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Assessment of the suitability of millet for the production of pasta

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ABSTRACT

In temperate climate zones such as Switzerland, wheat is exposed to increasing heat and water stress due to climate change. Millet is a promising alternative crop with a high heat resistance and the additional benefit of being gluten-free. However, the market for organic Swiss millet within Switzerland is saturated with the current product portfolio of flakes or dehulled millet. Therefore, novel end products with a high millet content, such as pasta, could play a key role in increasing consumer demand.

Against this background, the suitability of the millet (*Panicum miliaceum* L.) variety Alba for producing spaghetti was investigated. To optimize the quality of the millet spaghetti, different pre-treatments and recipes were tested, i.e., hull particles were sieved out of the flours and blends with other gluten-free and gluten-containing flours were tested. Finally, the best types of spaghetti were subject to sensory testing, and the color and texture were both quantified. In addition, nutritional quality was assessed.

The analytical results showed that a firmness comparable to durum spaghetti was reached for pure millet, 50% millet mixed with 50% corn and rice flour (95:5), and 15% millet mixed with 85% durum wheat. The brownish appearance, slightly rough surface, and nutty flavor of the spaghetti made from millet was especially popular among consumers with a diet-conscious lifestyle. The millet pasta had a high content of iron, zinc and dietary fiber. Since the production processes were able to be implemented in industry without major additional costs, implementation in the market seems feasible.

1. Introduction

Millet *(Panicum miliaceum* L.*)* is one of the oldest crops planted in Switzerland but the area under cultivation had shrunken to near existence by the middle of the last century (Koblet, 1965). As the potential of millet is seen as high in connection with climate change because of its short vegetation phase (100 days), low level of nutrient requirements and the fact that millet can grow at high temperatures with little water, in-depth research on cultivation with new varieties has been performed in Switzerland since the early 2000s' (Hiltbrunner et al., 2018). From a nutritional perspective, millets offer a protein content (11.5–13.5%) comparable to wheat and corn but without gluten. The dietary fiber content (14.2%) is higher than for wheat (12.9%) and much higher than in white rice (5.2%) giving the chance to produce gluten free pasta with high fiber content. Further, millet is rich in micronutrients and minerals. Besides niacin, vitamin B6 and folic acid, millet is especially rich in potassium, iron and manganese and contains significant amounts of magnesium and silicic acid (Amadou et al., 2013; Kalinova & Moudry, 2006; Kalinova, 2007).

While millet is, therefore, interesting from both an agricultural and a nutritional point of view, consumer demand is surprisingly only moderate. Millet pasta is seen as a promising vehicle to increase consumption as it is simple to prepare and is part of a large number of traditional dishes. However, to date, few types of pure millet spaghetti are commercially available which are comparable in quality with respect to structural integrity before cooking and texture thereafter. Pasta is classically produced from durum wheat and water. The structure and resulting texture of the cooked pasta depends very much on the quality and quantity of gluten in the raw material as upon mixing, kneading and shaping the pasta, gluten forms a network around the native starch granules. This structure is further stabilized during the drying process. Upon cooking, the starch kernels are gelatinized and swell, while the gluten network solidifies and gives cohesion to the product. If the gluten network is not sufficiently strong, the starch kernels swell excessively during cooking, leading to a soft and sticky texture (Bonomi et al., 2012; Güler et al., 2002; Marti & Pagani, 2013; Marti et al., 2013). It has been shown that up to 30% of durum semolina can be replaced by alternative raw materials without significant losses in quality (Romano et al., 2021; Khan et al., 2014). To completely replace durum wheat and produce pasta purely from gluten-free raw materials such as millet, the network forming ability of gluten needs to be replaced by a matrix formed by starch. Starch consists of the two polymers amylose and amylopectin out

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of which amylose is able to form crystal-like structures upon complexation with lipids. These amylose-lipid complexes can form a network-like structure and replace the structural function of the gluten network. To form amylose-lipid complexes, native starch needs to be gelatinized, i.e., heated in moist form to temperatures above the gelatinization temperature (Nebesny et al., 2005). Therefore, in comparison to the processing of gluten containing pasta, an additional heating step needs to be included in the production of gluten-free pasta. This step can be a pretreatment of the raw material or the usage of a so-called warm extrusion process where steam is added either in the mixing or in the kneading process (Cervantes-Ramirez et al., 2020).

The extent to which the formation of amylose-lipid complexes can be furthered by adding fatty acids to the raw material blend depends on both type and quantity of the fatty acids (Cervantes-Ramirez et al., 2020). Industrially, the addition of small quantities of emulsifiers, often consisting of mono- and diglycerides, is common. The emulsifier acts as a lubricant, allowing a better detachment of the pasta from and a reduced wear of the die (Lai, 2002). Further, improved firmness and reduced stickiness was observed in the end product (Charutigon et al., 2008; Marti & Pagani, 2013). On a structural level, the addition of emulsifiers was found to lead to reduced starch swelling for raw materials rich in amylose (Lai, 2002; Kaur et al., 2005) as the additionally available lipids support the formation of amylose-lipid complexes (Bhatnagar & Hanna, 1994). Optimal gluten-free raw materials with a good amylose-lipid ratio, such as corn-rice mixtures, can, however, be processed without additives (Padalino et al., 2016; Marti & Pagani, 2013).

A further improvement in the quality of gluten-free pasta can be achieved by the addition of hydrocolloids. Hydrocolloids bind water well and, hence, limit the water uptake of the starch during cooking. This leads to improved firmness, reduced stickiness and reduced cooking loss (Marti & Pagani, 2013; Padalino et al., 2016). Tests by Silva et al. (2013) showed that a 4% addition of guar flour, xanthan gum or hydroxymethyl cellulose reduced the cooking loss and the starch swelling, while a study by Sozer (2009) found similar effects already at low addition levels of 0.5% guar in combination with casein and egg white, and Sabbatini et al. (2014) an optimal 'al dente' bite by adding 2% guar flour.

The present study focuses on the comparison of millet pasta produced from the Alba variety with mixtures of Alba millet with either corn-rice or durum, of pure corn-rice and pure classic durum pasta. Processability, color, cooking properties, texture and sensory quality were assessed.

2. Materials and methods

2.1. Production of pasta

The naturally free threshing millet variety Alba (originating from Russia but grown for experimental purposes in Switzerland) was milled in an impact rotor mill (type SR300, Retsch AG, DE-Haan) with a 200 μm sieve and a rotational speed of 5000 rpm corresponding to a shear rate of 6071 s^{-1} (rotor diameter 131 mm, gap size 5.7 mm). The resulting flour was either mixed with durum semolina (pasta flour, Meyerhans Mühlen AG, Villmergen, Switzerland) or a corn-rice mixture (Bio corn flour, Zwicky AG, Müllheim-Wigoltingen, Switzerland and rice flour, la riseria, Taverne, Switzerland) Additionally, for the production of pure millet pasta the flour was sieved in a sieve tower (AS200, Retsch AG, DE-Haan) with a 250 μm sieve for 2 min in interval mode and an amplitude od 3.00 mm to remove any remaining hull particles that had passed through the milling sieve due to their elasticity and. Thus, particle sizes above 250 μm could be eliminated as these negatively influence structure formation during pasta extrusion.. Further pasta was produced from a corn-rice mixture as reference.

Pasta was produced on a pilot scale pasta extruder (Italpast MAC 30/LAB, Italpast, Fidenza, Italy). The moisture of the flours was measured in a halogen drier (type HR82, Mettler-Toledo, Columbus, US) using 3 g of flour and dried at a standard temperature of 180 °C. The flour was then added to the mixing trough and 20 °C warm water was added according to the dosages given in Table 1. The optimal water dosage was determined in preliminary trials based on processability of the pasta, i.e., extrudability and breakage free drying, depending on the total moisture content of the dough and was set at 32% for millet-durum pasta and 41% for all gluten-free pasta.

Steam was added for 15 min in order to reach a dough temperature of 98 ± 1 °C which is above the melting temperature of the millet as measured through differential scanning calorimetry (TA Instruments, type DSC Q2000, New Castle, US) using the heating profile 20–180 °C at 10 °C/min at a flour-water ratio of 1:3 (number of replications: 6). The necessary duration of steam addition (15 min) led to a total dosage of steam of 12.83%. For pasta from millet plus durum wheat, no steam was added in order to avoid the dough being heated. Mixing was carried out for 15 min to allow even hydration of the flour, resulting in a crumbly dough.

Detailed recipes of millet, millet-corn-rice, millet-durum and corn-rice pasta are given in Table 1.

The dough was then transferred to the extrusion trough. Extrusion took place at a shear rate of 77 1/s (screw diameter 46 mm, gap width 1 mm, rotational speed 32 rpm) at 30–60 bar pressure and a maximal temperature of 45 °C which was controlled through a temperature sensor and cooling of the extruder housing with cold water. To avoid air pockets in the product, a vacuum of 0.6 bar absolute pressure was set to the extrusion trough before starting the extrusion. A 1.4 mm spaghetti die made from teflon was used. The spaghetti was cut with scissors to a length of 70 cm, hung over the bars, shortened to a length of 30 cm and dried in a pasta drying cabinet (Italpast EC LAB/E, Italpast, Fidenza, Italy). The drying profile was 10 min at 50 °C and 80% relative air humidity rH (pre-conditioning), 100 min at 82 °C and 74% rH (pre-drying), 74 min at 90 °C and 70% rH (drying), 128 min at 80 °C (stabilization), and 74% rH, 53 min at 30 °C and 30% rH (cooling).

Pasta production was reproduced every day for 3 days for each recipe (number of replications: 3).

Barilla pasta, spaghetti shapeNo. 3(with a diameter of 1.4 mm) were used as a reference in the study.

2.2. Analyses

Color: For the determination of the color of the dry spaghetti, a batch of 100 g was homogenized in a thermomix (Thermomix TM5-1, Vorwerk, Wuppertal, Germany) for 30 s at the highest speed (level 10) with a cutter. The resulting powder was added to a measuring cup in the Chromameter (Chroma meter CR-410, Konica Minolta, Tokyo, Japan) in the $L^*a^*b^*$ color scheme (number of replications per trial repetition = 4 resulting in a total of 12 measurements per sample).

Spaghetti diameter: The diameter of the dried spaghetti was measured with a digital caliper (number of replications = 6).

Texture analysis of uncooked spaghetti: The resistance against breakage and the elasticity of the dry spaghetti were measured in a texture analyzer (TA-XT plus with a 5 kg load cell, Stable Micro Systems, Godalming, England) with the program 'dry lasagna bending'). For each measurement, one strand of spaghetti was put under the knife geometry (Warner Bratzler blade from blade set HDP/BS) and the force necessary to break the spaghetti was measured. Resistance against breakage was determined as the maximum force (number of replications per trial repetition = 6 giving a total of 18 measurements per sample), elasticity as the path between first contact and breakage (number of replications per trial repetition = 6 giving a total of 18 measurements per sample).

Cooking method and time: The spaghetti was cooked in a pot (height 0.16 m, diameter 0.135 m) with 100 g dry spaghetti in 900 g water. For gluten-free spaghetti, the water was brought to boiling point on a heating plate (highest setting, i.e., 14), the spaghetti added, then the heating immediately reduced to half (setting 7) as is suggested for commercially available millet and other gluten free spaghetti. For gluten containing pasta, the spaghetti was also added as soon as the water started to boil

Table 1
Pasta recipes for pure Alba millet pasta, Alba millet-durum pasta, Alba millet-corn-rice pasta and corn-rice pasta. Composition was adapted to reach a total moisture content of 41% for millet, millet-corn-rice and corn-rice pasta doughs and to 32% for millet-durum doughs through an adaptation of the water addition. The moisture of the flours was measured in a halogen drier (type HR82, Mettler-Toledo, Columbus, US) using 3 g of flour and dried at a standard temperature of 180 °C. Average values and standard deviations of the three production days are given.

	Millet [%]	Durum [%]	Corn [%]	Rice [%]	Water [%]	Steam [%]
Millet pasta*	66.7 ± 0.05	0	0	0	20.5 ± 0.05	12.83 ± 0.00
Millet – durum pasta**	11.3 ± 0.05	64.2 ± 0.31	0	0	24.4 ± 0.36	0
Millet-corn-rice pasta**	33.4 ± 0.19	0	31.8 ± 0.18	1.7 ± 0.01	20.4 ± 0.39	12.83 ± 0.00
Corn-rice pasta	0	0	62.8 ± 0.20	3.3 ± 0.01	21.1 ± 0.21	12.83 ± 0.00

* Millet milled and sieved.
** Millet milled but unsieved.

but the heating plate was kept at maximum heat (setting 14) during the entire cooking time. The optimal cooking time was determined according to AACC 66-50.01 (AACC, 1999) by sampling one piece of spaghetti every 30 s and pressing it between two object plates with the adaptation that the spaghetti to water ratio was 1:9 instead of 1:12 and the use of tap water instead of distilled water. The first time when no white core remained visible was defined as the optimal cooking time. Cooked spaghetti was shock-cooled with cold tap water to avoid overcooking.

Texture analysis of cooked spaghetti: The firmness of spaghetti cooked to its optimal cooking time (millet pasta: 10.5 min, millet-corn-rice pasta: 11.5 min., millet-durum pasta: 9.5 min., corn-rice pasta: 11 min., durum pasta Barilla: 8 min.) and employing the optimal cooking method was determined with the texture analyzer (TA-XT plus, Stable Micro Systems, Godalming, England) using the program 'AACC spaghetti firmness' which measures the force necessary to compress the spaghetti (AACC, 1999). 5 cooked spaghetti strands were placed next to each other and a measuring knife (Warner Bratzler blade from blade set HDP/BS) applied (number of replication per trial = 6 resulting in a total of 18 measurements per sample).

Nutritional analyses: Analysis of energy content (calculated according to regulation 1169/2011), fat content (laboratory internal method), fatty acid distribution (laboratory internal method), carbohydrates (calculated), dietary fiber (laboratory internal method), protein (laboratory internal method), water (laboratory internal method), ash (laboratory internal method) as well as alpha-Tocopherol (method EN 12822:2014), Niacin (method EN 15652:2009), Folate (method: NMKL 111:1985), Zinc (method DIN EN ISO 17294-2 (2017-01), mod), Iron (method: DIN EN ISO 17294-2 (2017-01), mod), silicon dioxide (laboratory internal method) were carried out by the accredited lab Eurofins Scientific (Schönenwerd, Switzerland), amylose content was determined by the analytical laboratory of Bühler AG (Uzwil, Switzerland) using UV/Vis spectroscopy (ISO method 6647, standard deviations at $p = 95\%$ were 0.3 g/100 g, 0.5 g/100 g and 0.8 g/100 g for the laboratories' reference samples with 15.4 g/100 g, 23.1 g/100 g and 27.7 g/100 g, respectively).

Sensory assessment of raw and cooked spaghetti: Both descriptive profiling and hedonic testing were carried out by testers familiar with durum semolina spaghetti. In the descriptive sensory analysis, the attributes color and surface of the uncooked spaghetti and the attributes firmness at first bite, sliminess during chewing, surface smoothness, color after cooking, whole grain taste and bitterness were judged on a scale from 1 to 9 by 37 testers. In order to standardize the assessment, reference samples were given for all attributes. In addition, hedonic testing was applied to assess the desirability of the products, i.e., how well the spaghetti was liked and whether the 37 testers would buy the spaghetti.

Statistical analysis: All results were analyzed using the software R (version 4.0.3 for windows) and the interface R-studio. A Kruskal-Walis test followed by an unpaired Wilcoxon test were applied. The significance of the results for a significance level of $p < 0.05$ was indicated by letters in all graphs.

3. Results and discussion

The color of the different recipes, as well as images of the corresponding spaghetti, are shown in Fig. 1. All spaghetti containing millet was darker in color than the corn-rice pasta and the durum pasta and had a brownish tint. In addition, small white spots are visible in all millet pasta, indicating uneven moisture distribution within the product. It is highly probable that this is caused by the less narrow particle size distribution of the millet milled on the lab mill compared to the corn and rice flour and the durum semolina bought from commercial suppliers. Comparing the samples 'millet' with 'millet-corn-rice' and 'millet-durum', the surface of the pure millet pasta is more even as it was necessary to remove all particles above 250μm through sieving in order to be able to produce pasta with good cohesion and no breakage. The removed particles were mostly bran particles. Concretely, the millet flour before / after sieving consisted of the following fractions: 9.55/0% >250 μm, 5.37/5.94% 200–250 μm, 8.66/9.57% 125–200 μm, 70.75/7 8.22% 45–125 μm, 5.67/6.27% < 45 μm. Further, the surface of the durum pasta has no fissures at all, while the durum-millet spaghetti show fissures on a length of about 10 μm and all gluten-free pasta on a length of 100 μm and more.

Spaghetti from 100% millet had a slightly smaller diameter (1.38 ± 0.01 mm) than all other spaghetti types (millet-corn-rice: 1.47 ± 0.01 mm, millet-durum: 1.44 ± 0.02 mm, corn-rice: 1.47 ± 0.01 mm and durum Barilla: 1.42 ± 0.01 mm). The high fat content of the 100% millet pasta (4.4 g/100 g) compared to 1.3–2.8 g/100 g for the other recipes is assumed to be the cause. Kaur et al. (2005) and Lai (2002) have shown that fat does not only influence the formation of amylose-lipid complexes but further acts as a lubricant in the extruder die resulting in reduced pressure buildup. This is in line with the author's own findings where the pressure in the die was 27.8 ± 1.12 bar for the pure millet pasta compared to 41.1 ± 1.58 bar for millet-corn-rice, 67.3 ± 4.32 bar for millet-durum and 45.8 ± 0.41 bar for maize-rice pasta.

The durum pasta from Barilla had the highest resistance against breakage (2.80 ± 0.47 N; see Fig. 2). Out of the spaghetti produced in the pilot plant, the millet-durum mixture was the most resistant against breakage (2.36 ± 0.18 N) followed by millet (1.86 ± 0.19 N), millet-corn-rice (1.74 ± 0.32 N) and corn-rice pasta (1.60 ± 0.33 N) which did not differ significantly in its resistance to fracture. With respect to elasticity, pasta made from pure millet showed the second highest elasticity (2.35 ± 0.32 mm) after the Barilla durum pasta (3.14 ± 0.40 mm). All other pasta was less elastic (millet-durum: 1.97 ± 0.18 mm, millet-corn-rice: 1.88 ± 0.34 mm, corn-rice: 1.70 ± 0.36 mm) and the types did not differ significantly from each other.

Both elasticity and resistance against breakage are linked to the structure which, again, depends on both the recipe and the drying method (Bresciani et al., 2022). Gluten forms strong networks which suitably explains why pure durum as well as millet-durum pasta is more resistant against breakage than the gluten-free spaghetti (Marti & Pagani, 2013). Further, the microfissures visible in Fig. 1 in all gluten-free

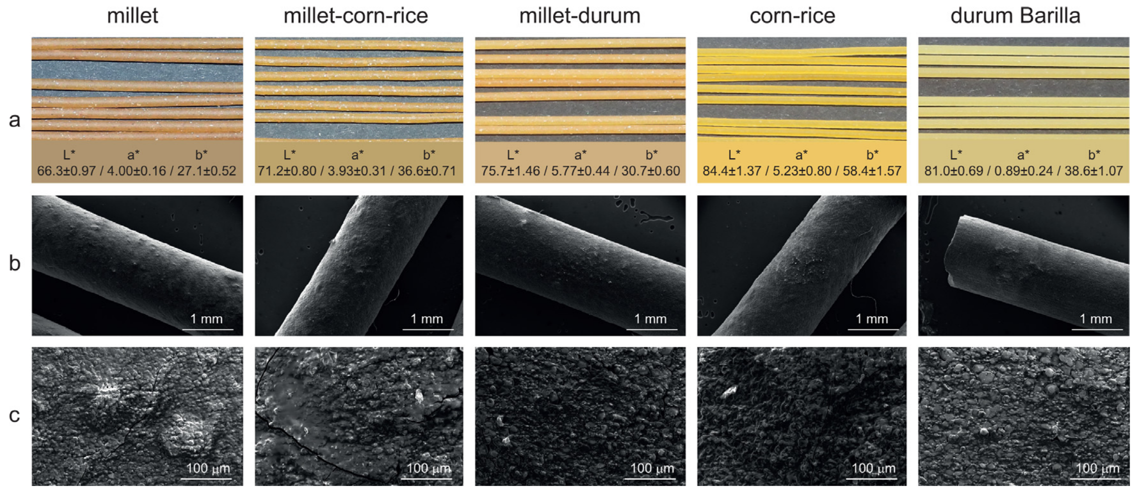

Fig. 1. Color measurements (line a) and SEM images (lines b and c) of dry spaghetti. Color measurements after grinding in a Chroma meter depicted as colors of the L*a*b* color spectrum (number of replications: 6). Pasta recipes include (i) 100% millet, (ii) 50% millet blended with maize-rice at a ratio of 95:5, (iii) 15% millet blended with 85% durum, (iv) 95% maize blended with 5% rice and (v) Barilla pasta made from 100% durum.

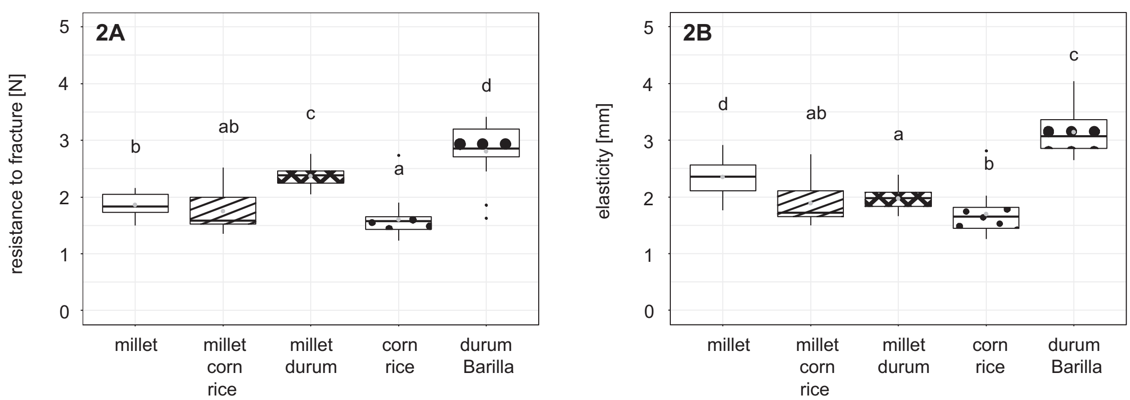

Fig. 2. Resistance against breakage of uncooked spaghetti (A) and elasticity of uncooked spaghetti (B), number of replications: 18, $p < 0.05$. Pasta recipes include (i) 100% millet, (ii) 50% millet blended with corn-rice at a ratio of 95:5, (iii) 15% millet blended with 85% durum, (iv) 95% corn blended with 5% rice and (v) Barilla pasta made from 100% durum.

spaghetti, and to a lesser extent in the durum-millet pasta, support this theory. The higher elasticity of pure millet pasta over millet-corn-rice and millet-durum mixtures is not yet clear: while the higher fat content of the pure millet sample (see Table 2) might have enhanced the formation of amylose-lipid complexes, the overall lower amylose content of the pure millet pasta (32.0% in dry matter in pure millet versus 35.0% amylose in dry matter in millet-corn-rice spaghetti) would have achieved the opposite effect.

With respect to elasticity, Liu et al. (1997) showed that low dough moisture and an optimal drying method can help avoid fissuring of the spaghetti as both factors result in a reduction of internal stresses. In addition to raw material differences, the industrially applied, highly optimized drying method might be the reason why Barilla spaghetti produced using state-of-the art industrial equipment shows the highest elasticity. Within the author's own samples, which were all dried in the same drier and applying the same protocol, the higher homogeneity of the pure millet sample compared to the flour mixtures used in all other samples might have supported structural uniformity and integrity. Similar effects were observed by Sudha and Leelavathi (2012) for wheat-green pea flour blends where fissures occurred unless additives, such as e.g., glycerol mono stearate, were added to the recipe.

Firmness of the tested spaghetti (Fig. 3) was highest for durum spaghetti from Barilla (6.00 ± 0.57 N), followed by millet-durum (4.64 ± 0.19 N) and corn-rice spaghetti (4.65 ± 0.66 N), millet-corn-rice 3.43 ± 0.20 N) and millet spaghetti (3.00±0.30 N). Compared to measurements by Sissons et al. (2008), the absolute firmness of the durum spaghetti is high. Such differences are to be expected between differently produced spaghetti with the same ingredients as firmness depends strongly on processing conditions, cooking procedure and time (Zweifel et al., 2003; Sissons et al., 2008; Sissons et al., 2022). Furthermore, the significantly lower firmness of the millet-durum pasta might indicate that even 15% inclusion of millet weakens the gluten network, but might also be a result of the different production process used to produce the Barilla spaghetti. Comparing the sample of millet pasta with the firmness of the millet-durum one, a higher firmness is observed, indicating the strength deriving from the gluten network (Romano et al., 2021). The observation that the pure corn-rice pasta was comparable in firmness to millet-durum pasta and higher in firmness than the millet and millet-corn-rice pasta might be a consequence of the amylose-amylopectin ratio of the corn-rice spaghetti (amylose content in dry matter: 38.4% in corn-rice, 30.7% in millet-durum, 32% in pure millet, 35.0% in millet-corn-rice spaghetti). Marti et al. (2013) observed that corn-rice mixtures contain an optimal amylose-amylopectin ratio to form amylose-lipid complexes and, thus, allow a texture to be reached after cooking which is close to durum spaghetti. This might explain the high level of firmness of the tested corn-rice spaghetti.

For the sensory assessment (Fig. 4), all pasta was cooked according to recipe-dependent optimal cooking procedure and time, cooled

Table 2
Nutritional analysis of dry spaghetti; analyses performed by the accredited laboratory Eurofins Scientific AG and the analytical laboratory of Bühler AG.

Nutrients	Unit	Millet	Millet – corn - rice	Millet - durum	Corn - rice	Durum Barilla
Energy (calculated)	kJ/100 g	1588	1553	1548	1557	1538
Energy (calculated)	kcal/100 g	376	367	365	367	363
Fat	g/100 g	4.4 ± 0.6	2.8 ± 0.5	2.2 ± 0.5	1.3 ± 0.4	1.4 ± 0.4
Saturated fatty acids	g/100 g	0.5 ± 0.3	0.4 ± 0.3	0.4 ± 0.3	0.5 ± 0.3	0.4 ± 0.2
Mono-unsaturated fatty acids	g/100 g	1.0 ± 0.4	0.7 ± 0.3	0.5 ± 0.3	0.6 ± 0.3	0.3 ± 0.2
Polyunsaturated fatty acids	g/100 g	2.7 ± 0.6	1.6 ± 0.5	1.1 ± 0.4	0.1 ± 0.1	0.6 ± 0.3
Carbohydrates (calculated)	g/100 g	76.5	79.8	70	83.5	73.2
Amylose	%	32.0*	35.0*	30.7*	38.4*	30.5*
Dietary fiber	g/100 g	4.1 ± 1.4	4.7 ± 1.5	4.6 ± 1.5	2.1 ± 1.1	2 ± 1.0
Protein	g/100 g	10.5 ± 0.5	8.6 ± 0.5	14.1 ± 0.6	7.0 ± 0.5	13.3 ± 0.5
Water	g/100 g	7.8 ± 0.5	8.4 ± 0.5	7.9 ± 0.5	8.5 ± 0.5	9.4 ± 0.5
Ash	g/100 g	1.76 ± 0.17	1.14 ± 0.11	1.25 ± 0.12	0.33 ± 0.06	0.75 ± 0.08
a-tocopherol	mg/100 g	<0.08**	<0.08**	<0.08**	<0.08**	0.202**
Niacin	mg/100 g	0.432***	0.261***	0.603***	0.103***	0.481***
Folate	mg/kg	0.23****	0.19****	0.372****	0.133****	0.368****
Iron	mg/kg	50±10	33±6.6	36±7.2	5.8 ± 1.2	13±2.6
Zinc	mg/kg	27±5.4	16±3.2	19±3.8	4.2 ± 0.9	13±2.6
Silicium dioxide	g/100 g	0.483*****	0.351*****	0.108*****	<0.0043*****	<0.0043*****

* standard deviations at p = 95% were 0.3 g/100 g, 0.5 g/100 g and 0.8 g/100 g for the laboratories' reference samples with 15.4 g/100 g, 23.1 g/100 g and 27.7 g/100 g, respectively.
** Measurement uncertainty: 16%.
*** Measurement uncertainty: 14%.
**** Measurement uncertainty: 30%.
***** Measurement uncertainty: 15.8%.

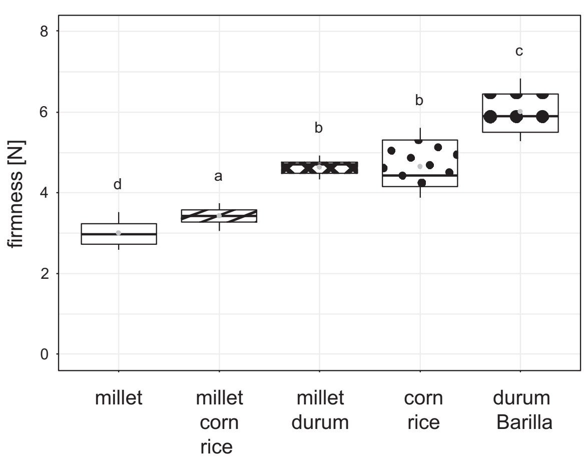

Fig. 3. Firmness of spaghetti cooked with recipe-dependent optimal cooking procedures, number of replications: 18, $p < 0.05$. Pasta recipes include (i) 100% millet, (ii) 50% millet blended with corn-rice at a ratio of 95:5, (iii) 15% millet blended with 85% durum, (iv) 95% corn blended with 5% rice and (v) Barilla pasta made from 100% durum.

for 5 s in cold water, then served. Corn-rice spaghetti had a firmer bite than durum, pure millet and millet-durum spaghetti, while millet-corn-rice spaghetti was not significantly different in bite from all other spaghetti types. In contrast to a study by Martinez et al. (2007), the sensory results do not correlate well with the analytically determined firmness, where difference between most of the samples were found and millet was clearly lowest in firmness while durum pasta was highest. It is possible that the analytically determined differences were too small to be perceived as different by the consumer, especially considering that forces between 100 and 350 N are applied during chewing (Kohyama et al., 2004) compared to differences of about 3 N between the softest and hardest spaghetti samples in this study. Hence, it is concluded that differences are too small to be of importance for consumer preferences. With respect to sliminess, no significant differences between any of the samples were detected sensorially. However, the two samples with durum had a smoother surface, of which pure durum pasta had the smoothest. This might be attributable to the superior gluten network as well as the optimal particle size distribution of commercially milled durum semolina for pasta production. The color perception after cooking was comparable to the analytically assessed color before cooking, i.e., durum and corn-rice pasta were lightest in color followed by millet-durum, millet-corn-rice and millet pasta. With respect to taste, a strongest wholegrain-like taste was detectable for pure millet and millet-corn-rice spaghetti followed by millet-durum and corn-rice, while a lower wholegrain taste was found for Barilla durum spaghetti. Bitterness was comparable for Barilla durum and corn-rice pasta, for corn-rice, millet-durum and millet pasta, for millet, millet-corn-rice and millet-durum pasta with a tendendy to be highest in all millet containing pasta. Wang et al. (2014) showed that the bitterness of millet products can be caused by fat oxidation which might be an issue for millet containing pasta due to the high fat content of the raw material but could be avoided by choosing optimal storage conditions. In addition, some testers observed a nutty flavor of the millet pasta. Separate tests on preference on a 9-point scale resulted in the durum spaghetti from Barilla as the winner with 6.03 ± 2.15 but with no significant difference compared to all other pasta types due to high standard deviations (pure millet: 5.24 ± 2.07, millet-durum: 5.86 ± 1.51, millet-corn-rice: 5.19 ± 2.05 and corn-rice 5.03 ± 1.85). Upon asking for the most preferred option for health-conscious buyers, all three types of pasta with millet were significantly preferred over the classic durum spaghetti, while the corn-rice pasta was not rated as being significantly different from any of the other samples (millet: 6.35 ± 1.92, millet-corn-rice: 6.46 ± 1.98, millet-durum: 6.30 ± 1.80, corn-rice: 5.46 ± 1.93, durum 4.46 ± 2.37). This preference might be influenced by the darker color and wholegrain-like taste of the pasta with millet which might be linked to the product's health qualities.

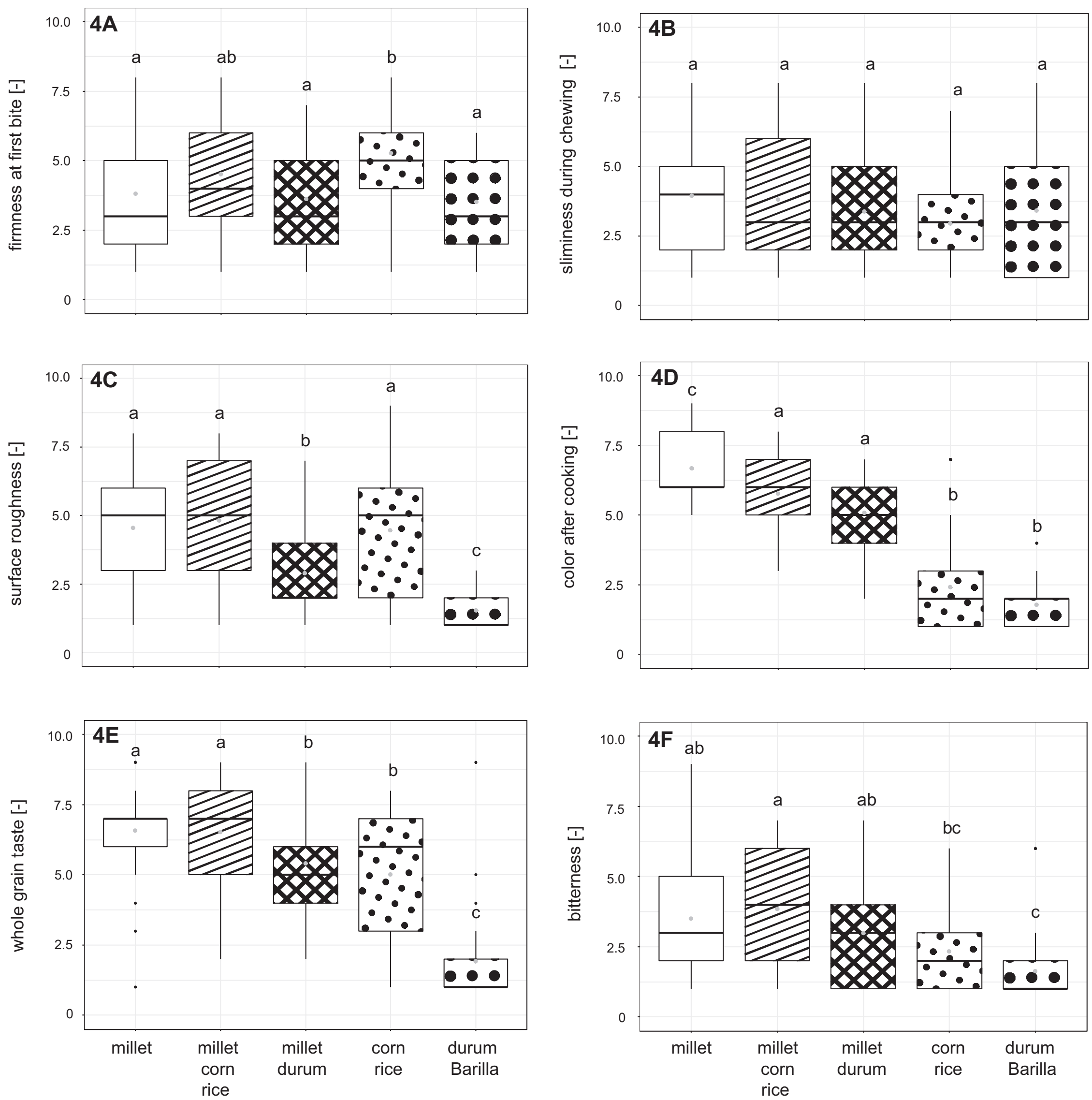

Fig. 4. Descriptive sensory assessment of 'al dente' cooked spaghetti on a 9-point scale using the attributes firmness (A with 1 = soft, 9 = hard), sliminess (B with 1 = little, 9 = strong), surface roughness (C with 1 = smooth, 9 = rough), color (D with 1 = yellow, 9 = brown), wholegrainy taste (E with 1 = little, 9=strong), bitterness (F with 1 = little, 9 = strong), number of replications = 37, $p < 0.05$.

The nutritional analysis (Table 2) of the different types of spaghetti shows no major difference in energy content, while the fat content increases with the proportion of millet in the recipe. Overall, spaghetti made from 100% millet has a fat content which is 3.1 times higher than the durum pasta made from Barilla. The dietary fiber content of all three types of spaghetti containing millet was more than twice as high as the two types of spaghetti used as a reference, namely those made from durum and maize-rice. Measurements resulted in the highest protein content in millet-durum spaghetti, closely followed by pure durum spaghetti, then the pure millet pasta. The differences in protein content compared to the mixing ratios of durum and millet can be attributed to the raw materials used in pilot scale trials and the store-bought durum spaghetti. Corn-rice spaghetti contained much less protein (7 g/100 g) compared to millet-durum spaghetti (14.1 g/100 g). The niacin and folic acid content were especially high in the combined millet-durum pasta, while the iron content was strongly and the zinc content moderately to strongly elevated in all pasta containing millet. Finally, the silicium dioxide content increased strongly, up to a factor of 100 for pure millet pasta compared to the reference pasta types.

The differences in nutrient content can be mainly attributed to differences in raw material composition of the different spaghetti types. Some influence of extrusion processing on heat labile vitamins is to be expected and might impact the absolute values of α-tocopherol and folic acid in the durum Barilla pasta compared to all other pasta types for which the process was identical (Riaz et al., 2009).

Based on the nutrient contents listed in Table 2 and according to the Swiss decree on food information (Swiss degree on food information, 2017), pure millet pasta can be advertised for its high zinc content and as a source of dietary fiber and iron, millet-durum pasta and millet-corn-rice pasta as a source of iron, zinc and dietary fiber, and millet-durum pasta in addition as a source of protein. The claim 'protein source' can also be used for pure durum pasta, while none of the mentioned claims can be made for corn-rice pasta.

4. Conclusion

It can be concluded that the millet variety Alba is a promising alternative raw material for pasta as the texture in both the uncooked and cooked state were comparable to pasta containing gluten, and whilst the sensory perception was, in some aspects, different from durum pasta, it was nevertheless well liked by the tasting panel and the final product was superior with respect to its nutritional content. In addition, processability in a gluten-free process is possible without any issues and the addition of steam to an existing pasta plant is doable. Based on all these findings, further in-depth consumer tests are recommended to position millet pasta optimally in the pasta currently available today, especially in view of the finding that health-conscious consumers showed a preference for this pasta type.

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Ethical review

Participants were aware that their responses are treated confidentially and agreed to participate in the survey.

Informed consent

Not applicable.

Code availability

Not applicable.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

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