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Effect of extrusion conditions on breaking strength index of lentil extrudates

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Lentil semolina was extruded in a laboratory single screw extruder (Brabender 20 DN, Germany) with screw diameter 20 mm and die diameter 5 mm. A central composite rotatable design (CCRD) was adopted to study the effect of moisture content, barrel temperature, metering zone temperature, screw speed, and screw compression ratio on breaking strength index of lentil extrudates. The breaking strength index of the extrudate was determined using a texture analyser TA.XT Plus (Stable Micro Systems, England) and calculated using peak breaking force divide by extrudate diameter. The breaking strength index values varied from 12.2 to 32.87 N/mm. Analysis of variance indicates that linear effect due to the moisture content of lentil semolina had the highest impact on the breaking strength index. The regression model fitted to the experimental data showed comparatively high coefficient of determination.

Keywords: breaking strength index, extrusion, lentil, extrudate, texture analyser

INTRODUCTION

Extrusion cooking is a modern high-temperature short-time processing technology, gaining ground in certain industries for various reasons. It offers several advantages over other types of cooking processes, such as faster processing times and significant reduction in energy consumed, which consequently results in lower prices for the final products. However, when they are produced by modern extrusion technology, the various types of extrudate are produced in very different shapes. These depend not only on processing conditions, but also on the size and shape of the die, and the speed of the final cutting device [1].

The quality of extrudate produced can be determined using different methods according to their applicability in a variety of food-industry sectors.

Texture testing is a well-established technique for evaluating the mechanical and physical properties of raw ingredients, food structure, and design, and for pre- and post-quality control checks [2]. Texture testing has applications across a wide range of food types, including baked goods, cereals, confectionaries, snacks, dairy, fruit, vegetables, gelatins, meat, poultry, fish, pasta and even pet food. Since texture is a property related to the sense of touch, it can be measured easily by mechanical methods in units such as force [3].

In food texture testing, standard tests such as compression, tension, and flexure are used to measure hardness, crispiness, crunchiness, softness, springiness, tackiness, and other properties of food [4-6].

For processed food, the textural properties can be used to optimize the process. Food texture analysis can highlight quality improvement opportunities throughout the supply chain and the production process. In production, food texture analysis is used for the measurement and control of process variations such as temperature, humidity and cooking time [7].

Different types of testing instrumentation available, from manual and motorized food firmness testers to fully software-controlled texture analyzers. The texture analyzers perform the test by applying controlled forces to the product and recording its response in the form of force, deformation and time [8, 9].

The purpose of this research was to investigate the effect of moisture content, barrel temperature, metering zone temperature, screw speed, and screw compression ratio on breaking strength index of lentil extrudates produced with a single screw extruder.

EXPERIMENTAL DETAILS

Raw material and preparation

Representative sample of commercial lentil cultivar, namely Ilina, was obtained from Dobroudja Agricultural Institute, General Toshevo, Bulgaria.

Lentil seeds were ground using a hammer mill and passed through standard sieves. Prepared particle size of lentil semolina was about 0.5 mm. Lentil semolina was mixed with distilled water to

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be obtained various moisture contents (Table 1). The wet materials were placed and kept in sealed plastic bags for 12 h in a refrigerator at 5ºC. The samples were tempered for 2 h at room temperature prior to extrusion.

Extrusion

Lentil semolina was extruded in a laboratory single screw extruder (Brabender 20 DN, Germany). The compression ratio of the screw was 1:1, 2:1, 3:1, 4:1, 5:1 according to the experimental design (Table 1). The extruder barrel (476.5 mm in length and 20 mm in diameter) contained three sections and independently controlled die assembly electric heaters. The screw speed was 132, 160, 180, 200, 228 rpm. The temperature of the feed zone was 150ºC, that of the metering zone was 136, 150, 160, 170, 184ºC, and that of the extruder die was 136, 150, 160, 170, 184ºC. The feed screw speed was fixed at 70 rpm and the die diameter was 5mm.

Hardness and breaking strength index

Hardness and breaking strength index of the extrudates were determined using a texture analyzer TA.XT Plus (Stable Micro Systems, England), with a 50 kg load cell and a 2-bladed Kramer shear cell (2 mm thick, 32 mm high, 119 mm wide, 4 mm apart). The test settings were as follows: Pre-test speed 2 mm/s, Test speed 1 mm/s, Post-test speed 10 mm/s.

Hardness of the extrudates was the peak in the Force / Distance curve when the sample is broken (peak breaking force or collapse). Breaking strength index (BSI, N/mm) was calculated using peak breaking force (N) divided by the extrudate diameter (mm) [10, 11]. The reported values were the average of 20 determinations.

Bulk density

Bulk density (g/cm^3) of the extrudates was calculated by measuring the actual dimensions of the extrudates. The diameter and length of 10 pieces of randomly selected extrudate samples were measured by Vernier caliper. The weight of these extrudate pieces was determined by electronic weighing balance having an accuracy of 0.001 g. The bulk density was calculated using the following formula, assuming a cylindrical shape of extrudate [12, 13]:

$$Density = \frac{4W}{\pi D^2 L} \quad (1)$$

where W is weight (g), D is diameter (cm), and L is the length of the extrudate (cm).

Experimental design and data analysis

The central composite rotatable design (CCRD) is a widely adopted tool for optimization and drastically reduces the number of experiments for studies involving more than two independent variables [14, 15]. In the present study CCRD was used to show interactions of moisture content (X_1), barrel temperature (X_2), metering zone temperature (X_3), screw speed (X_4), and screw compression ratio (X_5) on the extrudate in 52 runs of which 32 were for the factorial points (run № 1-32), 10 were for axial points (run № 33-42), and 10 were for replications at the central point of the design (run № 43-52). The levels of the independent variables were established according to literature information and preliminary trials. The outline of the experimental design is outlined in Table 1.

To estimate moisture content, barrel temperature, metering zone temperature, screw speed, and screw compression ratio effects each objective response, the standardized scores were fitted to a quadratic polynomial regression model by employing a least square technique [16, 17]. The model proposed for the response of Y was:

$$y = b_0 + \sum_{i=1}^{n} b_i . x_i + \sum_{i=1}^{n} b_{ii} . x_i^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} b_{ij} . x_i . x_j \quad (2)$$

where y = the response (breaking strength index), b_0 = intercepts, b_i are linear, b_{ii} are quadratic, and b_{ij} are interaction regression coefficient terms. Coefficients of determination (R^2) were computed. The adequacy of the model was tested by separating the residual sum of squares into pure error and lack of fit. For each response, response surface plots were produced from the equations, by holding the variable with the least effect on the response equal to a constant value, and changing the other two variables [17].

SYSTAT statistical software (SPSS Inc., Chicago, USA, version 7.1) and Excel were used to analyze the data results.

RESULTS AND DISCUSSION

Chemical changes taking place during extrusion influence the development of textural and mechanical properties such as hardness and breaking strength in extrudates. Breaking strength index is the measure of the strength of cell wall which is expected to affect the texture and sensory crispiness of the extruded product [18]. The mean values of breaking strength index (BSI) of the extruded lentil semolina are shown in Table 1. BSI is in the range of 12.2 – 32.87 N/mm.

The results of the statistical analysis of variance (ANOVA) for the breaking strength index show that 6 effects have p-values less than 0.05, indicating that they are significantly different from zero at the 95.0% confidence level. The R-squared statistic is 0.82; the standard error of the estimate – 2.61, the mean absolute error – 1.58. The regression equation describing the effect of extrusion variables on the breaking strength index of extruded lentil semolina is given in Table 2. The coefficients in the regression equation can be used to examine the significance of each term relative to each other when used with coded values.

Table 1. Central composite rotatable design in coded form and natural units of independent variables and experimental data for breaking strength index

Run №	Independent variables in coded form					Independent variables in natural units					BSI (Y), N/mm	
	X_1	X_2	X_3	X_4	X_5	X_1	X_2	X_3	X_4	X_5	Experi-mental	Predicted
1	-1	-1	-1	-1	-1	22	150	150	160	2:1	20.23	25.80
2	+1	-1	-1	-1	-1	28	150	150	160	2:1	21.92	18.23
3	-1	+1	-1	-1	-1	22	170	150	160	2:1	25.92	27.00
4	+1	+1	-1	-1	-1	28	170	150	160	2:1	15.86	17.05
5	-1	-1	+1	-1	-1	22	150	170	160	2:1	32.87	27.63
6	+1	-1	+1	-1	-1	28	150	170	160	2:1	14.58	18.63
7	-1	+1	+1	-1	-1	22	170	170	160	2:1	29.86	27.97
8	+1	+1	+1	-1	-1	28	170	170	160	2:1	17.02	16.60
9	-1	-1	-1	+1	-1	22	150	150	200	2:1	19.51	18.56
10	+1	-1	-1	+1	-1	28	150	150	200	2:1	13.56	14.68
11	-1	+1	-1	+1	-1	22	170	150	200	2:1	19.55	20.54
12	+1	+1	-1	+1	-1	28	170	150	200	2:1	13.16	14.28
13	-1	-1	+1	+1	-1	22	150	170	200	2:1	21.03	22.96
14	+1	-1	+1	+1	-1	28	150	170	200	2:1	17.38	17.65
15	-1	+1	+1	+1	-1	22	170	170	200	2:1	22.19	24.09
16	+1	+1	+1	+1	-1	28	170	170	200	2:1	14.53	16.41
17	-1	-1	-1	-1	+1	22	150	150	160	4:1	25.59	22.15
18	+1	-1	-1	-1	+1	28	150	150	160	4:1	15.82	16.94
19	-1	+1	-1	-1	+1	22	170	150	160	4:1	28.96	26.70
20	+1	+1	-1	-1	+1	28	170	150	160	4:1	17.62	19.11
21	-1	-1	+1	-1	+1	22	150	170	160	4:1	16.71	18.24
22	+1	-1	+1	-1	+1	28	150	170	160	4:1	13.80	11.59
23	-1	+1	+1	-1	+1	22	170	170	160	4:1	19.27	21.94
24	+1	+1	+1	-1	+1	28	170	170	160	4:1	14.30	12.92
25	-1	-1	-1	+1	+1	22	150	150	200	4:1	14.67	16.17
26	+1	-1	-1	+1	+1	28	150	150	200	4:1	12.41	14.64
27	-1	+1	-1	+1	+1	22	170	150	200	4:1	20.21	21.50
28	+1	+1	-1	+1	+1	28	170	150	200	4:1	16.24	17.60
29	-1	-1	+1	+1	+1	22	150	170	200	4:1	15.31	14.83
30	+1	-1	+1	+1	+1	28	150	170	200	4:1	12.20	11.87
31	-1	+1	+1	+1	+1	22	170	170	200	4:1	19.88	19.31
32	+1	+1	+1	+1	+1	28	170	170	200	4:1	13.86	13.98
33	-2.378	0	0	0	0	18	160	160	180	3:1	31.18	31.06
34	2.378	0	0	0	0	32	160	160	180	3:1	17.64	15.72
35	0	-2.378	0	0	0	25	136	160	180	3:1	13.02	13.17
36	0	2.378	0	0	0	25	184	160	180	3:1	19.29	17.10
37	0	0	-2.378	0	0	25	160	136	180	3:1	23.56	20.87
38	0	0	2.378	0	0	25	160	184	180	3:1	18.10	18.74
39	0	0	0	-2.378	0	25	160	160	132	3:1	19.77	21.95
40	0	0	0	2.378	0	25	160	160	228	3:1	18.82	14.60
41	0	0	0	0	-2.378	25	160	160	180	1:1	25.00	22.66
42	0	0	0	0	2.378	25	160	160	180	5:1	15.13	15.43
43	0	0	0	0	0	25	160	160	180	3:1	19.60	17.90
44	0	0	0	0	0	25	160	160	180	3:1	18.61	17.90
45	0	0	0	0	0	25	160	160	180	3:1	17.11	17.90
46	0	0	0	0	0	25	160	160	180	3:1	17.39	17.90
47	0	0	0	0	0	25	160	160	180	3:1	16.73	17.90
48	0	0	0	0	0	25	160	160	180	3:1	19.23	17.90
49	0	0	0	0	0	25	160	160	180	3:1	18.42	17.90
50	0	0	0	0	0	25	160	160	180	3:1	17.10	17.90
51	0	0	0	0	0	25	160	160	180	3:1	18.38	17.90
52	0	0	0	0	0	25	160	160	180	3:1	17.82	17.90

X_1 - moisture content (W, %), X_2 - barrel temperature (T_m, °C), X_3 - metering zone temperature (T_2, °C), X_4 - screw speed (rpm), X_5 - screw compression ratio.

Table 2. Regression equation coefficients and analysis of variance for BSI of lentil extrudates

Variables	Coefficients	*DF*	*MS*	*p* values
Constant	95.7743			
X_1	-4.7449	1	450.600	0.0000*
X_2	2.0568	1	29.5114	0.0457*
X_3	-0.6338	1	8.7126	0.2666
X_4	-1.2378	1	103.329	0.0005*
X_5	-0.8916	1	99.9447	0.0006*
X_1X_1	0.1077	1	54.9907	0.0079*
X_2X_2	-0.0049	1	14.0505	0.1609
X_3X_3	0.0034	1	6.6256	0.3315
X_4X_4	0.0002	1	0.2481	0.8499
X_5X_5	0.2012	1	2.3699	0.5595
X_1X_2	-0.0198	1	11.2813	0.2075
X_1X_3	-0.0119	1	4.0613	0.4458
X_1X_4	0.0154	1	27.1584	0.0546
X_1X_5	0.1958	1	11.0450	0.2122
X_2X_3	-0.0021	1	1.4365	0.6492
X_2X_4	0.0010	1	1.2246	0.6744
X_2X_5	0.0838	1	22.4785	0.0789
X_3X_4	0.0032	1	13.2355	0.1732
X_3X_5	-0.1436	1	65.9526	0.0040*
X_4X_5	0.0157	1	3.1626	0.5006

*Significant at 95% confidence level, *DF* – degrees of freedom, *MS* - mean square

Each of the estimated effects and interactions are shown in the standardized diagram - the Pareto diagram (Fig.1). It consists of horizontal blocks with lengths proportional to the absolute values of the estimated effects, divided by their standard errors. The vertical line in the Pareto diagram represents the value of the Student criterion at 95 % confidence level and separates factors that are significant to those that are not. The diagram shows the predominance of the moisture content (factor A). Other researchers also found that feed moisture is the main factor affecting the physicochemical properties of extrudates [12, 15]. Next in order of importance is the screw speed (factor D) and screw compression ratio (factor E). The least influential parameter is the barrel temperature (factor B). The metering zone temperature (factor C) has no significant effect on BSI.

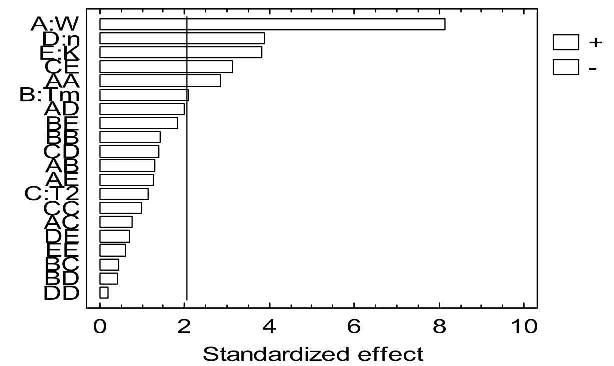

Fig.1. Estimated effects of regression model coefficients on breaking strength index

Response surface plots are developed based on the regression equations (see Table 2) to understand the effect of extrusion process variables on BSI. Surface plots are drawn for each of the two variables, where the other three variables are kept at the center point of the experimental design. Some important surface plots are given in Fig.2 and Fig.3.

It is well known that the decrease of moisture content in extrusion tends to increase specific mechanical energy, and consequently to favor macromolecular degradation of starch though dextrinization. The resulting melt then gives more fragile structures leading to low resistant cell walls and more structural fractures. In contrary, lentil flour (protein source) resulted in more rigid structures and elevated values of elastic modulus. Our results show that the breaking strength index of the extruded lentil semolina decreases about 2 times with raising the moisture content from 18 to 32% at barrel temperature 160ºC, metering zone temperature 160ºC, screw speed 180 rpm, and screw compression ratio 3:1. Gujska and Khan [19] have extruded high starch fractions of navy, pinto and garbanzo beans with different moisture contents. They have reported that increasing moisture content resulted in decreased density for navy and garbanzo beans and an increase for pinto bean. Decreased bulk density of extrudates was associated with high expansion index, low hardness and breaking strength [20]. Avin et al. [21] reported that density of extruded red bean is not influenced by temperature, moisture, or screw speed. Balandran-Quintana et al. [22] have extruded pinto bean flours at three different die temperatures (140, 160, and 180ºC), feed moisture content (18, 20, and 22%), and screw speeds (150, 200, and 250 rpm). They have reported that the density was influenced by moisture and temperature and it decreased with increasing temperature for 18 and 20% moisture feed. For 22% moisture the density decreased between 140 and 160ºC and increased abruptly between 160 and 180ºC.

An increase in screw speed resulted in an extrudate with lower hardness and breaking strength (see Fig.3). It is possible that an increase in screw speed may be expected to lower the melt viscosity of the material in the extruder, resulting in a less dense, softer extrudate [12].

Breaking strength index of lentil extrudates is positively correlated with hardness (R^2 = 0.77, $p <$ 0.05) (Fig.4) which is determined by measuring the maximum force required to break the extruded samples. Breaking strength index is also positively correlated with density (R^2 = 0.77, $p < 0.05$) (Fig.5). Similar results are observed by Altan et al. [23]. They investigated the effect of screw configuration and raw material on some properties of barley extrudates and established that hardness of extrudates is positively correlated with bulk density and breaking strength ($R^2 = 0.725$, $R^2 = 0.865$, $p < 0.05$), whereas negatively correlated with sectional expansion index ($R^2 = 0.470$, $p < 0.05$). High density product naturally offers high breaking strength while the increase in pore size together with a decrease in cell wall thickness results in weak extrudate structures. Breaking strength is affected by the strength of cell walls, as influenced by starch gelatinization and protein denaturation [24].

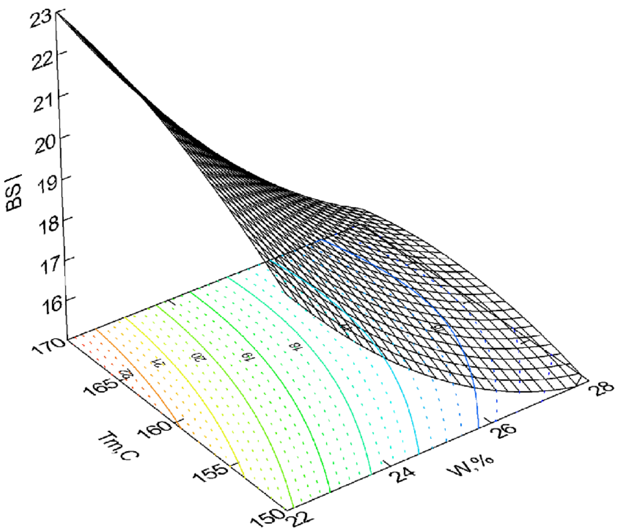

Fig.2. Effect of moisture content and barrel temperature on breaking strength index

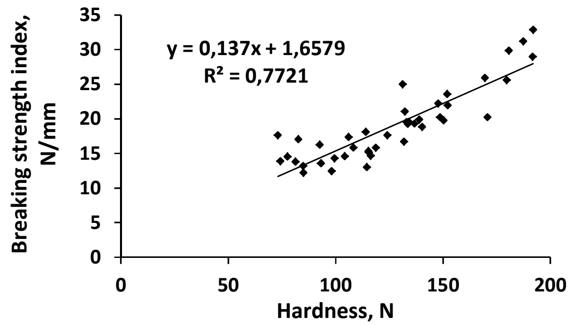

Fig.4. Breaking strength index versus hardness

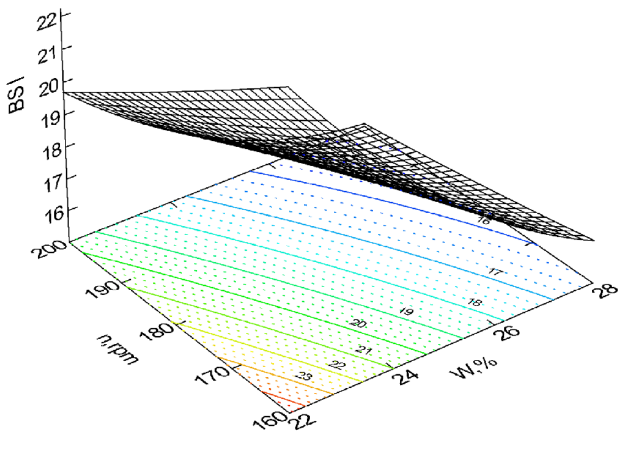

Fig.3. Effect of moisture content and screw speed on breaking strength index

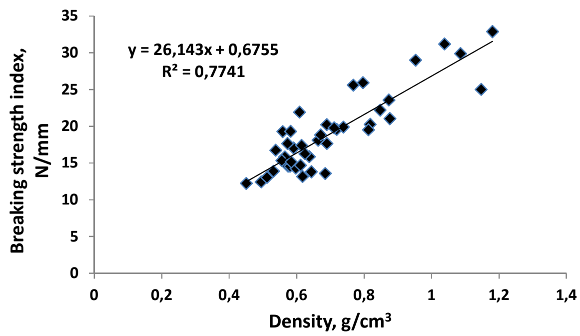

Fig.5. Breaking strength index versus density

CONCLUSION

The breaking strength index of lentil extrudates produced on a laboratory single screw extruder was dependent on several process variables. Moisture content, barrel temperature, screw speed, and screw compression ratio had some significant effect on BSI. The metering zone temperature had no significant effect on BSI. The breaking strength index was found to be most dependent on moisture content. The study showed that BSI of the extruded lentil semolina decreased with raising the moisture content. An increase in screw speed resulted in an extrudate with lower breaking strength. Breaking strength index of lentil extrudates was positively correlated with hardness and bulk density.

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