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Microstructure and cooking quality of barley-enriched pasta produced at different process parameters

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Abstract: Pasta is one of the most popular meals in the world. It is affordable, easy to combine with other foods and easy to cook. Unfortunately, pasta is energy-rich and nutrient-poor. Whole-wheat pasta is somewhat better in nutritional quality, but further improvements may be made. One option is to add different raw materials and specific nutritive components (vitamins, polyphenols, fiber, protein, etc.) to semolina. However, this approach changes its physico-chemical properties, e.g. cooking loss, texture, etc., which cannot be disregarded. The current research investigates possibilities for production of barley-enriched pasta with acceptable cooking qualities. To ensure the beneficial health effects of β-glucan, β-glucan-rich barley was selected asa starting material. Pasta enriched with 10–50% β-glucan-rich barley flour was produced in the mini-press and the laboratory extruder and then dried at low, medium and high temperature regimes. Colour, cooking quality and microstructure of the enriched pasta were investigated to determine its acceptability. The research showed that barley-enriched pasta of good cooking quality might be produced by selecting an optimal combination of suitable production parameters for forming and drying.

Keywords: Barley, cooking quality, drying regimes, extrusion, pasta

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INTRODUCTION

Pasta is very popular, yet nutrition-poor. Traditionally, it is made from durum wheat semolina, and it is a good source of low glycaemic index carbohydrates [1]. It is affordable, easily to cook and convenient, which makes it a staple food both in low-income and high-income countries. Since consumers' awareness regarding food quality and its health impact is rising, current food industry, including pasta producers, is forced to seek solutions for healthier products with quality and taste similar to the ones consumers are used to.

Recently, health benefits of β-glucan have gained much attention both in scientific and consumer community [2]. In 2009 and 2011 [3–4], the European Food Safety Authority (EFSA) published scientific opinion regarding the beneficial effect of β-glucan on cholesterol level and postprandial glucose in blood. Primarily, barley used to be grown for brewery and animal feed, but it is a rich source of β-glucan. Thanks to the novel understanding of health effects of β-glucan, crops rich in β-glucan are now produced for human consumption [5]. Among barley varieties, hull-less barley is recognized for its superior nutritional quality [6].

There have been a number of research that dealt with the influence of flour, flour fractions and β-glucan enriched flours on pasta quality [7–10]. They showed that addition of fibre, starch and/or other flours led to 'dilution' of gluten and resulted in reduced cooking quality. Hence, pasta manufacturers have to find an appropriate solution to overcome this problem. Pressure applied during pasta forming process and the drying temperature influence its texture properties and cooking quality. For instance, higher drying temperature would result in increased hardness of pasta due to a more pronounced protein denaturation, resulting in a more compact gluten network [11–13]. The aim of the present research was to enrich durum wheat pasta with β-glucan-rich barley flour and to define the influence of pasta forming process and drying temperature on product features.

STUDY OBJECTS AND METHODS

The durum semolina was produced by Sgambaro, Italy, and the hull-less barley Osvit (harvest 2015) was kindly provided by Agricultural Institute Osijek. The hull-less barley was milled in a laboratory mill (IKA WERKE 10.1, Staufen, Germany) with a 1 mm sieve. The durum semolina had 11.06% moisture, 1.07% d. m.

minerals, 11.77% d. m. proteins, 1.11% d. m. fat and 70.36% d. m. starch. The barley flour contained 10.14% moisture, 2.32% d. m. minerals, 14.11% d. m. proteins, 2.42% d. m. fat and 54.72% d. m. starch, and was used as a source of β-glucan (it contained 5.16% β-glucan). For pasta formulations, tap water (40 ± 2°C) was used.

Pasta preparation. Control pasta sample was produced from semolina, without barley flour (BF) addition. For barley-enriched pasta, samples with 10, 20, 30, 40 and 50% of BF were prepared.

For pasta produced in the laboratory pasta press Fimar MPF2.5N (Lineapasta, Cittadella (PD), Italy), dry ingredients were added directly into the press, and calculated amount of tap water was added through the opening in the press with stirring to obtain a dough with 36% moisture. After the water was added, the dough was stirred for 15 min, at which point the press was turned on to pasta formation process. At the exit of the press, a fettuccine die was placed to cut pasta into specified length. Finally, the pasta was put on perforated drying plates.

In case of the pasta produced in the laboratory extruder, mixtures were prepared in the laboratory mixer. Dry ingredients were added to the mixing bowl of the laboratory mixer (Kenwood KMM020, JVCKenwood, Uithoorn, Netherlands), and tap water was added with stirring until 34% moisture was reached. After the water was added, stirring continued for further 10 min, at which point the dough was placed into a plastic bag and conditioned for 30 min to ensure that moisture spread evenly. Extrusion was performed in the laboratory single-screw extruder 19/20 DN (Brabender, Duisburg, Germany) with the following parameters: screw 3:1, temperature regime 35/40°C, cooling with water in last section, just before the die, 7 × 2 mm fettuccine die coated with teflon. The extruded pasta was cut by hand and put on perforated drying plates. The moistures of the samples were set according to a preliminary research, where optimal water quantity had been investigated.

The fresh pasta was dried in Climacell 111 chamber (MMM GmbH, Munchen, Germany), with pre-drying at 40°C and air moisture 60% for 35 min. The main drying was performed at one of the following conditions: 50°C/air moisture 70%/450 min; 70°C/air moisture 70%/240 min; 90°C/air moisture 70%/120 min. The specified drying time was determined during a preliminary research of the time necessary for pasta moisture to sink below 13.5% at the end of the process. After drying, the pasta was conditioned at the ambient temperature, packed into plastic bags and stored in the refrigerator at 4°C before analysis.

Colour determination. The colour of the samples was measured by Konica Minolta CR-400 chromameter (Konica Minolta, Japan) after calibration of the apparatus on the white calibration tile. Five fettuccini were placed closely together on a white mat, and their colour was measured in 5 replicates in CIELab* system, where *L* denoted lightness (0 is black and 100 white), *a* – redness (positive values)/greenness (negative values) and *b* – yellowness (positive values)/blueness (negative values).

Total colour change *ΔE* was calculated according to equation (1) in relation to the control sample (without barley flour):

$$\Delta E = \sqrt{(L - L_0)^2 + (a - a_0)^2 + (b - b_0)^2}, \quad (1)$$

where *L, a, b* represent values for the sample and L_0, a_a, b_0 – values for the control sample.

Cooking quality. *The optimal cooking time* and cooking loss were determined in two parallels [14]. Briefly, 10 g of pasta was added to 200 mL of boiling water, and after 5 min loss of white core was monitored every 30 sec by squeezing pasta between two glass tiles.

The cooking loss was determined after cooking pasta for optimal cooking time. Briefly, cooking water and the water used to wash pasta were collected and dried at 115°C until the constant mass was reached, and the cooking loss *(CL)* was calculated according to Eq. 2:

$$CL\ (\%) = (\text{weight of dry residue/weight of dry pasta}) \times 100. \quad (2)$$

The water absorption index and *the swelling index* were determined in two parallels [4]. Briefly, after being cooked for an optimal period of time, the pasta was washed over a colander, drained, weighed and dried at 105°C to constant mass. The water absorption index (*WAI*) was calculated according to Eq. 3:

$$WAI\ (\%) = [(\text{mass of cooked pasta} - \text{mass of dried pasta})/\text{mass of dried pasta}] \times 100 \quad (3)$$

and swelling index (*SI*) – according to Eq. 4:

$$SI\ (\text{g } H_2O/\text{g dried pasta}) = (\text{mass of cooked pasta} - \text{mass of pasta after drying})/\text{mass of pasta after drying}. \quad (4)$$

Microstructure of pasta. The microstructure of the selected pasta samples was determined by Scanning Electron Microscope JSM 7000F (Jeol USA Inc., Peabody MA, USA) at 1000 × magnification. The cooked samples were freeze-dried prior to analysis.

Statistical analysis. Statistical analysis was performed using Statistica® 12 (StatSoft Inc, USA), by Main effects ANOVA and Fisher's LSD at $p < 0.05$.

RESULTS AND DISCUSSION

The colour of pasta samples is shown in Table 1. Barley flour addition resulted in a darker surface of the fresh pasta, expressed as reduction of L^* values (eg. from 78.78 ± 1.54 for fresh control sample to 71.72 ± 0.22 for fresh sample with 50% barley flour produced in the extruder), with more pronounced differences for samples produced in the laboratory pasta press (from 75.72 ± 0.39 to 67.88 ± 0.31, respectively). a^* values increased, indicating increase of red component, while b^* values decreased (decreased yellow component) proportionally to barley flour addition, again, with more pronounced effects for samples produced in the press. Compared to the samples with the same proportion of barley flour produced in the extruder, the fresh samples produced in the press had lower L^* and b^* and higher a^* values, probably due to higher moisture. Total colour change *ΔE* increased with the increase of barley flour proportion regardless of process used.

Table 1. Colour of pasta samples measured in CIELab* system, with total colour difference Δ*E* calculated in relation to corresponding sample without barley flour

	Extruder				Press			
Fresh pasta								
Barley flour (%)	*L**	*a**	*b**	Δ*E*	*L**	*a**	*b**	Δ*E*
0	78.78 ± 1.54^{e}	-3.96 ± 0.11^{a}	35.40 ± 0.48^{f}		75.72 ± 0.39^{e}	-3.35 ± 0.13^{a}	28.35 ± 0.45^{e}	
10	77.07 ± 0.26^{d}	-2.14 ± 0.19^{b}	33.16 ± 0.52^{e}	03.35	72.26 ± 0.16^{d}	-0.93 ± 0.15^{b}	24.13 ± 0.43^{d}	05.97
20	74.90 ± 0.55^{c}	-0.60 ± 0.14^{c}	30.85 ± 0.53^{d}	06.86	71.47 ± 0.20^{c}	-0.34 ± 0.20^{c}	23.12 ± 0.19^{c}	07.38
30	73.92 ± 0.49^{b}	0.48 ± 0.15^{d}	28.98 ± 0.54^{c}	09.20	68.87 ± 0.38^{b}	0.82 ± 0.16^{d}	22.67 ± 0.26^{c}	09.83
40	72.32 ± 0.33^{a}	1.42 ± 0.16^{e}	26.94 ± 0.43^{b}	11.92	68.20 ± 0.45^{a}	1.50 ± 0.23^{e}	21.04 ± 0.66^{b}	11.56
50	71.72 ± 0.22^{a}	2.02 ± 0.08^{f}	25.01 ± 0.61^{a}	13.91	67.88 ± 0.31^{a}	1.81 ± 0.08^{f}	19.46 ± 0.25^{a}	12.93
Dried pasta								
	50°C			Δ*E*	50°C			Δ*E*
	*L**	*a**	*b**		*L**	*a**	*b**	
0	73.29 ± 0.27^{f}	-2.47 ± 0.21^{a}	20.50 ± 0.63^{d}		75.38 ± 0.40^{f}	-3.33 ± 0.26^{a}	26.28 ± 0.54^{e}	
10	72.20 ± 0.24^{e}	-1.98 ± 0.12^{b}	20.09 ± 0.60^{d}	01.26	71.69 ± 0.80^{e}	-1.92 ± 0.51^{b}	25.96 ± 0.28^{e}	03.96
20	71.40 ± 0.31^{d}	-0.86 ± 0.22^{c}	18.84 ± 0.24^{c}	02.99	65.91 ± 0.53^{d}	0.48 ± 0.30^{c}	23.44 ± 0.19^{d}	10.59
30	69.21 ± 0.39^{c}	1.30 ± 0.13^{d}	18.19 ± 0.13^{b}	06.02	63.30 ± 0.47^{c}	1.55 ± 0.27^{d}	22.38 ± 0.46^{c}	13.59
40	67.76 ± 0.36^{b}	1.92 ± 0.11^{e}	18.03 ± 0.06^{ab}	07.47	60.37 ± 0.35^{b}	3.15 ± 0.19^{e}	21.34 ± 0.37^{b}	17.08
50	66.52 ± 0.41^{a}	2.71 ± 0.22^{f}	17.50 ± 0.37^{a}	09.03	58.97 ± 0.30^{a}	3.52 ± 0.26^{e}	19.75 ± 0.26^{a}	18.94
	70°C			Δ*E*	70°C			Δ*E*
	*L**	*a**	*b**		*L**	*a**	*b**	
0	74.47 ± 0.30^{f}	-3.03 ± 0.31^{a}	21.72 ± 0.35^{f}		75.28 ± 0.26^{e}	-3.39 ± 0.17^{a}	29.34 ± 0.78^{e}	
10	73.73 ± 0.28^{e}	-2.18 ± 0.18^{b}	20.55 ± 0.30^{e}	01.62	66.10 ± 0.59^{d}	1.09 ± 0.28^{b}	25.52 ± 0.50^{d}	10.91
20	72.53 ± 0.31^{d}	-1.42 ± 0.27^{c}	19.56 ± 0.44^{d}	03.32	65.98 ± 0.13^{d}	1.37 ± 0.32^{bc}	23.44 ± 0.35^{c}	12.00
30	71.43 ± 0.35^{c}	-0.98 ± 0.14^{d}	18.68 ± 0.29^{c}	04.76	65.12 ± 0.43^{c}	1.68 ± 0.14^{c}	23.10 ± 0.33^{c}	12.96
40	68.42 ± 0.29^{b}	0.60 ± 0.30^{e}	18.15 ± 0.29^{b}	07.91	58.96 ± 0.14^{b}	3.84 ± 0.21^{d}	22.20 ± 0.28^{b}	19.23
50	66.52 ± 0.33^{a}	2.40 ± 0.29^{f}	17.11 ± 0.04^{a}	10.66	57.80 ± 0.35^{a}	4.46 ± 0.35^{e}	21.46 ± 0.40^{a}	20.73
	90°C			Δ*E*	90°C			Δ*E*
	*L**	*a**	*b**		*L**	*a**	*b**	
0	69.46 ± 0.31^{f}	-1.92 ± 0.21^{a}	24.33 ± 0.45^{f}		72.52 ± 0.37^{f}	-2.49 ± 0.12^{a}	31.35 ± 0.21^{f}	
10	68.19 ± 0.22^{e}	-1.12 ± 0.07^{b}	23.26 ± 0.28^{e}	01.83	70.36 ± 0.39^{e}	-0.59 ± 0.27^{b}	28.38 ± 0.37^{e}	04.13
20	66.74 ± 0.42^{d}	-0.20 ± 0.06^{c}	22.00 ± 0.40^{d}	03.97	67.33 ± 0.36^{d}	1.53 ± 0.34^{c}	27.25 ± 0.24^{d}	07.74
30	65.98 ± 0.09^{c}	1.08 ± 0.08^{d}	20.54 ± 0.53^{c}	05.95	65.47 ± 0.43^{c}	2.14 ± 0.24^{d}	23.47 ± 0.31^{c}	11.54
40	65.30 ± 0.28^{b}	2.08 ± 0.05^{e}	19.53 ± 0.21^{b}	07.50	62.26 ± 0.41^{b}	3.52 ± 0.34^{e}	23.05 ± 0.14^{b}	14.50
50	64.58 ± 0.32^{a}	3.12 ± 0.10^{f}	17.70 ± 0.49^{a}	09.65	61.44 ± 0.31^{a}	4.63 ± 0.37^{f}	22.26 ± 0.16^{a}	16.01
Cooked pasta								
	50°C			Δ*E*	50°C			Δ*E*
	*L**	*a**	*b**		*L**	*a**	*b**	
0	76.31 ± 0.82^{f}	-3.54 ± 0.24^{a}	19.90 ± 0.95^{b}		76.85 ± 0.76^{d}	-4.29 ± 0.25^{a}	25.34 ± 2.24^{c}	
10	75.35 ± 0.60^{e}	-2.72 ± 0.27^{b}	19.19 ± 0.49^{b}	01.46	72.63 ± 0.73^{c}	-2.07 ± 0.40^{b}	25.51 ± 1.64^{c}	04.77
20	74.57 ± 0.67^{d}	-1.30 ± 0.38^{c}	17.65 ± 0.90^{a}	03.62	69.29 ± 1.33^{b}	-0.38 ± 0.14^{c}	22.17 ± 0.73^{b}	09.09
30	73.20 ± 0.29^{c}	0.06 ± 0.60^{d}	17.34 ± 0.05^{a}	05.41	67.66 ± 1.88^{b}	0.91 ± 0.60^{d}	21.98 ± 0.84^{b}	11.09
40	72.08 ± 0.19^{b}	1.13 ± 0.47^{e}	17.05 ± 0.04^{a}	06.92	62.94 ± 1.74^{a}	2.68 ± 0.59^{e}	20.16 ± 1.32^{a}	16.40
50	70.49 ± 0.53^{a}	2.15 ± 0.28^{f}	16.91 ± 0.06^{a}	08.67	62.45 ± 2.09^{a}	2.61 ± 0.53^{e}	18.51 ± 0.16^{a}	17.37
	70°C			Δ*E*	70°C			Δ*E*
	*L**	*a**	*b**		*L**	*a**	*b**	
0	76.52 ± 0.86^{d}	-3.51 ± 0.04^{a}	19.97 ± 1.56^{d}		76.53 ± 0.41^{c}	-4.13 ± 0.19^{a}	28.43 ± 2.26^{d}	
10	76.30 ± 0.09^{cd}	-3.22 ± 0.10^{b}	19.53 ± 0.11^{cd}	00.57	67.71 ± 2.35^{b}	0.37 ± 1.09^{b}	23.88 ± 1.39^{c}	10.89
20	75.85 ± 0.13^{c}	-2.07 ± 0.08^{c}	18.89 ± 0.10^{bc}	01.92	67.03 ± 2.41^{b}	0.89 ± 1.14^{b}	23.05 ± 1.85^{bc}	12.01
30	75.11 ± 0.10^{b}	-1.16 ± 0.07^{d}	18.02 ± 0.07^{ab}	03.63	67.30 ± 1.14^{b}	1.07 ± 0.54^{b}	22.08 ± 0.85^{abc}	12.34
40	74.94 ± 0.08^{b}	-0.18 ± 0.08^{e}	17.58 ± 0.07^{a}	04.39	60.49 ± 2.24^{a}	3.28 ± 0.74^{c}	21.42 ± 0.88^{ab}	19.01
50	74.21 ± 0.09^{a}	1.22 ± 0.07^{f}	17.11 ± 0.04^{a}	05.99	60.32 ± 1.56^{a}	3.68 ± 0.25^{c}	20.06 ± 1.75^{a}	19.84
	90°C			Δ*E*	90°C			Δ*E*
	*L**	*a**	*b**		*L**	*a**	*b**	
0	72.56 ± 1.64^{c}	-1.92 ± 0.21^{a}	23.15 ± 1.33^{d}		74.07 ± 0.41^{e}	-4.01 ± 0.30^{a}	30.35 ± 0.46^{c}	
10	72.31 ± 0.44^{c}	-1.12 ± 0.07^{b}	21.17 ± 0.17^{c}	2.15	72.29 ± 1.32^{d}	-0.89 ± 0.43^{b}	25.84 ± 1.85^{b}	5.77
20	71.99 ± 0.09^{c}	-0.20 ± 0.06^{c}	20.67 ± 0.32^{c}	3.06	68.50 ± 1.17^{c}	0.98 ± 0.46^{c}	26.11 ± 1.28^{b}	8.59
30	70.50 ± 0.46^{b}	1.08 ± 0.08^{d}	19.34 ± 0.20^{b}	5.26	66.54 ± 1.16^{b}	1.83 ± 0.48^{d}	21.22 ± 0.60^{a}	13.20
40	70.01 ± 0.17^{ab}	2.08 ± 0.05^{e}	18.46 ± 0.40^{a}	6.67	63.36 ± 1.40^{a}	3.01 ± 0.52^{e}	22.21 ± 0.98^{a}	15.18
50	69.23 ± 0.18^{a}	3.12 ± 0.10^{f}	18.12 ± 0.10^{a}	7.96	63.00 ± 1.58^{a}	3.29 ± 0.51^{e}	21.12 ± 1.18^{a}	16.15

Note. Data are presented as mean value ± standard deviation (n = 5)
Different letters in the same column for appropriate drying temperature represent statistically significant difference ($p \leq 0.05$)

Addition of barley flour reflected in the decrease of $L*$ and $b*$ values, as well as in the increase of $a*$ values in the dried samples. When comparing drying conditions, the brightest samples were obtained in the medium temperature regime (70°C), followed by samples dried at the low- (50°C) and high temperature (90°C) regimes. There was no statistically significant difference between colour parameters $L*$ and $a*$ of the samples dried at low- and high temperature regime, as shown in Fig. 1. However, $b*$ values significantly increased following the increase of drying temperature. These phenomena may be ascribed to Maillard reactions during drying at elevated temperatures [15]. Drying at 70°C was much shorter than drying at 50°C, resulting in a similar advancement of Maillard reactions, unlike drying at 90°C, where the high temperature had a much more pronounced influence on the reaction progress. The trend of influence of barley flour addition on the colour of cooked pasta was similar to the dried samples, with a slightly larger statistical significance (Fig. 1).

Only trained sensory analysts can perceive the colour difference between the dried control sample and the dried sample with 10% barley flour produced in the extruder, regardless the drying temperature [16]. Addition of 40% and 50% of barley flour resulted in a large colour difference, easily perceived by ordinary people. When samples were produced in the pasta press, an obvious colour difference was perceived already at 20% barley flour, and a further increase in barley flour content made the colour difference extreme [16]. This can also be ascribed to higher initial moisture of the samples, which enabled a higher extent of browning reactions, such as Maillard reactions.

When considering barley content regardless of production and drying processes, it is evident that it has a significant influence on pasta colour (Fig. 1). Production process also produced a visible effect, which cannot be said about the drying temperature, except for high temperature drying, in which case statistical significance is evident (Fig 1).

The optimal cooking time is shown in Table 2. Barley addition did not significantly influence the optimal cooking time (F-test, p-value = 0.018) (Fig. 2), as opposed to pasta enriched with quinoa flour [17] and amaranth [18], in which case the optimal cooking time was significantly reduced. However, both quinoa and amaranth contain less fibre than barley examined in this research, and when a part of semolina was replaced with carob fibre, it did not influence the optimal cooking time significantly [19].

The press-made pasta had a shorter cooking time than the extruder-made samples regardless the barley content and drying temperature (Table 2, Fig. 2). This can be ascribed to lower mechanical energy applied during production in the press, which results in a less compact product that needs less time to fully gelatinise [20].

When considering the influence of drying regimes, it is evident that pasta dried at low-temperature regime requires longer cooking time than the one dried at medium- and high temperature, and there is no statistical difference between the latter two (F-test, p-value < 0.001) (Table 2, Fig. 2). There was no difference in cooking time between the semolina pasta dried at low- and high temperature regimes [20], while "the optimum cooking time for spaghetti samples decreased as the drying temperature profile decreased" [21]. Padalino et al. [22] stated that "higher temperatures induced cross-link density of both protein and starch, decreasing water diffusion". The present research differs from that performed by Padalino et al. in the aspect of barley flour added, which probably interfered with the effect of temperature on protein cross-linking.

Unlike cooking time, barley flour proved to be an important factor when it comes to cooking loss (F-test, p-value < 0.001) (Table 2, Fig. 2), increasing it proportionally, with minor exceptions. Addition of barley flour caused formation of a weaker and discontinuous protein network, reducing its ability to hold dry matter during cooking, and starch leached into the surrounding water [5]. Similar results were reported for pasta with barley β-glucan [7], with oat β-glucan [21] and oat flour [23]. On the contrary, β-glucan does not influence cooking loss significantly [7].

The extruder-produced samples had a smaller cooking loss than their press-made counterparts, probably because a larger pressure during extrusion in the extruder results in a more compact protein network that holds dry matter better during cooking (F-test, p-value < 0.001).

The increase of drying temperature resulted in the decrease of cooking loss (F-test, p-value < 0.001) (Table 2, Fig. 2). The same trend for pasta made from semolina was reported, which can be explained by protein denaturation and formation of stronger protein network at higher temperatures [24], and by the fact that "the increase in drying temperature (90°C vs. 55°C) promoted the covalent aggregation of proteins in pasta, enhancing their resilience and reducing their cooking loss, without altering the degree of protein hydrolysis" [25].

The water absorption index decreased slightly, although not significantly, after adding barley flour (F-test, p-value = 0.250) (Table 2, Fig. 2) [9]. Although high fibre content should theoretically raise the hydration, Aravind et al. [9] assumed that β-glucan competed for water with gluten and starch during mixing and therefore did not have significant influence on water absorption during cooking [9]. On the contrary, an increase of the water absorption index after addition of different fibres was reported; however, the authors also noticed that some types of fibres influenced it to a lesser degree [26]. They ascribed it to the particle size and the structural difference between the fibres.

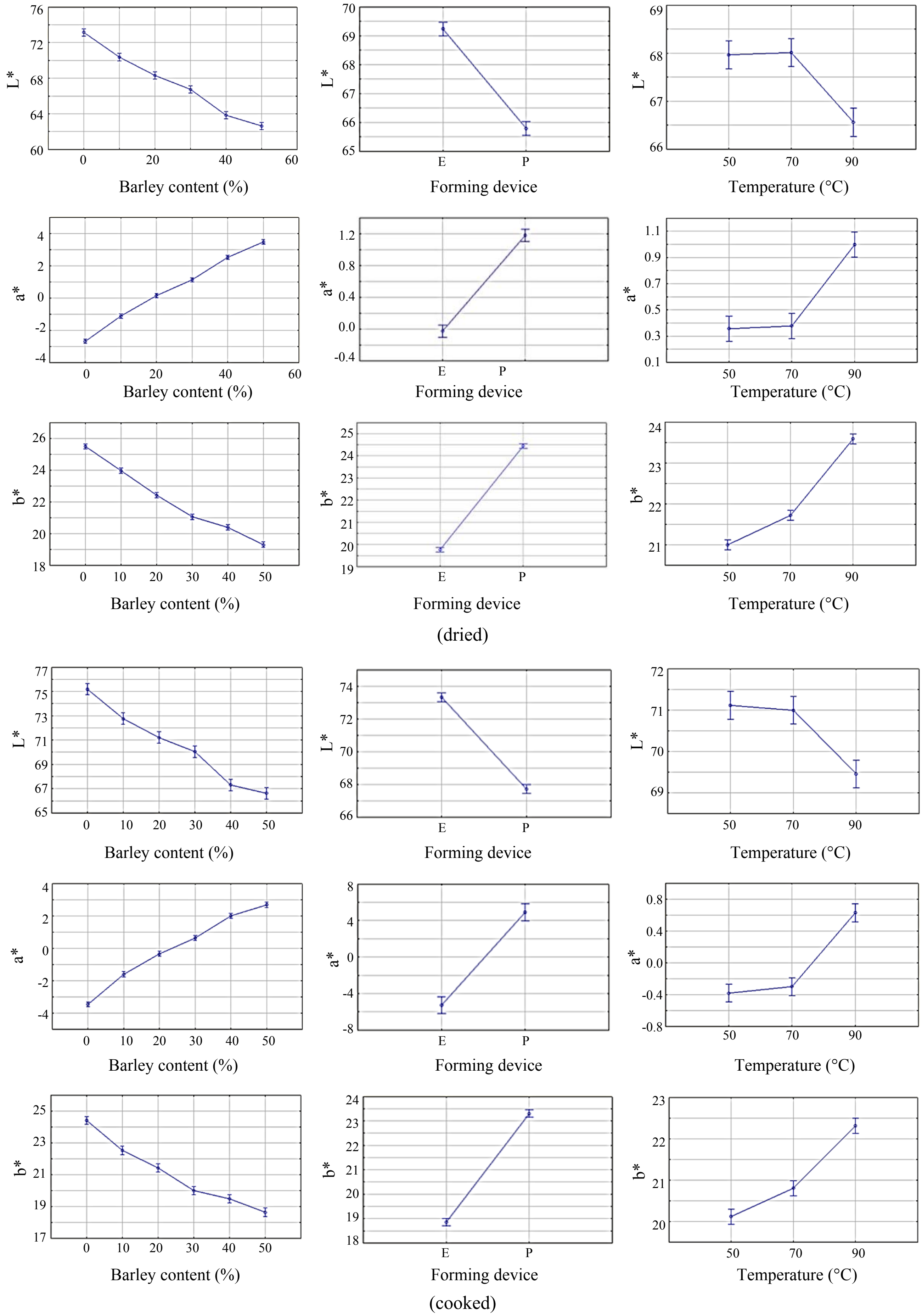

Fig. 1. Statistical influence of barley flour content, forming device (E – extruder, P – press) and drying temperature on colour parameters of dried and cooked pasta. Interval for each value represents statistical error.

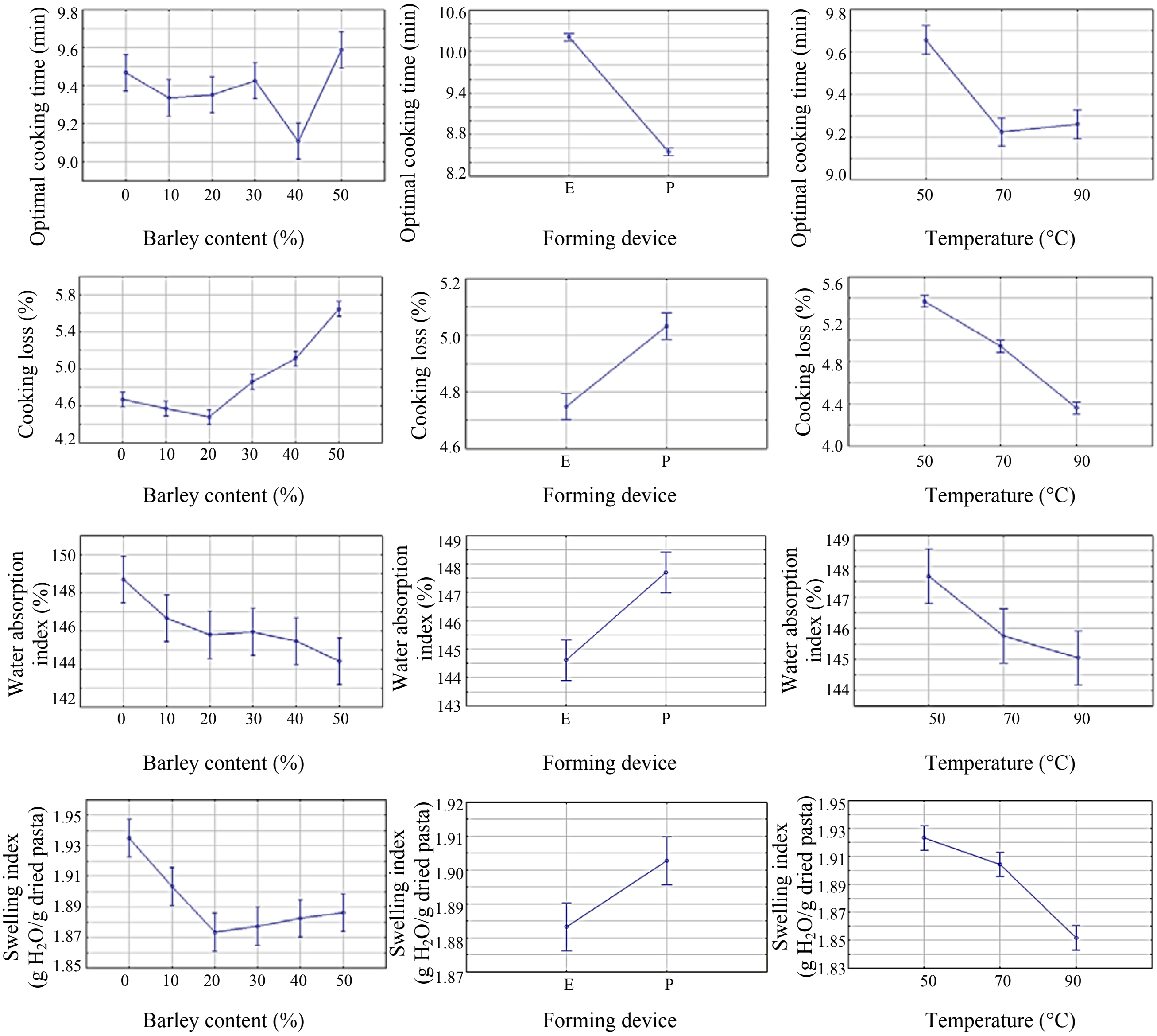

Fig. 2. Statistical influence of barley flour content, forming device (E – extruder, P – press) and drying temperature on pasta cooking quality. Interval for each value represents statistical error.

The water absorption index of the press-made pasta is evidently larger than the extruder-made counterparts (F-test, p-value = 0.003) (Fig. 2). As it has already been mentioned in regard to cooking time, the pasta production in the extruder resulted in formation of a more compact network, which hindered water molecules penetration, whereas in the case of the press-made pasta, protein network is weaker and water penetrates more easily.

The swelling index generally followed the same trend as the water absorption index and was consistent with the previous research [9, 27]. It is worth specifying that only addition of 10 and 20% barley flour had a significant influence on swelling reduction. A further increase of barley content slightly raised it, but with no statistical significance (Fig 2).

The microstructures of selected dried and cooked pasta samples are shown in Fig. 3–5.

The microstructure of the samples without barley flour revealed that combination of extrusion with medium and high drying temperature influenced starch granules (Fig. 3 A, C, E), causing their disruption and starch leakage, gelatinisation and interactions (starch-protein, starch-lipid, starch-starch complexes). In the press-made samples, starch granule disruption was reduced significantly even when high drying temperature was applied (Fig. 3 B, D, F), but granules did swell partially. In the samples with 50% barley flour the same trend was observed: the extruded samples dried at high temperatures had fewer untacked starch granules, and the press-made samples demonstrated partially swollen granules (Fig. 4).

Table 2. Cooking quality of pasta with addition of 10–50% barley flour, produced in the extruder and in the mini-press, dried at 50, 70 and 90°C

Barley flour (%)	Extruder			Press		
			optimal cooking time (min)			
	50°C	70°C	90°C	50°C	70°C	90°C
0	10.17 ± 0.10^{bc}	10.17 ± 0.15^{c}	10.33 ± 0.06^{ab}	9.44 ± 0.05^{a}	8.39 ± 0.04^{b}	8.31 ± 0.01^{c}
10	10.14 ± 0.05^{bc}	10.45 ± 0.05^{a}	10.20 ± 0.26^{ab}	9.46 ± 0.05^{a}	7.52 ± 0.05^{d}	8.25 ± 0.05^{c}
20	10.28 ± 0.09^{ab}	10.18 ± 0.08^{bc}	10.23 ± 0.38^{b}	9.25 ± 0.05^{ab}	8.27 ± 0.06^{b}	8.29 ± 0.09^{c}
30	10.11 ± 0.09^{c}	10.11 ± 0.11^{c}	10.30 ± 0.53^{ab}	9.18 ± 0.28^{c}	8.28 ± 0.03^{b}	9.48 ± 0.03^{a}
40	10.38 ± 0.08^{a}	10.34 ± 0.08^{ab}	10.14 ± 0.09^{ab}	8.45 ± 0.06^{d}	8.25 ± 0.30^{c}	7.48 ± 0.08^{d}
50	10.40 ± 0.10^{a}	10.27 ± 0.03^{bc}	10.37 ± 0.12^{a}	9.09 ± 0.03^{b}	9.27 ± 0.28^{a}	8.55 ± 0.05^{b}
			cooking loss (%)			
	50°C	70°C	90°C	50°C	70°C	90°C
0	4.85 ± 0.19^{c}	4.36 ± 0.41^{cd}	3.95 ± 0.23^{b}	5.09 ± 0.11^{c}	5.02 ± 0.05^{c}	4.75 ± 0.19^{b}
10	4.84 ± 0.22^{c}	4.32 ± 0.21^{d}	4.01 ± 0.23^{b}	5.16 ± 0.06^{c}	4.79 ± 0.16^{c}	4.31 ± 0.06^{d}
20	5.18 ± 0.02^{bc}	4.03 ± 0.23^{d}	4.00 ± 0.07^{b}	5.26 ± 0.15^{c}	4.16 ± 0.06^{d}	4.26 ± 0.10^{d}
30	5.30 ± 0.21^{bc}	4.03 ± 0.04^{bc}	4.30 ± 0.20^{ab}	5.32 ± 0.04^{c}	5.00 ± 0.15^{c}	4.39 ± 0.13^{cd}
40	5.62 ± 0.23^{ab}	5.11 ± 0.12^{b}	4.30 ± 0.23^{ab}	5.79 ± 0.15^{b}	5.41 ± 0.11^{b}	4.61 ± 0.08^{bc}
50	5.90 ± 0.22^{a}	6.15 ± 0.12^{a}	4.50 ± 0.06^{a}	6.09 ± 0.14^{a}	6.12 ± 0.14^{a}	5.11 ± 0.12^{a}
			water absorption index (%)			
	50°C	70°C	90°C	50°C	70°C	90°C
0	148.87 ± 1.67^{c}	147.45 ± 0.10^{c}	154.24 ± 7.32^{b}	151.82 ± 1.38^{bc}	144.76 ± 5.37^{a}	145.05 ± 2.34^{a}
10	142.67 ± 1.63^{ab}	155.48 ± 3.60^{d}	141.65 ± 1.03^{a}	151.73 ± 0.21^{bc}	145.07 ± 2.97^{a}	143.36 ± 1.83^{a}
20	142.66 ± 4.11^{ab}	146.09 ± 2.65^{bc}	147.37 ± 0.11^{ab}	149.65 ± 0.63^{a}	145.66 ± 0.36^{a}	143.31 ± 0.46^{a}
30	146.23 ± 2.67^{bc}	142.03 ± 0.08^{ab}	143.45 ± 2.95^{a}	151.60 ± 0.43^{b}	146.05 ± 0.74^{a}	146.30 ± 1.93^{a}
40	139.02 ± 2.06^{a}	143.03 ± 0.21^{bc}	144.00 ± 0.04^{a}	152.68 ± 0.32^{bc}	147.16 ± 4.44^{a}	146.88 ± 1.73^{a}
50	141.70 ± 2.06^{ab}	137.57 ± 2.47^{a}	139.53 ± 1.06^{a}	153.50 ± 1.00^{c}	148.72 ± 0.96^{a}	145.42 ± 2.10^{a}
			swelling index (g H_2O/g dried pasta)			
	50°C	70°C	90°C	50°C	70°C	90°C
0	1.95 ± 0.01^{b}	1.91 ± 0.02^{b}	1.92 ± 0.09^{b}	1.96 ± 0.02^{d}	1.93 ± 0.00^{b}	1.92 ± 0.04^{b}
10	1.89 ± 0.01^{a}	2.03 ± 0.07^{c}	1.78 ± 0.00^{a}	1.93 ± 0.00^{bcd}	1.91 ± 0.01^{ab}	1.88 ± 0.01^{ab}
20	1.90 ± 0.03^{ab}	1.89 ± 0.03^{ab}	1.87 ± 0.01^{ab}	1.89 ± 0.01^{a}	1.87 ± 0.04^{a}	1.83 ± 0.03^{a}
30	1.92 ± 0.04^{ab}	1.86 ± 0.01^{ab}	1.82 ± 0.03^{a}	1.92 ± 0.01^{b}	1.89 ± 0.01^{ab}	1.85 ± 0.01^{ab}
40	1.89 ± 0.01^{a}	1.89 ± 0.00^{ab}	1.84 ± 0.01^{ab}	1.93 ± 0.01^{bc}	1.92 ± 0.01^{b}	1.82 ± 0.02^{a}
50	1.93 ± 0.02^{ab}	1.82 ± 0.02^{a}	1.78 ± 0.00^{a}	1.95 ± 0.02^{cd}	1.93 ± 0.01^{b}	1.90 ± 0.04^{b}

Note. Data are presented as mean value ± standard deviation (n = 2)
Different letters in the same column for appropriate drying temperature represent statistically significant difference ($p \leq 0.05$)

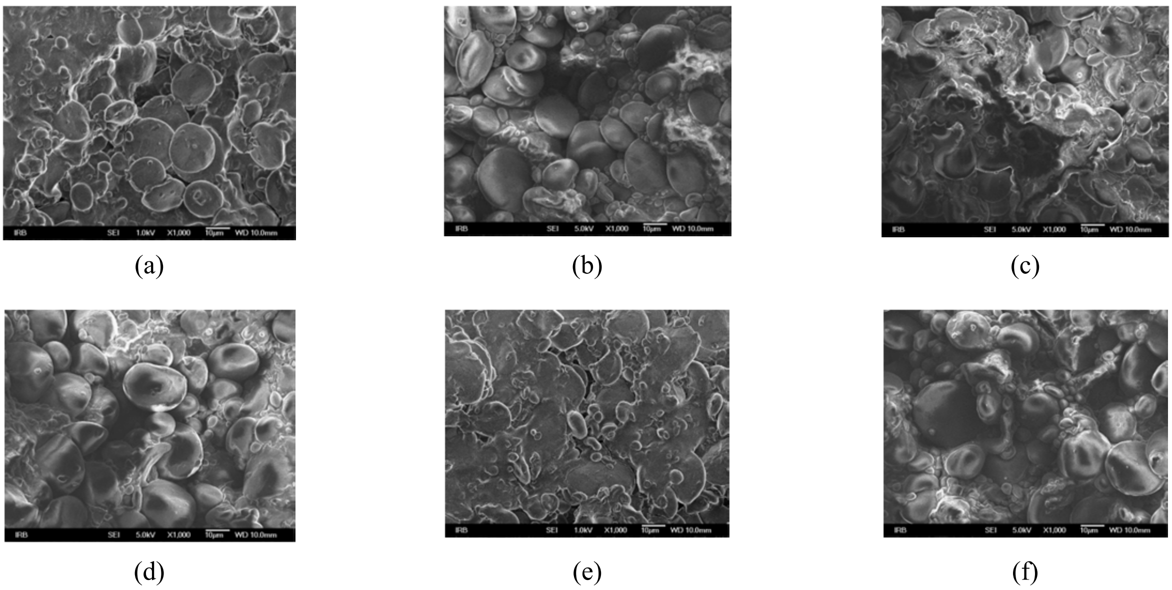

Fig. 3. SEM microstructure (1000 ×) of dried pasta produced in the extruder (a, c, e) and in the press (b, d, f) without barley flour, dried at 50°C (a, b), 70°C (c, d) and 90°C (e, f).

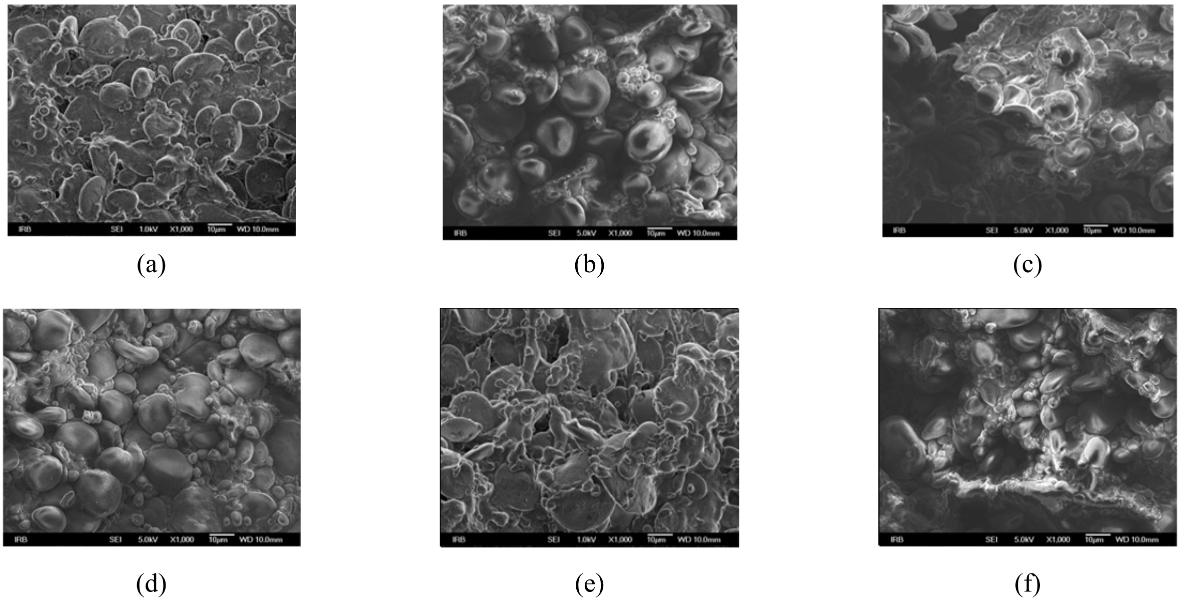

Fig. 4. SEM microstructure (1000 ×) of dried pasta with 50% barley flour, produced in the extruder (a, c, e) and in the the press (b, d, f), dried at 50°C (a, b), 70°C (c, d) and 90°C (e, f).

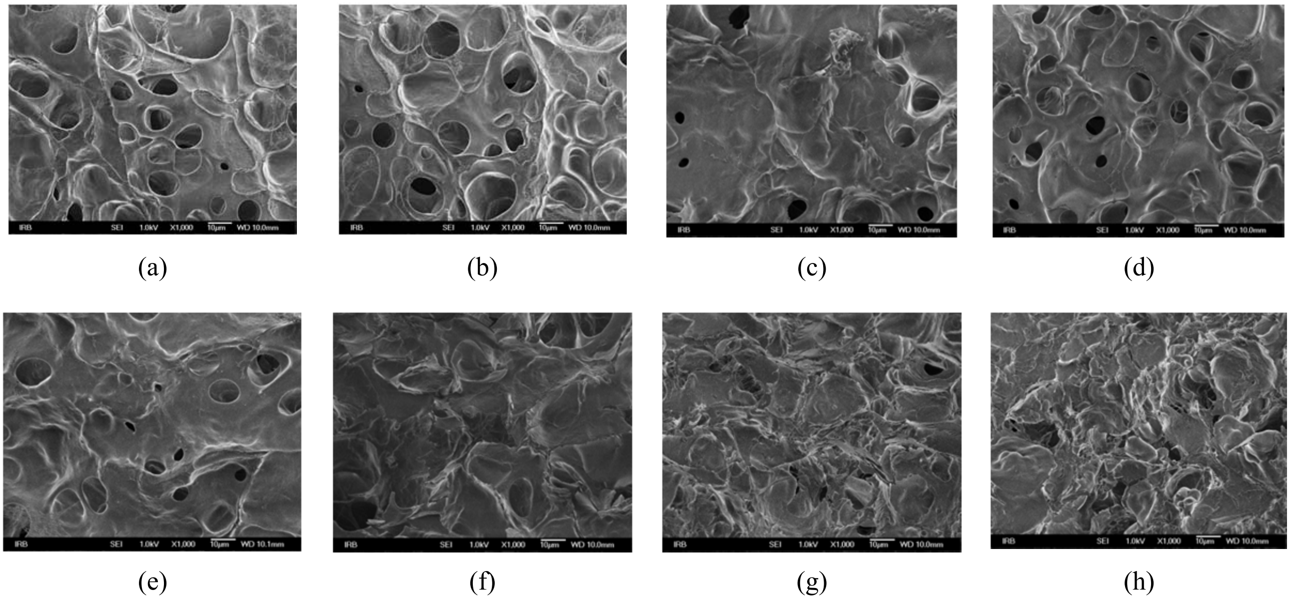

Fig. 5. SEM microstructure (1000 ×) of cooked pasta without barley flour produced in the extruder (a, c) and in the press (b, d), dried at 50°C (a, b) and 90°C (c, d), and the cooked pasta with 50% barley flour produced in the extruder (e, g) and in the press (f, h), dried at 50°C (e, f) and 90°C (g, h).

All micrographs revealed that starch granules were incorporated in the protein network to a lesser extent in the press-made pasta, and this influenced cooking time, absorption and swelling. Gelatinised starch complexes with lipids and proteins rather easily, and formation of compounds requires far more energy. Starch in granules starts to gelatinise during cooking, and the afore-mentioned complexes do not influence cooking time that much [19].

During cooking, starch gelatinises completely, and a unique network of starch and proteins is formed (Fig. 5). The micrographs in Fig. 5 show orifices where starch has leached. In the samples dried at 50°C, the number of thus formed cavities was larger compared to the samples dried at 90°C, and the extruder-made samples had fewer cavities than the press-made samples, all of which can be linked to cooking loss.

CONCLUSION

This research aimed to explore the potentiality of barley-enriched pasta production with acceptable physical properties important for consumer acceptance. Two processes for production and different drying regimes were investigated in order to tackle the problem of "diluted" gluten network and its effect on cooking loss. Although addition of barley flour reduced the cooking quality of pasta, thus increasing the cooking loss, it can be successfully applied as a source of polyphenols and β-glucan in pasta. The pasta produced in the extruder required a longer time to cook, but had a lower cooking loss than in case of the pasta produced in the laboratory press, and medium- and high drying temperature regimes resulted in a shorter cooking time and a lower cooking loss. The results obtained in this research show that a proper combination of production conditions (pressure and temperature during the extrusion process) and drying conditions can compensate for gluten network "dilution" due to addition of barley flour. Further research is needed to establish the optimal combination of barley flour content and production conditions to obtain nutritionally valuable pasta of optimal physical properties.

CONFLICT OF INTEREST

Authors declare no conflict of interest.

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