УДК 664.2

OPTIMIZATION OF EXTRUSION PROCESS FOR PRODUCTION OF APPLE POMACE AND WHEAT SEMOLINA EXTRUDATES

Petrova Todorka Valkova

Associate Professor. Institute of Food Preservation and Quality — Plovdiv (IFPQ). Plovdiv, Bulgaria. E-mail: dorrapetrova@abv.bg

Ruskova Milena Metodieva

Associate Professor. Institute of Food Preservation and Quality — Plovdiv (IFPQ). Plovdiv, Bulgaria. E-mail: mmruskova@gmail.com

Penov Nikolay Dimitrov

Professor, Technological Faculty. University of Food Technologies. Plovdiv, Bulgaria. E-mail: npenov@yahoo.com

Ivanova Kristina Atanasova

Assistant Professor. Institute of Food Preservation and Quality — Plovdiv (IFPQ). Plovdiv, Bulgaria. E-mail: kriss_k@abv.bg

Momchilova Maria Marianovna

Assistant Professor. Institute of Food Preservation and Quality — Plovdiv (IFPQ). Plovdiv, Bulgaria. E-mail: masha821982@abv.bg

ОПТИМИЗАЦИЯ ПРОЦЕССА ЭКСТРУЗИИ ДЛЯ ПРОИЗВОДСТВА ЭКСТРУДАТОВ ИЗ ЯБЛОЧНЫХ ВЫЖИМОК И МАННОЙ КРУПЫ

Петрова Тодорка Вълкова

Доцент. Институт переработки и качества пищевых продуктов. Пловдив, Болгария. E-mail: dorrapetrova@abv.bg

Рускова Милена Методиева

Доцент. Институт переработки и качества пищевых продуктов. Пловдив, Болгария. E-mail: mmruskova@gmail.com

Пенов Николай Димитров

Профессор. Технический факультет. Университет пищевых технологий. Пловдив, Болгария. E-mail: npenov@yahoo.com

Иванова Кристина Атанасова

Главный научный сотрудник. Институт переработки и качества пищевых продуктов. Пловдив, Болгария. E-mail: kriss_k@abv.bg

Момчилова Мария Мариановна

Ассистент. Институт переработки и качества пищевых продуктов. Пловдив, Болгария. E-mail: masha821982@abv.bg

Следует цитировать / Citation:

Petrova T. V., Ruskova M. M., Penov N. D., Ivanova K. A., Momchilova M. M. 2019. Optimization of extrusion process for production of apple pomace and wheat semolina extrudates. Health, Physical Culture and Sports, 4 (15), pp. 212–219. (in English). URL: http://journal.asu.ru/index.php/zosh.

*Петрова Т. В., Рускова М. М., Пенов Н. Д., Иванова К. А., Момчилова М. М***.** Оптимизация процесса экструзии для производства экструдатов из яблочных выжимок и манной крупы // Здоровье человека, теория и методика физической культуры и спорта. — 2019. — №4 (15). Спецвыпуск по гранту РФФИ №19–013–20149\19. — С. 212–219. URL: http://journal.asu.ru/index.php/zosh

Поступило в редакцию / Submitted 20.08.2019

Принято к публикации / Accepted 25.10.2019

Abstract. Apple pomace — wheat semolina blends were extruded in a laboratory single screw extruder (Brabender 20 DN, Germany) with screw diameter 19 mm and die diameter 5 mm. Central Composite Rotatable Design was used to optimize the extrusion parameters of the mixture for obtaining instant product. Effects of apple pomace content in the blends, moisture content, screw speed, and barrel temperature on the specific mechanical energy, total color difference, hardness, and water absorption index of the extruded products were studied. Response surface methodology with combinations of apple pomace content in the blends (10, 30, 50, 70, 90%), moisture content (17, 20, 23, 26, 29%), screw speed (120, 150, 180, 210, 240 rpm), and barrel temperature (130, 140, 150, 160, 170 °C) was applied. Feed screw speed was fixed at 70 rpm. The compression ratio of the screw was 3:1. The temperatures of the feed and II-nd zone were 150 and 160°C, respectively. The criterion established to determine the optimal extrusion conditions of the apple pomace — wheat semolina blend was to find the conditions leading to high values of water absorption index, and low values of specific mechanical energy, hardness, and total colour difference. Optimization was carried out by the superposition of several contour surfaces of competing responses. The response surface plots were generated for interaction of any two independent variables, while holding the value of all the rest as constant (at the central value). Moisture content from 22 to 26%, content of apple pomace from 30 to 50%, barrel temperature of 150°C, and screw speed of 180 rpm could be recommended as optimal extrusion conditions for obtaining an instant product from apple pomace and wheat semolina.

Key words: Optimization, Extrusion, Apple pomace — wheat semolina blends, Response surface methodology.

Аннотация. Смесь из яблочных выжимок и манной крупы экструдировали на лабораторном одношнековом экструдере (Brabender 20 DN, Germany) с диаметром шнека 19 мм и диаметром головки 5 мм. Центральная составная вращающаяся конструкция была использована с целью оптимизации параметров экструзии смеси для получения быстрорастворимого продукта. Было изучено влияние содержания яблочной выжимки в смесях, содержания влаги, скорости шнека и температуры цилиндра на удельную механическую энергию, общую разницу цветов, твердость и на показатель водопоглощения экструдированных продуктов. Была применена методология анализа поверхности отклика по комбинациям содержания яблочной выжимки в смесях (10, 30, 50, 70, 90%), при содержании влаги (17, 20, 23, 26, 29%), со скоростью вращения винта (120, 150, 180, 210, 240 об/мин), при температуре цилиндра экструдера (130, 140, 150, 160, 170 °C). Скорость загрузки шнека была зафиксирована на уровне 70 об/мин. Степень сжатия винта составляла 3:1. Температуры загрузки и II-й зоны составляли 150 и 160°C соответственно. Критерий, установленный для определения оптимальных условий экструзии смеси яблочных выжимок и манной крупы, заключался в нахождении условий, приводящих к высоким значениям показателя водопоглощения и низким значениям удельной механической энергии, твердости и общей цветовой разницы. Оптимизация осуществлялась путем наложения нескольких контурных поверхностей конкурирующих откликов. Графики поверхности отклика были сгенерированы для взаимодействия любых двух независимых переменных, сохраняя значение всех остальных переменных постоянными (при центральном значении). Содержание влаги от 22 до 26%, содержание яблочной выжимки от 30 до 50%, температура корпуса 150°С и скорость шнека 180 об/мин могут быть рекомендованы в качестве оптимальных условий экструзии для получения быстрорастворимого продукта из яблочных выжимок и манной крупы.

Ключевые слова: оптимизация, экструзия, смесь из яблочных выжимок и манной крупы, методология анализа поверхности отклика.

Actuality. Apple pomace is the main by-product of cider processing and poses a serious environmental problem due to the large amounts produced every year. Apple pomace is composed mainly of carbohydrates and dietary fibre, small amounts of protein, fat and ash [1, pp. 687]. Apple pomace is a good source of phytochemicals primarily phenolic acids and flavonoids [2, pp. 61].

The common applications of this by-product are the direct disposal to soil in a landfill and for pectin recovery usage. In recent years, investigations into the incorporation of apple pomace in foods especially in baked foods [1, pp. 686; 3, pp. 255; 4, pp. 618].

Extrusion, classified as a high-temperature short-time process, is a versatile, low cost, efficient, and widely used industrial technology for the continuous production of expanded product from cereals. It is a modern procedure for processing different types of raw materials and production of wide range of food products [5, pp. 299; 6, pp. 142].

Extruded snack products made predominantly from cereal flour tend to be low in protein with low biological value. The incorporation of enriched fibre flours with significant values of antioxidants is a way to improve the nutritional value of these snacks [7, pp. 702; 8, pp. 554; 9, pp. 469]. Apple pomace rich in fibre with significant amounts of antioxidants can be incorporated in human food-chain thus generating new potential functional foods.

The quality of the end product depends upon how the thermal performance of the extruder is controlled and what the thermomechanical history of the product is inside the extruder. Indeed the control of the particular thermal conditions in every process must be perfect if its operation is to be optimized. The parameters it is important to control are the material temperature and pressure, the barrel temperature, the mechanical and thermal power levels involved, and the temperatures of the barrel and the material under given operating conditions [10, pp. 83–105].

Objectives and tasks of the research. The objective of this study was to optimize the extrusion conditions for obtaining an instant product from apple pomace and wheat semolina.

In order to achieve this goal, the following tasks were formulated during the elaboration of the research:

1. To plan an experiment;
2. To obtain regression mathematical models;
3. To optimize an extrusion process.

Materials and methods.

1. Materials

Apple pomace is a by-product obtained during juice processing. Commercial apples (Granny Smith variety) are refrigerated and stored until the juice processing. The apple pomaces are dried a laboratory heat dryer at 60 °C. The dried pomaces were ground using a hammer mill then mixed with commercial wheat semolina and distilled water to be obtained the desired ratios (Table 1). The prepared wet samples were placed and kept in sealed plastic bags for 12 h in a refrigerator at 5 °C. The samples were tempered for 2 h at room temperature prior to extrusion.

Table 1

Independent variable values and corresponding levels

Independent variables	Levels				
	–2	–1	0	+ 1	+ 2
Apple pomace content in the blends (C_{pom}), % — X_1	10	30	50	70	90
Moisture content (W), % — X_2	17	20	23	26	29
Screw speed (n), rpm — X_3	120	150	180	210	240
Barrel temperature (Tm), °C–X_4	130	140	150	160	170

2. Extrusion

The samples were extruded in a laboratory single screw extruder (Brabender 20 DN, Germany). The extruder barrel (476.5 mm in length and 20 mm in diameter) contained three sections and independently controlled die assembly electric heaters. The feed screw speed was fixed at 70 rpm. The screw speed was 120, 150, 180, 210, 240 rpm according to the experimental design (Table 1). The compression ratio of the screw was 3:1. The temperatures of the feed and kneading zone were 150 and 160°C, respectively. The temperature of the final cooking zone was 130, 140, 150, 160, 170 °C. The die diameter was 5 mm.

3. Specific mechanical energy (*SME*, kJ/kg)

The specific mechanical energy was calculated using the equation [11, pp. 25]:

$$SME = \frac{2\pi \cdot Mn \cdot n / 60}{\dot{m}} \cdot 3{,}6 \qquad (1)$$

where *Mn* is the corrected torque (N.m), *n* — the screw speed (rpm), $\dot{m}$ — the feed rate (kg/h).

4. Total color difference (*ΔE*)

The extrudates were finely ground using a laboratory hammer mill. The color parameters determined for the raw blends (non-extruded) and extruded samples included L*, a* and b* values (CIE Lab system) using a colorimeter Colorgard 2000, BYK — Gardner Inc., USA. Total color difference (*ΔE*) was calculated applying the equation:

$$\Delta E = \sqrt{(L - L_o)^2 + (a - a_o)^2 + (b - b_o)^2} \qquad (2)$$

where *L*, *a*, and *b* are the values for the extruded samples; L_o, a_o, and b_o are the values for the raw blends (Table 2).

The color parameters are the mean values of ten observations.

Table 2

Color parameters (L^*, a^*, and b^* values) of non-extruded apple pomace — wheat semolina blends

Apple pomace content (%)	L^*	a^*	b^*
10	89.28	1.99	24.54
30	83.24	3.36	28.74
50	80.31	4.00	30.09
70	80.45	3.98	30.46
90	81.26	3.79	29.76

5. Hardness (*H*, N)

The hardness of the extrudates is measured in tenfold with a TA.XT Plus Texture Analyser (Stable Micro Systems Ltd., England) using a 50 kg load cell and a 2-bladed Kramer shear cell. The test settings are as follows: Test speed 1.0 mm/s, Distance 10 mm.

A force-distance curve is recorded and analyzed by Texture Exponent 32 to calculate the peak force. The highest value of force is taken as a measurement for hardness.

6. Water absorption index (*WAI*, g/g)

The extrudates were finely ground using a laboratory hammer mill and sieved through a 500 µm sieve. A 0.2 g sample was placed in a tared centrifuge tube and 5 ml distilled water added. After standing for 30 min at 30°C (with intermittent shaking every 5 min), the sample was centrifuged at 3000 rpm for 20 min using a centrifuge CH 90–2A. The supernatant was decanted into a tared aluminium pan and weight gain in the gel was noted. Water absorption index was calculated as [6, pp. 54–55]:

$$WAI = \frac{m_g}{m_o} \qquad (3)$$

where m_g is the weight gain of the gel (g), m_o — the weight of dry sample (g).

Experimental design and data analysis

A central composite rotatable design (Table 1) was used to show interactions of feed composition (apple pomace content) — X_1, moisture content — X_2, screw speed — X_3, and barrel temperature — X_4 on the extrudate in 29 runs of which 16 were for the factorial points, 8 were for axial points, and 5 were for centre points [12, pp. 489–558].

A second order polynomial model for the dependent variable was established to fit the experimental data:

$$y = b_0 + \sum_{i=1}^{n} b_i \cdot x_i + \sum_{i=1}^{n} b_{ii} \cdot x_i^2 + \sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij} \cdot x_i \cdot x_j \quad (4)$$

where b_o, b_i, b_{ii} and b_{ij} are constant coefficients. The significance of the effect was given as a p-value. The effect was considered significant if the p-value for each factor or interaction is less than 0.05.

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

Results and discussion. Extrudates of different physical structure were obtained by single screw extrusion of apple pomace — wheat semolina mixtures at different combinations of processing parameters (Table 1).

The total colour differences between the extruded and non-extruded samples expressed by ΔE, specific mechanical energy, hardness, and water absorption index are given in Table 3.

Regression analyses of the physicochemical properties of the extrudates indicated that all the second order polynomial models correlated well with the measured data and were statistically significant ($p < 0.05$).

The resulting models, after removing the non-significant terms, were evaluated in terms of uncoded factors and are presented below:

$$SME = 2504.3 - 2.7C_{pom} + 13.6W - 26.8T_m + 0.1C_{pom}W - 0.3WT_m + 0.1T_m^2, \text{кJ/kg } (R^2 = 0.86) \quad (5)$$

$$\Delta E = 60.62 + 0.60C_{pom} - 2.06W - 0.60T_m - 0.003C_{pom}T_m + 0.06W^2 + 0.0004n^2 \ (R^2 = 0.8) \quad (6)$$

$$H = 641.14 + 30.75C_{pom} - 7.14T_m - 0.04C_{pom}^2 - 0.11C_{pom}T_m + 1.56W^2 - 0.02n^2, \text{N} (R^2 = 0.9) \quad (7)$$

$$WAI = 108.54 - 0.14C_{pom} + 0.01T_m^2, \text{g/g } (R^2 = 0.85) \quad (8)$$

Table 3

Specific mechanical energy, total color differences, hardness, and water absorption index of extruded apple pomace — wheat semolina blends

№	***SME*, kJ/kg**	***ΔE***	***H*, N**	***WAI*, g/g**
1.	121.56	6.59	118.10	7.144
2.	71.29	10.40	314.57	4.812
3.	93.69	7.19	138.50	7.906
4.	80.17	10.88	300.44	5.194
5.	83.43	7.01	122.57	7.265
6.	75.87	9.60	306.95	5.276
7.	74.44	9.58	152.25	8.344
8.	108.64	10.94	311.30	5.514
9.	98.28	6.52	125.30	7.867
10.	69.17	10.31	259.72	5.330
11.	45.62	9.07	156.18	7.166
12.	36.53	8.34	229.27	7.176
13.	96.50	6.82	126.23	7.970
14.	74.77	6.60	225.14	6.648
15.	71.36	7.91	211.29	8.682
16.	57.65	7.91	239.65	5.403
17.	62.30	9.09	109.87	8.904

Table 3

№	*SME*, kJ/kg	*ΔE*	*H*, N	*WAI*, g/g
18.	40.36	8.51	282.30	5.136
19.	78.41	8.24	283.03	5.547
20.	45.11	10.41	358.98	5.804
21.	44.99	9.77	205.31	7.447
22.	70.94	7.95	194.60	7.145
23.	133.74	9.35	320.21	9.777
24.	54.63	8.06	230.75	8.568
25.	62.81	7.18	224.14	6.512
26.	63.25	6.99	253.81	6.439
27.	63.15	6.79	240.14	6.501
28.	62.92	7.23	232.55	6.491
29.	63.23	6.88	241.10	6.462

The criterion established to determine the optimal extrusion conditions of the apple pomace — wheat semolina blends was to find the conditions leading to high values of water absorption index (WAI > 6.5 g/g) and low values of hardness (H < 250 N), total color difference (ΔE < 8), and specific mechanical energy (SME < 75 kJ/kg).

An increase in apple pomace content resulted in an extrudate with higher density and hardness.

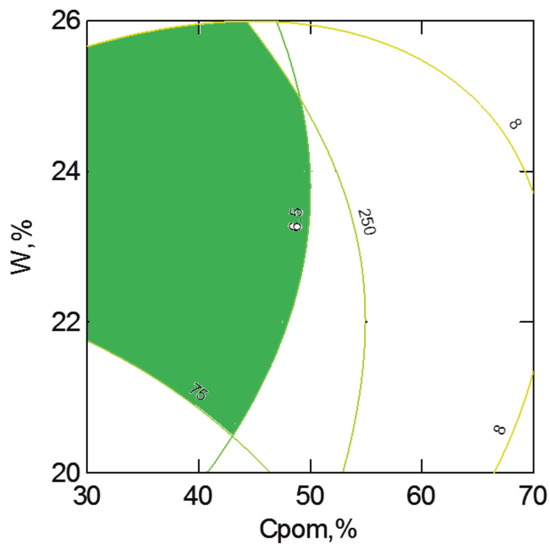
Increased feed moisture leads to higher mechanical strength of the cell wall [13, pp. 22]. Increased moisture content during extrusion make for an increase in plasticization of the melt, resulting in reduced the degree of starch's depolymerization and increasing the mechanical strength of extrudate.

An increase in the barrel temperature increases the degree of superheating of water in the melt encouraging bubble formation, resulting in an increase in the expansion and a reduction in the density of the extrudate leading to reduced hardness [14, pp. 145].

Specific mechanical energy is the amount of mechanical energy dissipated as heat inside the material, expressed per unit mass of the material. Specifically, it is the work input from the drive motor into material being extruded and thus provides a good characterization of the extrusion process. SME values indicate the extent of molecular breakdown or degradation the material undergoes during the extrusion process [15, pp. 377]. SME was found to be most dependent on barrel temperature. An increase in the temperature will decrease SME. Higher temperature facilitated the transformation from solid flow to viscoelastic flow, and higher moisture produced a lubricating effect, resulting in less energy use [16, pp. 1803].

Optimization was carried out by the superposition of several contour surfaces of competing responses. The response surface plots were generated for interaction of any two independent variables, while holding the value of all the rest as constant (at the central value).

The best conditions that correspond to shaded areas, obtained by superimposing contour plots of water absorption index, hardness, total color difference, and specific mechanical energy during extrusion process are shown in Figure.



Graphics optimization of extrusion process of apple pomace — wheat semolina blends (software)

From a convenience and practical point of view, moisture content from 22 to 26%, apple pomace content from 30 to 50%, barrel temperature of 150°C, and screw speed of 180 rpm could be recommended as optimal extrusion conditions for obtaining an instant product from apple pomace and wheat semolina.

Conclusions. Apple pomace — wheat semolina blends were extruded in a laboratory single screw extruder (Brabender 20 DN, Germany). A central composite rotatable design was used with four controlled variables: apple pomace content (10, 30, 50, 70, 90%), moisture content (17, 20, 23, 26, 29%), screw speed (120, 150, 180, 210, 240 rpm), and barrel temperature (130, 140, 150, 160, 170 °C).

Moisture content from 22 to 26%, content of apple pomace from 30 to 50%, barrel temperature of 150°C, and screw speed of 180 rpm could be recommended as optimal extrusion conditions for obtaining an instant product from apple pomace and wheat semolina.

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