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Impact of rotational speed of extruder cutter on the quality of corn extrudates in the function of raw material moisture and flow rate

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Abstract: *Impact of rotational speed of extruder cutter on the quality of corn extrudates in the function of raw material moisture and flow rate.* The research objective was to examine the impact of cutter rotational speed on the quality of corn extrudates. The regulated variables used in the design of experiment (DOE) included also such variables as: raw material feed rate, raw material moisture. In the research project, a co-rotating twin-screw extruder was used of the screw length to diameter ratio of 27 : 1. Research analysis showed changes in the extrudate quality parameters due to settings of the cutter, which could be observed, in particular, in the case of sectional expansion and resistance parameters of extrudates. The research conducted also confirmed that the quantity and moisture of raw material used exert significant influence on the quality of extrudate obtained.

Key words: extruder cutter, twin-screw extruder, extrusion

INTRODUCTION

The quality of food products depends upon raw materials processed in the extrusion process, as well as settings of various process parameters. Many publications in the field of extrusion are based on settings of the basic variables, such as: the temperature profile, rotational speed of the screws, diameter of the outlet nozzle, ratio of the screws (length to diameter), raw material flow rate, as well as the content of the mix, its moisture and fragmentation [Yoshitomi 2004, Obatolu et al. 2006, Pilli et al. 2007, Perez et al. 2008, Dibyakanta et al. 2015]. Adjustment of these parameters usually provides a number of opportunities of obtaining various extruded products, which allows for determination of optimum quality of the product designed [Ding et al. 2006, Bisharat et al. 2013]. Moreover, extrusion is a very sensitive process; therefore, even a small change in the value of one of the parameters of the raw materials processed or the process may influence others, which results in high sensitivity of the process to changes in quality of the material provided for processing. The impact of these changes is usually translated to changes in pressure of the head and nozzle (matrix) of the extruder, which are the so-called response variables of the extrusion process. Therefore, many authors, representing various trades, associate various quality features with pressure change, such as: density, expansion, porosity, resistance parameters, shape and others [Chuang and Yeh 2004, Lisowski et al. 2015]. Unfortunately, despite many parameters being provided by the authors, some of the results of research conducted under laboratory conditions cannot be reproduced easily in industrial production, which has been confirmed by discrepant results of some research projects conducted using similar settings of the extrusion process. This can be influenced, among other things, by the extruder design parameters, which are translated to their control capabilities [Mościcki 2007, Ekielski et al. 2015a, b]. Analyzing the available literature, one can also note that in the extrusion process research methodology, information on whether the extruder had a cutter connected is often missing; the same applies to the cutter rotational speed values. Taking into account the above, examination of the impact of cutter rotational speed on the selected quality indicators of extruded products seems reasonable.

The objective of research is to examine the impact of cutter rotational speed on the quality of corn extrudate. In order to achieve greater variability of results, the cutter was tested jointly with such extrusion process variables as the raw material flow rate in the extruder and its moisture.

MATERIAL AND METHODS

The research material consisted of extrudate of corn groats, purchased on the local market. The corn groats parameters were as follows: moisture 13.2%, granulation 0.16–0.60 mm, starch 70%, total protein 8.3%, total fat 0.9%, insoluble ash [in 10% HCL] 0.10%. In research, a co-rotating twin-screw laboratory extruder EVOLUM 25 CLEXTRAL was used with the screw length to diameter ratio L : D = 27 : 1 (the extruder is owned by the Food Technology and Gastronomy Institute of Lomza State University of Applied Sciences). The extruder cylinder was equipped with six heaters and a water cooling system. This number of sections, combined with the binary automatic system of the extruder allowed for very precise setting and controlling of the temperature profile during the extrusion process. The extruder was equipped with a calibrated volume feeder and a precise water pump, allowing for liquid metering directly to the extruder cylinder with the accuracy level of 0.001 $dm^3 \cdot min^{-1}$. In research, a single round outlet nozzle of diameter of 3.5 mm was used. The extruder was equipped with a cutter, allowing for rotational speed adjustment within the range of 0–1,400 rpm (four blades, rotor diameter of 128 mm). The extrudates obtained, prior to analysis, were cooled in room temperature until reaching stable moisture of 10–11% for the period of 2 to 3 h.

The course of the experiment

Research was conducted on the basis of a central composition plan (DOE) 2** 5-1 (Table 1) generated using Statistica software with interactions between individual factors, such as: raw material flow rate, raw material moisture and cutter rotational speed. The plan consisted of 16 repetitions, out of which three were center points, 13 were non-center points and one point marked as $n = 0$ (Table 1).

In order to adjust the results obtained to experimental data, a research model was constructed (model 1):

$$Z = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_7X_1X_2 + B_8X_1X_3 + B_9X_2X_3 + B_4X^2{}_1 + B_5X^2{}_2 + B_6X^2{}_3 \quad (1)$$

TABLE 1. Coded levels for design of the response area

Item	Raw material flow rate [kg·h^{-1}] X_1		Raw material moisture [%] X_2		Cutter rotational speed [rpm] X_3		Density [g·cm^{-3}]	Expansion [–]	Force [N]	Porosity [pore·cm^{-2}]
	coded	uncoded	coded	uncoded	coded	uncoded				
1	–1	6	–1	14	–1	200	7.02	4.80	0.12	63.00
2	–1	6	–1	14	1	400	6.02	4.80	0.09	62.00
3	–1	6	1	20	–1	200	11.48	4.50	0.14	43.00
4	–1	6	1	20	1	400	8.37	4.01	0.10	46.00
5	1	10	–1	14	–1	200	5.72	5.01	0.08	57.00
6	1	10	–1	14	1	400	4.62	4.69	0.07	54.00
7	1	10	1	20	–1	200	8.37	4.94	0.11	62.00
8	1	10	1	20	1	400	5.48	4.42	0.07	52.00
9	α	5	0	16	0	300	10.66	4.13	0.11	44.00
10	α	11	0	16	0	300	7.13	4.99	0.07	57.00
11	0	8	α	11	0	300	9.35	4.78	0.08	72.00
12	0	8	α	21	0	300	7.07	4.35	0.10	26.00
13	0	8	0	16	α	132	6.32	4.53	0.12	45.00
14	0	8	0	16	α	468	5.73	4.53	0.09	47.00
15	0	8	0	16	0	300	5.72	4.53	0.12	47.00
16	0	8	0	16	0	300	5.55	4.27	0.10	68.00

including the 2nd degree polynomial for dependent variables. Significance of the factors examined in the model was determined using the Anova test with statistical software: StatSoft, Inc. (2012), Statistica (data analysis software system), version 10. Significance was determined at various levels (0.1, 1 and 5%).

Analysis of quality parameters

In order to determine the physical properties of the samples obtained, four basic quality parameters were applied, such as: density, sectional expansion, resistance and porosity, measured over the cross-section of extrudate. For density tests, buoyancy method was used in accordance with the standard [BN-87/9135-05]. The sectional expansion coefficient was determined as the ratio of extrudate diameter to matrix outlet nozzle diameter according to the method [Alvarez--Martinez et al. 1988]. Resistance tests (texture characteristics) of extrudates were conducted using universal testing machine AXIS 500 (Poland) equipped with the force measurement head (max 25 N). The maximum force needed to pierce extrudate was examined. For this purpose, a round bolt of diameter of 2 mm was installed (rate of travel 0.02 mm·s^{-1}, displacement 12 mm). Samples used in the tests were of diameter of 5–10 mm and length of 8.2–12.4 mm.

Porosity tests were conducted on the image analysis workstation equipped with a microscope and image analysis software: a stereoscopic microscope Opta-Tech SL + camera 3 megapixel. The images were saved in TIF format in resolution of 2,048 × 1,536. Porosity was determined using the method of Gosselin and Rodrigue [2005], using the irregular envelope of the analyzed group of air pores in the images analyzed. For porosity analysis, LabView 2013 package was used with the Vision Assistant 7.1.1 software, where images were transposed to monochrome area and subjected to specialist graphic processing. Then, the obtained images of byte grayscale (56 levels) were converted to divalent bitmaps and appropriate shades of gray thresholds were chosen in the range of 1–255. In this manner, on the surface of sample cross-sections, porosity was determined as the number of pores per unit of area, expressed in cm^2, according to Hayter et al. [1989].

RESULTS

Coefficients taken into account in equation (1) and Table 2, obtained through reverse regression allowed for selection of the best adjusted model for empirical data, and the results were then obtained using 3D response surface.

It was found that the parameters that exerted the most significant influence on density changes was raw material moisture. with values significant at the level of 0.1%, and raw material feed rate (2nd degree polynomial), significant at the level of 1%. From the regression model analyzed, interactions (1 vs 2 and 1 vs 3) were removed, which resulted in in-

TABLE 2. Significant coefficients for the regression equations (1)[a] obtained for response surface

Coefficients	Estimated coefficients			
	Density [$g \cdot cm^{-3}$]	Expansion [–]	Force [N]	Porosity [$pore \cdot cm^{-2}$]
B0	–0.113730**	10.78393***	19.38330*	79.51141*
B1	0.024033***	–0.47167***	–1.17082	0.43432
B2	0.008832	–0.71095***	–2.04601*	–4.78427
B3	0.000104	0.00281	0.04349*	0.12744
B4	–0.000549***	0.01005***	0.05582*	–0.10070
B5	–0.000923**	0.03362***	0.10416*	0.22277
B6	–0.000000	0.00001**	–0.00004*	–0.00022
B7	–	0.02277***	–	–
B8	–	–0.00041**	–	–
B9	–0.000014**	–0.00026**	–0.00159	–
R^2	0.8914	0.8608	0.6821	0.575
$R^2_{adj.}$	0.87323	0.82783	0.62656	0.51342
MS	0.0000504	0.0137071	1.582716	61.3847

* Significant at the level of 5%, ** significant at the level of 1%, *** significant at the level of 0.1%,
[a] X_1 – raw material flow rate; X_2 – raw material moisture; X_3 – cutter rotational speed.

creased probability of the remaining variables. The density change results were presented in Figures 1 and 2. It was found that extrudate density depended on changes in rotational speed of the cutter and it changed significantly along with the raw material feed ratio (Fig. 1) and moisture (Fig. 2). Extrudate density decreased along with increase in the cutter speed at all levels of raw material feed intensity set. At the same time, increased feed rate resulted in substantial decreasing of extrudate density. On the other hand, increase in raw material moisture resulted in very substantial changes in density, particularly at high raw material moisture, in particular, with regard to cutter rotational speed of 100–300 rpm.

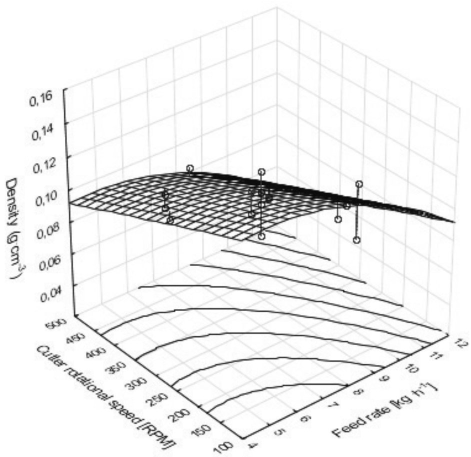

FIGURE 1. Extrudate density in the function of cutter rotational speed and raw material feed rate at moisture of 16%.

The impact of changes in the parameters of the extrusion process on the expansion level has been presented in Figures 3 and 4. It was found that this coefficient had significant influence on all process variables except for rotational speed (2nd degree polynomial). All interactions were also of significance, at the levels of 1 and 0.1. Figure 4 illustrates a substantial increase in the expansion degree at the minimum feed rate of 5 kg·h^{-1} along with increase in rotational speed of the cutter. At the highest feed rate and the lowest rotational speed of the cutter, the chart is reversed. Probably

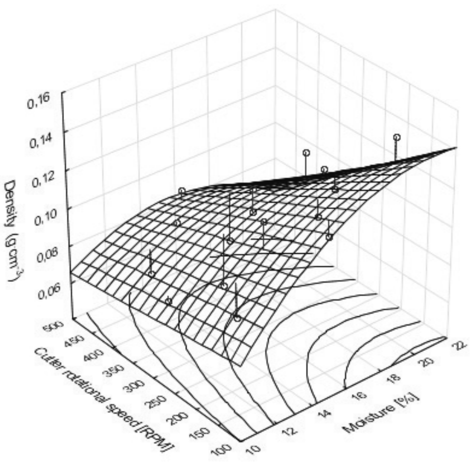

FIGURE 2. Extrudate density in the function of cutter rotational speed and raw material moisture at feed rate of 6 kg·h^{-1}

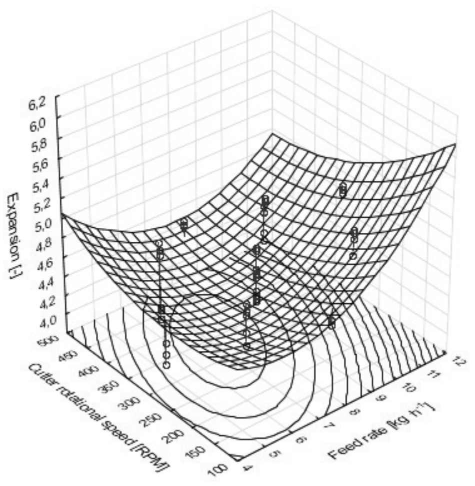

FIGURE 3. Extrudate expansion in the function of cutter rotational speed and feed rate at raw material moisture of 16%

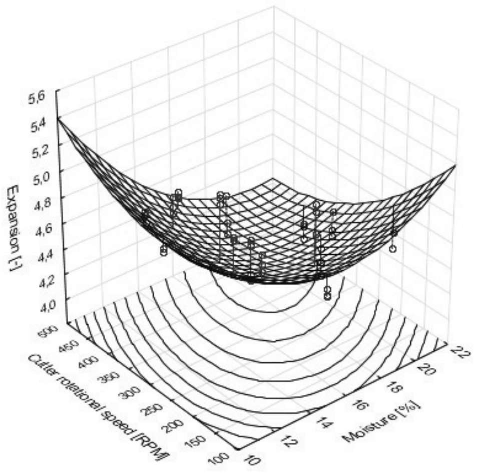

FIGURE 4. Extrudate expansion in the function of cutter rotational speed and moisture at feed rate of 6 kg·h^{-1}

with these parameters resistance of the cutter blade was lesser than resistance of the outlet nozzle itself. A sudden expansion increase could thus be caused by increased pressure in the extruder chamber due to the initiated process of raw material throttling in the extruder nozzle. Alvarez-Martinez et al. [1988] and Harper and Tribelhorn [1992] refer to the forces at the outlet nozzle to be the main factor influencing the expansion coefficient (die swell). These parameters, of course, depend very much on the extrusion process temperature. Moisture of the raw material fed and the difference between pressure inside the extruder cylinder and atmospheric pressure [Chuang and Yeh 2004].

The impact of changes in the extrusion process parameters analyzed on changes in the resistance parameters has been illustrated by Figures 5 and 6. It was found that extrudate resistance depended on such parameters of the extrusion process as: raw material feed rate, raw material moisture and cutter speed. All of the parameters marked were statistically significant at the level of 5%. It was found that extrudates characterized by the highest resistance were produced at cutter rotational speed of about 300 rpm. Both increasing of the cutter rotational speed and its decreasing resulted in deterioration of product resistance. It was also observed that increased raw material feed rate contributed to reduction of resistance parameters of the raw materials. Research using penetration tests were also conducted by [Desrumaux et al. 1999, Ding 2006]. The results obtained indicate that extrudate resistance may be correlated not only with feed rate, but also raw material temperature and moisture.

Figures 7 and 8 present the results of porosity tests in the function of cutter rotational speed and raw material feed rate or moisture. It was observed that changes in rotational speed on the chart assumed the shape of a small para-

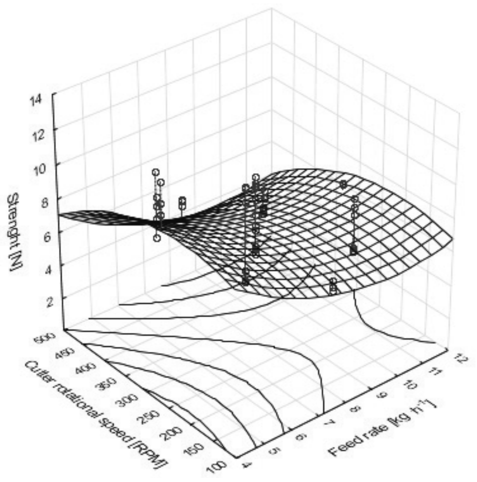

FIGURE 5. Extrudate resistance parameters in the function of cutter rotational speed and feed rate at raw material moisture of 16%

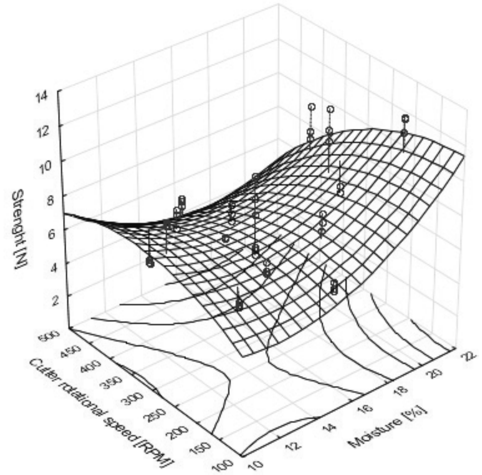

FIGURE 6. Extrudate resistance parameters in the function of cutter rotational speed and raw material moisture at feed rate of 6 k·h^{-1}

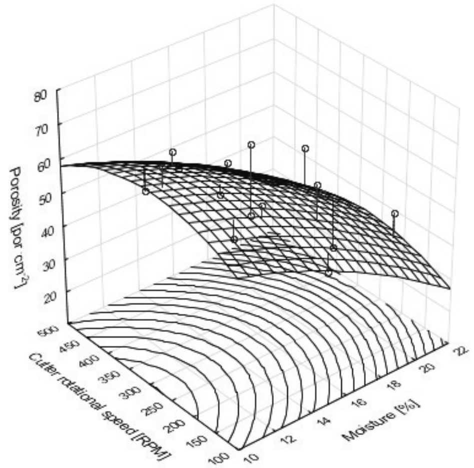

FIGURE 8. Resistance parameters of extrudate in the function of cutter rotational speed and raw material moisture at feed rate of 6 kg·h^{-1}

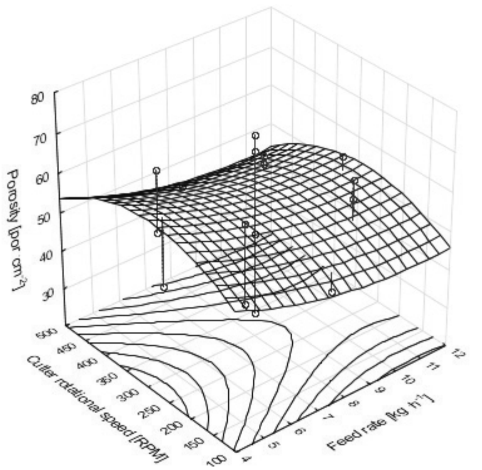

FIGURE 7. Extrudate porosity in the function of cutter rotational speed and raw material feed rate at raw material moisture of 16%

bolic curve, which confirms the thesis of non-significance of most variables. An exception here is raw material moisture – its increase results in reduced porosity. According to Ekielski et al. [2007], high porosity is usually a positive feature for raw materials extruded as it may prove high uniformity of the sample. Low porosity, on the other hand, may be translated to emergence of large pores of irregular shape. According to other authors. larger pores in general are characterized by more resistant and thicker walls, and thus products with large pores are usually rather crispy than brittle [Lanuay et al. 1983]. In general, it is also accepted that high porosity of extrudates may prove high sensory qualities of such raw materials [Ekielski et al. 2007].

In order to verify the model, the selected values obtained from regression analysis (forecasted values) were compared with the values obtained in empirical research (Table 3). Those were average values obtained from three repetitions with standard deviation. In order to check variability of forecasting of response in the model a bilateral t-test was conducted for independent samples. Since the test significance (p value) was greater than 0.05, there was no justification for rejection of the null hypothesis,

TABLE 3. Results of t-test conducted to compare the real experimental values with the expected values

Statistical coefficients	Density	Expansion	Force	Porosity
Expected value	7.457639	4.582083	6.357136	52.81250
Actual value*	7.458 +/–0.008	4.582083 +/–0.079	6.357136 +/–0.009	52.81250 +/–0.098
Quotient *F* variances	1.466	1.161715	1.151624	1.737507
p variances	0.193	0.609450	0.615251	0.061213
p bilateral	0.9833	1.000	0.9937	0.9141

Ho: $\mu_o = \mu_1 . t_{cal} < t_{table}$ at p <0.10.'Ho'was accepted.
*Average of three repetitions.

assuming equality of the averages between the empiric and forecasted values. In this case, the values were close to one; thus, it can be assumed that usability of the model for forecasting of various responses is high.

SUMMARY AND CONCLUSIONS

1. Extruder cutter rotational speed is the parameter, which is not always provided in the extruder setting specifications. Discrepant results of tests using the same raw materials in literature may depend, among other things, on lack of setting or varying settings of this parameter.
2. Research has confirmed that raw material feed rate and moisture exert impact on quality changes of the extruded products obtained. Research has shown, however, that correlation of these coefficients with the extruder cutter rotational speed may result in changes of such parameters as sectional expansion.
3. The research results obtained indicate that extrudate quality can be influenced even by external changes, associated with the extruder cutter activation.

REFERENCES

ALVAREZ-MARTINEZ L., KONDURY K., P., HARPER J. M., 1988: A general model for expansion of extruded products. Journal of Food Science 53: 609–615.

BISHARAT G.I., OIKONOMOPOULOU V.P., PANAGIOTOU N.M., KROKIDA M.K., MAROULIS Z.B. 2013: Effect of extrusion conditions on the structural properties of corn extrudates enriched with dehydrated vegetables. Food Research International 53: 1–14.

BN-87/9135-05. Pasze prasowane. Podstawowe właściwości fizykomechaniczne granul i brykietów.

CHUANG G.C.-C., YEH A.-I. 2004: Effect of screw profile on residence time distribution and starch gelatinization of rice flour during single screw extrusion cooking. Journal of Food Engineering 63 (6): 21–31.

DESRUMAUX A., BOUVIER J.M., BURRI J. 1999: Effect of free acids addition on corn grits extrusion cooking. American Association of Cereal Chemists 76 (5): 699–704.

DIBYAKANTA S., LAXMIKANT S.B., VIJAYALAKSHMI G. 2015: Effect of feed composition, moisture content and extrusion temperature on extrudate characteristics of yam corn-rice based snack food. Journal of Food Science Technology 52 (3): 1830–1838.

DING Q.-B., AINSWORTH P., PLUNKETT A., TUCKER G., MARSON H. 2006. The effect of extrusion conditions on the functional and physical properties of wheat-based expanded snacks. Journal of Food Engineering 73 (2): 142–148.

EKIELSKI A., ŻELAZIŃSKI T., JESIONEK A. 2015a: Changes in the parameters of the transfer function of a twin screw extruder. Annals of Warsaw University of Life Sciences – SGGW, Agriculture (Agricultural and Forest Engineering) 66: 79–88.

EKIELSKI A., MAJEWSKI Z., ŻELAZIŃSKI T. 2007: Effect of extrusion conditions on physical properties of buckwheat–maize blend extrudate. Polish Journal of Food and Nutrition Sciences 57, 2 (A): 57–61.

EKIELSKI A., MISHRA P.K., BILLER E., RATAJCZYK F. 2015b: Utilizing fractal dimensions of extrudate sectional images for describing their textural properties. 15th Multidiscipnary Scientific Geo Conference, Section: Micro and Nano Technologies, Advances in Biotechnology 1: 649–656. DOI:10.5593/sgem2015B61.

GOSSELIN R., RODRIGUE D., 2005: Cell morphology analysis of density polymer foams. Polymer Testing 24: 1027–1035.

HARPER J.M., TRIBELHORN R.E. 1992: Expansion of native cereal starch extrudates. In: Food Extrusion Science and Technology. M. Dekker, New York: 653–667.

HAYTER A.L., SMITH A. C., RICHMOND P. 1986: The physical properties of extruded food foams. Journal of Materials Science 21 (10): 3729–3736.

LANUAY B., LISCH J.M. 1983: Twin-screw extrusion cooking of starch pastes, expansion and mechanical properties of extrudates. Journal of Food Engineering 9 (2): 259–280.

LISOWSKI A., GRELA M., SYPUŁA M., ŚWIĘTOCHOWSKI A., DĄBROWSKA-SALWIN M., STĘPIEŃ W., KORUPCZYŃSKI R. Pellets and briquettes from fruit trees wood. Annals of Warsaw University of Life Sciences – SGGW, Agriculture (Agricultural and Forest Engineering) 66: 127–136.

MOŚCICKI L., MITRUS M., WÓJTOWICZ A. 2007: Technika ekstruzji w przemyśle rolno-spożywczym. PWRiL, Warszawa.

OBATOLU W. A., OLUSOLA O., ADEBOWALE A. 2006: Qualities of extruded puffed snack from maize/soybean mixture. Journal of Food Process Engineering 29 (2): 149.

PEREZ A.A., DRAGO S.R., CARRARA, C.R., De GREEF D.M. 2008: Extrusion cooking of a maize/soybean mixture: Factors affecting expanded product characteristics and flour dispersion viscosity. Journal of Food Engineering 87 (3): 323–332.

PILLI T. DeCARBONE B.F., FIORE A.G., SEVERINI C. 2007: Effect of some emulsifiers on the structure of extrudates with high content of fat. Journal of Food Engineering 79: 1351–1358.

YOSHITOMI B. 2004: Effect of extrusion cooking temperature on the microstructure of extruded pellets. Fisheries Science 70 (6): 1157–1163.

Streszczenie: *Wpływ prędkości obrotowej obcinarki na jakość ekstrudatów kukurydzianych w funkcji natężenia przepływu surowca i jego wilgotności.* W pracy przedstawiono wyniki badań wpływu ustawień obcinarki ekstrudera na jakość ekstrudatów kukurydzianych. Celem badań jest zatem wskazanie, czy prędkość obrotowa obcinarki ekstrudera wpływa na podstawowe parametry jakościowe typowych ekstrudatów kukurydzianych. W badaniach wykorzystano centralny plan kompozycyjny, wygenerowany w programie Statistica 12, który obejmował 16 powtórzeń. Zmiennymi regulowanymi wykorzystywanymi w planie doświadczania (DOE) były dodatkowo takie parametry, jak: ilość podawania surowca, wilgotność surowca. W badaniach wykorzystano współbieżny, dwuślimakowy ekstruder o stosunku długości do średnicy ślimaka wynoszącym 27 : 1. Analiza badań wykazała, że zmiany prędkości obrotowej obcinarki ekstrudera mają wpływ na jakość uzyskiwanych produktów. Stwierdzono, że zmiany parametrów jakościowych ekstrudatów na skutek ustawień obcinarki można było zaobserwować szczególnie w przypadku ekspansji radialnej oraz parametrów wytrzymałościowych ekstrudatów.

Przeprowadzone badania potwierdziły również, że ilość podawanego surowca i jego wilgotność wpływają istotnie na zmiany jakościowe uzyskiwanych ekstrudatów.

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