INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Int. Agrophys., 2023, 37, 401-413
doi: 10.31545/intagr/171927

Effect of apple pomace (*Malus domestica* 'Gala') addition on the processing conditions and antioxidant potential of extruded snacks

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Received June 22, 2023; accepted September 6, 2023

A b s t r a c t. This article presents the results of an analysis of the extrusion-cooking process and of the antioxidant potential of extruded snack pellets and expanded snacks enriched with apple pomace. The use of pomace in the production of food extrudates has great processing potential as it not only contributes to reducing the negative impact of fruit industry by-products on the environment, but also allows for the enrichment of snack products with valuable nutrients. The purpose of this study was to determine the effect of the addition of apple pomace on the extrusion-cooking process and also to determine the antioxidant activity of the obtained products. In the research conducted it was observed that the addition of pomace has the effect of reducing the energy consumption of the extrusion-cooking process, and that the efficiency of the manufacturing process decreases slightly with an increase in the amount of pomace addition in the mixture. During the chemical analyses, it was noted that increases in the phenolic compound content is accompanied by increases in the functional additive content. The results obtained demonstrate that apple pomace is an additive with a functional nature with possible uses in the production of extruded snack pellets.

K e y w o r d s: extrusion-cooking, apple pomace, extruded snack pellets, process parameters, antioxidant potential

1. INTRODUCTION

The extrusion-cooking process is considered to be a practical method of pressure-thermal processing. In this study, a raw material is subjected to high temperatures over a short time period in the presence of shear forces and increased pressure (Singha and Muthukumarappan, 2018). This technology allows for the processing of various products of plant origin. This results in extrudates of various types, including breakfast foods, substrates used for biogas production, thermoplastic starch granules for environmentally friendly films, animal feeds and food snack pellets (Lisiecka *et al.,* 2021a).

During the extrusion-cooking process, as a result of thermomechanical interactions, raw materials undergo numerous physicochemical transformations including starch gelation and the denaturation of proteins and enzymes. Moreover, the formation of amylase and fat complexes occurs. Such transformations significantly affect the quality, shape and structure of the extrudates produced (Zaborowska *et al.,* 2015). The previously developed formulation with an appropriate moisture content is introduced into a machine with a high temperature and where it is processed into the final product due to the pressure and shear forces generated (Offiah *et al.,* 2018). In order to carry out this process, it is necessary to use extruder-cookers, which consist of working elements such as a screw and forming die. The screw may be divided into such sections as transport, compression and the elements responsible

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for extrusion-cooking. Depending on the design of the plasticizing unit, we can distinguish between single-screw, twin-screw, and multi-screw extruders (Wójtowicz, 2018).

Although the extrusion-cooking process is considered to be rapid and relatively inexpensive, it nevertheless requires the prior analysis of many variables and their appropriate optimization. The main factors affecting the optimization of the process are the physical properties of the raw materials, the speed of the screw, the ratio of the diameter to the length of the entire screw, and also, the temperature and the moisture content of the processed mixture (Oniszczuk *et al.,* 2019). Achieving optimal processing and physicochemical values can help to reduce the energy consumption of the extruder-cooker, which is a desirable feature in times of energy crisis. This gives the extrusion-process the potential of replacing other types of thermal processing which are characterized by high energy consumption (O'Shea *et al.,* 2014).

As the development of civilization proceeds, the agro-food industry is making significant contributions to the aggravation of environmental problems. The huge amount of post-production waste and by-products that are generated are often mismanaged and thus they negatively affect the environment. Some of the by-products of the agri-food industry are characterized by a high content of nutrients, *i.e.* vitamins, polyphenols or dietary fibre. Thus, such materials can be added to many food products, these include the snack pellets produced by extrusion-cooking. Such measures allow for the attainment of full-flavored products with beneficial environmental effects (Kawacka and Galus, 2021).

Apple pomace is a raw material with a high degree of application potential. It is produced as a by-product of the juice-pressing process. After the production process, about 20% of the raw material remains in the form of by-products, and these contain many valuable nutrients and health-promoting components, *i.e.* fibre, sugars, pectins, polyphenolic compounds, and many others (Borycka, 1999; Peschel *et al.,* 2006; Shalini and Gupta, 2010). It is, however, a microbiologically unstable raw material, but immediate on-site processing of the pomace may provide a solution to this problem. It may be stabilized through drying or freezing or perhaps pre-processing (*e.g.*, thermally). Pomace may be suitable for further use in other production processes (Tarko, 2009; Kawecka, 2021). Agri-food industry by-products, including apple pomace, could be used to make a significant contribution to the production of a new type of wholesome food product while simultaneously reducing the negative environmental impact of the processes involved in food processing (Wójtowicz *et al*., 2014).

The aim of the study was to determine the ways in which the addition of apple pomace to a wheat and corn flour-based recipe mix affects the extrusion-cooking process and also to determine the amount of polyphenols in extruded snack pellets and finished snacks.

2. MATERIALS AND METHODS

Apple pomace (*Malus domestica* 'Gala' variety) purchased from a local supplier (Tomasz Rychlik, Elizówka Exchange, Lublin, Poland) was used for the study. The pomace was mixed proportionally with Type 450 wheat flour (Lubella, Lublin, Poland), corn flour (EDMIR-POL, Chorzów, Poland), salt (Culine, Janikowo, Poland), soda (Gellwe, Zabierzów, Poland) and sugar (Polski Cukier, Toruń, Poland) (Table 1). The pomace was added to make a concentration of 10, 20, and 30%. A mixture without the addition of pomace (the control sample) was also prepared. These particular concentrations of apple pomace were used because the composition of the resulting mixtures ensured the stability of the process, which allowed for an accurate comparison of antioxidant properties to be made *versus* a constant increase in apple pomace concentration. Before the initiation of the extrusion-cooking process, the moisture content of the prepared mixtures was assessed, and, if necessary, it was adjusted to 34%.

Table 1. Percentage content of individual components in mixtures

Raw material (%)	Control sample	Apple pomace (%)		
		10	20	30
Apple pomace	0	10	20	30
Wheat flour	82.5	72.5	62.5	52.5
Corn flour	15	15	15	15
Salt	2	2	2	2
Soda	0.5	0.5	0.5	0.5

The extrusion-cooking process was carried out on a prototype single-screw extruder-cooker Zamak Mercator EXP-45-32, the ratio of the length of the working part to the diameter of the screw being L/D = 20. Trials were carried out at variable screw speeds of 60, 80, and 100 revolutions per minute. The dough was pressed through a single flat hole with dimensions of 0.3×25 mm. Immediately after leaving the die, the extrudate, in the form of a belt, was guided through a roller system equipped with a fan cooling system and leading to the cutting system, which formed the pellets to a size of 25×25 mm. The final extrudate obtained in this way was carefully spread on metal grids and placed in a shelf laboratory dryer in order to achieve the appropriate moisture content of 9.5-10.5%.

A portion of the pellets, were first properly dried in the laboratory dryer, and then fried in a 2-chamber electric fryer (Caterina Stalgast, Radom, Poland) with a power of 6 kW, in vegetable oil heated to 200°C for several seconds until expanded wheat-corn snacks were obtained. The products thus obtained in the frying process were drained on a previously prepared strainer and then placed on a paper towel to remove excess fat.

The remainder was expanded using a microwave oven (MCP 349/SL, Whirlpool, Benton Harbon, USA) with a power output of 800 W. The products were placed about 0.5 cm apart, on the outside of the plate, in a single row and expanded for 30 s.

The pellets and expanded snacks were then stored in sealed containers, from which samples were taken for individual tests in the subsequent testing phases. In order to carry out some of the tests, the pellets and expanded snacks were ground with an LMN100 laboratory grinder (TestChem, Radlin, Poland) into a uniform powder with particles smaller than 0.3 mm in diameter.

The moisture content of the raw material mixtures and the manufactured food pellets was tested using the drying method described by Wójtowicz and Mościcki (2008) and by applying PN-EN ISO 712:2012. Three measurements were taken for each recipe mixture. The moisture content was determined using the following formula:

$$W = (a - b)\,(a - c)^{-1} \times 100\%, \tag{1}$$

where: W is the moisture content of the test sample (%), a is the weight of the weighing container with the sample before drying (g g^{-1}), b is the weight of the weighing container with the sample after drying (g g^{-1}), c is the weight of the empty weighing container (g).

In order to obtain the assumed moisture content of the raw material mixtures (34%), the samples were prepared for the extrusion-cooking process according to the formula by Jurga (1985), given below. Measurements were taken in triplicate for each raw material mixture, and the arithmetic mean was considered as the final result, this was rounded to the nearest 0.1%:

$$m_w = (m_x\,(w_k - w_p))\,(100 - w_k)^{-1}, \tag{2}$$

where: m_w is the amount of water to be added to increase the moisture content of a given sample (kg kg^{-1}), w_p is the initial moisture content of the test sample (%), w_k is the desired moisture content of the test sample (%) and m_x is the mass of the given sample (kg kg^{-1}).

The study of the efficiency of the extrusion-cooking process was carried out by determining the weight of the pellets produced at a specific time for all of the prepared raw material mixtures based on the process parameters used. The efficiency was determined using an electronic stopwatch and a balance (DS-788 YAKUDO, Tokyo, Japan) in triplicate for each series of tests. The final result was assumed to be the average of the measurements. The efficiency was calculated according to the formula given by Matysiak *et al.* (2018):

$$Q = m\,t^{-1}, \tag{3}$$

where: Q is the efficiency (kg h^{-1}), m is the mass of extrudate obtained during measurement (kg), and t is the measurement time (h).

Energy consumption was measured using a standard wattmeter which is an accessory to the extruder-cooker. After evaluating the parameters of the motor mounted in the extruder-cooker, selecting the motor load and the efficiency obtained in given tests, the obtained values were converted into coefficients of specific mechanical energy consumption (*SME*) according to a formula given by Matysiak *et al.* (2018):

$$SME = (n\,N^{-1})\,(L\,100^{-1})\,(P\,Q^{-1}), \tag{4}$$

where: *SME* is the specific mechanical energy consumption rate (kWh kg^{-1}), n is the extruder-cooker screw speed (1 s^{-1}), N is the maximum screw speed 1 s^{-1}), L is the motor load relative to the maximum (A), P is the rated power (kW kW^{-1}) and Q is the process output (kg h^{-1}).

The stability of the extrusion-cooking process was registered and recorded continuously for each of the prepared mixtures. Temperature changes in each section of the extruder-cooker were recorded to an accuracy of 0.1°C. The measurements were made possible by the thermocouples built into the extruder-cooker cylinder and connected to a meter located in the device's control module. In addition, the temperature of the pellets produced was measured immediately after leaving the die (to the nearest 0.1°C) using an electronic thermometer (ST25 Raytek, Everest, USA). The measurement was carried out three times for each raw material mixture, and the average of the measurements was taken as the final result.

The total content of Polyphenolic Compounds (TPC) was measured (it was obtained using ultrasound-assisted extraction) by applying a modified method employing the Folin-Ciocalteu (FC) reagent that was suggested in Kasprzak *et al.* (2018). For this purpose, 200 μL of extract was blended with 1.8 mL of water, Folin reagent (200 μL) was then added, and the mixture was stirred vigorously. Five minutes after the reaction was initiated, 2 mL of 7% Na_2CO_3 was introduced. The sample was subsequently incubated at 40°C for 60 min. Absorbance was measured with the use of a UV-VIS spectrophotometer at 760 nm. The total polyphenolic content was expressed in terms of mg of gallic acid equivalents (GAE) per g of dry mass (d.m.).

Free Radical Scavenging Activity was ascertained using the DPPH (2,2-diphenyl-1-picrylhydrazyl) method in order to determine the free radical scavenging activity of the extracts. The studies were performed based on a modified method originated by Burda and Oleszek (2001) with the use of a UV-VIS spectrophotometer Genesys 20 UV-VIST (Thermo Scientific, Waltham, MA, USA). The following parameters were used: 517 nm wavelength, measurements every 5 min for 30 min, and the calibration was based on pure methanol. All measurements were repeated three times. The obtained results are presented in terms of RSA and TEAC values.

The Ferric-Reducing Antioxidant Power FRAP reagent was made from solutions prepared in the following way. Acetate buffer (0.3 M, pH 3.6) was mixed with aqueous iron (III) chloride solution (0.02 M) and TPTZ solution (0.01 M) in a 10:1:1 ratio, respectively; then, 500 µL of each extract was placed into separate vials, and 2.5 mL of FRAP basic reagent was added. The vessels were closed, mixed, and placed in a 37°C water bath for 30 min. Absorbance was measured using a UV-VIS spectrophotometer set at 593 nm against a control, in which the extract was replaced with methanol. Each measurement was performed in triplicate. The obtained results are presented as FRAP units (mM of Trolox g^{-1} d.m.) (Soja *et al*., 2023).

These analyses were carried out in order to check the extrusion-cooking process of the selected recipes in detail taking into account the energy consumption and stability of the process. In addition, the analyses were carried out to check the antioxidant potential of both semi-finished products (pellets) and finished products (snacks) in order to choose the best low energy requirement method for obtaining wholesome snacks with apple pomace.

A principal component analysis (PCA) and a determination of correlations were performed at a significance level of $\alpha = 0.05$. The principal component analysis was used to determine the relationship between the degree of apple pomace addition and the physical parameters describing the obtained products. Statistica software (version 13.0, StatSoft Inc., Tulsa, OK, USA). The PCA data matrix for the statistical analysis of the test results was composed of 13 columns and 13 rows. The input matrix was scaled automatically. The optimal number of principal components was determined on the basis of the Cattel criterion.

3. RESULTS AND DISCUSSION

At the beginning of the study, the moisture content of the raw material mixtures prepared for the extrusion-cooking process was determined. Due to the examination of the moisture content it was possible to calculate the appropriate amount of water to moisten the mixtures to the assumed optimal moisture content of 34%, which is the optimum value for the mixtures to produce high-quality snack pellets (as determined through preliminary research).

It was observed that the moisture content of the mixtures increased by 6-7.5% with increasing proportions of apple pomace in the raw material mixture. To increase the moisture content of the mixtures with 0, 10, 20, and 30% additions of pomace, 1085, 732, 465, and 125 ml of water were added, respectively, to maintain a 34% moisture content.

The pellets obtained by extrusion-cooking, after temperature and moisture content stabilization in the laboratory dryer, had a moisture content of 9.6 to 10.4%, with the lowest moisture content obtained for pellets without the addition of pomace and the highest for pellets with the addition of 30% apple pomace. The final moisture content values obtained were in accordance with production standards, which assume an optimal storage moisture content for pellets ranging from 9.5 to 11.5% (Standards and Recommendations of Jedność Ltd., 2022).

In the case of the research conducted by Lisiecka and Wójtowicz (2020), the addition of fruit and vegetable pulp had a very substantial effect on reducing water consumption during the extrusion-cooking process. Trials conducted with mixtures using a 30% addition of leek pulp almost completely eliminated the need to add water to the mixtures immediately before the extrusion-cooking process. A similar relationship was observed in the present study, where the need to add water to the recipe mixture with 30% apple pomace addition relative to the control mixture decreased by 9 times. This is a very good result relative to the results produced by dried fruit additives with reference to the possibility of using pomace in terms of reduced water addition. The possibility of reducing water consumption to add moisture to the mixtures is simultaneously associated with the management of full-value products in the form of pomace and can also produce a positive impact on the perception of the food industry, which, in recent years, has been perceived to have a substantial adverse impact on the environment.

The efficiency of the extrusion-cooking process of producing pellets with apple pomace additives ranged from 19.20 to 32.88 kg h^{-1} (Fig. 1). In considering the blends with additives and blends without additives, the lowest (14.64 kg h^{-1}) and highest efficiencies (38.88 kg h^{-1}) were observed for the extrusion-cooking of the control samples. For the pellets with apple pomace additives, the lowest value was registered for blends with 20 and 30% apple pomace additives and processed at a 60 rpm screw speed (19.20 kg h^{-1}). The highest degree of efficiency

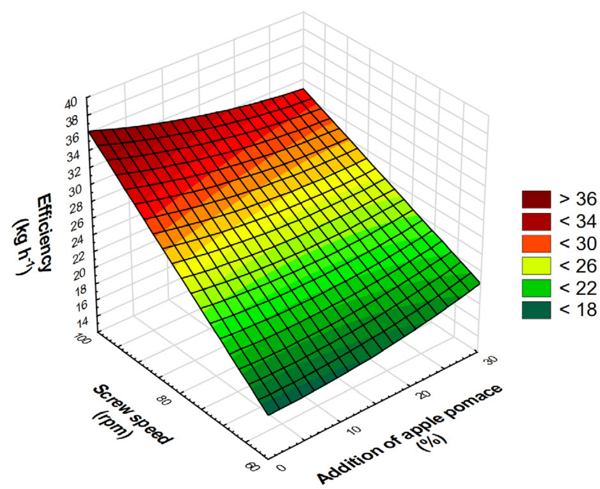

Fig. 1. Results of snack pellets processing efficiency depend on addition of apple pomace and screw speed.

Table 2. Response surface fitting models for extrusion-cooking process efficiency as a function of screw speed and the amount of apple pomace addition

Extruder-cooker plasticizing system	Response surface fitting model (quadratic polynomial)	Coefficient of correlation
L/D=20	Q (kg h^{-1}) = -10.787 + 0.4223x + 0.466y + 0.0036x^2 - 0.0071xy + 3.75^{E-5}y^2	0.936

x – addition of apple pomace (%), y – screw speed (rpm).

(32.90 kg h^{-1}) was registered for the raw material mixture with the addition of 30% pomace obtained using the highest speed of the extruder-cooker screw (Table 2).

After analysing the results of the study, it was noted that the main factor influencing the performance of the extrusion-cooking process was the screw speed. In the case analysed, increasing the screw speed resulted in a higher process efficiency. A similar trend was observed by Matysiak *et al.* (2018), who obtained the highest efficiency value at the highest screw speed. In their study, they also showed that a mixture with a 34% moisture content had the highest degree of efficiency as compared to mixtures with other moisture contents. Moreover, the addition of apple pomace had a significant effect on the amount of extrudate produced. Lisiecka and Wójtowicz (2020) noted a decrease in the efficiency of the extrusion-process with increases in additional ingredients in the form of vegetables. During their ongoing research, they determined that increasing the addition of apple pomace resulted in a slight decrease in process efficiency.

Apple pomace is a raw material with a high processing potential, as it is characterized by its irregular shape and specific chemical composition, in particular, its high content of pectin, which is distinguished by its gelling, thickening, and stabilizing properties. Such traits can affect the course of the extrusion-cooking process in a beneficial way (Kawecka and Galus, 2021). The positive effect on performance was mainly due to the appropriate preparation of the mixture, wherein the hard parts of the pomace (seeds, peel, seed chamber and seed nest shells) were properly crushed with a food processor and formed a coherent part of the whole mixture.

During our study, the energy consumption of the extrusion-cooking process (*SME*) ranged from 0.007 to 0.042 kWh kg^{-1} depending on the process parameters used, including the amount of apple pomace addition (Fig. 2). The lowest *SME* value was recorded for a mixture with 30% apple pomace addition at a screw speed of 100 rpm, while the highest power consumption was evident during the extrusion-cooking process of a mixture with a 10% apple pomace content processed at a screw speed of 60 rpm. Based on the results obtained, it was concluded that the energy consumption of the extrusion-process is substantially influenced by both the screw speed and the addition of apple pomace. In their study on corn extrudates with the addition of carrots, Lisiecka and Wójtowicz (2019) observed a decrease in *SME* with the increasing share of the addition of this vegetable to the blend (%), and recorded energy consumption values in the range of 0.021-0.028 kWh kg^{-1} (Lisiecka and Wójtowicz, 2019). Similar relationships were noted in the present study, in that the reduction in *SME* occurred after the addition of apple pomace was significant and in the range of 0.007-0.042 kWh kg^{-1} (Table 3). However, it was observed that the *SME* value decreased at higher screw speeds, which was a different result from the studies of other authors, who observed in their work that when the screw speed was increased, the *SME* value also increased (Kręcisz and Wójtowicz, 2017).

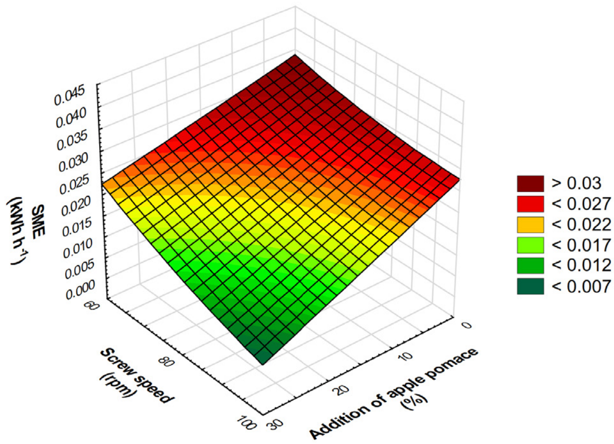

Fig. 2. Results of snack pellets processing specific energy consumption depend on addition of apple pomace and screw speed.

As the rotational speed increased for most of the processed raw material blends, the temperature of each section of the extruder-cooker also increased, this affected the viscosity of the processed formulation. These correlations ultimately affected the reduced *SME* value for the apple pomace blends that were processed at higher screw speeds. In considering the dependence of the cylinder temperature on the rotational speed, a similar result was presented in the work of Munazah *et al.* (2018), who also argued for a decrease in *SME* with higher extruder-cooker cylinder temperatures, this was due to a decrease in the viscosity of the processed blend.

The temperature that prevailed in the individual sections of the extruder-cooker (excluding the die) ranged from 55.6 to 94.2°C, with a higher temperature being recorded in the fifth section of the extruder-cooker, where material

Table 3. Response surface fitting models for the specific mechanical energy (*SME*) of the extrusion-cooking process as a function of screw speed and the amount of apple pomace addition

Extruder-cooker plasticizing system	Response surface fitting model (quadratic polynomial)	Coefficient of correlation
L/D=20	*SME* (kWh kg^{-1}) = 0.061+8.6374^{E-5} x-0.0006 y +4.8675^{E-7} x^2-7.9463^{E-6} x y +2.995^{E-6} y^2	-0.476

Explanations as in Table 2.

plasticization and compression took place before shaping occurred within the head of the device. At this location, the temperature ranged from 81.3 to 92.3°C (Table 4). Such a temperature range was used to obtain stabilized processing (pressure, intensity of raw material transport through the extruder-cooker barrel). The temperatures used made it possible to obtain a plasticized, homogeneous mass that had no physical damage or scorching after exiting the die. The temperatures in the various sections of the extruder-cooker were characterized by stability relative to the original settings. A similar temperature profile was noted in the study by Lisiecka *et al.* (2021b). During their research which was related to the determination of the effect of the addition of plant products to raw material mixtures on the course of the extrusion-cooking process and the physicochemical properties of the obtained snack pellets, the temperatures of the individual extruder-cooker sections were found to be in the range of 50-105°C.

The highest temperature of the finished product at the exit of the extruder-cooker die (101.7°C) was recorded for a sample with 10% apple pomace and a speed of 80 rpm. By contrast, the lowest temperature (72.1°C) was registered for the control sample, it was obtained at a screw speed of 60 rpm (Fig. 3). Based on the data obtained, it was concluded that the process was stable for all the process variables used (Table 5).

Based on the results of the measurements of product temperatures, it was found that the temperature of the pellets depended on the content of apple pomace additive in the processed raw material mixture and also on the speed of the extruder-cooker screw. In the study, it was observed that the temperature of the pellets gradually increased with increases in the screw speed. Moreover, depending on the amount of apple pomace addition introduced, the temperature increased for mixtures of 10 and 20% and then decreased for pellets with a 30% addition. It should also be noted that the relatively high product temperature was also affected by the small die opening gap (0.3×25 mm), which limited the possibility of free mass flow while leading to greater product heating while it was leaving the extruder-cooker die.

In their study, Trela and Mościcki (2007) showed that the temperature of an extruded product based mainly on grain raw materials was similar for all processed blends and was 90-100°C. In our work, similar temperature ranges

Table 4. Temperature measurements during the extrusion-cooking process of apple pomace pellets using an L/D=20 plasticizing system

Sample		Temperature (°C)				
Addition of apple pomace (%)	Screw speed (rpm)	Section 1	2	3	4	5
0	60	55.6	74.5	88.7	86.0	81.6
	80	58.4	75.4	86.5	83.8	82.1
	100	58.5	75.4	87.8	85.0	81.3
10	60	59.1	82.7	86.7	84.1	81.3
	80	60.2	80.3	86.7	84.7	81.5
	100	60.5	80.2	86.8	84.8	81.7
20	60	59.4	79.6	86.4	94.2	82.3
	80	60.1	80.1	86.6	84.7	81.4
	100	61.1	79.6	86.8	84.8	82.3
30	60	59.9	79.6	86.8	84.2	81.5
	80	61.0	80.2	86.4	83.7	82.1
	100	60.2	80.1	86.6	93.9	92.3

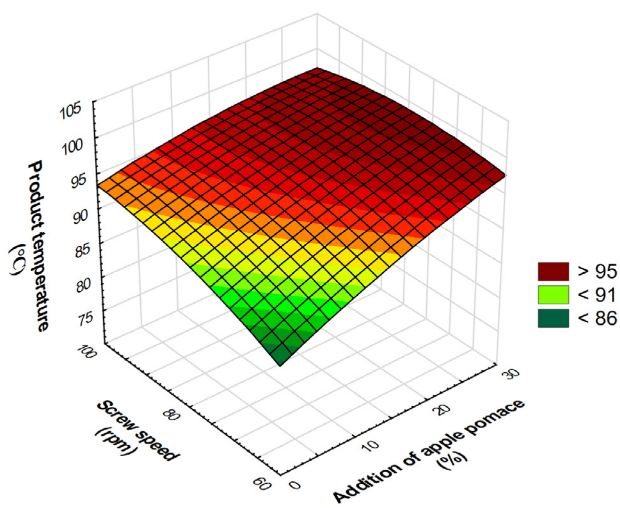

Fig. 3. Results of snack pellets temperature depend on addition of apple pomace and screw speed.

Table 5. Response surface fitting models for the temperature of the pellets emerging from the extruder-cooker as a function of screw speed and the amount of apple pomace addition

Extruder-cooker plasticizing system	Response surface fitting model (quadratic polynomial)	Coefficient of correlation
L/D=20	T(°C) = 100.315+0.2059x - 0.2039y - 0.0114x^2 + 0.002xy + 0.0017y^2	0.456

Explanations as in Table 2.

Table 6. Polyphenol content per gallic acid (mg GAE g^{-1} d.m. of product) in pellets and expanded snacks with apple pomace

Method of preparation	Screw speed (rpm)	Apple pomace addition (%)	Polyphenol concentration (mg GAE g^{-1} d.m.) ± RSD%
Pellet	60	10	0.052 ± 4.44
		20	0.055 ± 3.27
		30	0.071 ± 4.63
	80	10	0.048 ± 3.12
		20	0.065 ± 4.90
		30	0.074 ± 3.84
	100	10	0.046 ± 3.92
		20	0.070 ± 2.76
		30	0.089 ± 4.09
	60 80 100	0	0.048 ± 3.19
Expanding in a fryer	60	10	0.118 ± 4.68
		20	0.106 ± 1.48
		30	0.152 ± 3.97
	80	10	0.106 ± 2.29
		20	0.119 ± 1.28
		30	0.155 ± 3.11
	100	10	0.086 ± 3.74
		20	0.131 ± 3.45
		30	0.171 ± 2.35
	60 80 100	0	0.100 ± 0.59
Expanding in the microwave oven	60	10	0.124 ± 2.77
		20	0.169 ± 0.64
		30	0.156 ± 1.82
	80	10	0.120 ± 3.93
		20	0.127 ± 3.90
		30	0.137 ± 2.94
	100	10	0.118 ± 4.72
		20	0.142 ± 3.02
		30	0.166 ± 1.12
	60 80 100	0	0.062 ± 2.37
Apple pomace			0.313 ± 2.21

were observed, with the highest values being recorded for pellets based on blends with a 20% expeller addition and processed at the highest screw speed (100 rpm).

The Folin-Ciocalteu (F-C) method was used to determine the total polyphenol content, and the test result was converted to a GAE gallic acid equivalent (mg GAE g^{-1} product dry mass).

In the vast majority of cases, as the content of the functional additive, apple pomace, increases, it was noted that the content of polyphenolic compounds increases (Table 6). Moreover, the polyphenol content retained a positive, and strong correlation with the increasing amount of apple pomace added. The correlation coefficients were found to range from 0.80 for pellets prepared at 60 rpm and using a deep fryer, to 0.97 for samples prepared at 100 rpm in a microwave.

The highest content of polyphenols was recorded in apple pomace (0.31 mg GAE g^{-1} d.m.), while the lowest content was recorded in pellets without additives, all screw speeds and all preparation methods were considered. Based on the results obtained, it was concluded that the high-pressure and high-temperature extrusion-cooking process did not degrade the polyphenolic active compounds, the content of which increases in proportion to the addition of apple pomace to the pellet (Table 6).

In plants, polyphenols occur mainly in a bound form, as components of lignins and tannins, esters, and glycosides. It is known that the appropriate selection of extrusion-cooking conditions can release phenol acids and flavonoids from the chemical bonds they form with other compounds, but without destroying and deactivating the aglycones (Neves *et al.,* 2021; Schmid *et al*., 2020; Khanal et *al.,* 2009). In this process, the intensive processing of raw materials takes place. From the research results published by Alonso *et al.* (2000), it is clear that the main factors contributing to the transformation of the input material during extrusion-cooking are related to high temperature and shear forces, which increase with increasing temperature and screw speed. Khanal *et al.* (2009) demonstrated the effects of this process on the content and profile of polyphenols in grape seeds and pomace from these fruits. The cited authors revealed that the application of extrusion-cooking caused a significant increase in the level of low-molecular-weight compounds and also released biologically active monomers and dimers from the polymer chains of polyphenols. In this case, the intensity of the changes taking place depended on the properties of the raw material (matrix) and the production parameters used. The authors thus confirmed that the appropriate selection of process conditions (temperature, screw speed, moisture content, homogenization) can release phenols from the chemical bonds they form with other compounds, without deactivating the aglycones. This is due to the breaking of the rigid plant tissue components under the influence of this high-temperature and high-pressure process (Kasprzak-Drozd *et al.,* 2022). However, in the case of the experiment that we conducted, there was no clear effect of the auger speed on the content of polyphenolic compounds.

This stage of the research was designed to determine the effect of the snack preparation method on the content of polyphenolic compounds. The results showed that the process of expanding the pellets using a microwave oven guarantees a higher content of polyphenols than processing in a deep fryer, with an analogous additive content and auger speed. The lowest content of polyphenolic compounds was recorded for raw pellets. Both preparation methods, due to the applied microwave energy or traditional heating (in the case of frying), allow for the release of polyphenolic compounds contained in the extrudates from their molecular combinations, hence the increased content of polyphenols in ready-to-eat products as compared to raw pellets.

It has long been known that the preparation of products for consumption results in changes in the content of active compounds in food, including antioxidants. It is widely believed that the effects of high temperatures on food processing are destructive. Indeed, hydrothermal processes (*e.g.*, cooking) have an adverse effect on the content of water-soluble antioxidants, such as polyphenols (Ramírez-Anaya *et al.,* 2015). Different effects may be observed when using processes with non-polar media, such as deep-frying. Frying processes deactivate enzymes and microorganisms present in food and contribute to the removal of non-nutritive components. They also frequently increase the bioavailability of nutrients and improve the texture of products (Szponar *et al.,* 2018). In addition, some authors have described the penetration into food during frying of polyphenolic compounds present in absorbed vegetable oil (Ramírez-Anaya *et al.,* 2015; Ramírez-Anaya *et al.,* 2019). In addition, an increase in the availability of phenols has been demonstrated due to the cracking, or softening, of rigid cell walls and other components of plant cells (vacuoles and apoplasts) with which these plants are associated.

In fried products, however, an increased fat content was noted, thus increasing the caloric content. The amount of fat absorbed depends mainly on the ratio of the outer surface of the product to the inner surface. Chips or cutlets reach a fat content of about 40%, while products with a smaller surface area, such as French fries, reach a content of up to 25% fat. Another disadvantage of frying is the excessive dehydration of the product, as a result of which it becomes hard and saturated with fat. In addition, during the storage of fats, due to the action of enzymes (lipases) contained in vegetable raw materials, hydrolysis and the formation of free fatty acids can occur. From a nutritional point of view, these are not dangerous, but they reduce the quality of food by causing hydrolytic rancidity. Taste, odour, and colour changes can also occur due to the oxidation of fatty acids under the influence of lipoxygenases (Szponar *et al.,* 2018).

During prolonged heating, under the influence of an elevated temperature, oxygen and the water contained in the fried product, fat breaks down and releases volatile (acrolein) and non-volatile compounds (hydroperoxide, acrylamide). These are toxic and impair the sensory quality of the products. However, it is possible to obtain a product with similar or even more favourable sensory qualities, but with a significantly lower caloric content and increased amounts of polyphenolic compounds by using microwave expansions.

Microwave energy arguably breaks the bonds by which polyphenols are linked to other compounds more effectively than the high temperatures found in frying, hence the increased content of these compounds. Taking steps toward more healthy ways of preparing food, including snacks, and lowering the caloric content of food, is important not only from the perspective of obesity prevention, but also from the point of view of preventing other non-communicable chronic diseases, such as diabetes, neurodegenerative diseases, and cancer. It is worth asking how true in this context Navarro's statement is that "science-based cooking can make a significant contribution to ensuring access to specific nutrients and other food components that generate health-promoting food functionality" (Navarro *et al.,* 2012).

The next step of the study was to analyse antioxidant properties in relation to the free stable radical DPPH. It was found that the free radical scavenging properties increased with the addition of apple pomace for all screw speeds, for both methods of preparing the pellets for consumption and for the raw product (Table 7).

It was also noted that the method used to prepare the pellets for consumption affected the scavenging capacity of the stable free radical DPPH. The product that was prepared in a microwave oven showed the best antioxidant activity. This was significantly greater than that of the raw pellets. Until recently, it was thought that processing contributed significantly to the degradation of natural antioxidants. However, studies conducted in recent years have revealed that the effect of processing on the activity of manufactured foods is inconclusive. Interestingly, a decrease in the content of some natural antioxidants may be accompanied by an increase in the antioxidant activity of the product, this is due to the increased availability of the remaining antioxidants. By contrast, in the processing of plant raw materials, the oxidation of antioxidants, the conversion of antioxidants from antioxidant to a pro-oxidant form, the complexation with other components, enzymatic

Table 7. Reducing power determined by the FRAP method per Trolox (mM Trolox g^{-1} d.m.) and DPPH scavenging capacity (%) as determined for pellets and expanded snacks with and without apple pomace

Method of preparation	Screw speed (rpm)	Apple pomace addition (%)	Fe^{3+} reduction capacity (mM Trolox g^{-1} d.m.) ± RSD % Fe^{3+}	DPPH scavenging capacity (%)
Pellet	60	10	0.751 ± 5.02	27.030 ± 2.46
		20	0.716 ± 4.20	27.979 ± 3.52
		30	1.289 ± 3.64	45.041 ± 2.12
	80	10	0.677 ±3.96	23.330 ± 4.02
		20	1.020 ± 4.76	34.043 ± 3.07
		30	1.408 ± 4.83	50.310 ± 1.36
	100	10	0.679 ± 4.15	22.302 ± 1.48
		20	1.088 ± 3.26	35.252 ± 0.97
		30	1.645 ± 5.13	52.128 ± 3.15
	60 80 100	0	0.702 ± 0.48	23.836 ± 2.22
Expanding in a fryer	60	10	2.913 ± 3.76	52.586 ± 3.34
		20	2.883 ± 4.42	57.524 ± 4.01
		30	3.750 ± 3.30	76.459 ± 0.19
	80	10	3.212 ± 4.15	51.974 ± 1.25
		20	2.845 ± 3.79	54.728 ± 2.45
		30	3.455 ± 2.40	75.517 ± 3.72
	100	10	2.040 ± 4.50	43.165 ± 4.66
		20	3.155 ± 3.51	64.889 ± 3.90
		30	3.755 ± 2.12	86.742 ± 1.88
	60 80 100	0	2.463 ± 4.31	45.565 ± 5.03
Expanding in the microwave oven	60	10	3.044 ± 4.39	59.851 ± 0.15
		20	3.491 ± 4.76	81.706 ± 3.34
		30	3.880 ± 5.18	81.398 ± 1.98
	80	10	2.907 ± 4.13	52.012 ± 4.81
		20	2.982 ± 1.04	68.008 ± 2.43
		30	3.195 ± 4.56	68.410 ± 1.11
	100	10	2.293 ± 3.34	56.740 ± 4.89
		20	2.982 ± 4.28	69.316 ± 2.39
		30	4.236 ± 1.52	89.928 ± 0.78
	60 80 100	0	2.463 ± 3.56	30.820 ± 2.45
	Apple pomace		867.204 ± 2.12	91.690 ± 2.34

modifications, and the increased oxidative potential of the environment all contribute to a decrease in the antioxidant potential of products (Gumul *et al.,* 2005). Previous work has demonstrated that the antioxidant activity of plant and food extracts depends not only on the quantitative content of polyphenolic compounds, but also on the number of -OH groups in the molecules of these compounds. Moreover, this activity can be significantly modified by spherical effects, for example, compounds that are derivatives of cinnamic acid are more effective antioxidants than derivatives of benzoic acid (Zielinski *et al.,* 2012).

In order to confirm the antioxidant properties of the tested samples used in our work, the reducing properties of the tested extracts were also measured using a FRAP assay.

This is based on an evaluation of the ability to reduce the iron complex Fe^{3+} - TPTZ (iron-2,4,6-tripyridyl-s-triazine complex) to the Fe complex^{2+}. The results were found to coincide with those obtained for DPPH, *i.e.*, the reducing properties of the tested extracts that were determined using the FRAP method generally increase with increases in the functional additive to the pellet (Table 7) and are highest for apple pomace (4.34 mM Trolox g^{-1} d.m.). The samples without an additive showed the lowest degree of iron III complex to iron II complex reduction in their group (0.70, 2.46, and 1.9 mM Trolox g^{-1} d.m., for raw, fried, and microwave-treated samples, respectively). The treated pellets, both microwaved and fried, showed much higher antioxidant properties as measured by the FRAP method than the raw pellets.

Antioxidant activity most often retains a high degree of positive correlation with the content of polyphenolic compounds. Aglycones have a greater antioxidant potential than glycosides, and high-temperature expansion processes (both due to frying and under microwaves) have the potential to contribute greatly to the breakdown of glycosidic bonds in phenolic compounds. Ramírez-Anaya *et al.* (2015) noted that the free radical DPPH scavenging capacity of foods processed in oil increased significantly. Similarly, a significant increase in antioxidant capacity was confirmed by Bellail *et al.* (2012), who used DPPH to test the free radical scavenging potential of raw and deep-fried potatoes. An increase in the antioxidant capacity was also found by Dini *et al.* (2013) using the FRAP method for fried pumpkin (relative to the raw version). This was determined using various methods, the antioxidant activity of the snacks retains a positive, and generally high correlation with the addition of apple pomace and polyphenol content (Table 8).

After the PCA analysis was performed, 11 new variables were obtained, and the first two principal components describe 81.97% of the variability of the system. The parameters that are contained between the two red circles have the greatest impact on its volatility (Fig. 4a). Pellet Polyphenol concentration (PPC), Expanding fryer Polyphenol concentration (EFPC), Expanding microwave oven Polyphenol concentration (EMOPC), Pellet Fe^{3+} reduction capacity (P Fe3+rc), Pellet DPPH scavenging capacity (P DPPH sc), Expanding fryer Fe^{3+} reduction capacity (EF Fe3+rc), Expanding fryer DPPH scavenging capacity (EF DPPH sc), Expanding microwave oven Fe^{3+} reduction capacity (EMO Fe3+rc), Expanding microwave oven DPPH scavenging capacity (EMO DPPH sc), *SME* and Product temperature (Product temp.) have the greatest influence over system variability. They had a slightly lesser effect on efficiency. A strong positive correlation has been shown between Pellet Polyphenol concentration (PPC), Expanding fryer Polyphenol concentration (EFPC), Expanding microwave oven Polyphenol concentration (EMOPC), Pellet Fe^{3+} reduction capacity (P Fe3+rc), Pellet DPPH scavenging capacity (P DPPH sc), Expanding fryer

Table 8. Pearson's correlation coefficient for pellets and expanded snack as determined using two methods

Variable	Screw speed (rpm)	Total polyphenols	% scavenging DPPH	FRAP	Total polyphenols	% scavenging DPPH	FRAP	Total polyphenols	% scavenging DPPH	FRAP
		Pellet			Expanded snack in a fryer			Microwave oven expanded snack		
% of apple pomace addition		0.922	0.873	0.785	0.802	0.953	0.898	0.884	0.932	0.962
total polyphenols	60	-	0.994	0.964	-	0.936	0.981	-	0.993	0.956
% DPPH scavenging		-	-	0.987	-	-	0.977	-	-	0.976
% of apple pomace addition		0.947	0.785	0.929	0.932	0.974	0.776	0.888	0.938	0.886
total polyphenols	80	-	0.900	0.981	-	0.906	0.740	-	0.956	0.999
% DPPH scavenging		-	-	0.957	-	-	0.693	-	-	0.947
% of apple pomace addition		0.934	0.791	0.925	0.884	0.926	0.851	0.974	0.992	0.937
total polyphenols	100	-	0.949	0.991	-	0.995	0.991	-	0.989	0.859
% DPPH scavenging		-	-	0.963	-	-	0.977	-	-	0.925

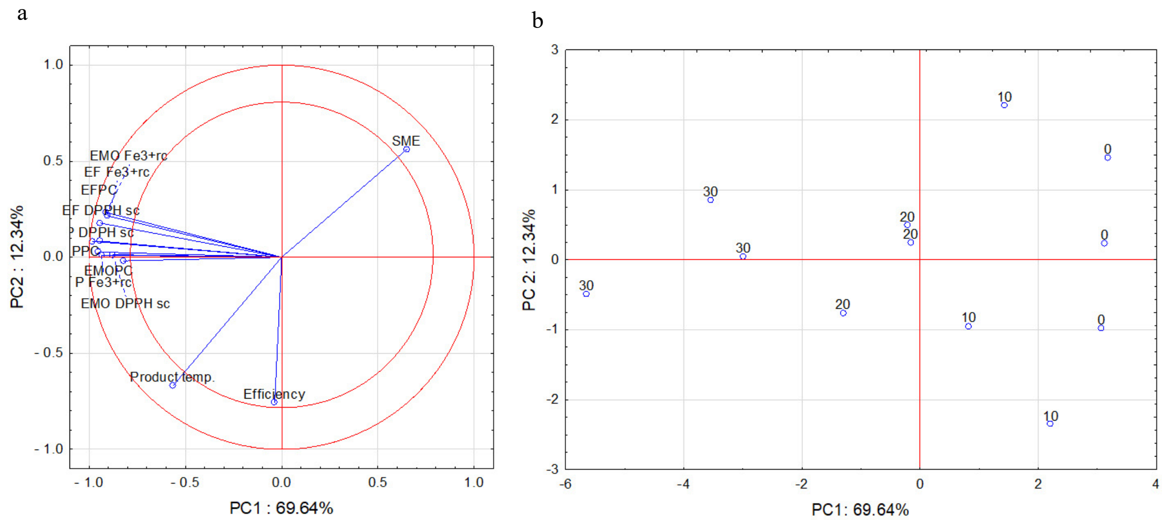

Fig. 4. Loading plot (a) and score plot (b) of the principal component analysis (PC1 and PC2) carried out for addition of apple pomace and tested parameters.

Fe^{3+} reduction capacity (EF Fe3+rc), Expanding fryer DPPH scavenging capacity (EF DPPH sc), Expanding microwave oven Fe^{3+} reduction capacity (EMO Fe3+rc) and Expanding microwave oven DPPH scavenging capacity (EMO DPPH sc). On the other hand, a substantially negative correlation was found between *SME* and Product temperature (Product temp.). There was no correlation found between Pellet Polyphenol concentration (PPC), Expanding fryer Polyphenol concentration (EFPC), Expanding microwave oven Polyphenol concentration (EMOPC), Pellet Fe^{3+} reduction capacity (P Fe3+rc), Pellet DPPH scavenging capacity (P DPPH sc), Expanding fryer Fe^{3+} reduction capacity (EF Fe3+rc), Expanding fryer DPPH scavenging capacity (EF DPPH sc), Expanding microwave oven Fe^{3+} reduction capacity (EMO Fe3+rc), Expanding microwave oven DPPH scavenging capacity (EMO DPPH sc) and Efficiency.

The PCA analysis shows that the first main component of PC1 in as much as 69.64% of cases describes the use of the apple pomace supplement (Fig. 4b). The positive higher PC1 principal component values describe the results without any use of the apple pomace additive, and the negative PC1 principal competitor values describe the results with the use of the apple pomace additive.

The same relationship was observed for the first (PC1) and third (PC3) principal components (Fig. 5a, b). The first (PC1) and third (PC3) principal components describe 79.09% of the variability of the system. However, only the parameters of polyphenols and FRAP in this system have the greatest impact on its variability. They are the Pellets Polyphenol concentration (PPC), Expanding fryer Polyphenol concentration (EFPC), Expanding microwave oven Polyphenol concentration (EMOPC), Pellet Fe^{3+} reduction capacity (P Fe3+rc), Pellet DPPH scavenging

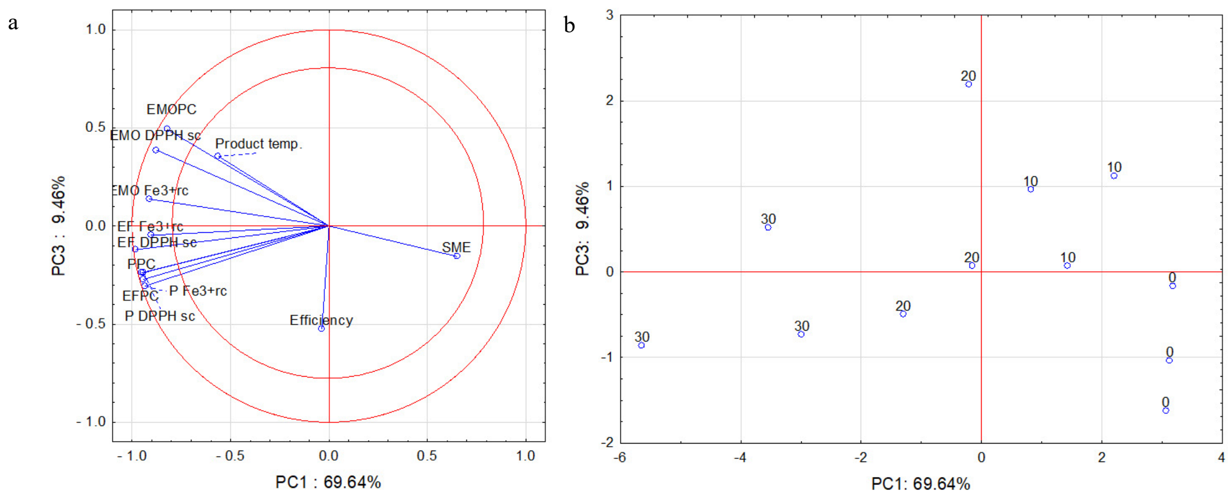

Fig. 5. Loading plot (a) and score plot (b) of the principal component analysis (PC1 and PC3) carried out for addition of apple pomace and tested parameters.

capacity (P DPPH sc), Expanding fryer Fe^{3+} reduction capacity (EF Fe3+rc), Expanding fryer DPPH scavenging capacity (EF DPPH sc), Expanding microwave oven Fe^{3+} reduction capacity (EMO Fe3+rc) and the Expanding microwave oven DPPH scavenging capacity (EMO DPPH sc) are substantially positively correlated with each other.

The pellet polyphenol concentration (PPC), expanding fryer polyphenol concentration (EFPC), expanding microwave oven polyphenol concentration (EMOPC), pellet Fe^{3+} reduction capacity (P Fe3+rc), pellet DPPH scavenging capacity (P DPPH sc), expanding fryer Fe^{3+} reduction capacity (EF Fe3+rc), expanding fryer DPPH scavenging capacity (EF DPPH sc), expanding microwave oven Fe^{3+} reduction capacity (EMO Fe3+rc), expanding microwave oven DPPH scavenging capacity (EMO DPPH sc) are all substantially correlated with the addition of apple pomace in a quantity of 30%, but *SME* is only positively correlated to a weak extent with no addition of apple pomace (Fig. 4a, b).

4. CONCLUSIONS

The responsible management of the by-products of the agri-food industry is an important element contributing to a reduction in the negative impact of the agri-food industry on the environment. The search for a way to process fruit industry by-products, allowing for the greatest possible recovery of the available and active substances in such products, has been a widely discussed topic in recent years.

The addition of apple pomace to food products is not only associated with the appropriate management of this type of product, which in turn is associated with a beneficial impact on the environment, but it also makes it possible to obtain a new type of product with a high nutritional potential due to the presence of health-promoting components (Kawecka and Galus, 2021).

Food products containing apple pomace can thus be classified as zero-waste products, which is consistent with the overall trends of the global market (Kaszuba and Pycia, 2022). Based on the research conducted, it may be concluded that apple pomace as a component of the raw material mixture of food pellets and added in the right amount, favourably affects the parameters of the extrusion-cooking process and significantly increases the antioxidant potential of snacks.

In our work, it was noted that the most favourable blends in terms of process parameters and antioxidant potential were those with 20 and 30% addition due to their high efficiency and relatively low specific mechanical energy values while showing a high antioxidant potential compared to the other blends.

Blends with a 20 and 30% addition had higher efficiency and lower specific mechanical energy values as compared to blends with a 10% addition. In addition, some blends with a 10% addition, and mixtures with a 20 and 30% addition showed a much lower polyphenol and 2,2-diphenyl-1-picrylhydrazyl scavenging capacity by up to about 25-30%.

Conflict of interest: The authors declare no conflict of interest.

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