooling cycles, while RFA analysis is performed upon heating. Hence, a correlation between these parameters is not obvious.

The gelatinization in excess water assessed through the DSC revealed that flour samples had a single endothermic peak during the heating process, which corresponded to the starch gelatinization. Particularly, T_p increased with the extraction rate, ranging from 58.99 ± 0.12 for 70% extraction rate flour to 66.58 ± 0.09 for 98% extraction rate flour. Moreover, an increase in both T_o and T_e was detected; thus, the curves resulted to be up/rightward shifted as a consequence of the delay of the process mainly because of the higher amount of fiber in the less refined flours which is able to bind the available water and thus hinder starch hydration and swelling process, which is the basis of the gelatinization of starch granules (Santos et al., 2008). The temperature range between the onset and the end of the peak (T_e–T_o) showed a decreasing trend with the extraction rate, as well as the gelatinization enthalpy (ΔH_n); thus, the gelatinization process needed less energy to occur in less refined flours. These observations agreed with previous findings that the higher the fiber concentration in the wheat flour-fiber blends, the higher the T_o and T_p and the lower the ΔH_n values (Santos et al., 2008). Nevertheless, no melting peak was observed in the present system, likely due to water was not as limiting as observed in the doughs used by Santos et al. (2008). It is important also to highlight the contribution of the damaged starch; the higher the amount of damaged starch, the lower the energy that the transition requires to occur (Santos et al., 2008). Therefore, the thermal characterization of flours was in accordance with the total and damaged starch levels (Table 1) and with the previously discussed results from RVA and RFA, indicating that starch gelatinization was negatively influenced by the extraction rate.

Principal Component Analysis and Flour Classification

Results were gathered in a PCA statistical analysis, which is an effective mathematical method to reduce the dimensionality of multivariate data, while preserving most of the variance. The KMO test indicated the sampling adequacy, while Bartlett's test of sphericity showing significance < 0.001 evidenced the good attendance of the statistical models. Proximate composition from Table 1 has been simplified without considering moisture, damaged starch, and soluble and insoluble fiber.

As it can be seen from the loading plot (Figure 2A), two principal components have been able to explain the 73.12% and 19.43% of total variability (cumulative explained variability = 93.36%). In particular, PC1 resulted to be mainly positively influenced by T_e and T_p from DSC analysis and SRC-S and WHC which are part of flour functional properties, while the main negative effect was exerted by SRC-B (functional properties); slope-α and maximum force from RFA; final viscosity, peak viscosity, and trough from RVA; and ΔH_n from DSC. In the case of PC2, a strong positive effect resulted due to SRC-LA and SC (functional properties) and final force and stability from RFA.

More in detail, it must be highlighted that within the plot, the closer the variables in the same zone, the stronger their positive correlation, while variables in opposite positions show inverse correlations. In this respect, fiber and ash contents represent the driving variables within PC1 positive values (fat showed a weaker influence on the analytical parameters). In the case of PC2, protein content affected its positive values, while negative values could be driven by breakdown values from both RVA and RFA and with $T_e - T_0$ from DSC, but their strength is low, and they cannot be significantly isolated only along PC2.

Together with SRC-S, thermal properties T_e and T_p resulted to be positively correlated with fiber, while final force and stability showed a strong correlation with protein that can be strictly related also with SRC-LA, FAC, and WHC. On the other hand, negative correlations with both fiber and protein were evidenced in the case of SRC-B (functional properties) and the other thermal characterization indices. In this respect, trough viscosity, peak viscosity, and final viscosity from RVA, slope-α and maximum force from RFA, and ΔH_n from DSC showed strong positive correlations with the starch content (inversely proportional with both fiber and protein contents that increased with the extraction rate).

Observing the score plot reported in Figure 2B, it was possible to clearly distinguish the samples according to PC1 and PC2. Particularly, in the lower left part of the plot were located flours with low fiber and protein contents and thus high starch levels, while the increasing of the extraction rate shifted the samples to the upper right zone. Moreover, a gradual increase in both PC1 and PC2 has been detected in all the samples, while WG (98% extraction rate) showed a strong increase, probably due to the very different amount of bran and thus fiber content (Table 2). Overall, it resulted that the increasing of the extraction rate led to the production of flours with higher hydration capacity and lower gelatinization ability, forming starch pastes with higher stability and lower viscosity, information that can be very useful to individuate the best productive destination of flours basing on their technological properties.

Fresh-Pasta Characteristics

Increasing amounts of water were needed to keep the dough with the selected consistency of ~3.00 Nm. In fact, in agreement with previous researches concerning the effect of flour extraction rate on dough rheology (Iacovino et al., 2024),

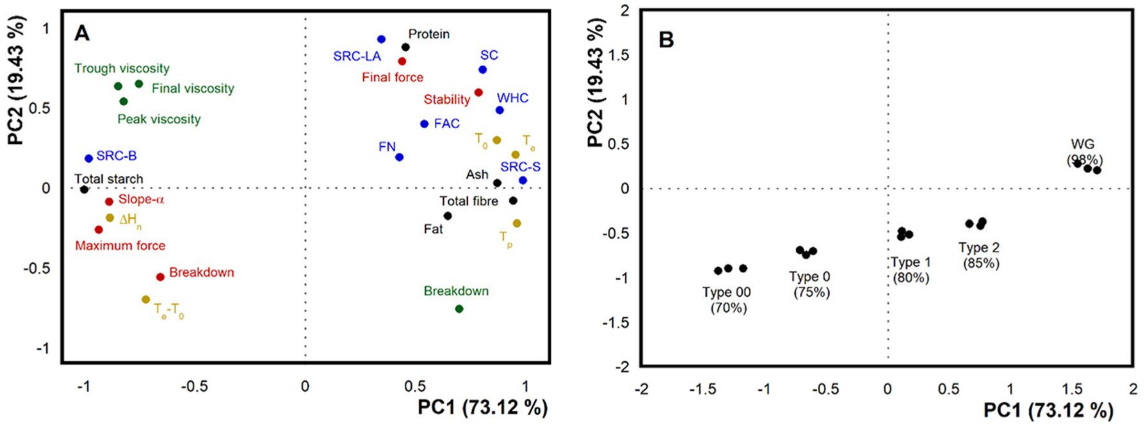

Fig. 2 **A** Loading plot of proximate composition (black), functional properties (blue), RFA (red), RVA (green), and DSC (yellow); **B** score plot for the classification of flours according to individual principal components related to their refining degree (extraction rate within brackets)

WA as well as DDT increased with the flour's degree of extraction (Table 1), indicating that the more water and time were required to produce the dough. Particularly, WA and DDT respectively increased from 43.0 (Type 00) to 50.0% (WG) and from 0.96 (Type 00) up to 1.88 min (WG).

The characteristics of the fresh-pasta are summed up in Table 3. The increase in the moisture content of samples from ~ 30% up to ~ 37% was consistent with WA values. It is important to note that fresh-pasta made with Type 2 and WG flours met the requirements of the European Regulation n. 1924/2006 (EC, 2006) for the utilization of the "source of fiber" nutritional claim since their fiber content was higher than 3% (3.15% ± 0.11 and 5.72% ± 0.15, respectively).

Regarding the general quality of fresh-pasta, a good product should be firm and resilient, with minimal surface stickiness and cooking loss (<10%), in order to provide an acceptable mouthfeel (Sissons et al., 2012). An increase in the CL with the increase of the extraction rate of the used flour could be observed, from 6.21% ± 0.31 for fresh-pasta made from Type 00 flour (70% extraction rate) up to 8.81% ± 0.24 for pasta made from whole grain flour (98% extraction rate). The presence of bran and germ interferes with the formation of a strong gluten network. When the gluten network is compromised, the pasta is less able to retain its structure during cooking, leading to increased solubilization and leaching of starch and other soluble components into the cooking water. Also, the rougher surface texture due to the presence of larger bran particles increases the interaction between the pasta and cooking water, facilitating the release of soluble substances and resulting in higher cooking loss.

Table 3 Characteristics of fresh-pasta produced with flours with different refining degrees (extraction rates indicated within brackets); *wb* wet basis

		Type 00 (70%)	Type 0 (75%)	Type 1 (80%)	Type 2 (85%)	WG (98%)
Proximate composition						
Moisture (%)		29.60^{c} ± 0.12	30.50^{c} ± 0.12	33.90^{b} ± 0.12	35.10^{b} ± 0.12	37.30^{a} ± 0.13
Fat (% wb)		0.61^{d} ± 0.04	0.84^{c} ± 0.03	1.38^{b} ± 0.03	1.39^{b} ± 0.04	1.78^{a} ± 0.03
Ash (% wb)		0.31^{d} ± 0.02	0.32^{d} ± 0.03	0.53^{c} ± 0.02	0.61^{b} ± 0.03	1.09^{a} ± 0.05
Carbohydrate* (% wb)		59.85^{a}	58.46^{b}	52.86^{c}	50.81^{d}	44.53^{e}
Protein (N 5.7, % wb)		8.24^{e} ± 0.02	8.39^{d} ± 0.02	8.71^{c} ± 0.04	8.94^{b} ± 0.03	9.58^{a} ± 0.04
Fiber (% wb)		1.39^{d} ± 0.09	1.49^{d} ± 0.08	2.62^{c} ± 0.13	3.15^{b} ± 0.12	5.72^{a} ± 0.15
Cooking quality						
WAI (%)		41.9^{a} ± 0.3	39.7^{b} ± 0.3	36.5^{c} ± 0.2	36.3^{c} ± 0.2	32.1^{d} ± 0.3
VI (%)		2.93^{a} ± 0.09	2.41^{b} ± 0.08	2.12^{c} ± 0.08	2.03^{c} ± 0.12	1.01^{d} ± 0.09
SI (g H_2O/g)		2.37^{a} ± 0.12	2.02^{b} ± 0.07	1.81^{c} ± 0.04	1.54^{d} ± 0.09	1.23^{e} ± 0.12
CL (%)		6.2^{c} ± 0.3	6.5^{c} ± 0.3	7.3^{b} ± 0.2	7.8^{b} ± 0.4	8.9^{a} ± 0.2
TSS (°Brix)		0.27^{c} ± 0.03	0.32^{c} ± 0.03	0.43^{b} ± 0.03	0.48^{b} ± 0.02	0.56^{a} ± 0.02
Mechanical properties						
Hardness (N)		1.86^{d} ± 0.13	2.32^{c} ± 0.12	2.68^{bc} ± 0.14	2.87^{b} ± 0.12	3.5^{a} ± 0.2
Firmness (N)		5.08^{e} ± 0.15	6.3^{d} ± 0.2	7.3^{c} ± 0.2	7.99^{b} ± 0.13	10.22^{a} ± 0.12
Elasticity (-)		0.59^{a} ± 0.02	0.54^{b} ± 0.02	0.52^{b} ± 0.02	0.48^{c} ± 0.02	0.46^{c} ± 0.02
Color						
Uncooked	***L****	79.93^{a} ± 0.09	77.67^{b} ± 0.12	74.14^{c} ± 0.13	72.14^{d} ± 0.09	64.89^{e} ± 0.09
	a*	1.95^{d} ± 0.08	2.82^{d} ± 0.05	3.61^{c} ± 0.09	4.62^{b} ± 0.05	9.31^{a} ± 0.04
	b*	21.59^{d} ± 0.03	21.65^{d} ± 0.04	22.24^{c} ± 0.03	22.83^{b} ± 0.03	23.29^{a} ± 0.04
	WI	70.45^{a} ± 0.03	68.74^{b} ± 0.03	65.71^{c} ± 0.05	63.67^{d} ± 0.04	56.85^{e} ± 0.02
	YI	38.58^{e} ± 0.04	39.82^{d} ± 0.09	42.85^{c} ± 0.08	45.23^{b} ± 0.05	51.27^{a} ± 0.03
Cooked	***L****	83.01^{a} ± 0.08	81.81^{b} ± 0.09	80.46^{c} ± 0.03	79.51^{d} ± 0.06	73.64^{e} ± 0.05
	a*	1.06^{e} ± 0.08	1.31^{d} ± 0.12	1.57^{c} ± 0.09	2.57^{b} ± 0.13	5.74^{a} ± 0.08
	b*	18.53^{e} ± 0.09	18.87^{e} ± 0.12	20.04^{c} ± 0.06	21.06^{b} ± 0.04	22.37^{a} ± 0.09
	WI	74.82^{a} ± 0.02	72.31^{b} ± 0.02	71.96^{c} ± 0.02	70.16^{d} ± 0.03	64.98^{e} ± 0.02
	YI	31.89^{e} ± 0.05	32.95^{d} ± 0.03	35.58^{c} ± 0.06	37.81^{b} ± 0.04	43.32^{a} ± 0.03
	ΔE	4.42^{d} ± 0.12	3.82^{e} ± 0.15	6.98^{c} ± 0.12	8.75^{b} ± 0.08	9.53^{a} ± 0.14

Values indicate mean ± standard deviation. Different superscript letters within a row indicate significant differences (p-value < 0.05). *WAI* water absorption index, *VI* volume increasing, *SI* swelling index, *CL* cooking loss, *TSS* total soluble solids, *L** lightness, *a** redness-greenness, *b** yellowness-blueness, *WI* whiteness index, *YI* yellowness index, *ΔE* color variation

*Carbohydrate values have been calculated by difference

In any case, obtained values are below the previously mentioned limit for acceptability.

The decreasing trends of water absorption index (WAI) and volume increase (VI) with the extraction rate of flours and, consequently, swelling index (SI) were in agreement with the previous works stating that bran is able to reduce pasta swelling due to the competition for water (Alzuwaid et al., 2020). Moreover, the disruption of the gluten matrix due to bran particles should be also considered since gluten functionality is essential for the binding of water.

The acceptability of end products is strongly dependent on their appearance, which is a very important trait for the evaluation of food, and a natural amber color is commonly associated with good quality pasta (Kaur et al., 2012). The outcomes we collected evidenced that lower refining degrees led to lower $L*$ and higher $a*$ (redness) and $b*$ (yellowness) values, thus indicating that the bran presence can be associated to the production of a darker and redder fresh-pasta (Kaur et al., 2012) due to the native color characteristics of the less refined flours. Consequently, the whiteness index (WI) of both the uncooked and cooked pasta was reduced, and the yellowness index (YI) increased with the extraction rate. Moreover, the lower values of $a*$ and $b*$ in the cooked samples, compared to uncooked ones, can mainly be explained by the thermal degradation, released of bran dark pigments in the cooking water and starch gelatinization, determining higher brightness of the fresh-pasta after cooking. Finally, an important indication about the color changing during fresh-pasta cooking was expressed by ΔE values. Generally, a visible difference between samples is considered for ΔE values above 2 (Sissons et al., 2012); thus, the color difference found in the samples was high enough to be appreciated. Moreover, ΔE was higher in fresh-pasta deriving from flours with higher extraction rates (the values changed from 4.42 ± 0.11 of 70% up to 9.53 ± 0.14 of 98%). This is not necessarily negatively penalized by the consumers as a more yellow color is desirable and a darker appearance is considered a healthier pasta as consumers are much more concerned about the health benefits of fiber intake.

Concerning the mechanical properties, the obtained results showed higher hardness and firmness values in fresh-pasta made with less refined flours. In fact, from Table 3, it can be seen that, when passing from pasta made from Type 00 flour (70% extraction) to pasta made from whole grain flour (98% extraction), hardness and firmness, respectively, changed from 1.86 ± 0.13 to 3.47 ± 0.12 N and from 5.08 ± 0.15 to 10.22 ± 0.11 N. In this respect, Muneer et al. (2018) related the increase in the overall firmness of fiber-rich pasta to the less covalent bonds between proteins, the chemical bond between fiber fraction and starch residues, and the higher water uptake as a consequence of the water binding ability of dietary fiber. Finally, the decrease in elasticity values from 0.59 ± 0.02 of 70% to 0.46 ± 0.02 of 98% fresh-pasta suggested that the higher the degree of extraction of the used flour, the less solid-like the final product (Martín-Esparza et al., 2021).

Fresh-Pasta Sensory Analysis

Sensory analysis represents a fundamental step in the characterization of end products because the consumers' acceptance is the most important factor for the success of every product. The Friedman statistical test showed that the 40 panelists appreciated significant differences among samples in global appearance and color at 95% and 99%, respectively, while in the case of consistency, stickiness, and taste, no significant differences were detected. Then, the Just-About-Right scale test (JAR) allowed us to check, for each of the fresh-pasta samples, which of the assessed attributes were above or below their ideal point in relation to the global acceptance score since it is important to take into consideration each single effect in the overall acceptance in order to individuate the parameters that

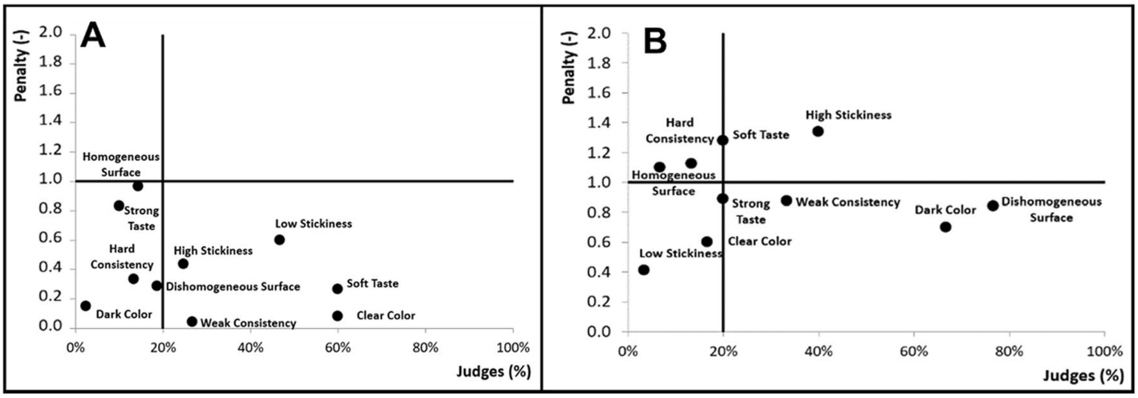

Fig. 3 Penalty score analysis from the Just-About-Right scale points (JAR) of fresh-pasta produced with **A** Type 00 (70%), Type 0 (75%), Type 1 (80%), and Type 2 (85%) flours (mean values) and **B** WG (98%) flour

should effectively be revised and/or improved (Li et al., 2014). Hence, the preference maps of the investigated attributes (Figure 3), reporting the absolute values of the penalty scores vs the % of judges notifying them, were elaborated basing on the penalty analysis method (Ares et al., 2017). Considering that the Fisher's minimum significant difference revealed that only 98% fresh-pasta was significantly notified as different from the others, two sets of samples have been compared: mean values referring to Type 00 (70%), Type 0 (75%), Type 1 (80%), and Type 2 (85%) fresh-pasta samples (Figure 3A) and WG (98%) fresh-pasta (Figure 3B). Since the overall acceptance of the product was 3.2 out of 5, low penalty scores were detected, and particularly, values below the penalty score of 1 and/or within a percentage of judges lower than 20% were considered negligible. Hence, the attributes that needed to be revised and/or improved are those in the upper-right side of the plot. Comparing the WG fresh-pasta with the ones deriving from refined flours that did not show any penalty score > 1, the excessive hardness, as well as the homogeneous surface and the soft taste, seemed to affect the overall acceptance since the penalty scores were higher than 1, but the % of panelists notifying them were < 20%; thus, these attributes can be considered negligible. Moreover, despite the inhomogeneous surface and the dark color of WG fresh-pasta being noticed by a high percentage of panelists (> 65%), the overall acceptance was again not affected because the penalty scores were lower than 1. Hence, the only parameter that showed a penalty score higher than 1 and that was noticed by more than 20% of the panelists was the stickiness (40% of judges notified a penalty score of 1.34) that should be revised or improved.

According to the preferences expressed by consumers through the sensory analysis, the utilization of Type 2 flour with an extraction rate of 85% (Table 1) seemed to be the best compromise for the production of a good quality fresh-pasta with naturally high nutritional value (the "source of fiber" nutritional claim can be labelled) that is not notified as different from the ones made with refined flours.

Conclusions

The decreasing of the refining degree led to the production of flours with higher hydration capacity and lower gelatinization ability, forming starch pastes with higher stability and lower viscosity. Concerning the produced fresh-pasta, as expected, the lower the refining degree of the flour, the darker, redder, and harder the end product, with the color difference after cooking that resulted to be higher upon the extraction rate increase. It is important to note that, despite the cooking loss being higher in fresh-pasta from less refined flours, the limit of acceptability was not exceeded. Finally, the sensory analysis evidenced that the utilization of 85% extraction rate wheat flour led to the production of fresh-pasta which was not notified as different from those made with white refined flours, thus representing a good compromise for the production of a good quality end product with a naturally high nutritional value. Overall, it is of great interest to gather information on the characteristics of flours in relation to the refining degree, to efficiently use them for producing high-quality products. Overall, the study confirms the impact of the flour refining degree on the quality of pasta. Unrefined and less refined flours including milling by-products represent a good option for the valorization of native bran, with significant repercussions in terms of by-product management, sustainability, and nutrient intake. Nevertheless, further understanding of the impact of the particle size distribution of the less refined flours would be advisable.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of Interest The authors declare no competing interests.

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