processes

MDPI

Article

Effect of Extruder Configuration and Extrusion Cooking Processing Parameters on Selected Characteristics of Non-Starch Polysaccharide-Rich Wheat Flour as Hybrid Treatment with Xylanase Addition

Piotr Lewko [1,2], Agnieszka Wójtowicz [1,*] and Monika Różańska-Boczula [3,*]

[1] Department of Thermal Technology and Food Process Engineering, University of Life Sciences in Lublin, Głęboka 31, 20-612 Lublin, Poland; piotr.lewko@up.lublin.pl
[2] PZZ Lubella GMW Sp. z.o.o., Wrotkowska 1, 20-469 Lublin, Poland
[3] Department of Applied Mathematics and Computer Science, University of Life Sciences in Lublin, Głęboka 28, 20-612 Lublin, Poland
* Correspondence: agnieszka.wojtowicz@up.lublin.pl (A.W.); monika.boczula@up.lublin.pl (M.R.-B.)

Abstract: The effects of a single-screw extruder configuration and processing variables such as conventional extrusion or hybrid treatments with xylanase were tested on the extrusion performance and selected characteristics of the developed non-starch polysaccharide-rich (NSP-rich) wheat flour. L/D 16 and 20 extruder configurations with various screw profiles were used. The interactions between processing variables (moisture content 23, 25, 27%; screw speed 40, 60, 80 rpm; xylanase level 0, 50, 100 ppm) were assessed to indicate energy consumption and the rheological properties of flour. The results showed that the possibility of obtaining enzyme-assisted extruded flour products derived from flours of varying characteristics depended on the processing conditions. The application of various extruder configurations and screw profiles showed significant effects on both processing behavior and rheological characteristics. The longer L/D 20 extruder configuration using a screw profile with mixing elements allowed us to obtain products with lower extrusion pressure (max. 20.8 bar) and energy requirements (max. SME = 33.1 kWh/kg) and better rheological properties (max. Hyd = 69.2%, less intensive starch gelatinization with max. C3 = 1.47 Nm) than the L/D 16 version. The extruded wheat flour was characterized by improved hydration properties and limited retrogradation tendency, especially when hybrid extrusion with xylanase was applied. This may lead to favorable results, as the newly developed enzymatic extrusion modification method produces NSP-rich wheat flour with specific techno-functional and rheological characteristics that can be seen as a potential "clean label" enhancer in bakery products. Our statistical analysis confirmed feed moisture and screw speed to be the variables with the most significant effect on wheat flour features.

Keywords: extrusion; screw configuration; processing variables; screw speed; energy consumption; wheat flour; rheological properties; hydration; RSM analysis

check for updates

Citation: Lewko, P.; Wójtowicz, A.; Różańska-Boczula, M. Effect of Extruder Configuration and Extrusion Cooking Processing Parameters on Selected Characteristics of Non-Starch Polysaccharide-Rich Wheat Flour as Hybrid Treatment with Xylanase Addition. *Processes* **2024**, *12*, 1159. https://doi.org/10.3390/pr12061159

Academic Editor: Cunshan Zhou

Received: 29 April 2024
Revised: 25 May 2024
Accepted: 29 May 2024
Published: 4 June 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Extrusion cooking is an economical processing method that allows the rapid direct or indirect transformation of proteins, starch and cellulose polymers to be achieved [1]. The extrusion of cereal-based products has advantages over other processing methods because of its low cost, short processing time, high productivity, versatility, unique product shapes, and energy savings [2]. In order to produce extruded goods, it is crucial to understand that the physicochemical changes that occur during extrusion cooking processing depend on the conditions and equipment applied [3]. Extrusion is used for the production of ready-to-eat cereals, snacks and food additives with different swelling properties. Most changes during extrusion cooking (swelling, viscosity or water absorption) depend on

the initial starch content. The thermo-mechanical treatment of cereal materials causes starch modification, especially partial or full gelatinization, depending on the feed moisture content, temperature range, shearing intensity, extruder configuration, treatment intensity and processing conditions. Several authors reported various levels of starch damage and gelatinization depending on the processing variables used, especially water content, screw speed and energy input during processing [4–6]. Wheat flour also has a protein content of more than 10%, and a major part of wheat protein is gluten. This component is responsible for the unique structures of bakery products.

In extrusion cooking processing, the contained food components may have greater or lesser involvement in the formation of the specific textural and microstructural properties of the extrudates [7,8]. The main process connected with the extrusion of plant materials or cereals containing proteins is protein aggregation, or the simultaneous fragmentation and aggregation of wheat proteins due to intermolecular disulfide bonding. This can change the rheological behavior of dough [9–11]. In the work of Wu et al. [12], wheat flour was extruded by single- and a double-screw extruders under various parameters, followed by quantifying the protein content, analyzing the free sulfhydryl and disulfide bonds and lysinoalanine, and reducing the total sugar in the extruded flour. The extrusion of wheat and rye bran at variable conditions was found by Anderson et al. [13] to be an effective method for increasing the extractability of dietary fibers, especially AX, and the extruded bran showed improved nutritional properties, such as fermentability. Aktas-Akyildiz et al. [14] showed that extrusion treatment can be used to disrupt the microstructure of wheat bran and thus to increase its soluble fiber content. Demuth et al. [15] found significant changes in the structure of water-soluble wheat bran arabinoxylans processed through extrusion. Singkhornart et al. [16] noted a reduction in sugar and soluble arabinoxylan content in corn bran due to changes in feed moisture content and screw speed with/without chemical pretreatment. The combined enzymatic and thermal/extrusion treatments of cereal products may increase the changes in cereals after treatments. Kong et al. [17], for example, tested co-enzymatic and extrusion treatment of black wheat bran, using cellulase, xylanase, high-temperature α-amylase and acid protease individually or in combination. They noted significant increases in water extractable arabinoxylan content, water and oil holding capacity, and cholesterol adsorption capacity, probably due to the creation of a looser and more porous microstructure.

Enzymatic extrusion can be applied to cereal grains and flour under the conditions of high substrate concentration and under elevated temperature, pressure and shear stress at various moisture levels. However, the presence of thermolabile ingredients as enzymes or fat in flour requires the use of low processing temperatures with a consequent lack of product expansion and limited temperature-dependent changes in the extruded materials [18]. This can also be avoided by using thermostable enzymes that can improve product texture [19]. Bakery enzymes play important roles in dough formation and bread volume; product crispness, color and browning reactions during baking; and in reducing retrogradation and staling [20]. Research confirms the positive effect of cellulase or xylanase on the functionality of non-starch polysaccharides, found mainly in the outer layers of cereal grains [21]. Xylanase is responsible for water distribution from the pentosan phase to the gluten phase [22]. This is the cause of xylanase's impact on bread volume improvement via increasing the extensibility of gluten due to a rise in gluten volume fraction [23,24]. Additionally, xylanases have been shown to delay staling, enhance the texture of high-fiber bread and balance out the variable quality of flour used in baking wheat bread.

There are some reports about improving the properties of cereal products by extrusion or enzymatic extrusion treatments. Moreno-Rivas et al. [25] reported single-screw extrusion in the temperature range of 60, 70, 80 and 90 °C suitable for limiting fat extractability and increasing protein solubility in nixtamalized corn flour, without or with xylanase, which lowered this effect. Of note, limited fat content may extend the shelf life of extruded flour products [26]. Martinez et al. [27,28] tested the single-screw extrusion of common wheat flour with 4–16% initial water content and in the temperature range of 60–140 °C. These

extruded flours treated at variable conditions were added in concentrations of 5% and were used as additives in bread preparation. The authors found that the addition of extruded wheat flour caused an increase in dough hydration of about 9% when extreme conditions were applied, due to the higher starch gelatinization degree and damage. The stability of dough with added extruded flour decreased if more intensive treatment conditions were applied during extrusion. When alveographic analysis was performed on the supplemented flour, the results showed that a 5% addition had no negative effect on the overall strength values of the dough. The extrusion of flour decreased extensibility but improved dough tenacity, most visibly when extreme extrusion conditions were applied. Also, the addition of extruded flour may be suggested as a replacement for pregelatinized starch [28].

Bread improvers may be chemical agents with oxidation-reduction properties or directly added enzymes that may affect the gluten network of wheat flour. Industrial bread production and recipes have been changing in recent years due to growing consumer concerns about food ingredients. Some bread improvers are perceived as unknown and harmful chemicals, and some of them may cause health problems [29]. Extruded wheat flour may be an interesting additive as a replacement for chemically modified starches, pregelatinized (hydroxypropylated or cross-linked) starches [30] or hydrocolloids, and may change the properties of bread flour, especially in the context of increasing baking efficiency or bread texture [28,31]; however, the techno-functional properties of extruded flours may vary depending on the processing conditions. Moreover, there is a lack of knowledge about the impact of the single-screw extruder configuration or a multivariate analysis of the impact of processing conditions and enzyme levels on the extrusion behavior, technical–functional and rheological properties of wheat flour, especially those containing high levels of non-starch polysaccharides. So, the aim of this work was to apply variable conditions to the low-temperature single-screw extrusion process using two different extruder configurations (L/D 16 and L/D 20) and screw designs to modify the developed NSP-rich wheat flour in the absence/presence of xylanase and to evaluate the influence of variables on the process performance, techno-functional and rheological characteristics of the extruded flour.

2. Materials and Methods

2.1. Raw Materials and Proximate Composition

A new wheat flour blend (type 750 from common wheat of the Laudis variety), containing selected breaking, milling, reducing and sifting passages developed according to Lewko et al. [32] and characterized by a high content of non-starch polysaccharides, was used for tests. The proximate composition of NSP-rich wheat flour was tested according to the following methods: protein (Nx6.25) with the AACC 46–10 method, fat with the AACC 30–10 method, ash with the AACC 08–01 method [33] and total dietary fiber (TDF) and its soluble (SDF) and insoluble (IDF) fractions with the enzymatic–gravimetric 991.43 method [34]. Additionally, polysaccharide composition was tested by gas chromatography according to the method described by Lewko et al. [32]. All analyses were performed in triplicate. The enzyme VERON 292—Xylanase from *Aspergillus niger* with the declared enzyme activity of min. 1701 XylH/g was supplied by Barentz Sp. z o.o. (AB Enzymes, Darmstadt, Germany).

2.2. Extrusion Processing

The tests of conventional extrusion and hybrid enzyme-assisted extrusion treatments were carried out with the use of a prototype single-screw extruder, EXP-45-32, with a forming die of 3 mm (built by Zamak Mercator, Skawina, Poland). Two versions of the extruder with L/D = 16 and L/D = 20 were used: a conventional screw with a continuous spiral pattern in the shorter version, and a newly designed screw with mixing elements (helices with indentations on a spiral pattern located alternately with a continuous spiral pattern) placed on three-quarters of the screw length in the longer version. Three variables were applied in the experiment: feed moisture, screw speed and enzyme dose. The newly developed

wheat flour blend [32] was fortified with the addition of powdered xylanase in amounts of 50 and 100 ppm and dry-mixed. In conventional extrusion, this step was avoided. Next, the mixtures were moistened to obtain the initial blend moisture contents of 23, 25 and 27%, left for 2 h for enzyme activation and sieved to ensure the homogeneity of composition and moisture distribution. Moistened samples were subsequently subjected to low-temperature extrusion cooking at the screw speeds of 40, 60 and 80 rpm at temperatures ranging from 40 to 80 °C in the individual zones of the extruder. In the L/D 16 version, four sections were used, with the temperature settings starting from the feeding zone being 30, 40, 60 and 80 °C, while in the L/D 20 version, five sections were used with the temperature settings starting from the feeding zone being 30, 40, 60, 80 and 80 °C. The forming die temperature was 80 °C. Temperature and screw speeds (rpm) were kept constant throughout individual experiments at each variable setting. The EXP-45-32 single-screw extruder is well equipped with a precise barrel heating/cooling system combined with individual chillers for each section, so the temperature control was very stable. Samples were collected after process stabilization at least 30 min after changing variables. The obtained extrudates were cut into small pieces by a cutting device connected to the extruder and dried in a laboratory shelf dryer at 40 °C to a final moisture content below 9% and ground on an LMN-100 knife mill (TestChem, Radlin, Poland) to powder with a particle size below 300 µm. The final moisture content was tested with the moisture analyzer MA.50.R.WH (Radwag, Radom, Poland).

2.3. Extrusion Performance

During the single-screw extrusion (with two different extruder L/D configurations being applied), the processing conditions were monitored and the following data shown on the LCD screen of the extruder control cabinet were archived: the extrusion pressure (bar), torque (Nm), engine load (%) and active power (kW). The processing efficiency (kg/h) was calculated as the amount of flour obtained at a certain time according to the following equation [35,36]:

$$Q = \frac{m}{t} \text{ (kg/h)} \quad (1)$$

where: Q—processing efficiency (kg/h), m—mass of the obtained extrudate (kg), and t—measurement time (h).

Specific mechanical energy (SME) was calculated based on the extruder characteristics and the obtained process output according to the following equation [35,36]:

$$SME = \frac{n \times L \times P}{n_{max} \times 100 \times Q} \text{ (kWh/kg)} \quad (2)$$

where: SME—specific mechanical energy (kWh/kg), n—screw rotations (rpm), P—electric power (kW), L—engine load (%), n_{max}—maximum screw rotations (rpm), and Q—process efficiency (kg/h).

All parameters were registered in triplicate.

2.4. Rheological Properties of Modified Flour

The selected techno-functional and rheological characteristics were tested in conventional extrusion-treated and hybrid enzymatic-extrusion-treated flours without and with the addition of xylanase enzyme and subjected to diverse extrusion procedures. The rheological properties of modified flours were examined by using Mixolab® (Chopin Technologies, Villeneuve-la-Garenne, France) according to ISO 17718-1:2013 [37]. In brief, the Chopin+ flour protocol with the following settings was used: mixing speed—80 rpm, total analysis time—45 min, dough weight—75 g, hydration water temperature—30 °C. Modified flour and water were added accordingly to obtain a dough with a maximum consistency of 1.10 Nm (±0.05) during the first test phase. The Mixolab test was performed using a standard protocol: 8 min at 30 °C, heating for 15 min at a rate of 4 °C/min, holding at 90 °C for 7 min, cooling for 10 min to 50 °C at a rate of 4 °C/min and holding at 50 °C for

5 min [38]. The following techno-functional and rheological features were tested with the Mixolab procedure: water absorption (Hyd), based on the amount of water necessary to reach maximum torque during mixing (1.10 Nm); dough stability (Stab.); protein weakening (C2), based on the mechanical work and temperature increase; maximum torque during the heating stage (C3), expressing the rate of starch gelatinization; minimum torque during the heating period (C4), indicating the stability of the hot gel formed and the amylase activity; C5, the torque after cooling at 50 °C, representing starch retrogradation during the cooling stage; slope α—between the end of the 30 °C period and C2, showing the speed of the protein weakening under a heating effect; slope β—between C2 and C3, acting as an indicator of pasting (gelatinization) speed; and slope γ—between C3 and C4, showing enzymatic (α-amylase) degradation speed [36,39,40]. All the measurements were performed in triplicate.

2.5. Statistical Analysis

Table 1 presents the experimental design along with the coded value representations.

Table 1. Experimental design trials with coded value representations.

Trial Number	M = Feed Moisture (%)	M Code	S = Screw Speed (rpm)	S Code	E = Enzyme Dose (ppm)	E Code
1	23	−1	40	−1	0	−1
2	23	−1	40	−1	50	0
3	23	−1	40	−1	100	1
4	23	−1	60	0	0	−1
5	23	−1	60	0	50	0
6	23	−1	60	0	100	1
7	23	−1	80	1	0	−1
8	23	−1	80	1	50	0
9	23	−1	80	1	100	1
10	25	0	40	−1	0	−1
11	25	0	40	−1	50	0
12	25	0	40	−1	100	1
13	25	0	60	0	0	−1
14	25	0	60	0	50	0
15	25	0	60	0	100	1
16	25	0	80	1	0	−1
17	25	0	80	1	50	0
18	25	0	80	1	100	1
19	27	1	40	−1	0	−1
20	27	1	40	−1	50	0
21	27	1	40	−1	100	1
22	27	1	60	0	0	−1
23	27	1	60	0	50	0
24	27	1	60	0	100	1
25	27	1	80	1	0	−1
26	27	1	80	1	50	0
27	27	1	80	1	100	1

All responses from extrusion processing and the rheological properties of the modified wheat flours were subjected to response surface analysis using RSM (Response Surface Methodology) using the input variables [41]. The test results were analyzed with RSM by selecting the independent factors of moisture content, screw speed, enzyme dose and its interactions, for the L/D 16 and L/D 20 extruder configurations separately. RSM with quadratic fit was applied and models were created for each combination of independent factors. For each extruder configuration, the second-order regression equations were independently applied using Statistica 13.3 (Statsoft, Tulsa, OK, USA) and the open-source software R, version 4.3.1, package: RSM, version 2.10.4 [42]:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11}(X_1)^2 + \beta_{22}(X_2)^2 + \beta_{33}(X_3)^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 \quad (3)$$

where Y is the response factor being indicated, β_0 represents a constant value, β_i for $i = 1, 2, 3$ represents a linear coefficient, β_{ij} where $i = j$ represents a quadratic coefficient, and β_{ij} where $i \neq j$ represents an interactive coefficient when $i, j = 1, 2, 3$. X_i and X_j represent the input variables of moisture (M), screw speed (S) and enzyme dose (E) and were coded at levels of −1, 0 and 1 for each factor, respectively. All coefficients were characterized for significance as either slightly significant ($p < 0.10$), significant ($p < 0.05$) or very significant ($p < 0.01$).

The coefficient of determination (R^2) expressed the model's validation and a F-test ascertained its statistical significance. The significance of differences was assessed by the analysis of variance test (ANOVA) followed by the Tukey post hoc test at the 0.05 significance level. Homogenous groups were indicated with similar letters at the significance level of 0.05.

3. Results and Discussion

3.1. Effect of Variables on Extrusion Performance

NSP-rich wheat flour from selected breaking, milling, reducing and sifting passages was developed [32] to determine the possibility of using previously unused passages produced in the milling factory with increased content of polysaccharides and arabinoxylans. The proximate composition of NSP-rich wheat flour was as follows (g/100 g): protein 14.62 ± 0.06, fat 1.31 ± 0.01, ash 0.72 ± 0.02, insoluble dietary fiber 3.94 ± 0.04, soluble dietary fiber 2.86 ± 0.02 and total dietary fiber 6.80 ± 0.03. Additionally, the polysaccharide composition of the flour used in the experiment was as follows: total arabinoxylans 1.91 ± 0.06, including 1.31 ± 0.04 of insoluble fraction and 0.60 ± 0.02 of soluble fraction, and total non-starch polysaccharides 3.40 ± 0.00, including 2.06 ± 0.01 of insoluble fraction and 1.34 ± 0.00 of soluble fraction. Wheat flour may vary depending on the content and composition of the milling fractions. Previously, an aleurone-rich wheat milling fraction was developed at the industrial scale [43]. Bucsella et al. [44] found and characterized an aleurone-rich flour composed from bran-rich milling fractions that lacked the outer layers of the grain. This aleurone-rich flour showed a different composition (20% protein, 15% dietary fiber) to that of commercial fiber-rich wheat fractions (9–13% protein, 9% dietary fiber). The higher amount of inner layers on the seed coat than in white or wholegrain flour resulted in a higher fat content (4%), which may decrease the shelf life of bran-rich wheat flour products. Thermal treatments, such as dry thermal heating, hydrothermal treatment or extrusion, may increase the storage stability of wholegrain flour or bran-rich products due to the formation of lipid–amylose complexes [3]. Additionally, extrusion seems to be a processing method that increases the proportion of extractable dietary fiber, including arabinoxylans, and makes cereal bran and bran-rich flours more sensorially acceptable [45].

Extrusion processing was tested using either a conventional treatment or a hybrid treatment with the addition of xylanase to check the possibility of obtaining extruded flour with certain characteristics that depended on processing conditions (two different extruder configurations and screw profiles). During the low-temperature extrusion processing of the developed NSP-rich wheat flour without or with the addition of xylanase, several features were monitored and registered—the extrusion pressure (bar), torque (Nm), engine load (%), active power (kW), processing efficiency (kg/h) and specific mechanical energy (SME)—separately for both extruder configurations, L/D 16 and L/D 20, used in the experiment.

Figure 1 shows the results of extrusion pressure affected by L/D configuration and the interaction of each of the two input variables if L/D 16 and L/D 20 were applied for processing, respectively: E × M (Figure 1a,d), E × S (Figure 1b,e) and M × S (Figure 1c,f).

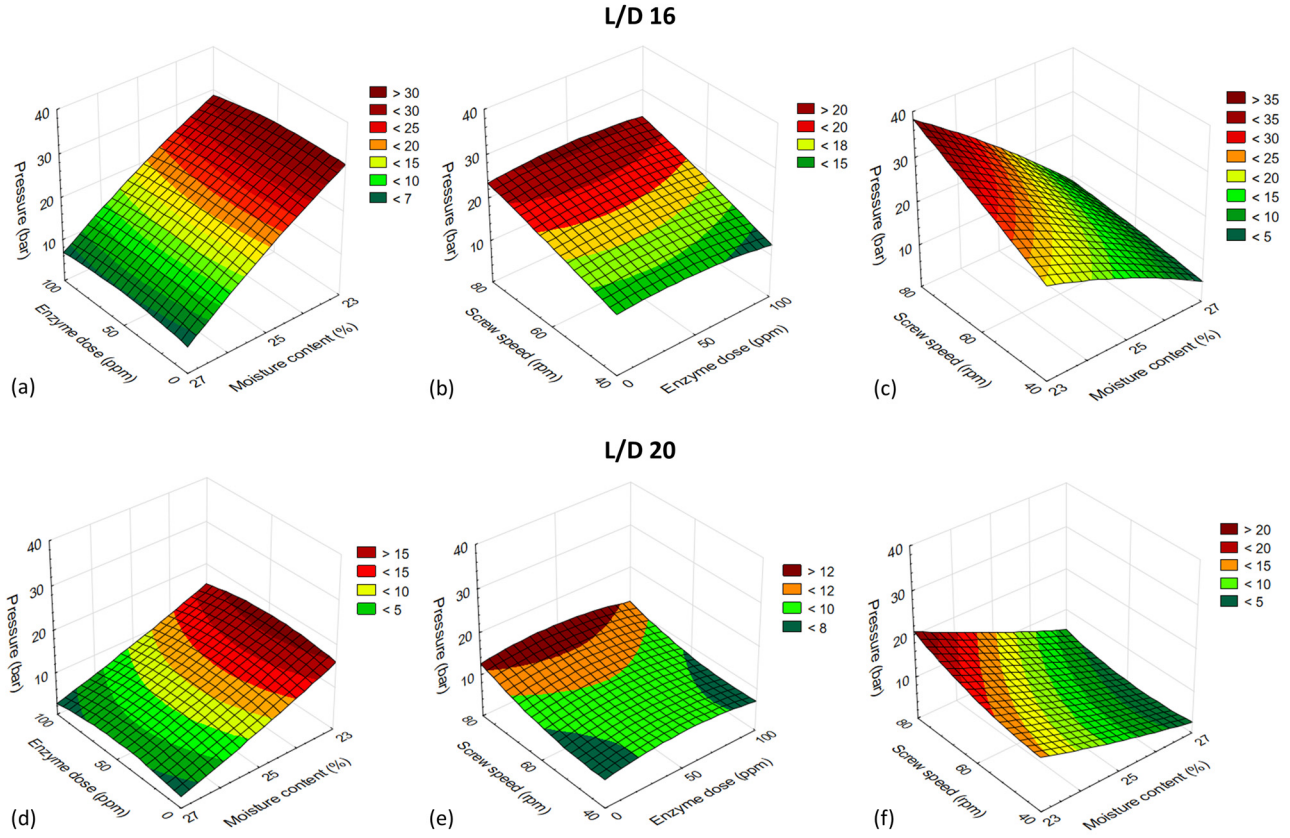


Figure 1. Processing pressure during the extrusion cooking of wheat flour with xylanase enzyme. L/D 16: (**a**) E × M, (**b**) E × S, (**c**) M × S; L/D 20: (**d**) E × M, (**e**) E × S, (**f**) M × S. M—moisture; S—screw speed; E—enzyme dose.

Pressure results varied from 3.5 to 41.7 bar for the short extruder and from 2.5 to 21.3 bar for the elongated configuration. The lowest pressure was noted at the highest (27%) moisture content and increased to max values when extrusion was carried out at 23%—the lowest feed moisture. The most significant parameters affecting the changes in extrusion pressure were the feed moisture and screw speed applied in both versions of the extruder. In the shorter version of the extruder, much higher pressure was generated at a similar flour feed rate due to the smaller internal space. This may have affected the filling degree of the interzonal elements of the screw helix or flights and, consequently, much higher pressure was required to transfer the hot, high-viscosity molten mass in through the forming die. The application of a newly designed screw profile with mixing elements (a helix with indentations on a spiral pattern alternating with a continuous spiral pattern) in the L/D 20 extruder configuration induced better mixing and disengagement of the molten dough. This resulted in much lower pressure results and less intensive compression of the material between the external surfaces of the screw and the internal grooved surfaces of the barrel. Such an outcome can also modify the residence time distribution during processing and thus may have effect on wheat flour components transformation intensity. NSP-rich wheat flour was found to have significant negative linear relationships between pressure and M but significant positive linear relationships between pressure and S for L/D 16 and L/D 20 (Table 2).

Table 2. Regression coefficients for response surface models of processing conditions of wheat flour, using coded inputs.

	Pressure (bar)	Torque (Nm)	Load (%)	Active Power (kW)	Process Efficiency (kg/h)	SME (kWh/kg)
			L/D 16			
Const.	20.640 ***	69.181 ***	19.542 ***	0.881 ***	25.991 ***	0.214
M	−11.557 ***	16.581 ***	4.684 ***	−0.090	−0.720	−0.006
S	5.150 ***	−1.966	−0.556	−0.010	8.827 ***	−0.019
E	−0.350	0.120	0.034	0.005	−0.800	0.005
M × M	−1.160	26.089 ***	7.370 ***	−0.303 ***	−0.773	−0.039
S × S	−0.248	−7.076	−1.999	0.015	0.507	−0.001
E × E	−1.203	3.323	0.939	−0.289 **	0.107	−0.087
M × E	0.601	−4.346	−1.228	0.005	−0.040	−0.005
S × E	0.509	1.987	0.562	−0.091	0.080	−0.023
M × S	−3.123 ***	1.181	0.333	0.012	0.240	−0.005
p-value of F test	<0.0001 ***	0.0431 **	0.0431 **	0.0736 *	<0.0001 ***	0.2325
R^2	0.913	0.356	0.356	0.299	0.885	0.142
			L/D 20			
Const.	9.4098 ***	112.420	31.754	0.272 ***	27.004 ***	0.099 ***
M	−6.435 ***	14.803	4.180	0.047	0.787	0.035 **
S	2.608 ***	−0.799	−0.223	−0.057	7.347 ***	−0.025
E	−0.227	6.265	1.772	0.068	−0.147	0.040 **
M × M	0.467	−5.042	−1.422	−0.019	−6.093 ***	0.025
S × S	1.576 **	−20.803	−5.873	−0.012	−0.093	−0.036
E × E	−1.837 **	18.051	5.100	0.106	1.587	0.044
M × E	0.154	6.494	1.831	0.092	−0.460	0.048 **
S × E	−0.361	7.511	2.126	−0.131 **	−1.020	−0.037 **
M × S	−1.426 **	4.815	1.356	−0.080	0.860	−0.031
p-value of F test	<0.0001 ***	0.3593	0.3596	0.0412 **	0.0007 ***	0.0035 ***
R^2	0.915	0.062	0.062	0.357	0.700	0.551

SME—specific mechanical energy; M—moisture; S—screw speed; E—enzyme dose. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

The pressure was also found to have a significant positive quadratic relationship with S and a significant negative quadratic relationship with E if the L/D 20 extruder was used. A significant minor effect of the M × S interaction was found in both extruder configurations (L/D 16, L/D 20). The interaction between moisture and screw speed significantly influenced the extrusion pressure. An antagonistic effect indicates that higher moisture levels combined with an increased screw speed resulted in a lower extrusion pressure (L/D 16). The high coefficient of determination R^2 and the significant result of the F test proved that the obtained model can adequately describe pressure. Upon comparing the constant values of pressure models as prepared for both configurations of the extruder, in the L/D 20 configuration, a significantly lower pressure was generated. Moreover, in each configuration, the pressure decreased significantly with an increase in the initial moisture content M (r = −0.866 for L/D 16 and r = −0.869 for L/D 20). Because many of the regression coefficients deviated further from zero for the L/D 16 configuration, this means that pressure-related changes are more important for L/D 16 than for L/D 20. The longer barrel length and mixing element of the screw resulted in a longer residence time and a lower compression of the extruded material within the internal spaces between barrel and screw, so the pressure observed during the extrusion of wheat flour was twice as low in the L/D 20 configuration than in the L/D 16 version. Increasing the initial moisture of the flour during processing in the L/D 16 configuration also lowered the pressure inside the barrel. Here, only a slight effect of enzyme dose was evident (if 100 ppm was used). The decrease in pressure was noted at the lowest initial moisture content, suggesting the partial hydrolysis of fibrous fractions by xylanase and thus a loosening of the structure of the treated material.

Pilli et al. [19] found significant effects of independent variables on the die pressure during twin-screw extrusion of wheat flour with enzymes added. They reported this parameter as negatively influenced by barrel temperature and dough moisture, i.e., pressure decreased at high barrel temperature and dough moisture. Die pressure decreases when water content increases because of the reduction in molten/gelatinized starch viscosity inside the extruder [46,47]. Also, Kantrong et al. [48] found the feed moisture of the material to be the most important process parameter affecting pressure inside the extruder barrel, the strain applied to the extrudates and the SME, resulting in differences in a product's characteristics. The interaction between dough moisture and xylanase shows a positive effect on the pressure, which, in our experiment, increased with the increase in dough moisture and xylanase content, and this could be attributed to the decrease in enzymatic activity caused by the high moisture content [46]. Water is required to maintain the catalytically active conformation of an enzymatic system. On the other hand, during the denaturation process, it acts as a plasticizer, which allows the enzyme molecules to unfold, resulting in the loss of native conformation [49].

The screw construction used in the experiment in both configurations had a compression ratio of 3:1, so along with the extruder length, the flow of the melted material was limited by a shallow channel impeding the flow of material inside the barrel as a result of the non-Newtonian behavior of the raw plant materials during extrusion. This effect is opposite to that of plastic or rubber [2,3]. The application of a screw profile with a mixing element in L/D 20 caused a loosening of the compaction of the molten material, which was once again agglomerated just before the forming die. This is the effect of viscosity changes within the transferred material due to it being heated, melted and compressed, as well as its change from a powder form to a viscous liquid due to the addition of water inside the barrel sections towards the exit of the forming die [2].

In Tables 3 and 4, torque, load and active power data are listed for both extruder configurations, L/D 16 and L/D 20, as dependent on processing variables. As the viscosity is measured through torque determination in the RVA system, the higher viscosity may also be interpreted by the torque obtained in the extrusion process. Because the torque value is measured in the extrusion process, the extruder can also be treated as a torque rheometer [50]. Here, it is evident that torque (Nm) values were in general higher in the L/D 20 version of the extruder (with its additional mixing zone). The torque reported for L/D 16 varied between 56.6 and 130.6 Nm, while that of the L/D 20 version was between 59.0 and 178.3 Nm (Table 3). This difference is due to the presence of an additional mixing element within the screw configuration in the L/D 20 version, and hence a longer material residence time, and also some disturbance of the material flow inside the barrel. In the case of engine torque, a significant positive linear and quadratic relationship with M was found, but only for L/D 16 (Table 2). This means that the torque values during the extrusion of NSP-rich wheat flour with this extruder configuration increased with the increase in M. For the L/D 20 configuration, no statistically significant relationships between torque and the tested factors were demonstrated (Table 2, p-value > 0.05). The obtained data weakly fit the applied model due to the low R^2 values.

Increasing torque, when the initial moisture content was increased, may be the effect of a higher dough viscosity inside the barrel due to the initiation of the gelatinization of wheat starch under processing temperatures, as well as the greater addition of water to the treated mass. This observation and conclusion were confirmed by the positive linear and quadratic relationship with M. Similar observations were reported by Kowalski et al. [47], who tested the extrusion of a waxy wheat variety through a co-rotating twin-screw extruder. In their experiment, they found a significant positive quadratic feed moisture effect and positive interactive effect of feed moisture and screw speed with respect to motor torque. They also noted that a non-waxy wheat flour produced much higher pressure and torque as compared to waxy varieties during extrusion. However, there were insignificant and ambiguous dependencies observed between the processing variables and the levels of enzyme added.

Table 3. Torque, load and active power registered during wheat flour extrusion for the L/D 16 extruder configuration (mean values, n = 3).

Processing Variables			L/D 16		
M	**S**	**E**	**Torque (Nm)**	**Load (%)**	**Active Power (kW)**
23	40	0	$60.4 \pm 7.6^{a,b}$	17.1 ± 2.5^{a}	$0.477 \pm 0.093^{e,f,g}$
		50	$106.3 \pm 11.1^{d,e,f,g}$	$30.0 \pm 4.4^{b,c,d,e,f}$	$0.863 \pm 0.080^{i,j}$
		100	$76.9 \pm 7.4^{a,b,c,d}$	$21.7 \pm 3.0^{a,b,c,d}$	$0.473 \pm 0.057^{e,f,g}$
	60	0	$77.3 \pm 8.8^{a,b,c,d}$	$21.8 \pm 3.1^{a,b,c,d}$	$0.301 \pm 0.065^{a,b,c,d,e}$
		50	$59.5 \pm 6.3^{a,b}$	16.8 ± 2.7^{a}	$0.898 \pm 0.080^{i,j}$
		100	$82.3 \pm 8.6^{a,b,c,d,e}$	$23.3 \pm 3.0^{a,b,c,d,e}$	$0.435 \pm 0.061^{c,d,e,f,g}$
	80	0	$73.9 \pm 7.5^{a,b,c,d}$	$20.9 \pm 2.9^{a,b,c}$	$0.412 \pm 0.080^{c,d,e,f,g}$
		50	$75.1 \pm 7.7^{a,b,c,d}$	$21.2 \pm 2.0^{a,b,c,d}$	$0.199 \pm 0.092^{a,b,c}$
		100	$74.1 \pm 6.3^{a,b,c,d}$	$20.9 \pm 2.9^{a,b,c}$	$0.307 \pm 0.074^{a,b,c,d,e}$
25	40	0	$64.8 \pm 5.7^{a,b}$	$18.3 \pm 1.7^{a,b}$	$0.335 \pm 0.070^{a,b,c,d,e,f}$
		50	$65.2 \pm 6.4^{a,b}$	$18.4 \pm 1.6^{a,b}$	$0.421 \pm 0.025^{c,d,e,f,g}$
		100	$65.0 \pm 6.5^{a,b}$	$18.4 \pm 2.1^{a,b}$	$0.591 \pm 0.063^{g,h}$
	60	0	$59.7 \pm 5.4^{a,b}$	16.9 ± 1.3^{a}	$0.407 \pm 0.051^{b,c,d,e,f,g}$
		50	$90.7 \pm 10.3^{b,c,d,e,f}$	$25.6 \pm 3.2^{a,b,c,d,e,f,g}$	1.155 ± 0.100^{k}
		100	$68.3 \pm 7.1^{a,b}$	$19.3 \pm 1.9^{a,b}$	$0.561 \pm 0.089^{f,g,h}$
	80	0	56.6 ± 4.7^{a}	16.0 ± 1.6^{a}	$1.024 \pm 0.095^{j,k}$
		50	$71.2 \pm 8.1^{a,b,c,d,e}$	$20.1 \pm 5.0^{a,b,c}$	1.194 ± 0.152^{k}
		100	$58.6 \pm 4.8^{a,b}$	16.6 ± 5.3^{a}	$0.594 \pm 0.072^{g,h}$
27	40	0	$117.8 \pm 12.4^{f,g}$	$33.3 \pm 4.1^{d,e,f,g}$	$0.229 \pm 0.029^{a,b,c,d}$
		50	$112.6 \pm 11.2^{e,f,g}$	$31.8 \pm 5.2^{c,d,e,f}$	$0.746 \pm 0.096^{h,i}$
		100	$84.2 \pm 9.9^{a,b,c,d,e}$	$23.8 \pm 3.3^{a,b,c,d,e,f}$	$0.467 \pm 0.071^{d,e,f,g}$
	60	0	129.2 ± 14.6^{g}	36.5 ± 4.5^{g}	$0.197 \pm 0.025^{a,b,c}$
		50	$104.5 \pm 12.5^{c,d,e,f,g}$	$29.5 \pm 3.2^{b,c,d,e,f}$	$0.304 \pm 0.065^{a,b,c,d,e}$
		100	127.6 ± 16.8^{g}	$36.1 \pm 6.4^{f,g}$	0.119 ± 0.018^{a}
	80	0	126.0 ± 17.9^{g}	$35.6 \pm 5.6^{e,f,g}$	$0.168 \pm 0.075^{a,b}$
		50	$121.7 \pm 16.5^{f,g}$	$34.6 \pm 6.1^{e,f,g}$	$0.420 \pm 0.087^{c,d,e,f,g}$
		100	130.6 ± 18.9^{g}	36.9 ± 7.0^{g}	0.099 ± 0.017^{a}

M—moisture; S—screw speed; E—enzyme dose. $^{a–k}$—means indicated with similar letters in columns do not differ significantly at $\alpha = 0.05$.

The results of the engine load (%) during the extrusion cooking of wheat flour with xylanase enzyme, dependent upon L/D configuration and processing variables, are presented in Table 3. The results varied from 16.0 to 36.9% if L/D 16 was employed (Table 3) and from 16.7 to 47.3% if L/D 20 was used for processing (Table 4). When analyzing the engine load, significant positive linear and quadratic relationships with M were obtained, but only if the L/D 16 configuration was used for treatment (Table 2). This implies that the load for this extruder configuration increased with the increase in the initial moisture of the treated wheat flour. Higher values were observed because the higher initial moisture contents brought about greater gelatinization and increased dough viscosity during flour extrusion. In contrast, with the L/D 20 configuration, no statistically significant relationships were evident for the load in relation to the tested factors (Table 2, *p*-values > 0.05).

The active power (kW) results for wheat flour without/with enzymes as extruded under variable processing conditions are summarized in Tables 3 and 4. Different factors determining changes in the active power depending on the extruder configuration were indicated. Accordingly, the L/D 16 configuration showed a significant negative quadratic relationship with M and E (Table 2), while the long L/D 20 version of the extruder displayed a significant negative relationship with the S × E interaction effect. On comparing the constant values of the obtained models in both configurations, it can be concluded that the active power was significantly higher for L/D 16, especially when low initial moisture and low screw speeds were applied during processing (Table 3). This may be connected

with the effect of pressure increase due to the formation of the melted starch–protein matrix (which demonstrates high viscosity due to being partly gelatinized because of access to heat and water). The lowest values were observed for both extruder configurations if the initial moisture and enzyme level were the highest. Strong correlation coefficients were found between active power and SME (r values were 0.883 for L/D 16 and 0.865 for L/D 20 extruder configurations). Due to the low R^2, the obtained models for active power (L/D 16, L/D 20) are not recommended to describe this factor. Further research is necessary to obtain more adequate models describing the variability of active power depending on important experimental factors.

Table 4. Torque, load and active power registered during wheat flour extrusion for the L/D 20 extruder configuration (mean values, n = 3).

Processing Variables			L/D 20		
M	**S**	**E**	**Torque (Nm)**	**Load (%)**	**Active Power (kW)**
23	40	0	$90.6 \pm 9.3^{a,b,c,d,e,f}$	$25.6 \pm 3.8^{a,b,c,d,e,f,g}$	$0.294 \pm 0.096^{a,b,c,d,e}$
		50	$87.6 \pm 8.1^{a,b,c,d,e,f}$	$24.7 \pm 3.6^{a,b,c,d,e,f,g}$	$0.133 \pm 0.085^{a,b}$
		100	$91.5 \pm 9.5^{a,b,c,d,e,f}$	$25.8 \pm 3.5^{a,b,c,d,e,f,g}$	$0.270 \pm 0.096^{a,b,c,d}$
	60	0	$150.0 \pm 18.5^{h,i,j,k}$	$42.4 \pm 4.3^{i,j,k,l}$	$0.176 \pm 0.032^{a,b,c}$
		50	$94.3 \pm 10.7^{a,b,c,d,e,f}$	$26.6 \pm 5.1^{a,b,c,d,e,f,g}$	$0.296 \pm 0.066^{a,b,c,d,e}$
		100	$80.9 \pm 8.6^{a,b,c,d,e}$	$22.8 \pm 3.9^{a,b,c,d,e}$	$0.512 \pm 0.098^{e,f,g}$
	80	0	59.0 ± 5.9^{a}	16.7 ± 2.5^{a}	$0.429 \pm 0.075^{d,e,f}$
		50	$78.6 \pm 7.8^{a,b,c,d,e}$	$22.2 \pm 3.6^{a,b,c,d,e}$	$0.195 \pm 0.092^{a,b,c}$
		100	$84.2 \pm 8.1^{a,b,c,d,e}$	$23.8 \pm 2.8^{a,b,c,d,e,f}$	0.103 ± 0.069^{a}
25	40	0	$64.4 \pm 6.2^{a,b}$	$18.2 \pm 3.4^{a,b}$	$0.313 \pm 0.093^{a,b,c,d,e}$
		50	$109.5 \pm 16.6^{c,d,e,f,g,h}$	$30.9 \pm 2.7^{b,c,d,e,f,g,h,i,j}$	$0.237 \pm 0.045^{a,b,c,d}$
		100	$112.4 \pm 15.9^{d,e,f,g,h,i}$	$31.8 \pm 3.8^{d,e,f,g,h,i,j}$	$0.692 \pm 0.073^{g,h,i}$
	60	0	178.3 ± 16.8^{k}	50.4 ± 6.2^{l}	$0.134 \pm 0.099^{a,b}$
		50	$66.6 \pm 5.3^{a,b,c}$	$18.8 \pm 2.6^{a,b,c}$	$0.251 \pm 0.032^{a,b,c,d}$
		100	$154.5 \pm 19.4^{i,j,k}$	$43.6 \pm 5.5^{j,k,l}$	$0.254 \pm 0.041^{a,b,c,d}$
	80	0	$70.7 \pm 7.9^{a,b,c,d}$	$20.0 \pm 2.9^{a,b,c,d}$	$0.555 \pm 0.086^{f,g,h}$
		50	$71.5 \pm 8.8^{a,b,c,d}$	$20.2 \pm 3.1^{a,b,c,d}$	$0.372 \pm 0.065^{c,d,e,f}$
		100	$167.4 \pm 19.9^{j,k}$	$47.3 \pm 5.3^{k,l}$	$0.197 \pm 0.084^{a,b,c,d}$
27	40	0	$102.7 \pm 15.5^{a,b,c,d,e,f,g}$	$29.0 \pm 3.8^{a,b,c,d,e,f,g,h}$	$0.340 \pm 0.076^{b,c,d,e,f}$
		50	$141.0 \pm 16.7^{g,h,i,j,k}$	$39.8 \pm 4.6^{h,i,j,k,l}$	$0.191 \pm 0.019^{a,b,c}$
		100	$110.2 \pm 12.7^{c,d,e,f,g,h}$	$31.1 \pm 3.1^{c,d,e,f,g,h,i,j}$	0.893 ± 0.098^{i}
	60	0	$128.6 \pm 17.5^{f,g,h,i,j}$	$36.3 \pm 4.5^{f,g,h,i,j,k}$	$0.270 \pm 0.061^{a,b,c,d}$
		50	$105.5 \pm 14.9^{b,c,d,e,f,g}$	$29.8 \pm 3.5^{b,c,d,e,f,g,h,i}$	$0.288 \pm 0.042^{a,b,c,d,e}$
		100	$131.2 \pm 17.1^{f,g,h,i,j}$	$37.1 \pm 3.7^{g,h,i,j,k}$	$0.782 \pm 0.069^{h,i}$
	80	0	$118.5 \pm 16.3^{e,f,g,h,i}$	$33.5 \pm 4.8^{e,f,g,h,i,j}$	0.086 ± 0.064^{a}
		50	$102.1 \pm 15.4^{a,b,c,d,e,f,g}$	$28.9 \pm 4.2^{a,b,c,d,e,f,g,h}$	$0.292 \pm 0.087^{a,b,c,d,e}$
		100	$143.3 \pm 18.8^{g,h,i,j,k}$	$40.5 \pm 5.6^{h,i,j,k,l}$	$0.112 \pm 0.032^{a,b}$

M—moisture; S—screw speed; E—enzyme dose; $^{a–l}$—means indicated with similar letters in columns do not differ significantly at $\alpha = 0.05$.

The extrusion cooking processing efficiencies of wheat flour with xylanase enzyme that are dependent on L/D configuration and processing variables are presented in Figure 2.

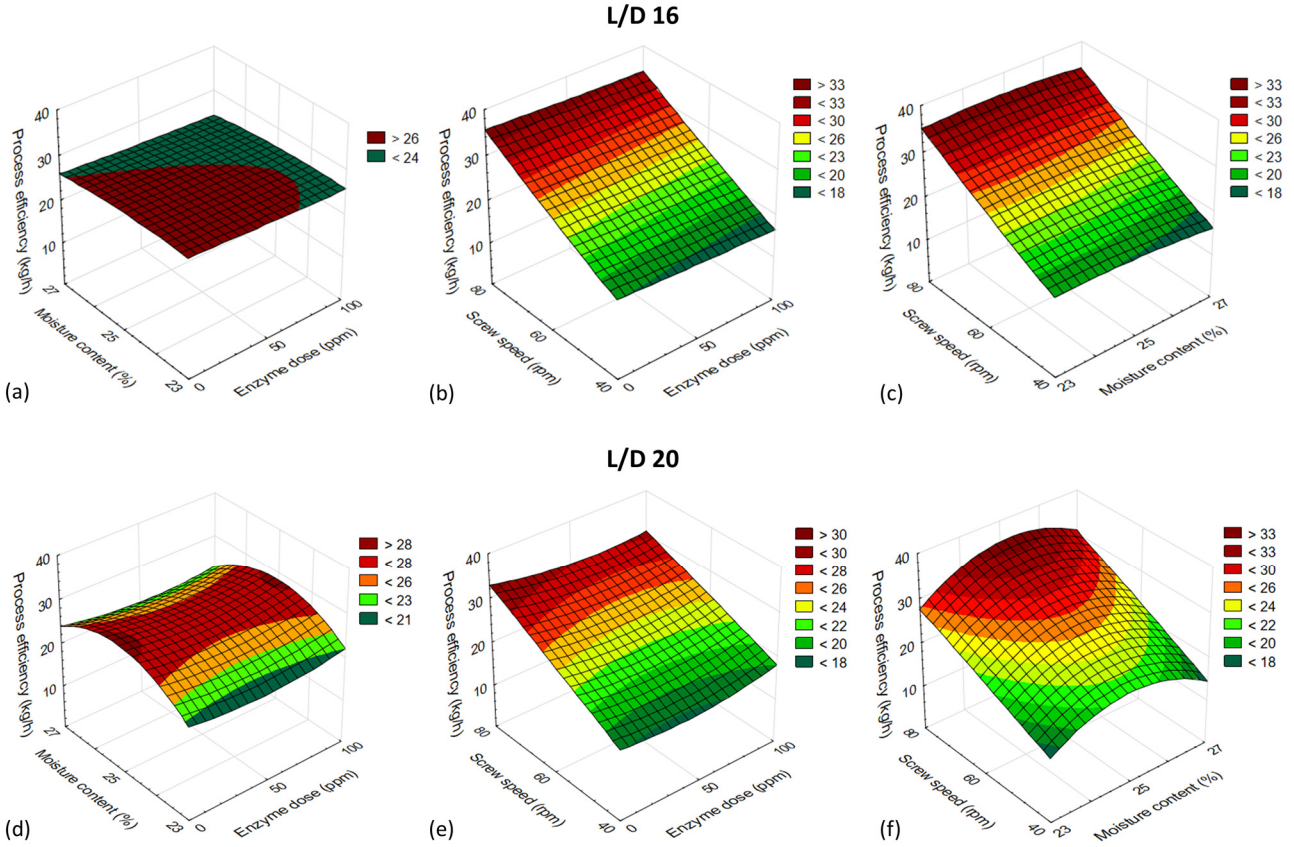


Figure 2. Processing efficiency during the extrusion cooking of wheat flour with xylanase enzyme. L/D 16: (**a**) E × M, (**b**) E × S, (**c**) M × S; L/D 20: (**d**) E × M, (**e**) E × S, (**f**) M × S. E—enzyme dose; M—moisture; S—screw speed.

Generally, processing with a longer extruder configuration (L/D 20) resulted in lower output due to the extended residence time of the treated flour inside the barrel. Accordingly, efficiency varied between 14.88 and 39.36 kg/h if L/D 16 was employed and between 13.92 and 36.96 kg/h if L/D 20 was used. More visible differences between the output results were observed with regard to the variables of the moisture content and enzyme addition. Here, the highest efficiency was evident at 25% initial moisture. A further increase in moisture slightly lowered processing output, probably due to more intense starch gelatinization and increased dough viscosity, and thus lowered the flow intensity of the dense and sticky material. In analyzing the extrusion processing efficiency of wheat flour with the addition of xylanase, a significant positive linear relationship with S was demonstrated for both configurations. This effect indicates that processing efficiency increased with the increase in S for both extruder configurations. High correlation coefficient values (r = 0.953 for L/D 16 and r = 0.792 for L/D 20, respectively) were indicated. The values of process efficiency were not susceptible to changes in the initial moisture content M of wheat flour and the enzyme addition E. When comparing the coefficients of both models, it can be concluded that the differences between the considered configurations with regard to processing efficiency were small. In the case of the longer configuration (L/D 20), a significant negative quadratic relationship with M was additionally demonstrated. This outcome was similar to that of previous studies. In the work of Wójtowicz et al. [35], the processing efficiency and SME of cereal-based snack pellets fortified with edible cricket flour processed with a similar extruder configuration to L/D 20 was noted for varying from 12.08 to 37.20 kg/h, with efficiency lowering with increasing initial water content, especially when a low screw speed was applied.

According to the outcome of our experiment, the specific mechanical energy (SME) requirements during the extrusion cooking of wheat flour amended with the xylanase

enzyme depend on the L/D configuration and processing values (Figure 3). The SME is a good quantitative descriptor of the extrusion processes of the extent of macromolecular transformations and interactions that take place, i.e., starch conversion, and consequently, the rheological properties of the melt [26]. A higher SME usually results in a greater degree of starch gelatinization and greater extents of starch molecular size reduction and extrudate expansion [41].

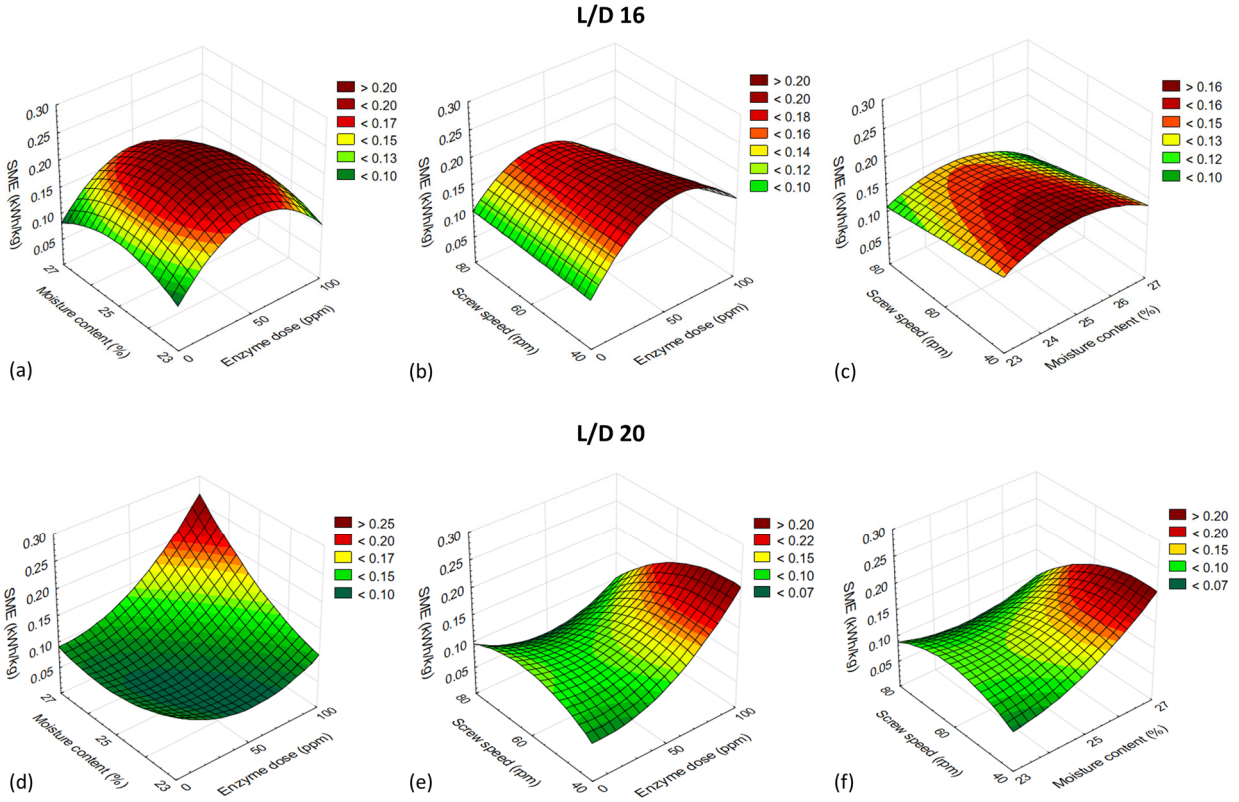


Figure 3. SME during the extrusion cooking of wheat flour with xylanase enzyme: L/D 16: (**a**) E × M, (**b**) E × S, (**c**) M × S; L/D 20: (**d**) E × M, (**e**) E × S, (**f**) M × S. SME—specific mechanical energy; E—enzyme dose; M—moisture; S—screw speed.

A statistically significant regression model for the SME (with a moderate value of the coefficient of determination and a significant F test result) was obtained only for the L/D 20 extruder configuration, indicating a positive linear relationship with M, E and the M × E interaction effect (Table 2). The combined effect of moisture and enzyme dose on the SME was observed. Both factors independently contributed to improving the SME (L/D 20). Moreover, the SME increased with increasing M and E for L/D 20. Still, the correlation coefficients were not significant for both L/D 16 and L/D 20. In L/D 16 extrusion, the SME was not significantly affected by changes in M, S or E (Table 2). Higher energy values were, however, noted for the L/D 20 configuration, especially at high moisture content and the highest dose of xylanase in the extruded blend. This consequence may have come about as a result of differences in dough structure, due to using the mixing element in screw construction and due to the presence of partly hydrolyzed polysaccharides being acted upon by xylanase under high-moisture extrusion at low temperatures (below 80 °C).

As is known, xylanase can change insoluble fractions of polysaccharides (especially xylans) into soluble and more reactive structures that absorb more water and make the treated dough denser, and hence require greater processing energy input. Deng et al. [50], for example, tested wheat bran processed by enzymatic extrusion at moisture levels of 30 and 40% and found higher specific mechanical energy input from the extruder at lower moisture, which softened the fiber. High mechanical energy input might be conducive

to forming a loose and porous structure that facilitates the penetration of the xylanase-containing solution. The lower screw speed is a result of longer residence time and lower mechanical force produced from the extruder [51]. Furthermore, an increase in the screw speed leads to higher specific mechanical energy SME input, which results in depolymerization of lignocellulose and conversion of arabinoxylan chains into soluble small molecules. This effect may create complexes with proteins and thus changes in the rheological characteristics of the wheat dough's protein-dependent functions. Therefore, it was inferred that extrusion at a higher screw speed produces more soluble pentose, even if no enzymes are added [51].

SME input is responsible for the intensity of changes during extrusion cooking, especially when HTST (high-temperature short-time) treatment is applied [1]. As a system parameter, SME represents the amount of mechanical energy transferred to the feed material during extrusion, and it can be used to indicate extrusion intensity. SME was found to be dependent on feed moisture, feed rate, screw speed and barrel temperature [47]. The presence of fiber and increased moisture may have provided a reduction in the viscosity of the melt in the extruder by changing the distributions of shear, mixing, mechanical heat and convective heat and thus affecting motor torque and SME [41]. At higher screw speed and temperature, a greater increase in SME was noticed by Kharat et al. [52] during the extrusion of select major millets. This can be attributed to the changes in the material viscosity in the barrel due to the increased shear. Ma et al. [50] extruded wheat flour with various co-rotating twin-screw extruders and they found decreased SME when the water content increased from 18 to 24% at both die temperatures of 95 °C and 139 °C. Allai et al. [53] also reported upon the effect of processing conditions on SME during the extrusion of wholegrain breakfast cereals. Here, feed moisture content and barrel temperature were found to be inversely proportional to SME. Wójtowicz et al. [35] stated that increased quantity of insect flour (20 and 30%) in wheat–corn-based snack pellets resulted in better SME stability at variable screw speeds and applied moisture content, and that SME results differed slightly between these extrudates because of the increased amount of fat from the cricket flour in the recipes. This fat played a lubrication role during processing (single-screw extruder), enhancing the slippage of the material. Kesre and Masatcioglu [54], in turn, noted a decrease in torque and SME values with increasing barrel temperature because of a reduction in dough viscosity. Fischer [55] concluded that the mechanical energy input during extrusion decreased with increasing extrusion temperature (140 to 180 °C) (wheat flour). In addition, higher moisture (24%) resulted in lower SME values and the difference between moisture levels decreased with increasing extrusion temperature. Robin et al. [56] extruded wholewheat flour in a co-rotating twin-screw extruder under water levels of 18 or 22%, screw speeds of 400 or 800 rpm and barrel temperatures of 140 or 180 °C, and noted that SME lowered when temperature and water content increased, and that SME was higher at a higher screw speed. Adding to the aforementioned, Lisiecka and Wójtowicz [36] found the lowest SME for extrudates supplemented with fresh onion and processed at the lowest screw speed by using a single-screw extruder. Moreover, Bouasla and Wójtowicz [57] reported that SME is significantly affected by feed moisture and screw speed, where increased feed moisture appeared to cause a slight increase in SME, but increased screw speed from 60 rpm to 100 rpm caused the SME to increase sharply when a single-screw extruder was used in pre-cooked rice pasta processing. This could be due to the higher viscosity of the dough inside the extruder, an effect caused by the more intensive gelatinization of the dough during processing when high moisture content (over 30%) and high screw speed (100 rpm) are applied. Kantrong et al. [48] used RSM to test the effect of processing conditions on several characteristics of twin-screw-extruded snacks and found that feed moisture had the most influence on SME—more than barrel temperature and applied screw speed. Moreover, they noted that higher levels of protein in the formula may contribute to higher dough viscosity, and thus higher SME is required. Feng and Lee [58], in turn, concluded that a decrease in SME significantly decreases rapidly digestible starch content and significantly increases slowly digestible starch (SDS) levels in rice-based snacks.

This outcome can have nutritionally positive effects in food products. In general, feed moisture content was reported as the most significant factor affecting the SME [41,47].

3.2. Rheological Characteristics of Extruded Flours

Wheat flours developed as a blend of selected breaking, milling, reducing and sifting passages can possess high arabinoxylan content. This results from the inclusion of waste fractions obtained during grain grinding [30], and can be valuable when selected and mixed in well-defined proportions. A flour richer in fibrous fractions, however, demonstrates different rheological characteristic than a common bread flour. In our work, the hydration ability of the flour we developed was 60.5 ± 0.1%, the development time was 1.92 ± 0.19 min. and dough stability was 9.73 ± 0.12 min. These characteristics are a bit lower than that of commercial bread flour, but allow the incorporation of large amounts of fractions usually wasted during grinding. This flour was processed either without or with xylanase enzyme and underwent diverse extrusion conditions (variations in initial moisture content, screw speed and enzyme levels), whereupon its rheological characteristics were analyzed. Schmiele et al. [40] reported 57.80% of water absorption, 11.25 min development time and 18.80 min dough stability for commercial wheat flour. Bucsella et al. [59] noted a water absorption 61.5%, 3.6 min DDT and around 7 min of dough stability for wheat flour when measured with Mixolab. Commercial bread and cake showed 58 and 60% water absorption, 6.6 and 7.9 min dough stability and 1.2 and 4.2 min of DDT, respectively [60].

Based on the obtained results presented in Tables 5 and 6, the water absorption of the extruded wheat flour with xylanase enzyme was found to depend upon processing variables and L/D configuration. Here, the water hydration of the extruded samples varied from 61.0 to 68.3% when L/D 16 was employed to pretreat the wheat flour, and from 63.9 to 69.3% when the components were processed in the L/D 20 configuration. Although in the case of the shorter L/D 16 extruded configuration, the F test result was statistically significant, due to the moderate R^2 result, the estimated model cannot be recommended for optimization purposes. It is probably necessary to fit a higher-order model, which requires conducting extended experimental studies. We found in the analyzed relationships of variables that when subject to extrusion through the L/D 20 apparatus, the hydration results were not susceptible to changes in initial moisture (M), screw speed (S) or enzyme dose (E) factors (Table 7). Butt et al. [61] reported bacterial xylanase as having a higher impact on water absorption capacity than fungal xylanase, but this application is more suitable for modifying bran fiber or high-fibrous fractions of flour. In our research, due to the application of bread flour, fungal xylanase was added due to being more reactive for the insoluble fractions of xylans present in the developed flour [62]. Xylanase can change the insoluble fractions of polysaccharides (especially xylans) into soluble and more reactive structures that absorb more water and make the treated dough more dense, and hence a requirement for more processing energy input is observed, as mentioned in Section 3.1. When 50 or 100 ppm was added to NSP-rich flour, the effect of the enzyme level was insignificant, as well as the other variables used in the experiment. Nevertheless, all treatments increased the extruded flour's hydration properties as compared to native flour (hydration of 60.5%), with a negligible effect of processing variables or xylanase enzyme level. Similar observations have been reported by Medina-Rendon et al. [8] when comparing the water absorption of non-extruded flour with the values of the extrudates obtained with a single-screw extruder. Herein, the extrudates showed equivalent or higher water absorption values. Extrusion has been demonstrated to contribute to the increase in the hydration properties of different products [63]. High shear at low moisture and high screw speed causes the degradation of starch with the crystal melting of amylopectin molecules as well as dextrinization, which have an effect on hydration properties. Also, protein hydrolysis, which is possible during extrusion, may affect water absorption, especially in raw materials with high protein content. The extruded flour obtained after processing with high moisture and low screw speed may be valuable for improving dough stability because of its nondestructive effects on hydrolysis or enzyme activity [63]. Higher feed moisture was found to

limit the mechanical disruption and fragmentation of starch granules because water acts as a plasticizer in the extruder [64]. Some research reported an association between the quantity of damaged starch and the water absorption of the extruded flour [4,5,65]. Studies performed with the application of extrusion to obtain pregelatinized starches indicated starch granule breakdown and damage during this process and increased water absorption due to the partial gelatinization of starch in the presence of water and heat. Pasqualone et al. [65] reported increased water absorption after industrial-scale extrusion cooking of lentil flour with two temperature/screw profiles, and they observed a significant increase in water absorption (90.8–94.7%) after processing at lower temperatures and screw speeds as compared to native lentil flour (41.1%). Similarly, Tao et al. [5] reported the increased water absorption of dough with added extruded wheat starch into bread formulation because of the crystallinity loss in the extruded starch that was beneficial for the quality of bread with the addition of extruded flour. Liu et al. [4] recommended single-screw extrusion at lower-than-conventional temperatures (50–150 °C) as an easy and flexible process to modify rice starch at the initial moisture from 30 to 70%, significantly improving the degree of gelatinization. Low temperatures are required for processing when enzymes are directly added to the extruder. In the extruder, during processing, a number of interactions occur between processing variables and enzymatic activity [19], and these affect the rheological behavior of the resulting dough. Martínez et al. [27] used extrusion to modify wheat flour, and the processing significantly increased hydration properties; specifically, 5-fold water binding capacity and 9-fold swelling compared with untreated wheat flour.

Of note, extruded wheat flours have been reported to increase the bread yield in bakery processes [28]. The composition of the blend may also have an effect on rheological properties. The physicochemical modification of fiber and fiber-rich fractions by using high temperatures and shear conditions of extrusion processing is possible for enhancing their functional properties. The dough-mixing and pasting properties of blends of wholewheat flour and different types (commercial yellow pea flour, yellow pea flour, green pea flour, red lentil flour, and chickpea flour) and amounts (5, 15 and 25%, based on total composite flour weight) of pulse flours were analyzed by Zhang et al. [66] using Mixolab. They found a higher water absorption value as the amount of pulse flour increased in the blend, compared to basic wholewheat flour. The rheological parameters of wheat flour provide a measure of dough water absorption, viscoelastic strength and stability for the tolerance of over-mixing dough. Usually, the wheat flours used in bread making containing high levels of good-quality gluten have good machinability properties and good tolerance to over-mixing in comparison to flours of poorer quality containing more outer layers from reducing and sifting passages, and which are richer in fiber and non-starch polysaccharides and arabinoxylans [32]. Lee et al. [67] found that extrusion was the most effective treatment approach for improving the dough-mixing properties of wholewheat meal containing bran, e.g., the resistance of a composed dough with puffed or HTHP-cooked wheat bran rapidly decreased after reaching a Mixograph peak, showing a significant increase in breakdown resistance. In contrast, the addition of extruded bran significantly increased the midline peak time by 0.5 min, as compared to untreated wheat bran.

Gómez et al. [68] found that extrusion increased the dough development time when bran was added to bread flour. However, the Mixograph results presented by Gajula et al. [31] indicate that high-temperature and high-shear-extrusion processing deteriorated protein quality and caused poor water absorption and viscoelastic strength in pre-cooked bran-supplemented flour as compared to control wheat flour. The high thermal and mechanical energy input during extrusion was found to have caused the denaturation of proteins, thus negatively affecting dough development, but this effect was especially noticeable when HTST treatment was applied with low feed moisture. In contrast, low temperatures and the low shear extrusion of flour caused a lower peak viscosity than under HTST conditions and resulted in improvements in the dough properties due to some kind of synergistic effect of the pre-cooked fiber and starch on water binding and swelling at low bran levels [31].

Table 5. Rheological properties of wheat flour extruded using L/D 16 extruder configuration (mean values, n = 3).

Processing Variables			L/D 16				
M	**S**	**E**	**Hyd (%)**	**Stab. (min)**	***α***	***β***	***γ***
23	40	0	67.0 ± 0.3 ^{g,h,i}	5.1 ± 0.12 ^{a,b,c}	−0.042 ± 0.002 ^{a,b,c,d}	0.236 ± 0.019 ^{a,b,c}	−0.042 ± 0.001 ^{a,b,c,d,e}
		50	68.0 ± 0.4 ^{h,i}	5.6 ± 0.15 ^{b,c,d}	−0.046 ± 0.017 ^{a,b,c,d}	0.158 ± 0.015 ^{a,b}	−0.046 ± 0.022 ^{a,b,c,d,e}
		100	67.2 ± 0.2 ^{g,h,i}	5.6 ± 0.2 ^{b,c,d}	−0.052 ± 0.022 ^{a,b,c,d}	0.240 ± 0.03 ^{a,b,c}	−0.080 ± 0.008 ^{a,b,c,d}
	60	0	67.3 ± 0.2 ^{g,h,i}	5.0 ± 0.16 ^{a,b}	−0.022 ± 0.015 ^{d}	0.192 ± 0.007 ^{a,b,c}	−0.028 ± 0.002 ^{b,c,d,e}
		50	63.8 ± 0.1 ^{d,e,f}	9.8 ± 0.12 ^{l}	−0.082 ± 0.02 ^{a,b}	0.240 ± 0.001 ^{a,b,c}	−0.080 ± 0.01 ^{a,b,c,d}
		100	67.5 ± 0.2 ^{h,i}	4.4 ± 0.1 ^{a}	−0.026 ± 0.015 ^{c,d}	0.204 ± 0.08 ^{a,b,c}	−0.098 ± 0.08 ^{a,b,c}
	80	0	68.3 ± 0.2 ^{i}	6.2 ± 0.5 ^{c,d,e,f}	−0.034 ± 0.02 ^{b,c,d}	0.204 ± 0.053 ^{a,b,c}	−0.028 ± 0.003 ^{b,c,d,e}
		50	65.9 ± 0.2 ^{g}	7.1 ± 0.2 ^{f,g,h,i,j}	−0.056 ± 0.008 ^{a,b,c,d}	0.142 ± 0.002 ^{a}	−0.072 ± 0.013 ^{a,b,c,d,e}
		100	68 ± 0.3 ^{h,i}	6.7 ± 0.2 ^{d,e,f,g}	−0.046 ± 0.002 ^{a,b,c,d}	0.288 ± 0.004 ^{c}	−0.084 ± 0.01 ^{a,b,c,d}
25	40	0	60.6 ± 0.2 ^{a}	7 ± 0.2 ^{f,g,h,i}	−0.090 ± 0.015 ^{a}	0.260 ± 0.025 ^{a,b,c}	−0.070 ± 0.015 ^{a,b,c,d,e}
		50	62.8 ± 0.1 ^{b,c,d,e}	5.6 ± 0.2 ^{b,c,d}	−0.070 ± 0.005 ^{a,b,c,d}	0.260 ± 0.03 ^{a,b,c}	−0.120 ± 0.010 ^{a}
		100	61.5 ± 0.2 ^{a,b,c}	10.2 ± 0.6 ^{l}	−0.078 ± 0.02 ^{a,b,c}	0.286 ± 0.025 ^{c}	0.002 ± 0.006 ^{e}
	60	0	61 ± 0 ^{a}	7.7 ± 0.3 ^{g,h,i,j,k}	−0.048 ± 0.001 ^{a,b,c,d}	0.270 ± 0.002 ^{b,c}	−0.064 ± 0.008 ^{a,b,c,d,e}
		50	63.9 ± 0.25 ^{d,e,f}	5.6 ± 0.05 ^{b,c,d}	−0.064 ± 0.002 ^{a,b,c,d}	0.202 ± 0.04 ^{a,b,c}	−0.088 ± 0.02 ^{a,b,c}
		100	62.5 ± 0.3 ^{b,c,d}	6.6 ± 0.2 ^{d,e,f,g}	−0.058 ± 0.04 ^{a,b,c,d}	0.278 ± 0.02 ^{b,c}	−0.066 ± 0.02 ^{a,b,c,d,e}
	80	0	61.5 ± 0.15 ^{a,b,c}	6.9 ± 0.2 ^{e,f,g,h}	−0.038 ± 0.005 ^{a,b,c,d}	0.300 ± 0.015 ^{c}	−0.030 ± 0.052 ^{b,c,d,e}
		50	64.5 ± 0.2 ^{g,h}	5.3 ± 0.23 ^{e,f,g,h}	−0.048 ± 0.02 ^{a,b,c,d}	0.242 ± 0.025 ^{a,b,c}	−0.110 ± 0.008 ^{a,b,c,d}
		100	61.4 ± 0.2 ^{a,b}	4.3 ± 0.08 ^{a}	−0.028 ± 0.012 ^{c,d}	0.262 ± 0.002 ^{a,b,c}	−0.108 ± 0.003 ^{a,b}
27	40	0	64.0 ± 0.2 ^{e,f}	5.6 ± 0.15 ^{b,c,d}	−0.074 ± 0.009 ^{a,b,c,d}	0.246 ± 0.030 ^{a,b,c}	−0.006 ± 0.005 ^{d,e}
		50	64.3 ± 0.3 ^{f}	8.5 ± 0.1 ^{k}	−0.066 ± 0.020 ^{a,b,c,d}	0.24 ± 0.020 ^{a,b,c}	−0.046 ± 0.00 ^{a,b,c,d,e}
		100	63.5 ± 0.2 ^{d,e,f}	8.1 ± 0.6 ^{i,j,k}	−0.064 ± 0.03 ^{a,b,c,d}	0.236 ± 0.030 ^{a,b,c}	−0.084 ± 0.003 ^{a,b,c,d}
	60	0	66.0 ± 0.3 ^{g}	7.9 ± 0.2 ^{h,i,j,k}	−0.064 ± 0.001 ^{a,b,c,d}	0.234 ± 0.090 ^{a,b,c}	−0.100 ± 0.025 ^{a,b,c}
		50	62.9 ± 0.2 ^{c,d,e,f}	5.8 ± 0.2 ^{b,c,d,e}	−0.058 ± 0.022 ^{a,b,c,d}	0.256 ± 0.019 ^{a,b,c}	−0.030 ± 0.035 ^{b,c,d,e}
		100	64.0 ± 0.1 ^{e,f}	7.4 ± 0.2 ^{g,h,i,j,k}	−0.062 ± 0.015 ^{a,b,c,d}	0.240 ± 0.004 ^{a,b,c}	0.004 ± 0.022 ^{e}
	80	0	68.0 ± 0.2 ^{h,i}	8.2 ± 0.2 ^{j,k}	−0.044 ± 0.02 ^{a,b,c,d}	0.198 ± 0.070 ^{a,b,c}	−0.044 ± 0.005 ^{a,b,c,d,e}
		50	67.3 ± 0.2 ^{g,h,i}	8.3 ± 0.3 ^{k}	−0.030 ± 0.023 ^{b,c,d}	0.208 ± 0.031 ^{a,b,c}	−0.024 ± 0.028 ^{c,d,e}
		100	63.5 ± 0.1 ^{d,e,f}	7.1 ± 0.2 ^{f,g,h,i,j}	−0.070 ± 0.005 ^{a,b,c,d}	0.212 ± 0.045 ^{a,b,c}	−0.090 ± 0.015 ^{a,b,c}

M—moisture; S—screw speed; E—enzyme dose; Hyd—hydration; Stab.—dough stability; *α*—slope of angle *α*; *β*—slope of angle *β*; *γ*—slope of angle *γ*; $^{a–l}$—means indicated with similar letters in columns do not differ significantly at $\alpha = 0.05$.

The stability time of the dough indicates the flour's strength. The dough stability results of enzymatic-extrusion-modified wheat flour, presented in Tables 5 and 6, demonstrate increased values with an increasing level of initial feed moisture, especially when the elongated extruder L/D 20 was employed for processing. The mixing elements incorporated into the longer extruder screw profile created a less compact and dense dough structure due to greater mixing, and this resulted in greater dough stability. No regression model was obtained in any extruder settings that could adequately describe the variability of the dough stability depending on the experimental factors tested (Table 7). We think that further research is necessary, with the application of a central composite design with levels based on the presented results to find an optimization method, either to develop a higher-level model (so far this is not possible in this research, because to develop a third-level model, research is needed that takes five levels of each factor into account) or take into account other factors that may affect dough stability. Dough stability was highly correlated with C2 values, indicating protein weakening (r values were 0.604 for L/D 16 and 0.829 for L/D 20), and with C5 values when the elongated extruder configuration was applied (r = 0.793).

Zhang et al. [69] reported decreasing dough strength, in some cases, almost double, when pulse flours were incorporated in blends with wholewheat-based dough, probably due to the dilution of gluten when grain flour was replaced by pulse flour. Pasqualone et al. [64] reported significantly increased stability time of extruded lentil flour after pro-

cessing with an industrial-scale line at two temperature/screw profiles (2.1–2.4 min) as compared to the native lentil flour (1.5 min). Martinez et al. [28] noted a decrease in protein stability in bread flours with the addition of extruded wheat flour in the amount of 5%; farinographic examination showed a connection with the degradation of the gluten matrix during extrusion as a result of an increase in temperature, even up to 140 °C.

Table 6. Rheological properties of wheat flour extruded using L/D 16 and L/D 20 extruder configurations (mean values, n = 3).

Processing Variables			L/D 20				
M	**S**	**E**	**Hyd (%)**	**Stab. (min)**	***α***	***β***	***γ***
23	40	0	68.0 ± 0.2 ^{h,i}	7.6 ± 0.2 ^{j,k}	−0.036 ± 0.005 ^{c,d,e}	0.262 ± 0.09 ^{a,b,c,d}	−0.070 ± 0.052 ^{a,b,c,d}
		50	67.0 ± 0.3 ^{e,f,g}	5.5 ± 0.2 ^{d,e,f}	−0.066 ± 0.02 ^{a,b,c,d,e}	0.224 ± 0.019 ^{a,b,c}	−0.090 ± 0.008 ^{a,b,c}
		100	66.5 ± 0.4 ^{d,e}	6.0 ± 0.2 ^{e,f,g}	−0.038 ± 0.012 ^{c,d,e}	0.222 ± 0.004 ^{a,b}	−0.108 ± 0.003 ^{a,b}
	60	0	69.2 ± 0.1 ^{k}	6.3 ± 0.2 ^{g,h}	−0.040 ± 0.009 ^{b,c,d,e}	0.224 ± 0.019 ^{a,b,c}	−0.088 ± 0.005 ^{a,b,c,d}
		50	66.8 ± 0.3 ^{e,f}	4.6 ± 0.3 ^{a,b,c}	−0.040 ± 0.02 ^{b,c,d,e}	0.234 ± 0.015 ^{a,b,c,d}	−0.060 ± 0.001 ^{a,b,c,d}
		100	67.2 ± 0.3 ^{f,g}	4.6 ± 0.2 ^{a,b,c}	−0.056 ± 0.03 ^{a,b,c,d,e}	0.268 ± 0.03 ^{a,b,c,d}	−0.066 ± 0.003 ^{a,b,c,d}
	80	0	66.8 ± 0.2 ^{e,f}	4.7 ± 0.1 ^{a,b,c}	−0.042 ± 0.015 ^{b,c,d,e}	0.276 ± 0.007 ^{a,b,c,d}	−0.062 ± 0.025 ^{a,b,c,d}
		50	66.5 ± 0.2 ^{d,e}	5.3 ± 0.2 ^{c,d,e}	−0.036 ± 0.005 ^{c,d,e}	0.240 ± 0.001 ^{c,d,e}	−0.034 ± 0.001 ^{b,c,d,e}
		100	67.0 ± 0.2 ^{e,f,g}	4.4 ± 0.2 ^{a}	−0.054 ± 0.002 ^{a,b,c,d,e}	0.246 ± 0.080 ^{a,b,c,d}	−0.084 ± 0.008 ^{a,b,c,d}
25	40	0	65.5 ± 0.1 ^{b,c}	6.2 ± 0.2 ^{f,g,h}	−0.066 ± 0.001 ^{a,b,c,d,e}	0.312 ± 0.700 ^{a,b,c,d}	−0.064 ± 0.02 ^{a,b,c,d}
		50	68.2 ± 0.0 ^{i}	8.4 ± 0.1 ^{l,m,n}	−0.034 ± 0.002 ^{c,d,e}	0.268 ± 0.031 ^{a,b,c,d}	−0.064 ± 0.02 ^{a,b,c,d}
		100	65.3 ± 0.1 ^{b}	7.6 ± 0.1 ^{j,k}	−0.098 ± 0.040 ^{a}	0.242 ± 0.045 ^{a}	−0.114 ± 0.035 ^{a}
	60	0	67.0 ± 0.3 ^{e,f,g}	8.8 ± 0.2 ^{n}	−0.078 ± 0.02 $^{a,b,c,d\ e}$	0.228 ± 0.053 ^{a,b,c,d}	−0.084 ± 0.022 ^{a,b,c,d}
		50	65.6 ± 0.2 ^{b,c}	5.3 ± 0.2 ^{c,d,e}	−0.017 ± 0.015 ^{e}	0.202 ± 0.002 ^{a,b,c,d}	−0.060 ± 0.005 ^{a,b,c,d}
		100	68.9 ± 0.1 ^{j,k}	7.8 ± 0.1 ^{k,l}	−0.056 ± 0.020 ^{a,b,c,d,e}	0.164 ± 0.004 ^{a,b,c}	−0.094 ± 0.028 ^{a,b,c}
	80	0	67.2 ± 0.2 ^{f,g}	6.0 ± 0.2 ^{e,f,g}	−0.026 ± 0.008 ^{d,e}	0.288 ± 0.025 ^{a,b,c,d}	−0.070 ± 0.015 ^{a,b,c,d}
		50	63.9 ± 0.2 ^{a}	4.5 ± 0.1 ^{a,b}	−0.040 ± 0.002 ^{b,c,d,e}	0.250 ± 0.030 ^{e}	0.028 ± 0.001 ^{e}
		100	67.0 ± 0.3 ^{e,f,g}	5.2 ± 0.6 ^{b,c,d}	−0.062 ± 0.001 ^{a,b,c,d,e}	0.228 ± 0.025 ^{a,b,c,d}	−0.056 ± 0.022 ^{a,b,c,d}
27	40	0	66.0 ± 0.2 ^{c,d}	8.6 ± 0.5 ^{m,n}	−0.078 ± 0.022 ^{a,b,c,d}	0.192 ± 0.002 ^{a,b,c,d}	−0.068 ± 0.008 ^{a,b,c,d}
		50	63.9 ± 0.1 ^{a}	8.8 ± 0.2 ^{n}	−0.082 ± 0.015 ^{a,b,c}	0.172 ± 0.030 ^{c,d,e}	−0.028 ± 0.003 ^{c,d,e}
		100	63.7 ± 0.2 ^{a}	6.8 ± 0.2 ^{h,i}	−0.070 ± 0.020 ^{a,b,c,d,e}	0.186 ± 0.020 ^{c,d,e}	−0.034 ± 0.013 ^{b,c,d,e}
	60	0	68.4 ± 0.3 ^{i,j}	8.5 ± 0.2 ^{l,m,n}	−0.040 ± 0.023 ^{b,c,d,e}	0.128 ± 0.030 ^{d,e}	−0.014 ± 0.010 ^{d,e}
		50	66.0 ± 0.3 ^{c,d}	7.4 ± 0.2 ^{i,j,k}	−0.068 ± 0.005 ^{a,b,c,d,e}	0.224 ± 0.040 ^{a,b,c,d}	−0.050 ± 0.015 ^{a,b,c,d}
		100	64.0 ± 0.2 ^{a}	6.9 ± 0.3 ^{h,i,j}	−0.080 ± 0.002 ^{a,b,c}	0.118 ± 0.020 ^{a,b,c,d}	−0.050 ± 0.010 ^{a,b,c,d}
	80	0	67.5 ± 0.3 ^{g,h}	8.0 ± 0.3 ^{k,l,m}	−0.092 ± 0.017 ^{a,b}	0.234 ± 0.015 ^{c,d,e}	−0.032 ± 0.002 ^{c,d,e}
		50	65.1 ± 0.1 ^{b}	4.5 ± 0.1 ^{a,b}	−0.046 ± 0.022 ^{a,b,c,d,e}	0.250 ± 0.025 ^{e}	0.028 ± 0.010 ^{e}
		100	68.1 ± 0.2 ^{h,i}	8.1 ± 0.2 ^{k,l,m,n}	−0.058 ± 0.015 ^{a,b,c,d,e}	0.186 ± 0.002 ^{b,c,d,e}	−0.038 ± 0.080 ^{b,c,d,e}

M—moisture; S—screw speed; E—enzyme dose; Hyd—hydration; Stab.—dough stability; *α*—slope of angle *α*; *β*—slope of angle *β*; *γ*—slope of angle *γ*; $^{a–n}$—means indicated with similar letters in columns do not differ significantly at *α* = 0.05.

Table 7. Regression coefficients for response surface model of rheological properties of wheat flour extruded via L/D 16 and L/D 20 using coded inputs.

	Hyd (%)	**Stab. (min)**	**C2 (Nm)**	**C3 (Nm)**	**C4 (Nm)**	**C5 (Nm)**	***α***	***β***	***γ***
					L/D 16				
Const.	61.985 ***	6.659	0.634	1.381 ***	0.972 ***	1.410 ***	−0.061	0.245	−0.081
M	−1.083 ***	0.633	0.013	0.029 **	0.050 ***	0.161 ***	−0.007	0.009	0.008
S	0.528	−0.067	0.000	−0.023 **	−0.029 **	−0.034 **	0.010	−0.006	−0.005
E	−0.256	0.044	−0.015	−0.016	−0.070 ***	−0.138 ***	−0.002	0.006	−0.011
M × M	3.728 ***	0.222	0.019	−0.082 ***	−0.083 ***	0.002	0.006	−0.041	0.018
S × S	0.528	0.056	0.006	0.007	0.027	0.070 **	0.000	−0.001	0.001
E × E	−0.222	−0.178	−0.016	0.032	0.048 **	0.149 ***	0.006	0.027	0.012
M × E	−0.592	0.042	−0.013	−0.016	−0.006	−0.033	0.001	−0.008	0.012
S × E	−0.458	−0.783	−0.008	0.006	0.007	0.006	−0.003	0.003	−0.011
M × S	0.583	−0.192	0.001	−0.014	0.003	0.003	0.005	−0.009	0.000
p-value of F test	0.001 ***	0.728	0.142	0.002 ***	0.0002 ***	<0.0001 ***	0.219	0.105	0.606
R^2	0.646	0.021	0.217	0.582	0.691	0.886	0.152	0.256	0.020

Table 7. *Cont.*

	Hyd (%)	Stab. (min)	C2 (Nm)	C3 (Nm)	C4 (Nm)	C5 (Nm)	α	β	γ
				L/D 20					
Const.	66.352	6.300 ***	0.639	1.354 ***	0.942 ***	1.573 ***	−0.042	0.221 ***	−0.051 ***
M	−0.683	1.033 ***	0.017	−0.030 ***	0.018	0.135 ***	−0.011	−0.028 ***	0.021 ***
S	0.278	−0.822 ***	−0.015	−0.004	−0.028 **	−0.117 ***	0.006	0.007	0.018 ***
E	−0.439	−0.406	−0.018	−0.063 ***	−0.055 ***	−0.123 ***	−0.004	−0.016	−0.005
M × M	0.028	−0.167	−0.010	−0.029 **	−0.004	−0.097 **	−0.004	−0.027	0.012
S × S	−0.722	−0.233	−0.016	0.021	0.015	0.022	−0.004	0.039 **	0.010
E × E	0.961	0.750	0.018	−0.016	0.033	0.164 ***	−0.012	−0.007	−0.030 ***
M × E	−0.233	0.025	0.002	−0.031***	−0.020	0.016	0.003	−0.003	0.003
S × E	0.383	0.083	0.006	−0.002	−0.019	−0.034	0.001	−0.002	0.003
M × S	0.692	0.092	0.014	0.016	−0.002	0.006	0.002	0.006	0.000
p-value of F test	0.131	0.021 **	0.196	<0.0001 ***	0.004 ***	<0.0001 ***	0.314	0.020 **	0.006 ***
R^2	0.227	0.424	0.170	0.783	0.551	0.810	0.089	0.427	0.512

M—moisture; S—screw speed; E—enzyme dose; Hyd—hydration; Stab.—dough stability; C2—protein weakening; C3—starch gelatinization; C4—amylase activity; C5—starch retrogradation; α—slope of angle α; β—slope of angle β; γ—slope of angle γ; ** $p < 0.05$, *** $p < 0.01$.

Figure 4 presents the example curves obtained via the Mixolab® Chopin+ procedure for a native flour and for extruded flours amended without/with xylanase. In Figure 4, the measure points for the main dough properties prepared from the treated flours are indicated as protein weakening (C2), starch gelatinization (C3), amylase activity (C4) and starch retrogradation (C5). The developed native NSP-rich wheat flour tested with Mixolab® showed C2 at 0.477 ± 0.01 Nm, C3 at 1.709 ± 0.01 Nm, C4 at 1.479 ± 0.01 Nm and C5 at 2.519 ± 0.00 Nm.

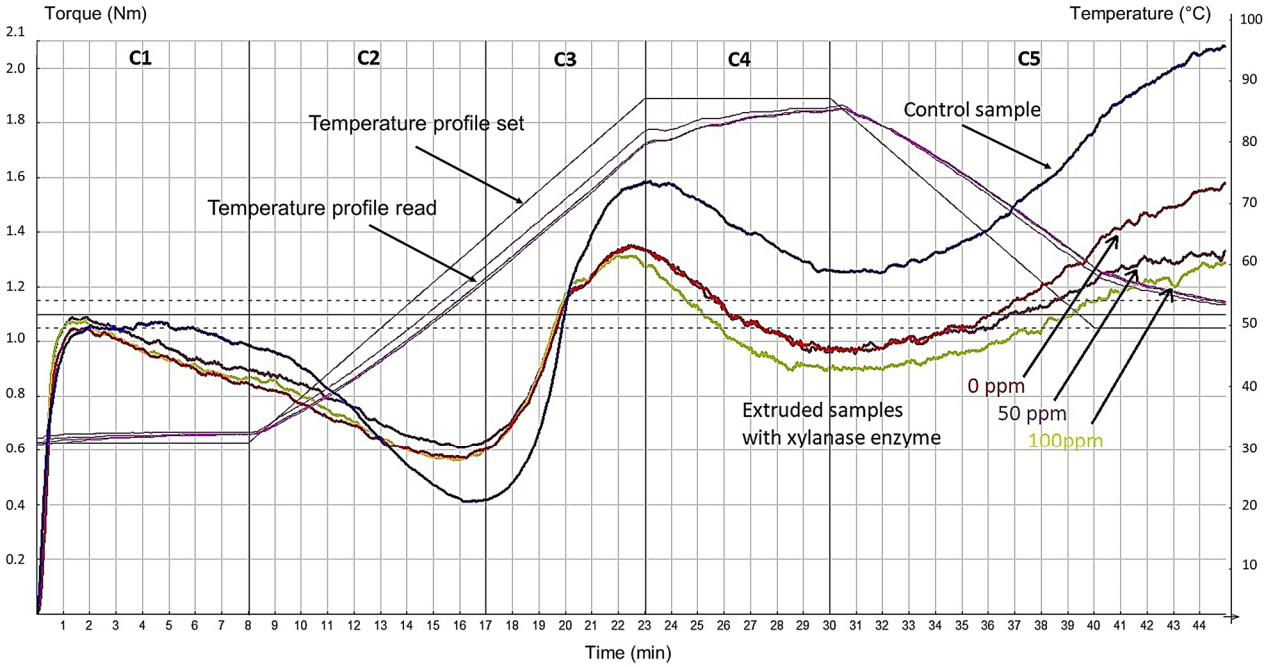


Figure 4. Mixolab® apparatus curve profile with identified tested points referring to rheological properties: results of control and hybrid enzymatic-extrusion-treated wheat flour extruded at 80 rpm and 23% of initial moisture. C1—beginning heating; C2—protein weakening; C3—starch gelatinization; C4—amylase activity; C5—starch retrogradation.

The rheological properties of the dough prepared from the extruded flours are presented in Figures 5–8 and in Tables 5 and 6. Our work demonstrates that the low-temperature extrusion process significantly affects some of the rheological properties of the NSP-rich wheat flour, and the scale of this depends on the L/D extruder configuration and

the processing variables applied. We noted that the single-screw extrusion treatment of the NSP-rich wheat flour without or with xylanase addition using two different extruder configurations slightly influenced C2 values (Figure 5), probably due to treatment at similar conditions. C2 for native wheat flour was 0.47 Nm. For extruded wheat flour, C2 was 0.61–0.67 Nm for L/D 16 and 0.59–0.65 Nm for L/D 20, so the extrusion treatment significantly increased the protein weakening of the treated flour. C2, as a protein weakening indicator, was measured at a temperature that may have denatured the protein, and protein weakening values were not differentiated significantly as extrusion-dependent variables. C2 parameters, registered in the first stage of dough heating, indicated that the modified flours were not susceptible to changes in the factors of initial moisture (M), screw speed (S) or enzyme dose (E) in any of the settings or extruder configurations: L/D 16 and L/D 20 (Table 7).

With regard to the changes in protein structure formed during extrusion at low moisture, some protein linkages were found to involve fewer disulfide bonds than those built up at higher moisture levels. We think that the protein network formed under low moisture extrusion could have incorporated more protein subunits, which would explain the lower protein solubility. Thus, besides the influence of thermal and mechanical energy input, moisture content is important for the nature of disulfide cross-linking during extrusion [55]. In both extruder configurations, we observed a slight increase in C2 parameter values when the initial feed moisture content increased (Figure 5a,c,d,f). Increased enzyme dose also had a slight effect on protein weakening values: lower C2 values were obtained when extrusion was undertaken with higher xylanase doses in both extruder configurations (Figure 5b,d,e). In general, the elongated L/D 20 extruder configuration allowed us to obtain lower C2 values, and this may be due to the application of a mixing element to the screw configuration mixing element, which loosened the melted dough and thus caused a less intensive treatment of protein components (especially gluten) in the tested NSP-rich flour.

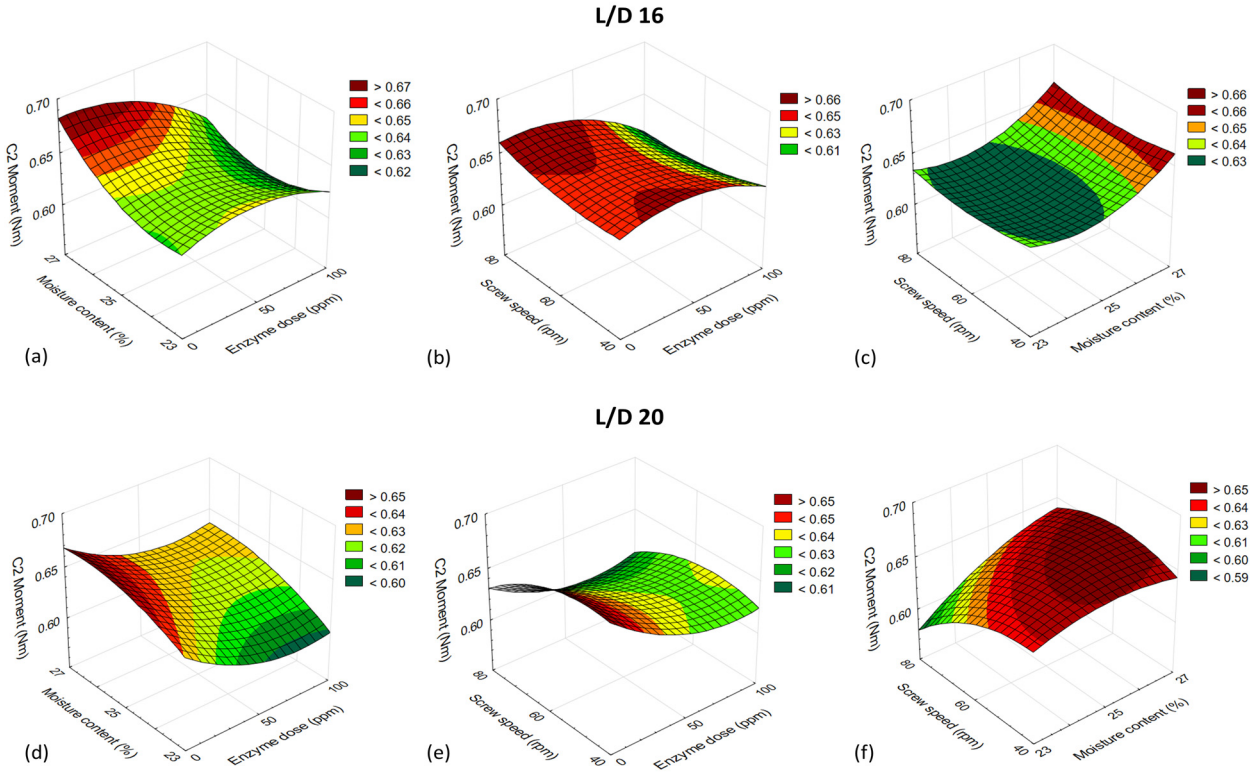


Figure 5. Processing variables and L/D configuration effects on the C2 of extruded wheat flour with xylanase enzyme: L/D 16: (**a**) E × M, (**b**) E × S, (**c**) M × S; L/D 20: (**d**) E × M, (**e**) E × S, (**f**) M × S. C2—protein weakening; E—enzyme dose; M—moisture; S—screw speed.

In general, extrusion processing caused an increase in protein weakening that can be observed as higher C2 values, especially at higher feed moisture. But the application of the enzyme limited the disruption of the protein network, giving lower C2 values. If C2 is high in value, the dough obtained with the treated flour is less elastic and exhibits limited development. Extruded flour itself is impossible to apply in bread making, but the partial replacement of bread flour with a low C2 characteristic with extruded flour can be helpful to slow down the formation of pores during fermentation and ovenspring and can positively maintain the internal structure of bread. Moreno−Rivas et al. [25] applied a single-screw laboratory extruder with L/D = 25:1, a nominal compression ratio of 2:1 and a die opening of 3 mm, working at 45 rpm and in the temperature ranges of 60, 70, 80, and 90 °C to treat nixtamalized corn flour with and without xylanase. They reported that the extruded nixtamalized corn flour, with and without xylanase, had increased protein solubility, and this effect was lower when extruded with xylanase. What is more, the addition of xylanase reduced the effect that the extrusion process had on the solubility proteins of the extruded nixtamalized corn flour. Additionally, fat content decreased significantly in the extruded products without and with xylanase enzyme, due to lipid breakdown or the formation of complexes between amylose and fatty acids, making it possible to extend the shelf life of extruded flour products [26]. Schmiele et al. [40] reported C2 values ranging from 0.46 to 0.58 Nm for wheat flour filled with soy protein and fructooligosaccharides depend on the content of additives. Bucsella et al. [60] reported significant changes after the treatment of cake and bread flour with thermal and hydrothermal methods. They found a slight increase in C2 values after hydrothermal treatment for 5 min, but longer treatment times (10 and 20 min) decreased the C2 values of both cake and bread wheat flour due to changes in protein conformation by heating.

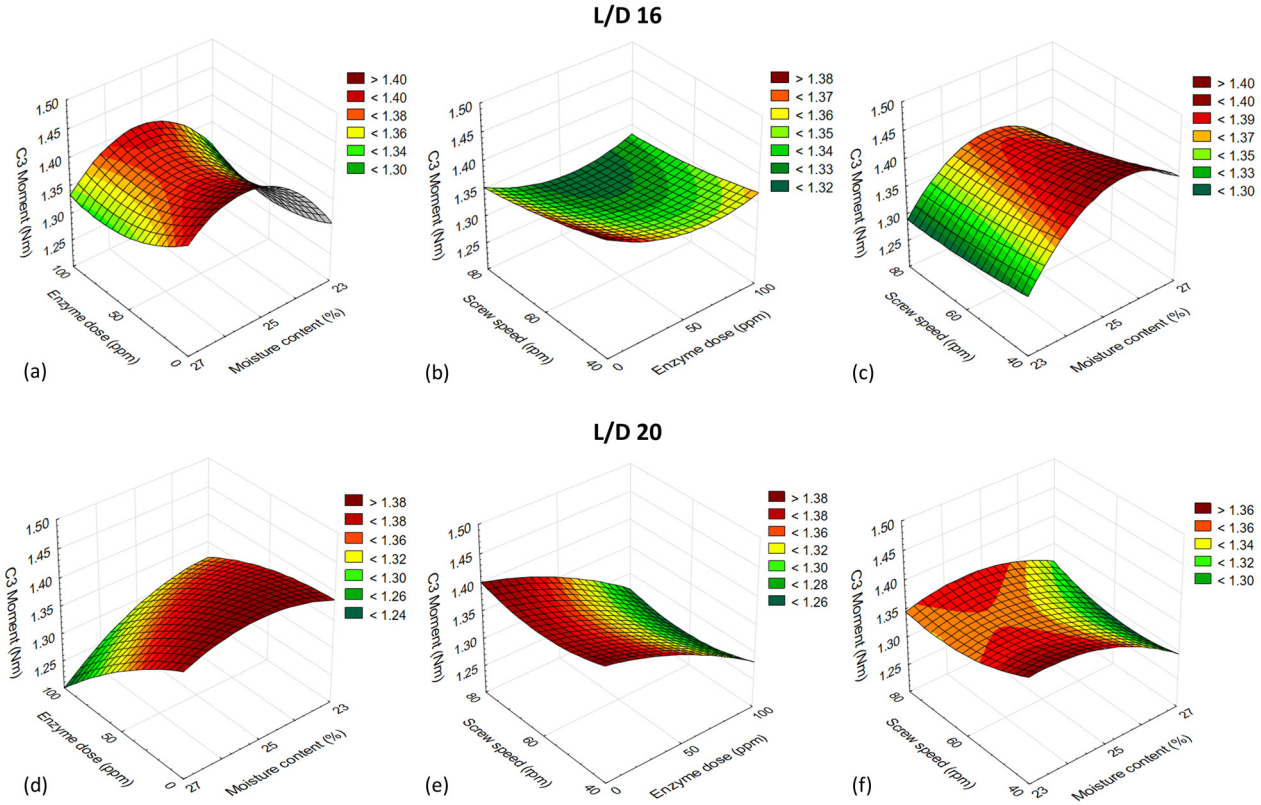


Figure 6. Processing variables and L/D configuration effects on the C3 of extruded wheat flour with xylanase enzyme: L/D 16: (**a**) E × M, (**b**) E × S, (**c**) M × S; L/D 20: (**d**) E × M, (**e**) E × S, (**f**) M × S. C3—starch gelatinization; E—enzyme dose; M—moisture; S—screw speed.

Figure 6 presents the C3 results (starch gelatinization torque data) of NSP-rich wheat flour exposed to variable conditions and either the L/D 16 or L/D 20 extruder configurations. The C3 for native flour was 1.71 Nm, and after processing, values ranged from 1.244 to 1.491 Nm when wheat flour was extruded with the short L/D 16 extruder configuration, and from 1.181 to 1.470 Nm if processed via the elongated extruder L/D 20. Treatment via the short L/D 16 version of the extruder engendered higher starch gelatinization levels due to more intensive treatment, in contrast to processing via the L/D 20 apparatus with a screw profile equipped with a mixing zone. In this case, the C3 results showed a strong negative correlation with enzyme dose ($r = -0.743$). This mixing zone allowed for a longer residence time of the treated wheat flour and the activation of the xylanase enzyme. Additionally, the screw mixing element loosened the internal structure of the melted treated flour, which could worsen the gelatinization levels of the starch present in wheat flour. For both extruder settings (L/D 16, L/D 20), regression models explaining the variability of C3 in relation to the experimental factors tested were estimated.

The significant results of the F test and the high values of the coefficient of determination confirmed the adequacy of the obtained relationships. Statistical analysis of the C3 values showed a positive linear C3 relationship with respect to M and a negative quadratic relationship with M, as well as a negative linear relationship with S (Table 7). The changes in the C3 values of the treated flour were more dominated by a parabolic (quadratic) relationship with initial feed moisture if the L/D 16 configuration was used for treatment. Regarding the C3 results obtained for the L/D 20 version, there was a small negative M × E interaction effect, indicating that C3 increases as M and E decrease for this device configuration. Both factors (M, E) independently contributed to the decrease in C3, indicating an additive effect of this interaction. It can be seen that in comparing the regression coefficients, the influence of enzyme dose is slightly stronger than other factors (Table 7). This could be due to the partial hydrolysis of polysaccharides by xylanase (probably either starch), the effect of which lowered C3 values in the obtained enzymatic-extruded flour. More important changes in modified flour caused by xylanase level were visible when the elongated L/D 20 extruder configuration was used for processing (Figure 6d,e), due to less intensive mechanical treatment via the mixing element and the possibly more intensive effect of the enzyme on flour structure. This resulted in lower gelatinization levels in the treated flour.

The amylographic profile of the dry-heated test wheat flour showed a drastic change, i.e., an earlier onset time and higher peak viscosity than that of the control, suggesting easier gelatinization after treatment [70]. Gujala et al. [31] used two extrusion conditions: low-temperature−low-shear (LTLS), where the barrel temperature was set at 30, 32, 34, 36, 38 and 40 °C in individual zones and a 200 rpm screw speed was used, and high-temperature−high-shear (HTHS), with temperature settings of 30, 40, 50, 60, 70, and 80 °C and a screw speed of 250 rpm was applied in a twin-screw extruder for pre-cooking wheat flours substituted with 0, 10, 20 and 30% wheat bran, and with a moisture content maintained at 30%. They found that the application of extrusion pre-cooking of fibers in bran-enriched flour led to synergistic interactions between the bran and other components, and increased its functionality for use in baked products. The dough rheological properties, measured using a Mixograph, showed dough behavior when heated above the characteristic temperature in the presence of water, where native starch granules undergo gelatinization, which essentially involves the disruption of the molecular order in the granules, causing the starch granules to swell and amylose to leach out.

Amylase activity (C4) is another rheological parameter possible to identify when the Chopin+ protocol is applied to wheat flour (1.48 Nm for native flour). We noted that the results of C4 obtained for the enzymatic-extruded wheat flour depended on the extruder configuration and processing variables (Figure 7). Values of amylase activity represented by C4 were slightly higher if L/D 20 was employed for processing, especially when the interactions of M and S were analyzed (Figure 7c and Figure 7f, for L/D 16 and L/D 20, respectively).

Increasing feed moisture content brought about higher values of C4, especially when the enzyme was not used in the processed blends (Figure 7a,c). However, the strongest changes in the C4 feature were obtained when the shorter L/D 16 configuration was employed for wheat flour processing. This generated a quadratic negative dependence on M (Table 7). Here, enzyme addition induced lower results that were independent of the extruder configuration used. For both extruder configurations, a significant negative linear relationship was obtained between C4 and S and E, which demonstrated that amylase activity decreases as S and E increase, with the effect of xylanase enzyme level being slightly stronger than the applied screw speed. For both configurations, the adequacy of the models describing C4 was demonstrated by moderate R^2 results and statistically significant F test results. Moreover, if the L/D 16 version was used for treatment, significant positive linear effects of M and quadratic E on the C4 values were demonstrated. Significant negative correlation coefficients were found between C4 and enzyme dose for both extruder configurations used (r values were −0.582 for L/D 16 and −0.649 for L/D 20). The effect of xylanase of various origins may have a variable impact on dough rheological properties tested with Mixolab, but, in general, xylanase supplementation decreases protein resistance to mixing that is connected with lowered protein weakening (C2). Moreover, wheat flour gelatinization decreases (C3–C2) and the stability of the hot-formed gel increases (C3–C4) [61].

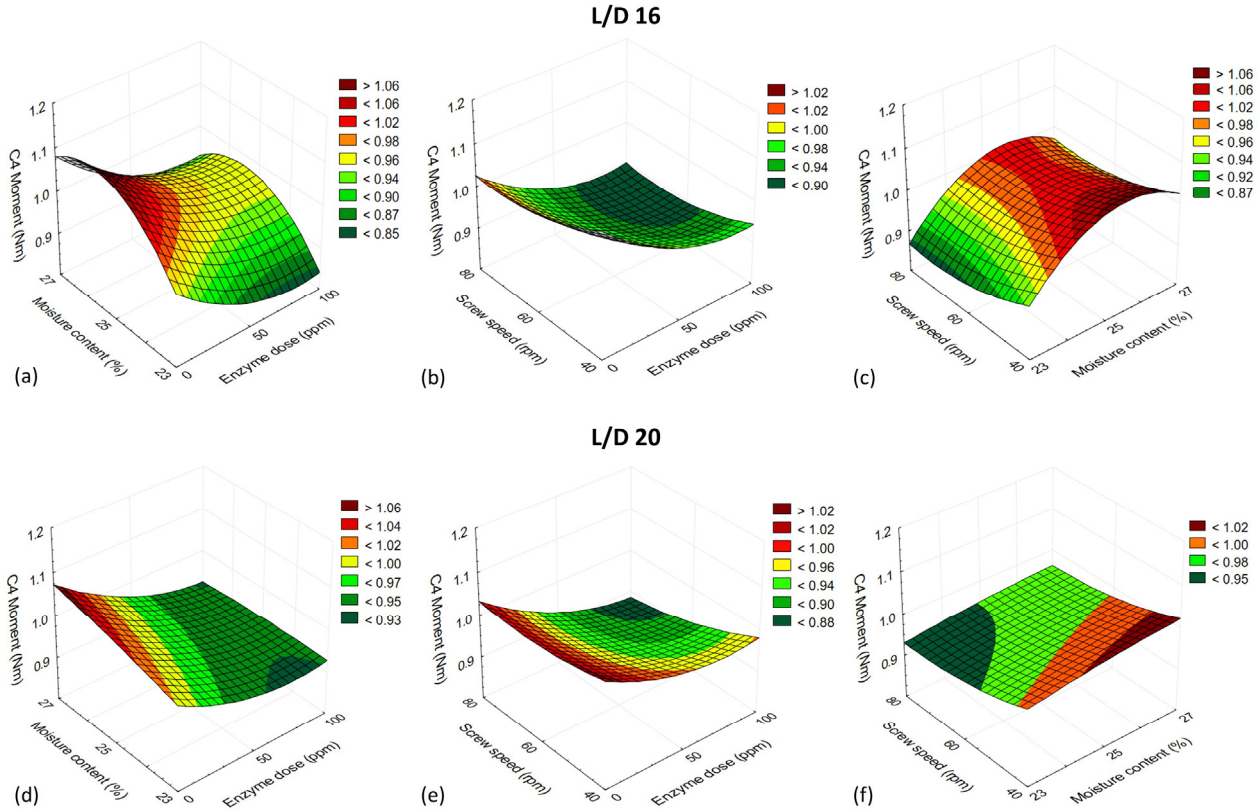


Figure 7. Processing variables and L/D configuration effects on the C4 of extruded wheat flour amended with xylanase enzyme: L/D 16: (**a**) E × M, (**b**) E × S, (**c**) M × S; L/D 20: (**d**) E × M, (**e**) E × S, (**f**) M × S. C4—amylase activity; E—enzyme dose; M—moisture; S—screw speed.

The C5 value indicates retrogradation tendency (as a starch gelling torque) and it was evident that the extrusion treatment lowered retrogradation tendency after cooling as compared to native flour (2.52 Nm). This outcome can have a positive effect on bread stability if extruded flour is added as a "clean label" water hydration improver, and limitation of bread staling with this additive is expected. In the cereal industry, hydrothermal and dry heat treatment processes are applied mainly for extending the shelf life of flours

or products (normally 3–9 months for wholegrain wheat flour and 9–15 months for white wheat flour—this may be extended by at least 3 months after treatment) and modifying the techno-functional properties of the flours during food production. The C5 values of the treated NSP-rich wheat flour are presented in Figure 8. As shown in Figure 8, increased levels of added xylanase decreased C5 values and lowered retrogradation tendencies in the hybrid enzymatic-extruded modified wheat flour. The C5 values presented in Figure 8a,b indicate a lowered retrogradation tendency with increasing enzyme level after NSP-rich wheat flour extrusion, and that this effect is not dependent on the extruder configuration. Slightly lower values were obtained after extrusion via the shorter L/D 16 configuration. This is especially noticeable when analyzing the combined effect of screw speed and feed moisture content (Figure 8c,f). For both configurations, the adequacy of the models describing C5 was demonstrated by high R^2 results and statistically significant F test results. On average, the C5 values were slightly higher for the L/D 20 extruder configuration (Figure 8). Strong correlation coefficients were found between C5 and C4 values for both extruder configurations applied (r values were 0.814 for L/D 16 and 0.767 for L/D 20). Additionally, C5 values were negatively correlated with extrusion pressure, with similar r values obtained for both L/D configurations (r = −0.649 and −0.642, respectively).

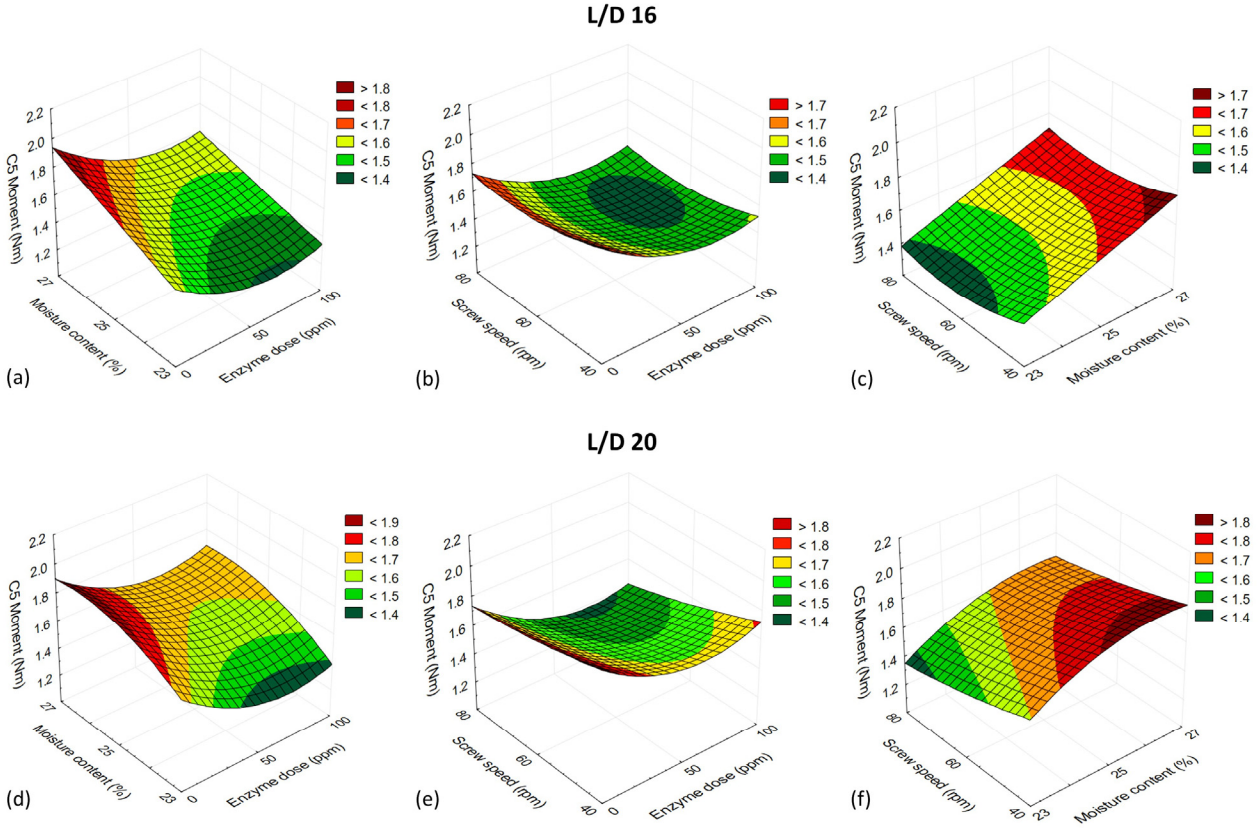


Figure 8. Processing variables and L/D configuration effects on the C5 of extruded wheat flour with xylanase enzyme: L/D 16: (**a**) E × M, (**b**) E × S, (**c**) M × S; L/D 20: (**d**) E × M, (**e**) E × S, (**f**) M × S. C5—starch retrogradation; E—enzyme dose; M—moisture; S—screw speed.

Slope α, between the end of the 30 °C period and C2, can be designated as the speed of the protein weakening (protein breakdown) (α, °) under the heating effect. Moreover, slope β, between C2 and C3, serves as an indicator of pasting (gelatinization) speed (β, °), and slope γ, between C3 and C4, represents the enzymatic (α-amylase) degradation speed (cooking stability rate) (γ, °) [32,70]. The greater angle of a slope indicates more intensive changes [41]. Results of measured values of slopes are presented in Tables 5 and 6, respectively, if L/D 16 and 20 was applied for wheat flour processing. The α slope of the

modified flour was not susceptible to changes in the tested factors, M, S or E, in either extruder configuration (L/D 16, L/D 20) (Table 7). In the case of the β angle values, a significant negative linear relationship with feed moisture M was obtained for the L/D 20 configuration, which indicates that the β slope decreases with the increase in M, and a positive relationship with the square of screw speed S were noted (Table 7). However, when the short extruder version L/D 16 was used for wheat flour processing, the β angle was not susceptible to initial moisture (M), screw speed (S) or enzyme dose (E) factor changes (Table 7). The values of this slope (Tables 5 and 6) were correlated with the C3 results of modified flour with r values of 0.684 and 0.644 for L/D 16 and 20, respectively. Similarly, the γ angle values, established between C3 and C4, obtained during the testing of the enzymatic-extruded wheat flour, were not susceptible to changes in the initial moisture (M), screw speed (S) or enzyme dose (E) processing variables when the L/D 16 extruder configuration was utilized (Table 7). If the elongated L/D 20 configuration was employed, significant positive linear dependences between the γ angle and M and S were obtained, which indicates that the γ slope increased with the increases in feed moisture M and screw speed S. A significant negative quadratic trend between the γ angle and enzyme dose E was also established. This parabolic relationship seems to have a stronger impact on the variability of γ in relation to the other variables (Table 7, coefficients further from zero).

The addition of xylanase enzyme may have effects on the handling properties of dough, the ovenspring and the bread volume. Hilhorst et al. [22] reported that the addition of xylanase to the dough increased loaf volume and improved the crumb structure of the baked product, but made the dough more sticky and less firm. Furthermore, staling was retarded. This effect has been ascribed to the redistribution of water from hemicellulose to gluten, which would render the gluten more extensible. Andersson et al. [13], in turn, reported the significant effects of screw speed, temperature and water content on oligosaccharide content, with the highest extractability found at high screw speed, high temperature and low water content. They also noted the significant effect of the interaction between screw speed and water content, with a more pronounced effect of screw speed at the lowest water content. The yield of oligosaccharides was significantly improved by traditional extrusion and enzymatic extrusion, which was mainly ascribed to extrusion-induced damage to the cell walls in the fiber-rich raw materials.

4. Conclusions

Low-temperature enzyme-assisted extrusion of NSP-rich wheat flour is possible with various extruder configurations and processing variables. The results show that the obtained extruded NSP-rich flour properties were significantly affected by processing conditions, especially the initial feed moisture and the screw speed applied during processing. The application of various extruder configurations and screw profiles demonstrated significant effects on both the wheat flour's processing behavior and rheological characteristics. The longer L/D 20 extruder configuration with a screw profile with mixing elements obtained a modified flour with lower extrusion pressure and energy requirements than the L/D 16 version. The results obtained for the extruded flours showed differences in water absorption, as well as in rheological characteristics. The extruded wheat flour was characterized by improved hydration properties (by 12.9% for L/D 16 and 14.4% for L/D 20 as compared to native flour) and limited retrogradation tendency (by 28.6% for L/D 16 and 24.6% for L/D 20 as compared to native flour). Moreover, the lower initial moisture level (23%) induced a higher hydration ability. The most significant differences were observed in C2 (protein weakening) if different configurations of the plasticizing unit L/D 16 or L/D 20 were used. The increased enzyme amount limited the negative effects of extrusion treatment on C2. Furthermore, starch gelatinization (C3) was lower when the enzyme was added prior to extrusion, and amylase activity (C4) decreased with increased xylanase addition. The addition of xylanase enzyme at the levels of 50 and 100 ppm in extruded wheat flour also limited C5—retrogradation tendency (by 8–24% for L/D 16 and 8–23% for L/D 20)—as compared to extruded wheat flour; hence, enzymatic-extruded flour used

as an additive in flour bread can elongate bread shelf life. Statistical analysis confirmed that feed moisture and screw speed were variables with the most significant effects on extrusion-modified wheat flour features. The most important factors from the point of view of the quality of the extruded NSP-rich wheat flour and its further use in bread flour mixtures should be low extrusion energy requirements, improved hydration properties and limited retrogradation tendency. So, the recommended single-screw extrusion conditions are 23% feed moisture, 40 rpm screw speed and 100 ppm enzyme addition before processing with an elongated L/D 20 extruder configuration utilizing a screw with mixing elements. Flour processed in these conditions may have a positive impact on the possibility of using modified wheat flour rich in NPS as a "clean label" improver in bakery products.

Author Contributions: Conceptualization, P.L. and A.W.; methodology, P.L. and M.R.-B.; software, P.L. and M.R.-B.; validation, P.L., A.W. and M.R.-B.; formal analysis, P.L. and M.R.-B.; investigation, P.L.; resources, P.L. and A.W.; data curation, P.L., A.W. and M.R.-B.; writing—original draft preparation, P.L. and A.W.; writing—review and editing, P.L., A.W. and M.R.-B.; visualization, P.L. and A.W.; supervision, A.W.; project administration, A.W.; funding acquisition, P.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by a grant from the Ministry of Science and Higher Education in Poland (grant number DWD/4/84/2020 "Implementation doctorate"). The funding organization had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Data Availability Statement: Data will be made available on request.

Acknowledgments: Particular acknowledgements to Krzysztof Gaczkowski, the manager of the wheat mill at PZZ Lubella GMW Sp. z.o.o., for his kind support during the research.

Conflicts of Interest: Author Piotr Lewko was employed by the company PZZ Lubella GMW Sp. z.o.o. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The PZZ Lubella GMW Sp. z.o.o. had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Alam, S.A.; Järvinen, J.; Kirjoranta, S.; Jouppila, K.; Poutanen, K.; Sozer, N. Influence of particle size reduction on structural and mechanical properties of extruded rye bran. *Food Bioprocess Technol.* **2014**, *7*, 2121–2133. [CrossRef]
2. Moscicki, L. *Extrusion-Cooking Techniques. Application, Theory and Sustainability*; Wiley-VCH: Weinheim, Germany, 2011.
3. Alam, M.S.; Kaur, J.; Khaira, H.; Gupta, K. Extrusion and extruded products: Changes in quality attributes as affected by extrusion process parameters: A review. *Crit. Rev. Food. Sci. Nutr.* **2016**, *56*, 445–475. [CrossRef] [PubMed]
4. Liu, Y.; Chen, J.; Luo, S.; Li, C.; Ye, J.; Liu, C.; Gilbert, R.G. Physicochemical and structural properties of pregelatinized starch prepared by improved extrusion cooking technology. *Carbohydr. Polym.* **2017**, *175*, 265–272. [CrossRef] [PubMed]
5. Tao, H.; Zhu, X.F.; Nan, B.X.; Jiang, R.Z.; Wang, H.L. Effect of extruded starch on the structure, farinograph characteristics and baking behavior of wheat dough. *Food Chem.* **2021**, *348*, 129017. [CrossRef]
6. Shukri, R.; Alavi, S.; Dogan, H.; Shi, Y.-C. Properties of extruded cross-linked waxy maize starches and their effects on extruded oat flour. *Carbohydr. Polym.* **2021**, *253*, 117259. [CrossRef] [PubMed]
7. Faubion, M.J.; Hoseney, R.C. High-temperature short-time extrusion cooking of wheat starch and flour. II. Effect of protein and lipid on extrudate properties. *Cereal Chem.* **1982**, *59*, 533–537.
8. Medina-Rendon, E.; Beltran-Medina, E.; Guatemala-Morales, G.; Padilla-Camberos, E.; Corona-González, R.; Mondragón-Cortez, P.; Arriola-Guevara, E. Optimization of extrusion conditions for an extruded food enriched with mango by-products (*Mangifera indica* var. Tommy Atkins) via Response Surface Methodology. *Processes* **2023**, *11*, 3182. [CrossRef]
9. Anderson, A.K.; Ng, P.K.W. Changes in disulfide and sulfhydryl contents and electrophoretic patterns of extruded wheat flour proteins. *Cereal Chem.* **2000**, *77*, 354–359. [CrossRef]
10. Day, L.; Swanson, B.G. Functionality of protein-fortified extrudates. *Compr. Rev. Food Sci. Food Saf.* **2013**, *12*, 546–564. [CrossRef]
11. Faubion, J.M.; Hoseney, R.C. High-temperature short-time extrusion cooking of wheat starch and flour. I. Effect of moisture and flour type on extrudate properties. *Cereal Chem.* **1982**, *59*, 529–533.
12. Wu, Y.; Xiao, Z.; Jiang, X.; Lv, C.; Gao, J.; Yuan, J.; Shan, L.; Chen, H. Effect of extrusion on the modification of wheat flour proteins related to celiac disease. *J. Food Sci. Technol.* **2022**, *59*, 2655–2665. [CrossRef]
13. Andersson, A.A.M.; Andersson, R.; Jonsäll, A.; Andersson, J.; Fredriksson, H. Effect of different extrusion parameters on dietary fiber in wheat bran and rye bran. *J. Food Sci.* **2017**, *82*, 1344–1350. [CrossRef]

14. Aktas-Akyildiz, E.; Masatcioglu, M.T.; Köksel, H. Effect of extrusion treatment on enzymatic hydrolysis of wheat bran. *J. Cereal Sci.* **2020**, *93*, 102941. [CrossRef]
15. Demuth, T.; Betschart, J.; Nystrom, L. Structural modifications to water-soluble wheat bran arabinoxylan through milling and extrusion. *Carbohydr. Polym.* **2020**, *240*, 116328. [CrossRef]
16. Singkhornart, S.; Lee, S.G.; Ryu, G.H. Influence of twin-screw extrusion on soluble arabinoxylans and corn fiber gum from corn fiber. *J. Sci. Food Agric.* **2013**, *93*, 3046–3054. [CrossRef]
17. Kong, C.; Duan, C.; Zhang, S.; Liu, R.; Sun, Y.; Zhou, S. Effects of co-modification by extrusion and enzymatic hydrolysis on physicochemical properties of black wheat bran and its prebiotic potential. *Foods* **2023**, *12*, 2367. [CrossRef]
18. Santala, O.; Nordlund, E.; Poutanen, K. Use of an extruder for pre-mixing enhances xylanase action on wheat bran at low water content. *Bioresour. Technol.* **2013**, *149*, 191–199. [CrossRef]
19. Pilli, T.D.; Legrand, J.; Giuliani, R.; Derossi, A.; Severini, C. Effect of processing variables and enzymatic activity on wheat flour dough extruded under different operating conditions. *Food Technol. Biotechnol.* **2009**, *47*, 404–412.
20. Melim Miguel, A.S.; Souza, T.; da Costa Figueiredo, E.V.; Paulo Lobo, B.W.; Maria, G. Enzymes in Bakery: Current and Future Trends. In *Food Industry*; Muzzalupo, I., Ed.; InTech Open (eBook): London, UK, 2013. [CrossRef]
21. Bender, D.; Nemeth, R.; Wimmer, M.; Gotschhofer, S.; Biolchi, M.; Török, K.; Tömösközi, S.; D'Amico, S.; Schoenlechner, R. Optimization of arabinoxylan isolation from rye bran by adapting extraction solvent and use of enzymes. *J. Food Sci.* **2017**, *82*, 2562–2568. [CrossRef]
22. Hilhorst, R.; Dunnewind, B.; Orsel, R.; Stegeman, P.; van Vliet, T.; Gruppen, H.; Schols, H.A. Baking performance, rheology, and chemical composition of wheat dough and gluten affected by xylanase and oxidative enzymes. *J. Food Sci.* 1999; 64, 808–813. [CrossRef]
23. Chen, H.; Chen, Z.; Fu, Y.; Liu, J.; Lin, S.; Zhang, Q.; Liu, Y.; Wu, D.; Lin, D.; Han, G.; et al. Structure, antioxidant, and hypoglycemic activities of arabinoxylans extracted by multiple methods from Triticale. *Antioxidants* **2019**, *8*, 584. [CrossRef]
24. Zhou, S.; Liu, X.; Guo, Y.; Wang, Q.; Peng, D.; Cao, L. Comparison of the immunological activities of arabinoxylans from wheat bran with alkali and xylanase-aided extraction. *Carbohydr. Polym.* **2010**, *81*, 784–789. [CrossRef]
25. Moreno-Rivas, S.C.; Medina-Rodríguez, C.L.; Torres-Chávez, P.I.; Ramírez-Wong, B.; Platt-Lucero, L.C. Changes in the solubility of corn proteins through interaction with the arabinoxylans in extruded nixtamalized corn flour treated with xylanase. *Plant Foods Hum. Nutr.* **2014**, *69*, 148–154. [CrossRef]
26. Hebeda, R.E.; Bowles, L.K.; Teague, W.M. Use of intermediate temperature stability enzymes for retarding staling in baked goods. *Cereal Foods World* **1991**, *36*, 619–624.
27. Martínez, M.; Rosell, C.; Gómez, M. Modification of wheat flour functionality and digestibility through different extrusion conditions. *J. Food Eng.* **2014**, *143*, 74–79. [CrossRef]
28. Martínez, M.; Oliete, B.; Gómez, M. Effect of the addition of extruded wheat flours on dough rheology and bread quality. *J. Cereal Sci.* **2013**, *57*, 424–429. [CrossRef]
29. Vargas, M.C.A.; Simsek, S. Clean label in bread. *Foods* **2021**, *10*, 2054. [CrossRef]
30. Miller, R.A.; Maningat, C.C.; Hoseney, R.C. Modified wheat starches increase bread yield. *Cereal Chem.* **2008**, *85*, 713–715. [CrossRef]
31. Gajula, H.; Liu, S.; Alavi, S.; Herald, T.; Madl, R.; Bean, S.R.; Tilley, M. Pre-cooked fiber-enriched wheat flour obtained by extrusion: Rheological and functional properties. *Int. J. Food Propert.* **2009**, *12*, 27–44. [CrossRef]
32. Lewko, P.; Wójtowicz, A.; Gancarz, M. Distribution of arabinoxylans and their relationship with physiochemical and rheological properties in wheat flour mill streams as an effective way to predict flour functionality. *Appl. Sci.* **2023**, *13*, 5458. [CrossRef]
33. *Approved Method of the AACC*, 9th ed.; American Association of Cereal Chemists: St. Paul, MN, USA, 2009. Available online: https://www.scirp.org/(S(czeh2tfqyw2orz553k1w0r45))/reference/ReferencesPapers.aspx?ReferenceID=1316335 (accessed on 2 August 2023).
34. McCleary, B.; DeVries, J.; Rader, J.; Cohen, G.; Prosky, L.; Mugford, D.C.; Champ, M.; Okuma, K. Determination of insoluble, soluble, and total dietary fiber (CODEX Definition) by enzymatic-gravimetric method and liquid chromatography: Collaborative study. *J. AOAC Intern.* **2012**, *95*, 3–824. [CrossRef]
35. Wójtowicz, A.; Combrzyński, M.; Biernacka, B.; Oniszczuk, T.; Mitrus, M.; Różyło, R.; Gancarz, M.; Oniszczuk, A. Application of edible insect flour as a novel ingredient in fortified snack pellets: Processing aspects and physical characteristics. *Processes* **2023**, *11*, 2561. [CrossRef]
36. Lisiecka, K.; Wójtowicz, A. Possibility to save water and energy by application of fresh vegetables to produce supplemented potato-based snack pellets. *Processes* **2020**, *8*, 153. [CrossRef]
37. *ISO 17718-1:2013*; Wholemeal and Flour from Wheat (*Triticum aestivum* L.)—Determination of Rheological Behaviour as a Function of Mixing and Temperature Increase. International Organization for Standardization: Geneva, Switzerland, 2013.
38. Szafrańska, A.; Rachoń, L.; Szumiło, G. Estimation of protein-starch complex of selected wheat species depending on production technology intensity. *Zesz. Probl. Postępów Nauk Rol.* **2015**, *582*, 81–90.
39. Dubat, A. A New AACC International Approved Method to measure rheological properties of a dough sample. *Cereal Foods World* **2010**, *55*, 150–153. [CrossRef]

40. Schmiele, M.; Felisberto, M.H.F.; Clerici, M.T.P.S.; Chang, Y.K. Mixolab™ for rheological evaluation of wheat flour partially replaced by soy protein hydrolysate and fructooligosaccharides for bread production. *LWT-Food Sci. Technol.* **2017**, *76*, 259–269. [CrossRef]
41. Oliveira, L.C.; Barros, J.H.T.; Rosell, C.M.; Steel, C.J. Physical and thermal properties and X-ray diffraction of corn flour systems as affected by whole grain wheat flour and extrusion conditions. *Starch-Stärke* **2017**, *69*, 1600299. [CrossRef]
42. Lenth, R.V. Response-Surface Methods in R, Using rsm. *J. Stat. Soft.* **2009**, *32*, 1–17. [CrossRef]
43. Bagdi, A.; Szabó, F.; Gere, A.; Kókai, Z.; Sipos, L.; Tömösközi, S. Effect of aleurone-rich flour on composition, cooking, textural, and sensory properties of pasta. *LWT-Food Sci. Technol.* **2014**, *59*, 996–1002. [CrossRef]
44. Bucsella, B.; Takács, Á.; von Reding, W.; Schwendener, U.; Kálmán, F.; Tömösközi, S. Rheological and stability aspects of dry and hydrothermally heat treated aleurone-rich wheat milling fraction. *Food Chem.* **2017**, *220*, 9–17. [CrossRef]
45. Yan, J.; Lv, Y.; Ma, S. Wheat bran enrichment for flour products: Challenges and solutions. *J. Food Process. Preserv.* **2022**, *46*, e16977. [CrossRef]
46. Thuwall, M.; Boldizar, A.; Rigdahl, M. Extrusion processing of high amylose potato starch materials. *Carbohydr. Polym.* **2006**, *65*, 441–446. [CrossRef]
47. Kowalski, R.; Gu, B.-J.; Jacob, P.; Hause, J.; Pietrysiak, E.; Dhumal, G.; Campbell, H.; Ganjyal, G. Waxy wheat extrusion: Impacts of twin-screw extrusion on hard red waxy wheat flour. *Cereal Chem.* **2020**, *97*, 1118–1132. [CrossRef]
48. Kantrong, H.; Charunuch, C.; Limsangouan, N.; Pengpinit, W. Influence of process parameters on physical properties and specific mechanical energy of healthy mushroom-rice snacks and optimization of extrusion process parameters using response surface methodology. *J. Food Sci. Technol.* **2018**, *55*, 3462–3472. [CrossRef]
49. Samborska, K.; Guiavarc'h, Y.; Van Loey, A.; Hendrickx, M. The influence of moisture content on the thermostability of *Aspergillus oryzae* α-amylase. *Enzyme Microb. Technol.* **2005**, *37*, 167–174. [CrossRef]
50. Ma, S.; Wang, H.; Cheng, H.; Li, J.; Xue, M.; Qin, Y. Modelling and comparison of wheat flour extrusion cooking behaviours in two different twin-screw extrusion systems. *Food Bioprocess Technol.* **2018**, *11*, 1381–1392. [CrossRef]
51. Deng, F.; Hu, X.; Wang, Y.; Luo, S.; Liu, C. Improving the yield of feruloyl oligosaccharides from rice bran through enzymatic extrusion and its mechanism. *Foods* **2023**, *12*, 1369. [CrossRef]
52. Kharat, S.; Medina-Meza, I.; Kowalski, R.; Hosamani, A.; Ramachandra, C.T.; Hiregoudar, S.; Ganjyal, G. Extrusion processing characteristics of whole grain flours of select major millets (foxtail, finger, and pearl). *Food Bioprod. Process.* **2019**, *114*, 60–71. [CrossRef]
53. Allai, F.M.; Azad, Z.R.A.A.; Dar, B.N.; Gul, K. Effect of extrusion processing conditions on the techno-functional, antioxidant, textural properties and storage stability of wholegrain-based breakfast cereal incorporated with Indian horse chestnut flour. *Ital. J. Food Sci.* **2022**, *34*, 105–123. [CrossRef]
54. Kesre, C.; Tugrul Masatcioglu, M. Physical characteristics of corn extrudates supplemented with red lentil bran. *LWT-Food Sci. Technol.* **2022**, *153*, 112530. [CrossRef]
55. Fischer, T. Effect of extrusion cooking on protein modification in wheat flour. *Eur. Food Res. Technol.* **2004**, *218*, 128–132. [CrossRef]
56. Robin, F.; Dubois, C.; Pineau, N.; Labat, E.; Théoduloz, C.; Curti, D. Process, structure and texture of extruded whole wheat. *J. Cereal Sci.* **2012**, *56*, 358–366. [CrossRef]
57. Bouasla, A.; Wójtowicz, A. Gluten-free rice instant pasta: Effect of extrusion-cooking parameters on selected quality attributes and microstructure. *Processes* **2021**, *9*, 693. [CrossRef]
58. Feng, Y.; Lee, Y. Effect of specific mechanical energy on in-vitro digestion and physical properties of extruded rice-based snacks. *Food Nutr. Sci.* **2014**, *5*, 1818–1827. [CrossRef]
59. Bucsella, B.; Molnár, D.; Harasztos, A.H.; Tömösközi, S. Comparison of the rheological and end-product properties of an industrial aleurone-rich wheat flour, whole grain wheat and rye flour. *J. Cereal. Sci.* **2016**, *69*, 40–48. [CrossRef]
60. Bucsella, B.; Takács, Á.; Vizer, V.; Schwendener, U.; Tömösközi, S. Comparison of the effects of different heat treatment processes on rheological properties of cake and bread wheat flours. *Food Chem.* **2016**, *190*, 990–996. [CrossRef]
61. Butt, M.S.; Tahir-Nadeem, M.; Ahmad, Z. Xylanases and their applications in baking industry. *Food Technol. Biotechnol.* **2008**, *46*, 22–31.
62. de Souza, T.; Kawaguti, H.Y. Cellulases, hemicellulases, and pectinases: Applications in the food and beverage industry. *Food Bioprocess Technol.* **2021**, *14*, 1446–1477. [CrossRef]
63. Mosibo, O.K.; Ferrentino, G.; Alam, M.R.; Morozova, K.; Scampicchio, M. Extrusion cooking of protein-based products: Potentials and challenges. *Crit. Rev. Food Sci. Nutr.* **2022**, *62*, 2526–2547. [CrossRef]
64. Natabirwa, H.; Muyonga, J.H.; Nakimbugwe, D.; Lungaho, M. Physico-chemical properties and extrusion behaviour of selected common bean varieties. *J. Sci. Food Agric.* **2018**, *98*, 1492–1501. [CrossRef]
65. Pasqualone, A.; Costantini, M.; Labarbuta, R.; Summo, C. Production of extruded-cooked lentil flours at industrial level: Effect of processing conditions on starch gelatinization, dough rheological properties and techno-functional parameters. *LWT-Food Sci. Technol.* **2021**, *147*, 111580. [CrossRef]
66. Zhang, Y.; Hu, R.; Tilley, M.; Siliveru, K.; Li, Y. Effect of pulse type and substitution level on dough rheology and bread quality of whole wheat-based composite flours. *Processes* **2021**, *9*, 1687. [CrossRef]

67. Lee, Y.Y.; Ma, F.; Byars, J.A.; Felker, F.C.; Liu, S.; Mosier, N.S.; Lee, J.H.; Kenar, J.A.; Baik, B.K. Influences of hydrothermal and pressure treatments on compositional and hydration properties of wheat bran and dough mixing properties of whole wheat meal. *Cereal Chem.* **2021**, *98*, 673–682. [CrossRef]
68. Gómez, M.; Jiménez, S.; Ruiz, E.; Oliete, B. Effect of extruded wheat bran on dough rheology and bread quality. *LWT-Food Sci. Technol.* **2011**, *44*, 2231–2237. [CrossRef]
69. Zhang, S.; Jia, X.; Xu, L.; Xue, Y.; Pan, Q.; Shen, W.; Wang, Z. Effect of extrusion and semi-solid enzymatic hydrolysis modifications on the quality of wheat bran and steamed bread containing bran. *J. Cereal Sci.* **2022**, *108*, 103577. [CrossRef]
70. Ozawa, M.; Kato, Y.; Seguchi, M. Investigation of dry-heated hard and soft wheat flour. *Starch-Stärke* **2009**, *61*, 398–406. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.