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Analysis of the Influence of Different Plasticizing Systems in a Single-Screw Extruder on the Extrusion-Cooking Process and on Selected Physical Properties of Snack Pellets Enriched with Selected Oilseed Pomace

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Abstract: By-products generated in the agri-food industry are frequently regarded as waste, despite their significant potential for reutilization as valuable raw materials with both nutritional and functional properties. Nigella and flaxseed pomace, as rich sources of bioactive compounds, have the capacity to enhance the nutritional profile and functional characteristics of extruded products while simultaneously contributing to the reduction in food waste. Uniquely, the present study analyzed the effect of extrusion-cooking process conditions on the efficiency, energy consumption, and selected physical properties of extrudates enriched with nigella and flaxseed pomace. The samples were made using a single-screw extruder-cooker. Two plasticizing (L/D 16 and 20) systems were compared. The highest efficiency, 23.16 kg/h, was reached using 20% nigella pomace with the L/D 16 system. During the whole process, the specific mechanical energy ranged from 0.006 to 0.105 kWh/kg. New information was obtained on the interaction between pomace content and the physical properties of the extrudates. The results showed that the use of 10% nigella pomace maximized the *WAI* 4.90 and *WSI* 11.73% for pellets with 30% of nigella seed pomace in the L/D 20 and influenced the change in bulk density, indicating a double innovation: an improvement in extrudate quality and the efficient use of by-products.

Keywords: extrusion-cooking process; process efficiency; plant pomace; processing parameters

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1. Introduction

Although the agri-food sector plays a critical role in global food security, it also presents significant environmental challenges [1]. Comprehensive operational framework, encompassing activities from agricultural production to industrial processing, results in the generation of significant volumes of by-products and waste [2,3]. In the absence of effective management strategies, these outputs have the potential to accelerate environmental degradation and compromise ecosystem stability [4]. Advances in technology and the

thorough analysis of by-products in the food industry, combined with initiatives promoting the zero-waste concept, have led to a significant rise in interest in their utilization within the sector [5]. These advancements have contributed to more efficient resource use, reduced waste, and the creation of sustainable and innovative solutions. Recent studies have increasingly explored the use of oilseed and other plant-based by-products in extrusion-cooking processes, demonstrating their potential to enhance the nutritional value, functional properties, and sustainability of extruded products [6,7]. By-products such as oilseed pomace are rich in nutrients and bioactive compounds that offer numerous health benefits [8–10]. They are a natural source of fiber, vitamins, and antioxidants and positively influence the body by improving digestion, boosting immune function, and providing protection against various diseases of the circulatory system [11,12]. Consequently, oilseed pomace holds significant potential beyond traditional use as feed or waste, serving as a valuable raw material in diverse food production processes and industrial applications [13–15].

Considering this potential, extrusion-cooking processing is an ideal method for transforming this type of pomace into functional food products [16]. This method is flexible and efficient because it continuously pushes raw material mixtures through a die, while controlling temperature, pressure, and shear [17–19]. The process shapes the material and enhances its texture, structure, and nutritional value. Adding nutrient-rich plant pomace enables the creation of food products with health benefits beyond basic nutrition [20–22]. This method helps retain and evenly distribute important bioactive compounds, such as fiber, vitamins, and antioxidants, in the final product [23].

Despite the wide potential of the extrusion-cooking process, achieving optimal conditions can be challenging due to the variable nature of plant-based extrudates. Unlike standard raw materials, pomace can differ greatly in terms of moisture content, particle size, fiber concentration, the quantity of fat, and the overall nutritional composition. These changes can influence process stability and the overall efficiency of the extrudates obtained. To ensure consistent results, the process settings must be precisely adjusted [24].

To achieve the desired product characteristics, adjustments often need to be made to major parameters, including screw speed, barrel temperature, and die configuration [25]. In some cases, modifications are required to the plasticization system and the overall application to manage the variability of extrudate properties. This iterative approach ensures the production of high-quality products that meet standards for texture, nutritional value, and sensory attributes [26].

Optimizing extrusion-cooking conditions is essential, not only for product quality but also for environmental and economic benefits. The efficient processing of pomace reduces waste, lowers energy and water consumption, and enhances the efficient use of raw materials, promoting sustainable production. Moreover, the ability to transform low-cost or underutilized by-products into nutritious food products offers significant economic advantages, establishing the extrusion-cooking process as a vital tool in sustainable food production [27].

The aim of this study was to analyze the effect of adding nigella seed (AN) and flaxseed (AF) pomace on the extrusion-cooking process and the properties of the extrudates obtained. Specifically, the study evaluated process efficiency, energy consumption, bulk density, and the functional properties of the extrudates, which were determined using the water absorption index (*WAI*) and the water solubility index (*WSI*). The research was conducted using two different plasticizing systems, L/D 16 and L/D 20, allowing for a comparative analysis of their impact on the parameters examined. The extrusion-cooking process was conducted using a ring-shaped forming die. The extrudates were cut immediately after passing through the extruder-cooker die. The results obtained provide insights into the relationships between raw material composition, process conditions, and the final

properties of the extrudates. The comparative analysis of the two plasticizing systems contributes to a better understanding of how technological parameters influence process efficiency and product quality. Importantly, the study represents a dual innovation by simultaneously focusing on enhancing extrudate quality and exploring the valorization of by-products, developments that together present a comprehensive approach to sustainable extrusion-cooking technology.

2. Materials and Methods

A research project was carried out at the Department of Food Process Engineering at the University of Life Sciences in Lublin. The studies focused on using an extrusion-cooking process to produce snack pellets enriched with by-products from the food industry. The aim was to create extrudates with better nutritional value and lower environmental impact. The recipes were based on previous work and included ingredients from local suppliers. The mixtures contained oilseed pomace, potato starch, potato flakes, canola oil, beet sugar, and salt. Food industry by-products were used to cut down the waste and improve sustainability. The extrusion-cooking process was carried out with two different plasticization systems, allowing researchers to analyze how varying process parameters affected the structure and quality of the pellets.

2.1. Extrudates Formulation and Production Using Extrusion-Cooking Process

At the initial stage of the work, mixtures were produced according to established recipes (Table 1). Each recipe included 10%, 20%, and 30% concentrations of nigella and flaxseed pomace. These concentrations were chosen based on the results of previous studies and a review of the available literature; we considered them sufficient to introduce the desired functional changes without negatively affecting the texture and sensory acceptance of the product [28]. The application of more than 30% additive in the mixture could lead to problems during production, such as unstable processing, changes in pressure or temperature, and lower-quality extrudates.

Table 1. The proportional shares of individual components in the mixtures.

Raw Materials	Control Sample	10% Pomace	20% Pomace	30% Pomace
Nigella seed, flaxseed pomace (%)	0	10	20	30
Potato starch (%)	82	72	62	52
Potato flakes (%)	15	15	15	15
Vegetable oil (%)	1	1	1	1
Sugar (%)	1	1	1	1
Salt (%)	1	1	1	1

The oilseed pomace was ground using Germin cup blender model CY-329 (Germin Berlinger, Jarosław, Poland). The mixtures were prepared in batches of 4.5 kg by precisely adjusting the proportions of the components according to the content of plant raw materials and moistured to 34%. To guarantee the consistent dispersion of the components and the correct moisture content, the samples were sieved using a 0.5 mm sieve. After that, blends were stored under controlled conditions for 24 h to stabilize and equalize the parameters of the mixtures.

The moisture content of each sample was determined using a precision moisture analyzer (Radwag, Radom, Poland) capable of measuring with an accuracy of 0.001%. Each mixture was moistured to a predetermined moisture level, as determined by previous research results and current technological recommendations. This stage was crucial to

ensuring that the parameters of the extrusion-cooking process were appropriate and that a product of the desired quality was obtained.

The manufacturing of extrudates containing oilseed pomace was conducted using a single-screw extruder-cooker (EXP-45-32, Zamak Mercator, Skawina, Poland). The extrusion-cooking system featured a plasticizing unit with total length-to-diameter (L/D) ratios of 16 and 20. The extrusion-cooking process was performed at 40, 60, and 80 rpm. The manufacturing of extrudates containing oilseed pomace was carried out using a single-screw extruder-cooker (EXP-45-32, Zamak Mercator, Skawina, Poland). The device was equipped with two plasticizing systems with different length-to-diameter (L/D) ratios—one at 16 and the other at 20. The extrusion-cooking process was conducted at screw speeds of 40, 60, and 80 rpm. The temperature in the various sections of the extruder-cooker was maintained between 30 and 95 °C (Table 2), ensuring optimal processing conditions throughout the extrusion-cooking process. In the case of the L/D 20 configuration, the plasticization system was equipped with an additional section (IV). The material exiting the extruder-cooker was shaped using a forming die in the shape of a ring with a slit thickness of 0.6 mm. Subsequently, the material was portioned using a cutting system located directly behind the extruder-cooker die. The extruded products were placed and dried in a laboratory shelf dryer at 40 °C for 12 h until their moisture content stabilized within the range of 8.5–9.5%. Following the drying process, the extrudates were sealed in ziplock bags to ensure proper storage until further processing.

Table 2. Temperature in different extruder-cooker sections for L/D 16 and 20.

Type of Plant Pomace	Content of the Additive [%]	Screw Speed [RPM]	Type of Plasticizion System [L/D]	Temperature of Section I [°C]	Temperature of Section II [°C]	Temperature of Section III [°C]	Temperature of Section IV [°C]	Temperature of Section V [°C]
Control sample	0%	40	16 20	31.40 ± 0.00 30.50 ± 0.00	60.33 ± 0.67 60.03 ± 0.15	75.63 ± 0.50 64.90 ± 0.10	N/A 71.57 ± 0.06	81.80 ± 1.91 72.67 ± 0.06
Control sample	0%	60	16 20	31.80 ± 0.20 30.70 ± 0.00	61.80 ± 0.26 59.93 ± 0.25	77.77 ± 0.31 64.90 ± 0.20	N/A 71.67 ± 0.06	80.40 ± 0.20 72.97 ± 0.06
Control sample	0%	80	16 20	32.37 ± 0.12 30.97 ± 0.12	59.60 ± 1.01 59.83 ± 0.55	76.93 ± 1.34 64.90 ± 0.17	N/A 70.47 ± 0.31	79.37 ± 0.71 69.67 ± 0.31
Nigella seed pomace	10%	40	16 20	37.10 ± 0.36 31.80 ± 0.10	60.00 ± 0.46 31.67 ± 0.29	68.03 ± 1.33 67.27 ± 0.15	N/A 71.57 ± 0.06	70.17 ± 0.06 72.93 ± 0.12
Nigella seed pomace	10%	60	16 20	35.03 ± 0.51 31.50 ± 0.00	60.07 ± 1.08 60.37 ± 1.69	69.77 ± 0.38 66.57 ± 0.59	N/A 71.57 ± 0.15	70.13 ± 0.06 72.67 ± 0.23
Nigella seed pomace	10%	80	16 20	33.33 ± 0.23 31.30 ± 0.00	61.73 ± 0.25 58.73 ± 1.34	69.87 ± 0.29 67.80 ± 0.75	N/A 70,60 ± 0.46	71.70 ± 1.47 70.60 ± 1.05
Nigella seed pomace	20%	40	16 20	38.27 ± 0.06 32.13 ± 0.12	60.03 ± 0.06 60.90 ± 1.21	68.53 ± 0.12 65.30 ± 1.15	N/A 71.83 ± 0.06	70.07 ± 0.06 72.90 ± 0.00
Nigella seed pomace	20%	60	16 20	35.50 ± 0.00 32.40 ± 0.00	60.00 ± 0.75 59.47 ± 0.21	71.73 ± 0.12 68.07 ± 0.06	N/A 75.73 ± 0.12	74.40 ± 0.17 76.77 ± 0.06
Nigella seed pomace	20%	80	16 20	35.03 ± 0.06 32.40 ± 0.00	60.80 ± 1.10 59.47 ± 0.21	72.67 ± 0.40 68.07 ± 0.06	N/A 75.73 ± 0.12	74.47 ± 0.15 76.77 ± 0.06
Nigella seed pomace	30%	40	16 20	34.07 ± 0.06 32.70 ± 0.26	60.20 ± 0.10 69.00 ± 1.39	70.07 ± 0.38 74.30 ± 1.08	N/A 75.57 ± 0.32	78.70 ± 0.10 76.33 ± 0.23
Nigella seed pomace	30%	60	16 20	34.20 ± 0.00 32.20 ± 0.00	60.20 ± 0.00 61.33 ± 1.72	70.90 ± 0.17 69.37 ± 1.93	N/A 75.10 ± 0.10	74.33 ± 0.49 76.07 ± 0.15
Nigella seed pomace	30%	80	16 20	34.53 ± 0.15 32.20 ± 0.00	59.63 ± 0.06 60.03 ± 0.12	69.27 ± 3.06 67.97 ± 0.15	N/A 75.00 ± 0.00	74.43 ± 0.15 75.73 ± 0.06
Flaxseed pomace	10%	40	16 20	36.57 ± 0.06 33.47 ± 0.06	60.20 ± 0.70 69.33 ± 0.40	67.97 ± 0.25 76.50 ± 0.10	N/A 75.80 ± 0.00	73.30 ± 0.10 77.43 ± 0.12
Flaxseed pomace	10%	60	16 20	36.27 ± 0.06 33.53 ± 0.06	59.50 ± 1.08 69.67 ± 0.23	68.07 ± 0.29 75.67 ± 0.06	N/A 75.93 ± 0.06	73.27 ± 0.12 77.37 ± 0.06

Table 2. *Cont.*

Type of Plant Pomace	Content of the Additive [%]	Screw Speed [RPM]	Type of Plasticizion System [L/D]	Temperature of Section I [°C]	Temperature of Section II [°C]	Temperature of Section III [°C]	Temperature of Section IV [°C]	Temperature of Section V [°C]
Flaxseed pomace	10%	80	16	35.60 ± 0.10	59.77 ± 0.67	68.37 ± 0.21	N/A	73.43 ± 0.15
			20	33.40 ± 0.00	69.70 ± 0.66	76.50 ± 0.26	76.23 ± 0.06	77.63 ± 0.06
Flaxseed pomace	20%	40	16	36.70 ± 0.00	60.73 ± 0.32	67.80 ± 0.36	N/A	73.50 ± 0.10
			20	33.57 ± 0.06	71.00 ± 1.35	75.13 ± 0.12	76.03 ± 0.06	77.30 ± 0.00
Flaxseed pomace	20%	60	16	36.90 ± 0.00	60.03 ± 0.15	68.17 ± 0.21	N/A	73.63 ± 0.06
			20	33.43 ± 0.06	69.43 ± 1.05	76.73 ± 0.46	76.10 ± 0.00	77.57 ± 0.06
Flaxseed pomace	20%	80	16	37.33 ± 0.06	59.77 ± 0.31	68.60 ± 0.10	N/A	73.70 ± 0.00
			20	33.40 ± 0.00	70.80 ± 0.60	76.37 ± 0.58	76.13 ± 0.06	77.70 ± 0.00
Flaxseed pomace	30%	40	16	39.80 ± 0.00	60.40 ± 0.17	68.03 ± 0.21	N/A	73.70 ± 0.00
			20	34.33 ± 0.06	69.83 ± 0.06	74.80 ± 0.17	76.10 ± 0.00	77.27 ± 0.06
Flaxseed pomace	30%	60	16	38.87 ± 0.15	60.00 ± 0.78	68.46 ± 0.40	N/A	73.60 ± 0.10
			20	34.73 ± 0.06	70.30 ± 0.17	75.50 ± 0.10	76.03 ± 0.06	77.37 ± 0.06
Flaxseed pomace	30%	80	16	38.87 ± 0.15	60.00 ± 0.78	68.46 ± 0.40	N/A	73.73 ± 0.06
			20	34.97 ± 0.06	70.67 ± 0.15	75.83 ± 0.31	76.30 ± 0.10	77.60 ± 0.10

N/A—not applicable (section IV was not applicable in this setup).

2.2. Efficiency of the Extrusion-Cooking Process

The efficiency of the extrusion-cooking process (Q) was evaluated by systematically measuring the mass of the extruded material exiting the forming die at 30 s intervals. Processing parameters and feed rates were consistently maintained at stable levels throughout the trial to uphold result accuracy. Each measurement was repeated three times to improve accuracy. The processing time was recorded using an electronic stopwatch, while the extrudates were weighed with a precision balance (DS-788 Yakudo, Tokyo, Japan) accurate to 0.001 kg. Repeating the procedure helped reduce possible errors and ensured more reliable results. The average of the three measurements was used to determine the final process efficiency. The calculation of process efficiency was conducted in accordance with the methodology proposed by Matysiak et al. [29]:

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

where Q represents the extrusion-cooking process efficiency (kg/h), m is the extrudate mass obtained through measurement (kg), and t denotes time (h).

2.3. Energy Consumption of the Extrusion-Cooking Process

The power consumption of the extruder-cooker was tracked in real time using a built-in wattmeter, an integral part of the machine's standard monitoring system. To evaluate energy usage, motor load data and process efficiency were analyzed in conjunction with motor specifications and recorded operational parameters. These values were then used to compute the specific mechanical energy (*SME*) consumption. The final value was calculated as the average of three repetitions. The calculation was carried out following the methodology described by Kręcisz [30], with measured data being systematically converted into *SME* according to a predefined formula:

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

SME—specific mechanical energy (kWh/kg); n—extruder-cooker speed (rpm); n_m—max extruder-cooker speed (rpm); O—engine load (%) based on nominal power (kW); Q—extrusion-cooking process efficiency (kg/h).

2.4. Bulk Density of Snack Pellets

The bulk density (*BD*) of the snack pellets was measured based on the mass and volume of the sample. The mass was recorded using a precision balance (DS-788 Yakudo, Tokyo, Japan) with an accuracy of 0.001 kg. The sample was put into a 0.001 m^3 container. Bulk density was calculated as the ratio of mass to volume. This parameter presents the relationship between product shape and weight. To ensure reliable results, the measurement was repeated three times, achieving a precision of 0.01 kg/m^3. The average of the three repetitions values was used as the final measurement. The bulk density was derived using the formula provided by Wójtowicz et al. [31]:

$$BD = \frac{m}{V} \ (kg/m^3) \tag{3}$$

where *BD* is the bulk density (kg/m^3), *m* is the measured mass of the sample (kg), and *V* represents the container's volume (m^3).

2.5. Water Absorption Index (WAI)

The water absorption index (*WAI*) was evaluated following the procedure established by Bouasla et al. [32]. A precisely weighed 0.7 g sample of finely ground extrudates was suspended in 7 mL of distilled water and shaken for 20 min to obtain a homogeneous suspension. After this process, the suspension was centrifuged at a speed of 15,000 rpm for 10 min using a Digicen 21 centrifuge (Labsystem, Kraków, Poland). The supernatant was carefully decanted, and the rest of hydrated gel was weighed using a high-precision balance (WPS 210/C, Radwag, Radom, Poland) with an accuracy of 0.001 g. The final value was calculated as the average of three repetitions. The *WAI* was calculated using the following formula:

$$WAI = \frac{m_g}{m_s} \ (g/g) \tag{4}$$

where *WAI* represents the water absorption index (g/g), m_g denotes the mass of the gel (g), and m_s refers to the mass of the dry sample (g).

2.6. Water Solubility Index (WSI)

The liquid fraction obtained after *WAI* analysis demonstrated evaporation at 110 °C in a laboratory dryer (SLW 53 STD, Pol-Eko Aparatura S.J., Wodzisław Śląski, Poland) until all the water content was completely evaporated. After drying, the solid residue was collected and weighed using a precise balance (WPS 210/C, Radwag, Radom, Poland) with an accuracy of 0.001 g. To ensure reliable results, the *WSI* was measured three times using the formula presented by Bouasla et al. [32]:

$$WSI = \frac{m_v - m_{dv}}{m_s} \times 100 \ (\%) \tag{5}$$

where *WSI* means the water solubility index (%), m_v is the mass of the vessel before drying process (g), m_{dv} is the mass of the vessel after drying process (g), and m_s denotes the mass of the dry sample (g).

2.7. Principal Component Analysis (PCA)

Statistical calculations were performed using the Statistica application software (version 12.0, StatSoft Inc., Tulsa, OK, USA). The methods applied included principal component analysis (PCA), analysis of variance (ANOVA), and correlation analysis. All analyses were carried out at a significance level of $\alpha = 0.05$. Principal component analysis was used to examine the relationships between selected process variables and measured extrudate characteristics. The variables included the type of additive, the amount of additive in the mixture, screw speed, and the length-to-diameter (L/D) ratio of the extrusion-cooking

system. To identify connections and patterns between tested factors, PCA was used along with separate data tables for each factor. The table for additive type included 5 columns, representing measured parameters, and 3 rows, each corresponding to a different additive. The table for additive amount had 5 columns and 4 rows, covering all tested concentration levels. For screw speed, the table also had 5 columns and 3 rows. The L/D ratio table included 5 columns and 4 rows. All data tables were automatically rescaled to allow for easy comparison between values. The number of principal components selected in each case was based on the Cattell criterion, which helps to identify the most meaningful components in the dataset.

3. Results and Discussion

This research presents the assessment of major processing parameters in the extrusion-cooking process, including efficiency and specific mechanical energy consumption, as well as an evaluation of the various physical properties of the extrudates obtained. The research compares two plasticizing system configurations (L/D 16 and L/D 20) and the effect of each on selected parameters. The results indicate the existence of differences in processing efficiency and specific mechanical energy consumption.

The extrusion-cooking process is a common method in food production that helps create expanded products with specific textures and properties. The extrudates analyzed in this study represent fully valuable products, offering potential alternatives to commercially available snack pellets. To enhance their nutritional and functional value, we use plant by-products in the form of oilseed pomace—specifically nigella seed and flaxseed. These ingredients not only contribute valuable bioactive compounds but also influence the physicochemical properties of the final product. The results show that changes in the L/D ratio, screw speed, and the amount of pomace have a significant impact on process efficiency end energy consumption. Additionally, the physical characteristics of the extrudates, including bulk density, water absorption index, and water solubility index, were analyzed. The findings show that bulk density varied depending on extrusion-cooking conditions, with structural differences observed between the two processing setups. The incorporation of oilseed pomace influenced *WAI* and *WSI* index values, suggesting that there are modifications in water retention capacity and solubility due to the presence of additional fiber, fat, and protein fractions. These differences are crucial for product texture and potential consumer applications.

3.1. Results of Extrusion-Cooking Efficiency and Energy Consumption

The data obtained were used to examine the effect of two different types of plant pomace (nigella seed and flaxseed), added at concentrations of 10%, 20%, and 30%, on the efficiency of the extrusion process. The efficiency was measured in kg/h at different screw speeds (40, 60, and 80 rpm) and two length-to-diameter (L/D) ratios of 16 and 20 (Figure 1).

For the control sample, increased efficiency was observed with increasing screw speed. At 40 rpm, the efficiency was 8.34 kg/h for L/D 16 and 8.48 kg/h for L/D 20. At 80 rpm, the efficiency reached 18.92 kg/h for L/D 16 and 14.36 kg/h for L/D 20, indicating a distinct increase in efficiency for the lower L/D ratio.

At a 10% concentration, Nigella seed pomace showed higher efficiency at lower rpm for L/D 16 compared to L/D 20. At 40 rpm, the efficiencies were 9.64 kg/h for L/D 16 and 9.52 kg/h for L/D 20. At 80 rpm, the material efficiency increased, reaching 17.88 kg/h for L/D 16 and 15.68 kg/h for L/D 20, indicating better process efficiency at a lower L/D ratio. At higher concentrations of nigella seed pomace, efficiency was also higher for L/D 16. At 20% pomace and 80 rpm, efficiency was 23.16 kg/h for L/D 16 and 19.20 kg/h for

L/D 20. A similar trend was observed at a 30% concentration. There was a higher amount of material at 80 rpm, with values of 23.00 kg/h for L/D 16 and 16.32 kg/h for L/D 20.

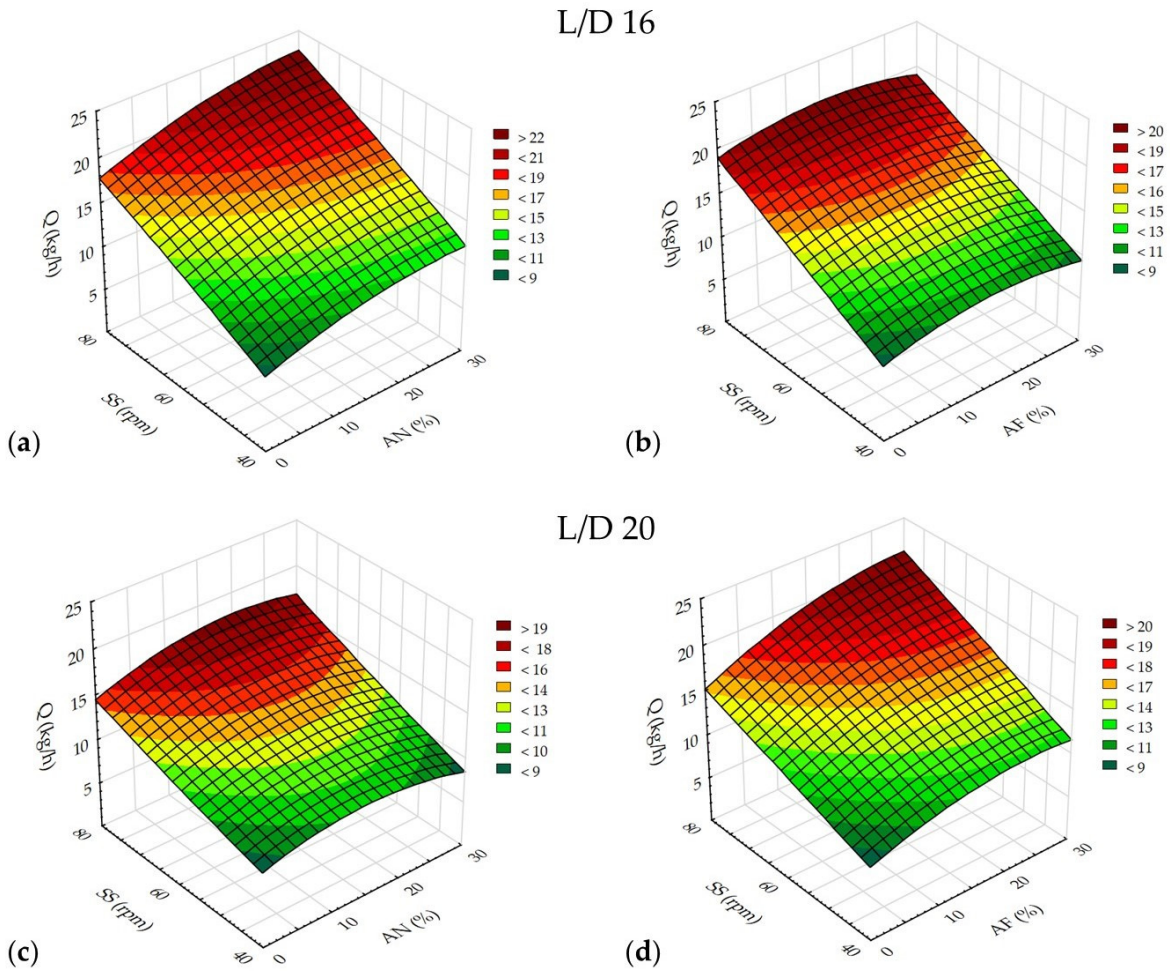


Figure 1. Trend plots of extrusion-cooking efficiency of snack pellets depending on selected plant pomace addition level, screw speed, and type of plasticizing system: (**a**) nigella seed pomace processed using L/D 16 plasticizing system; (**b**) flaxseed pomace processed using L/D 16 plasticizing system; (**c**) nigella seed pomace processed using L/D 20 plasticizing system; (**d**) flaxseed pomace processed using L/D 20 plasticizing system.

For flaxseed pomace, the efficiency generally increased with screw speed but shows a more balanced value across different concentrations. At 10% pomace, the efficiency at 40 rpm were 10.24 (L/D 16) and 9.84 kg/h (L/D 20), rising to 20.64 kg/h (L/D 16) and 19.24 kg/h (L/D 20) at 80 rpm. For 20% flaxseed pomace, the efficiency increased steadily from 10.84 kg/h (L/D 16) and 11.44 kg/h (L/D 20) at 40 rpm to 19.76 kg/h (L/D 16) and 20.64 kg/h (L/D 20) at 80 rpm. The highest efficiency for flaxseed pomace was recorded at a 30% concentration, with a maximum of 21.20 kg/h (L/D 20) at 80 rpm.

Statistical analysis indicates that while L/D 20 demonstrated higher efficiency at lower screw speeds (40 rpm) in some cases, L/D 16 generally ensured higher process efficiency, particularly at higher speeds (60 and 80 rpm). Similar findings were reported by Lewko et al. [33], who examined the extrusion of flour-based materials and observed a general decrease in efficiency for the L/D 20 plasticization system compared to L/D 16. The study also suggested that shorter plasticization systems may be more beneficial for processing flour-based products, as they provide improved material flow and processing stability. Similar to the findings of Lisiecka and Wójtowicz [34], an increase in efficiency

was observed at higher screw speeds, especially in the L/D 16 configuration. This suggests that higher screw speed enhances the efficiency of the extrusion-cooking process, likely by improving material flow dynamics and reducing processing resistance.

In conclusion, extrudates with nigella seed and flaxseed pomace contribute to improved process efficiency with increasing concentrations and screw speed, particularly at 80 rpm. Nigella seed pomace generally demonstrated a higher efficiency at L/D 16. The findings indicate that incorporating plant-based pomaces at different concentrations can significantly enhance the extrusion-cooking process, especially when operating at higher screw speeds and higher L/D ratios. However, efficiency declines at certain concentration levels and screw speeds, such as with nigella seed pomace at a 30% concentration and flaxseed pomace at 40 rpm, emphasizing the complex interaction between pomace concentration, screw speed, and overall process efficiency (Table 3).

Table 3. Response surface approximation models for evaluating the efficiency and specific mechanical energy consumption of the extrusion-cooking process of extrudates depending on the selected plant pomace addition level, screw speed, and type of plasticizing system.

L/D	Additive	Property	Model Equation	R^2
16	Nigella seed pomace	Q (kg/h)	$-2.653 + 0.214 \times AN + 0.302 \times SS - 0.005 \times AN^2 + 0.001 \times AN \times SS - 0.001 \times SS^2$	0.958
		SME (kWh/kg)	$0.047 - 0.002 \times AN - 0.0004 \times SS + 9.251 \times 10^{-5} \times AN^2 - 1.336 \times 10^{-5} \times AN \times SS + 2.939 \times 10^{-6} \times SS^2$	0.706
	Flaxseed pomace	Q (kg/h)	$-2.317 + 0.256 \times AF + 0.274 \times SS - 0.007 \times AF^2 - 0.001 \times AF \times SS - 0.0001 \times SS^2$	0.954
		SME (kWh/kg)	$0.078 - 0.002 \times AF - 0.001 \times SS + 1.706 \times 10^{-5} \times AF^2 + 1.937 \times 10^{-5} \times AF \times SS + 9.177 \times 10^{-6} \times SS^2$	0.729
20	Nigella seed pomace	Q (kg/h)	$4.063 + 0.1686 \times AN + 0.084 \times SS - 0.008 \times AN^2 + 0.002 \times AN \times SS + 0.001 \times SS^2$	0.940
		SME (kWh/kg)	$0.009 + 0.002 \times AN + 0.002 \times SS + 6.618 \times 10^{-5} \times AN^2 - 4.552 \times 10^{-5} \times AN \times SS - 1.561 \times 10^{-5} \times SS^2$	0.951
	Flaxseed pomace	Q (kg/h)	$0.818 + 0.199 \times AF + 0.189 \times SS - 0.006AF^2 + 0.002 \times AF \times SS - 0.0001 \times SS^2$	0.983
		SME (kWh/kg)	$0.143 + 0.001 \times AF - 0.004 \times SS + 8.592 \times 10^{-6} \times AF^2 - 2.089 \times 10^{-5} \times AF \times SS + 3.229 \times 10^{-5} \times SS^2$	0.930

During the analysis of energy consumption values (Figure 2) for the control sample, we observed that *SME* decreased as screw speed increased. Specifically, at 40 rpm, *SME* is 0.032 kWh/kg for the L/D 16 configuration and 0.036 kWh/kg for L/D 20. At 60 rpm, *SME* increases slightly to 0.042 kWh/kg for L/D 16 and 0.061 kWh/kg for L/D 20. However, at 80 rpm, *SME* decreases to 0.018 kWh/kg for L/D 16 and 0.048 kWh/kg for L/D 20. These results suggest that higher screw speeds lead to a reduction in *SME* for the control sample using L/D 16.

At 10% nigella pomace addition, the *SME* at 40 rpm were 0.024 kWh/kg for L/D 16 and 0.099 kWh/kg for L/D 20, indicating a fourfold increase for L/D 20, which suggests higher flow resistance in the longer system. At 60 rpm, the *SME* decreased to 0.020 kWh/kg (L/D 16) and 0.018 kWh/kg (L/D 20), implying that an increased screw speed reduces resistance and leads to lower mechanical energy consumption. However, at 80 rpm, the *SME* rose to 0.034 kWh/kg (L/D 16) but sharply declines to 0.010 kWh/kg (L/D 20), indicating that a longer screw zone at high speeds may reduce energy losses. Using 20% pomace, the highest *SME* was observed at 40 rpm for L/D 20 (0.035 kWh/kg), while the lowest *SME* occurred at 80 rpm and L/D 16 (0.010 kWh/kg), suggesting that at higher pomace

concentrations, increased screw speed can reduce energy consumption. Using 30% pomace, *SME* reached a peak at 40 rpm for L/D 20 (0.105 kWh/kg), whereas the lowest values were recorded at 80 rpm (0.040 kWh/kg for L/D 16 and 0.022 kWh/kg for L/D 20). This confirms that, at higher pomace concentrations, increasing the screw speed can effectively reduce the specific mechanical energy consumption.

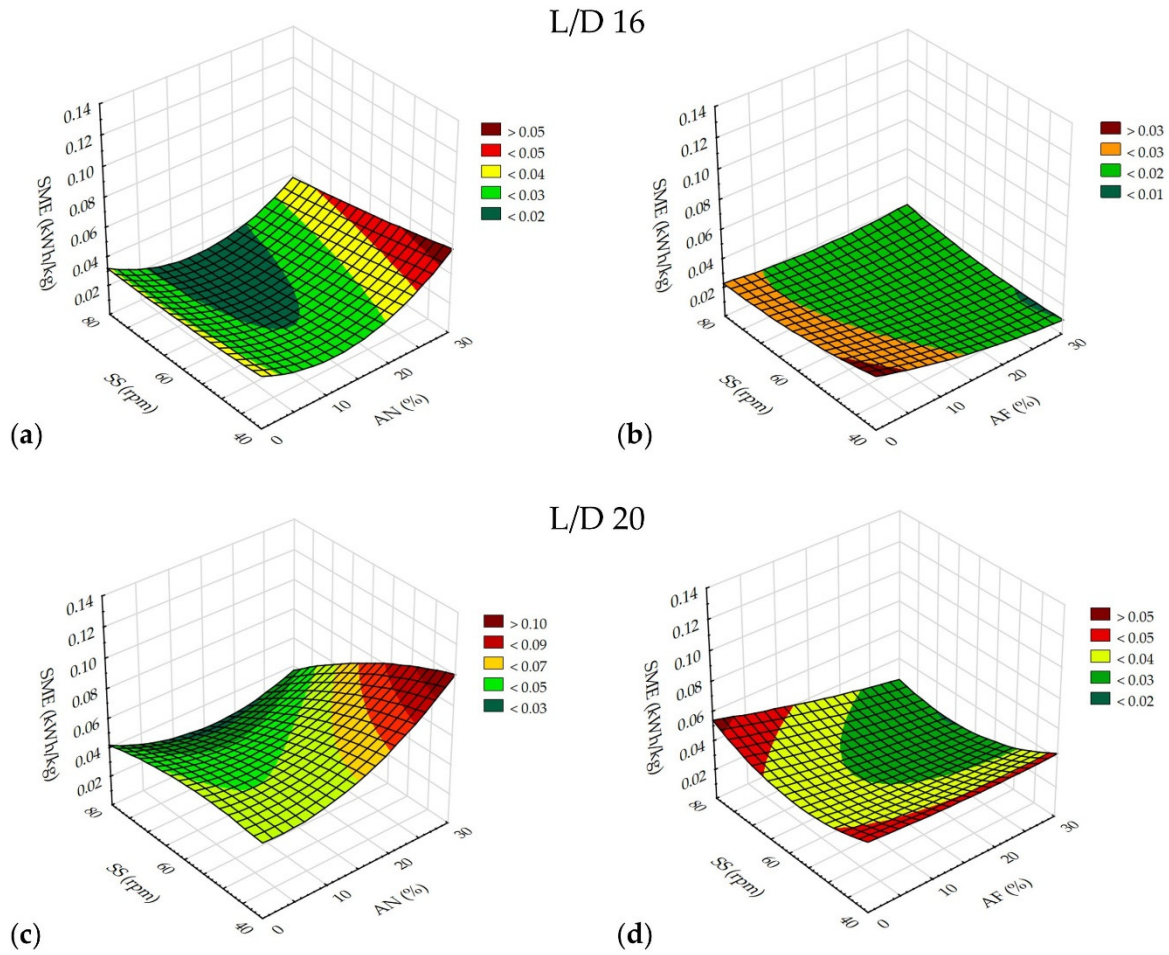


Figure 2. Trend plots of specific mechanical energy demand during the extrusion-cooking process of extrudates in relation to the inclusion level of the selected plant pomace, screw speed and type of plasticizing system: (**a**) nigella seed pomace processed using L/D 16 plasticizing system; (**b**) flaxseed pomace processed using L/D 16 plasticizing system; (**c**) nigella seed pomace processed using L/D 20 plasticizing system; (**d**) flaxseed pomace processed using L/D 20 plasticizing system.

In the case of flaxseed pomace, the changes in *SME* appeared more stable and predictable. For 10% pomace, at 40 rpm, the *SME* values were 0.021 kWh/kg for L/D 16 and 0.033 kWh/kg for L/D 20. At 60 rpm, the values decreased to 0.010 kWh/kg (L/D 16) and 0.016 kWh/kg (L/D 20), indicating that an increased screw speed leads to lower energy consumption. With 20% pomace, the *SME* for L/D 20 was significantly higher than for L/D 16 at 40 rpm (0.081 kWh/kg vs. 0.018 kWh/kg). However, at 80 rpm, the values dropped to 0.043 kWh/kg (L/D 16) and 0.015 kWh/kg (L/D 20), further confirming that an increase in screw speed reduces mechanical energy consumption. For 30% pomace, the differences in *SME* were less pronounced: at 40 rpm, the *SME* values were 0.013 kWh/kg (L/D 16) and 0.028 kWh/kg (L/D 20). At 60 and 80 rpm, the values stabilized (respectively, 0.010 and 0.012 kWh/kg for L/D 16, and 0.015 and 0.041 kWh/kg for L/D 20), suggesting a more uniform influence of flaxseed pomace on the process dynamics. The generally higher *SME* values observed for the L/D 20 configuration at a low screw speed may be attributed

to the increased material residence time and greater shear surface area due to the longer screw. This likely results in higher shear stress and internal friction, particularly in the presence of fibrous by-products such as pomace, which increases resistance to flow. As screw speed increases, the residence time shortens and material flows more efficiently, reducing the mechanical energy required. As observed in Soja's et al. [28] study, the present data indicate that pomace additives influence *SME* values, with the highest *SME* observed at lower additive concentrations, especially for nigella seed pomace. The maximum *SME* value for different pomace additives was approximately 0.100 kWh/kg, which aligns with the 10% nigella seed pomace addition, where *SME* reached 0.099 kWh/kg at 40 rpm for L/D 20. A comparison of results reveals a decline in *SME* at higher pomace concentrations, suggesting a reduction in process energy efficiency with an increased proportion of pomace in the material. Furthermore, similar to the findings of Kantrong et al. [35], who analyzed energy consumption during the extrusion-cooking process of mushroom rice snacks, the present study also observed irregularities in energy consumption, particularly when various screw rotational speeds were used.

A comprehensive comparative analysis, supported by statistical evaluation, reveals that nigella seed pomace exhibits significant fluctuations in *SME*, especially at a lower screw speed and within the extended L/D 20 system. This variability suggests that there is increased flow resistance and greater mechanical energy demand during processing. In contrast, flaxseed pomace demonstrates more stable *SME* values, indicating superior processing characteristics and a lower impact on energy consumption throughout the extrusion-cooking process (Table 3).

3.2. Results of the Analysis of Selected Physical Properties

Bulk density analysis provides a comprehensive assessment of the effects of different pomace additives and extrusion-cooking process parameters on material properties (Figure 3).

For the control sample, the bulk density remains relatively stable and increases slightly as screw speed rises. At 40 rpm, the values reached 402.19 kg/m^3 for L/D 16 and 405.81 kg/m^3 for L/D 20. A further increase in screw speed to 60 rpm resulted in a slight rise to 405.91 kg/m^3 (L/D 16) and 408.01 kg/m^3 (L/D 20). The highest screw speed of 80 rpm led to a minor decrease, with values dropping to 400.22 kg/m^3 (L/D 16) and 403.11 kg/m^3 (L/D 20). This reduction may indicate lower material compression due to increased flow dynamics.

The bulk density of extrudates with nigella seed pomace varies depending on concentration and screw speed. The 10% pomace addition results in a gradual increase in density with rising rpm. At 40 rpm, the values reached 407.43 kg/m^3 (L/D 16) and 409.82 kg/m^3 (L/D 20), while at 80 rpm, they increased to 422.29 kg/m^3 (L/D 16) and 425.49 kg/m^3 (L/D 20). This trend suggests that there is enhanced material compression at higher speeds, which may be beneficial for achieving a more compact structure. A 20% pomace addition leads to the opposite effect, with a decrease in bulk density, particularly for L/D 16, where the value at 40 rpm is only 379.53 kg/m^3, while for L/D 20 it reaches 399.98 kg/m^3. Although density slightly increases with higher screw speeds, it remains lower than that of the control sample. This result may indicate increased porosity and greater difficulty in compressing the material at higher concentrations of nigella seed pomace. The bulk density of samples with 30% additive rose again, reaching 397.19 kg/m^3 (L/D 16) and 404.82 kg/m^3 (L/D 20) at 40 rpm, and stabilizing at 398.64 kg/m^3 (L/D 16) and 409.79 kg/m^3 (L/D 20) at 80 rpm.

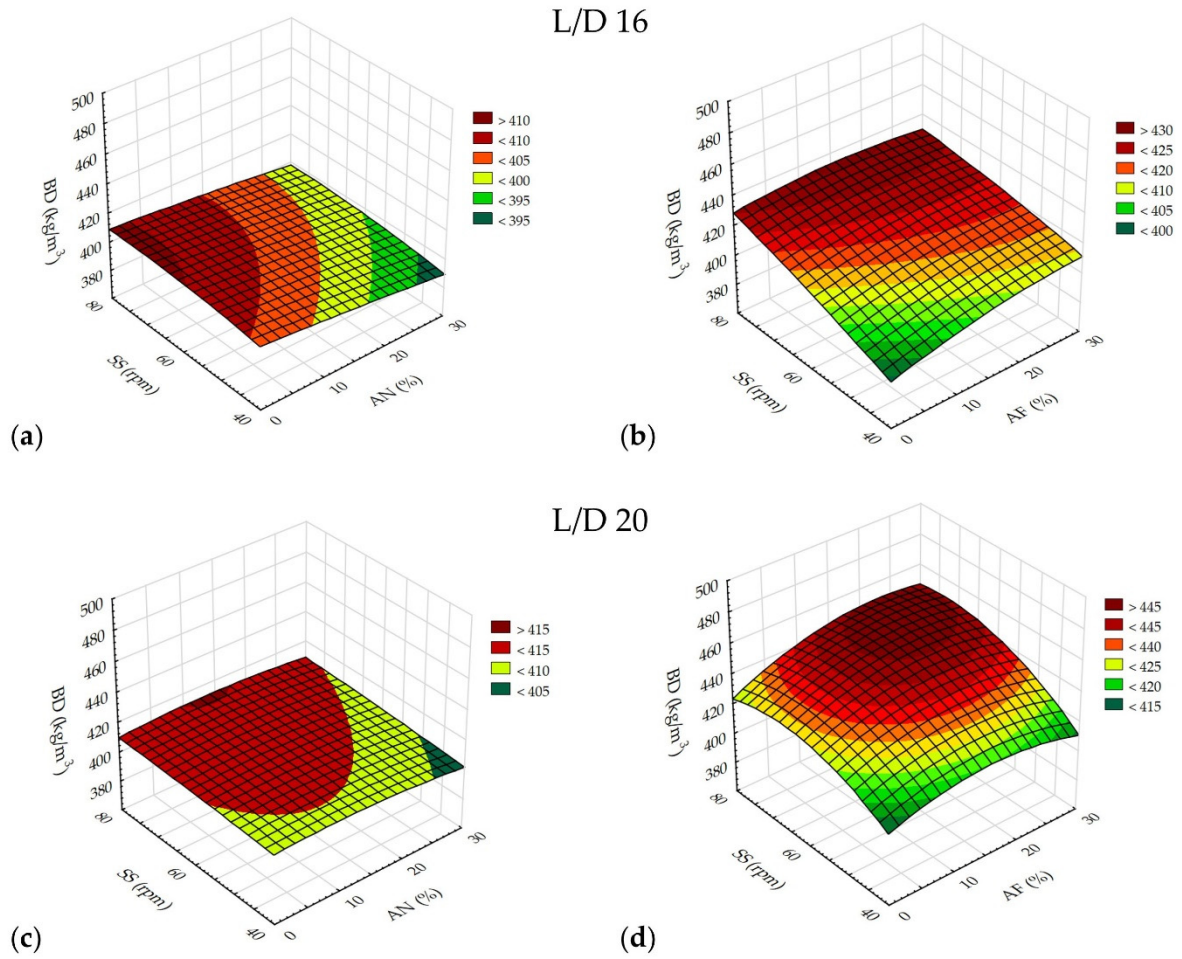


Figure 3. Trend plots of bulk density of extrudates depending on selected plant pomace addition level, processing parameters, and type of plasticizing system: (**a**) nigella seed pomace processed using L/D 16 plasticizing system; (**b**) flaxseed pomace processed using L/D 16 plasticizing system; (**c**) nigella seed pomace processed using L/D 20 plasticizing system; (**d**) flaxseed pomace processed using L/D 20 plasticizing system.

A different pattern of change was observed for extrudates with flaxseed pomace. At a 10% addition, bulk densities at 40 rpm were 396.19 kg/m^3 (L/D 16) and 435.09 kg/m^3 (L/D 20), while at 80 rpm, they increased sharply to 486.67 kg/m^3 (L/D 16) and 495.96 kg/m^3 (L/D 20). This suggests that flaxseed pomace has a higher capacity for compaction within the extruder-cooker system, particularly in the longer L/D 20 configuration and at a higher screw speed. At a 20% addition, bulk density values became more stable, reaching 386.56 kg/m^3 (L/D 16) and 390.49 kg/m^3 (L/D 20) at 40 rpm, and increasing to 411.35 kg/m^3 (L/D 16) and 400.14 kg/m^3 (L/D 20) at 80 rpm. For samples with 30% addition, bulk density increased significantly, reaching 425.69 kg/m^3 (L/D 16) and 423.06 kg/m^3 (L/D 20) at 40 rpm and further rising to 424.82 kg/m^3 (L/D 16) and 459.47 kg/m^3 (L/D 20) at 80 rpm. In the study conducted by Soja et al. [36], a different forming die was used compared to the present research, which may have contributed to the observed differences in bulk density values. However, both studies indicate that flaxseed pomace had a variable impact on this parameter, especially at higher concentrations. The higher bulk density values obtained in the current study may suggest improved compacting properties of the mixtures or more optimal extrusion process conditions. In the study conducted by Soja et al. [28], a different forming die was also used compared to the present research, which may have contributed to the differences in results. Despite this, both studies confirmed that there was a similar trend of decreasing bulk density with

an increasing percentage of nigella seed pomace. However, in the current study, unlike in Soja's findings, the positive effects of nigella seed pomace were more evident at both low (10%) and high (30%) concentrations.

A comparison of both additives, also considering statistical analysis (Table 4), reveals that nigella seed pomace exhibits greater fluctuations in bulk density, especially at moderate concentrations (20%), where values are lower than those of the control sample. This effect may result from increased material porosity or reduced compressibility under screw action. In contrast, flaxseed pomace demonstrates a more predictable and stable increase in bulk density, especially at a higher screw speed, suggesting superior compacting ability and the formation of a denser structure during extrusion-cooking process. The results indicate that the selection of pomace type and process parameters can significantly influence the final product properties, which should be considered in the optimization of the extrusion process.

The evaluation of the water absorption index serves as an indicator of a sample's capacity to retain water, a core aspect in the extrusion-cooking process that significantly affects both texture and the final characteristics of the product. This analysis investigates the influence of nigella seed pomace and flaxseed pomace at different concentrations (10%, 20%, and 30%), while also analyzing the effect of three screw speed (40, 60, and 80 rpm) under two different plasticizing system length-to-diameter (L/D) ratios (16 and 20) (Figure 4).

The control sample exhibited a stable water absorption index (*WAI*), which increased with screw speed. At 40 rpm, *WAI* values were 4.16 g/g (L/D 16) and 4.37 g/g (L/D 20), while at 80 rpm, they increased to 4.32 g/g (L/D 16) and 4.63 g/g (L/D 20). At 60 rpm, the intermediate values obtained, 4.25 g/g (L/D 16) and 4.88 g/g (L/D 20), confirm the existence of an upward trend with increasing screw speed. The effect observed is likely due to a higher level of starch gelatinization, caused by the temperature fluctuations seen at higher screw speeds.

At a 10% addition of nigella seed pomace, *WAI* values were higher than those of the control sample and increased with screw speed. At 40 rpm, *WAI* reached 4.53 g/g (L/D 16) and 4.84 g/g (L/D 20), going up to 4.62 g/g (L/D 16) and 4.86 g/g (L/D 20) at 60 rpm and further increasing to 4.73 g/g (L/D 16) and 4.90 g/g (L/D 20) at 80 rpm. This suggests that a low concentration of nigella seed pomace enhances water binding capacity, likely due to the presence of proteins and polysaccharides, which contribute to improved moisture retention. The *WAI* index for samples with a 20% addition shows a significant decrease, particularly at 40 rpm, where values dropped to 2.05 g/g (L/D 16) and 2.17 g/g (L/D 20). A slight increase was observed at 60 rpm, with values reaching 2.16 g/g (L/D 16) and 2.37 g/g (L/D 20). Subsequent increments were recorded at higher rotational speeds of 80 rpm, rising to 2.29 g/g (L/D 16) and 2.58 g/g (L/D 20). These results indicate that higher amounts of nigella seed pomace reduce water absorption capacity, likely by disrupting the starch structure and limiting gelatinization processes. At a 30% addition, *WAI* values reach their lowest levels. At 40 rpm, they dropped to 1.57 g/g (L/D 16) and 1.88 g/g (L/D 20), increasing only slightly at 60 rpm to 1.65 g/g (L/D 16) and 1.95 g/g (L/D 20). At 80 rpm, values reached 1.74 g/g (L/D 16) and 2.00 g/g (L/D 20). These findings indicate that higher concentrations of nigella seed pomace negatively impact water absorption, potentially leading to a harder, less porous structure in the final product.

For samples flaxseed pomace, the effect on *WAI* followed a more consistent pattern, exhibiting a progressive decrease in values with increasing addition levels. At a 10% addition, *WAI* values at 40 rpm were 3.12 g/g (L/D 16) and 3.38 g/g (L/D 20). As screw speed increased to 60 rpm, values rose to 3.30 g/g (L/D 16) and 3.59 g/g (L/D 20), reaching 3.40 g/g (L/D 16) and 3.76 g/g (L/D 20) at 80 rpm. At a 20% addition, *WAI* remained stable but lower than at a 10% addition. At 40 rpm, values were 2.59 g/g (L/D 16) and 2.71 g/g (L/D 20), while at 60 rpm, it increased faintly to 2.63 g/g (L/D 16) and 2.76 g/g

(L/D 20). At 80 rpm, *WAI* decreased to 2.43 g/g (L/D 16) and 2.49 g/g (L/D 20). At 30% addition, *WAI* reached the lowest values for extrudates with flaxseed pomace. At 40 rpm, they reached 2.34 g/g (L/D 16) and 2.46 g/g (L/D 20). At 60 rpm, the values remained nearly stable at 2.33 g/g (L/D 16) and 2.43 g/g (L/D 20), while at 80 rpm, they further decreased to 2.25 g/g (L/D 16) and 2.37 g/g (L/D 20). In the study conducted by Drożdż et al. [37], it was observed that increased addition of chokeberry presses residues also led to a reduction in *WAI* values in extruded corn snacks. A similar trend was reported by Wójtowicz et al. [38], where the initial addition of fresh chokeberry increased water absorption, but at higher concentrations (20–30%), a significant decline in *WAI* was observed. These findings align with the results of the present study, which demonstrated a comparable decrease in *WAI* with increasing nigella seed and flaxseed pomace concentrations.

A comparison of both additives used (Table 4) shows that nigella seed pomace reduces water absorption capacity more significantly at higher concentrations than flaxseed pomace. In contrast, flaxseed pomace exhibits a more gradual decrease in *WAI*, with 10% addition values are close to the control sample. This suggests that nigella seed pomace at higher levels may limit water binding, while flaxseed pomace affects this parameter in a more stable and predictable manner.

The water solubility index (*WSI*) is a crucial parameter that characterizes the degree of starch degradation and the solubility of components in water. *WSI* values were analyzed in relation to type and content pomace, screw speed, and the type of plasticization system (Figure 5).

Table 4. Response surface approximation models for evaluating the bulk density, water absorption index, and water solubility index of extrudates depending on the selected plant pomace addition level, screw speed, and type of plasticizing system.

L/D	Additive	Property	Model Equation	R^2
16	Nigella seed pomace	*BD* (kg/m^3)	$379.897 - 0.458 \times AN + 0.801 \times SS - 0.003 \times AN^2 + 0.002 \times AN \times SS - 0.006 \times SS^2$	0.992
		WAI (g/g)	$4.232 - 0.036 \times AN + 0.004 \times SS - 0.002 \times AN^2 + 1.25 \times 10^{-5} \times AN \times SS + 7.292 \times 10^{-6} \times SS^2$	0.999
		WSI (%)	$3.308 + 0.041 \times AN + 0.025 \times SS + 0.005 \times AN^2 + 0.001 \times AN \times SS - 0.0002 \times SS^2$	0.997
	Flaxseed pomace	*BD* (kg/m^3)	$337.811 + 1.834 \times AF + 1.514 \times SS - 0.018 \times AF^2 - 0.016 \times AF \times SS - 0.005 \times SS^2$	0.999
		WAI (g/g)	$3.685 - 0.104 \times AF + 0.014 \times SS + 0.002 \times AF^2 - 0.0003 \times AF \times SS - 6.771 \times 10^{-5} \times SS^2$	0.999
		WSI (%)	$3.786 + 0.304 \times AF + 0.008 \times SS - 0.005 \times AF^2 - 0.001 \times AF \times SS + 2.396 \times 10^{-5} \times SS^2$	0.998
20	Nigella seed pomace	*BD* (kg/m^3)	$397.729 + 0.152 \times AN + 0.261 \times SS - 0.014 \times AN^2 + 0.003 \times AN \times SS - 0.001 \times SS^2$	0.993
		WAI (g/g)	$4.369 - 0.039 \times AN + 0.008 \times SS - 0.002 \times AN^2 - 4.5 \times 10^{-5} \times AN \times SS - 2.292 \times 10^{-5} \times SS^2$	0.999
		WSI (%)	$1.922 + 0.253 \times AN + 0.084 \times SS + 0.001 \times AN^2 - 0.001 \times AN \times SS - 0.01 \times SS^2$	0.999
	Flaxseed pomace	*BD* (kg/m^3)	$284.776 + 0.921 \times AF + 4.383 \times SS - 0.049 \times AF^2 + 0.017 \times AF \times SS - 0.033 \times SS^2$	0.999
		WAI (g/g)	$3.479 - 0.101 \times AF + 0.029 \times SS + 0.002 \times AF^2 - 0.0004 \times AF \times SS - 0.0002 \times SS^2$	0.999
		WSI (%)	$3.65 + 0.193 \times AF + 0.048 \times SS - 0.004 \times AF^2 - 0.0003 \times AF \times SS - 0.0004 \times SS^2$	0.993

AN—addition of nigella seed pomace, AF—addition of flaxseed pomace; SS—screw speed, *BD*—bulk density, *WAI*—water absorption index, *WSI*—water solubility index.

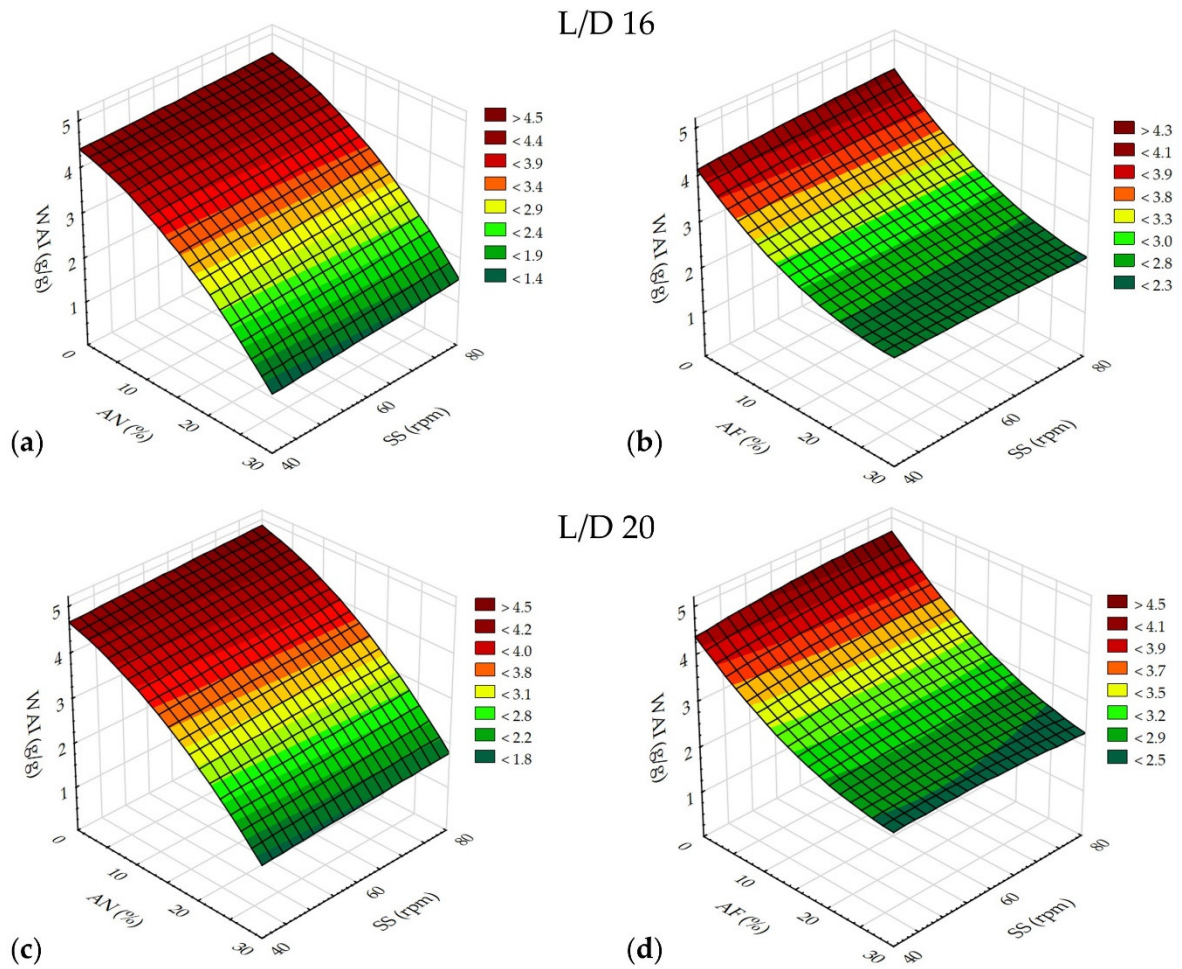


Figure 4. Trend plots of water absorption index of extrudates depending on selected plant pomace addition level, screw speed, and type of plasticizing system: (**a**) nigella seed pomace processed using L/D 16 plasticizing system; (**b**) flaxseed pomace processed using L/D 16 plasticizing system; (**c**) nigella seed pomace processed using L/D 20 plasticizing system; (**d**) flaxseed pomace processed using L/D 20 plasticizing system.

The control sample exhibited relatively stable *WSI* values, with higher values for L/D 20 than for L/D 16. At 40 rpm, *WSI* were 4.52% (L/D 16) and 4.85% (L/D 20), indicating a moderate solubility level. At 60 rpm, *WSI* slightly decreased to 4.37% (L/D 16) and 5.25% (L/D 20), possibly due to shorter exposure to shear forces in the extruder-cooker. At 80 rpm, *WSI* increased to 4.68% (L/D 16) and 5.45% (L/D 20), suggesting a higher release of soluble polymers as a result of more intense starch degradation. The addition of nigella seed pomace significantly influenced the water solubility index, with variations depending on the concentration level.

At a 10% addition, *WSI* values were similar to those of the control sample. At 40 rpm, *WSI* values were 4.07% (L/D 16) and 5.78% (L/D 20). A slight increase was observed at 60 rpm, reaching 4.18% (L/D 16) and 5.80% (L/D 20). However, at 80 rpm, values decreased to 3.98% (L/D 16) and 6.11% (L/D 20).

At a 20% addition, *WSI* values were significantly higher than in the control sample. At 40 rpm, *WSI* values reached 8.28% (L/D 16) and 9.97% (L/D 20), increasing to 8.92% (L/D 16) and 10.50% (L/D 20) at 60 rpm. The highest values were observed at 80 rpm, with 9.80% (L/D 16) and 10.59% (L/D 20), suggesting intensified starch degradation and the increased presence of water-soluble components.

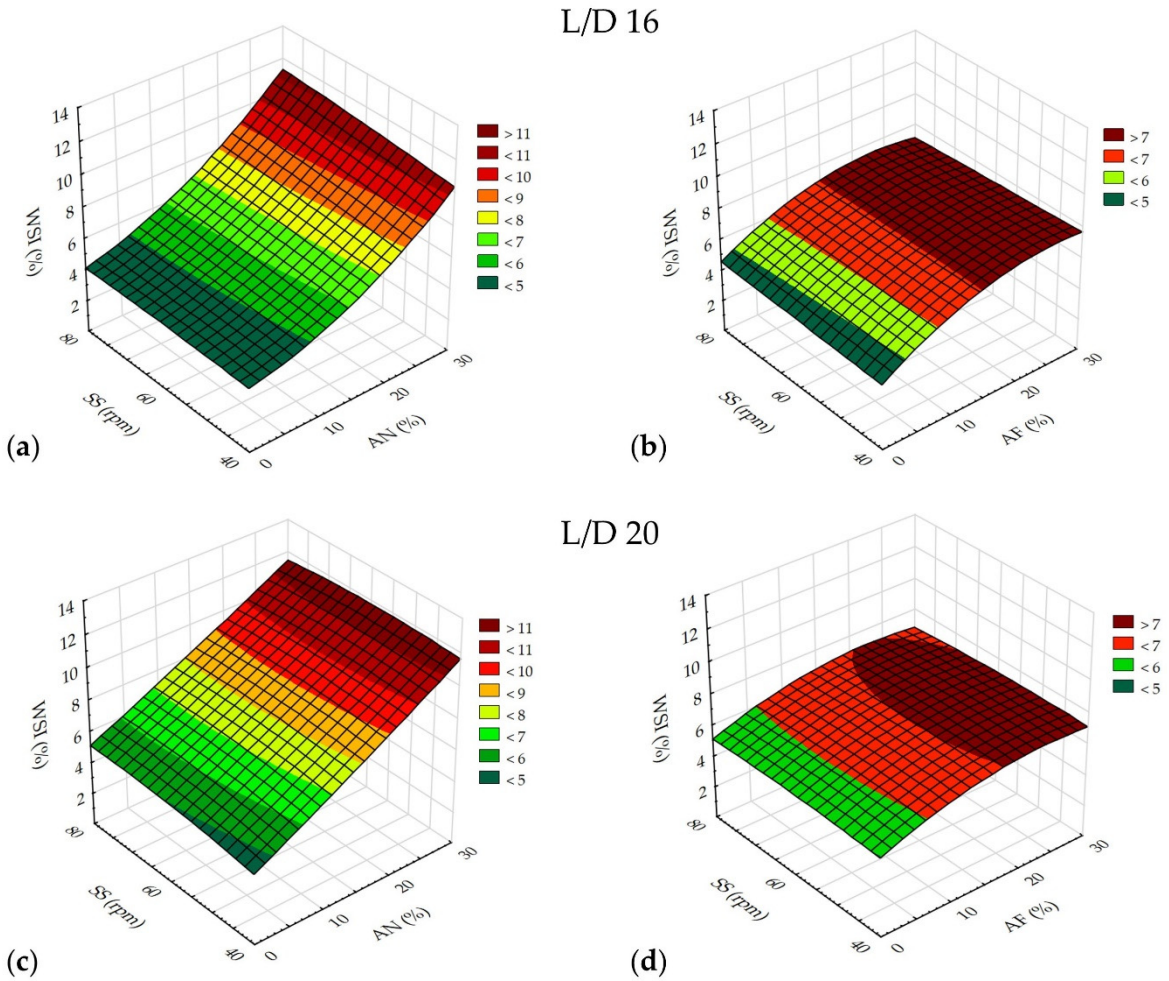


Figure 5. Trend plots of water solubility index of extrudates in relation to selected plant pomace addition level, screw speed, and type of plasticizing system: (**a**) nigella seed pomace processed using L/D 16 plasticizing system; (**b**) flaxseed pomace processed using L/D 16 plasticizing system; (**c**) nigella seed pomace processed using L/D 20 plasticizing system; (**d**) flaxseed pomace processed using L/D 20 plasticizing system.

At a 30% addition, *WSI* values increased further. At 40 rpm, *WSI* values were 9.90% (L/D 16) and 11.21% (L/D 20). At 60 rpm, values rose to 10.72% (L/D 16) and 11.73% (L/D 20), while at 80 rpm, there were faint declines to 10.56% (L/D 16) and 10.83% (L/D 20). These results indicated that a higher pomace content led to intensified starch degradation and an increase in water-soluble substances. However, at a higher screw speed, this effect appeared to be limited by the reduced residence time within the extruder-cooker.

The addition of flaxseed pomace influenced the water solubility index in a more complex manner compared to nigella seed pomace addition, as *WSI* values varied depending on the L/D ratio and screw speed.

A 10% addition of pomace resulted in minor variations in *WSI* values depending on the L/D ratio. At 40 rpm, *WSI* reached 5.56% for L/D 16 and 6.35% for L/D 20, indicating higher solubility with the longer screw. The increase in screw speed to 60 rpm led to a rise in *WSI* to 5.89% for L/D 16, while for L/D 20, it declined to 6.14%, suggesting that an extended screw zone might have restricted solubility at this speed. A further increase to 80 rpm led to a rise in *WSI* for L/D 16 (6.01%), while for L/D 20, values remained nearly unchanged (5.93%), implying that screw speed exerted a greater influence on starch degradation in shorter screw zones.

A comparable pattern emerged at a 20% addition. At 40 rpm, *WSI* values were 7.94% for L/D 16 and 7.56% for L/D 20, demonstrating similar solubility levels in both configurations. As the screw speed increased to 60 rpm, *WSI* values rose slightly to 8.16% for L/D 16 and 7.78% for L/D 20. However, at 80 rpm, a decline was observed with *WSI* values decreasing to 7.86% for L/D 16 and showing a significant drop to 6.88% for L/D 20. These results suggest that at a higher screw speed, an extended screw length may constrain starch degradation, thereby reducing the presence of water-soluble components.

A 30% pomace addition led to a decreasing trend in *WSI* values as screw speed increased for both L/D ratios. At 40 rpm, *WSI* values measured 7.57% for L/D 16 and 6.76% for L/D 20, indicating that a longer screw zone reduced solubility. At 60 rpm, *WSI* values decreased to 7.07% for L/D 16, while for L/D 20, values remained relatively stable at 6.83%. Further increasing the speed to 80 rpm caused *WSI* to drop to 6.91% for L/D 16, whereas L/D 20 exhibited a slight increase to 7.05%. These findings indicate a continued reduction in *WSI* for L/D 16, whereas in L/D 20, the minor increase suggests a complex interaction between screw speed and degradation processes. In their studies, Lisiecka and Wójtowicz [39] also observed that increased addition of plant-based ingredients in most extruded raw material blends led to a rise in the water solubility index (*WSI*). In the study by Combrzyński et al. [40], the addition of fresh lucerne sprouts increased *WSI*, reaching a maximum value of 13.07% at a 30% inclusion level and 100 rpm due to the presence of fiber and proteins. Similarly, in the present study, a general increasing trend in *WSI* was observed compared to the control sample, although at higher addition levels, the trend became irregular. Nevertheless, an overall increase in *WSI* was noted, indicating the impact of plant-based ingredients on solubility. Contrary to the findings of Chang and Ng [41], in the present study, screw speed was not the sole dominant factor influencing *WSI*—the type and concentration of additives also had a significant role. This suggests that during extrusion-cooking involving ingredients with irregular structure and high fiber content, the mechanisms of starch degradation may be modified by the presence of other components, which influence the solubilization of the extrudate in water.

Statistical analysis confirms that the impact of flaxseed pomace on *WSI* is more complex than that of nigella seed pomace (Table 4). At lower concentrations and higher screw speeds, *WSI* values tend to increase for L/D 16, whereas for L/D 20, a decline is observed. At higher concentrations (30%), a general decreasing trend in *WSI* is evident, which may be attributed to reduced starch degradation and a higher content of insoluble components, such as the presence of fiber and fat in flaxseed.

The results indicate that the interaction between screw speed, L/D ratio, and pomace concentration performs a significant role in determining *WSI* values. Higher flaxseed pomace levels limit starch solubility, likely due to the presence of structural components that hinder gelatinization and degradation processes.

Analysis of the data indicates the existence of transparent interrelations between mechanical energy consumption and the physical properties of the extrudates. Higher *SME* values, particularly at a lower screw speed and increased pomace concentrations, correspond with elevated *WSI* values, which suggests that there is intensified starch degradation under a greater mechanical load. Samples with lower bulk density typically showed higher *WAI* and *WSI* values, indicating that reduced structural compactness improves water interaction and solubility. These dependencies emphasize that extrusion-cooking efficiency, energy consumption, and hydration-related characteristics are closely linked and are influenced jointly by pomace type, concentration, and screw configuration.

Principal component analysis (PCA) was performed for different types of additives. The results showed that the first two components (PC1 and PC2) explain all the changes in the data—100% of the variability. The most important parameters are marked between

two red circles in the graph (Figure 6a). These have the biggest effect on the results. Each of the tested parameters influences the system. Efficiency and *WSI* are strongly and negatively linked to *WAI*. This means that when efficiency or *WSI* goes up, *WAI* goes down. A strong negative link was also seen between bulk density and *SME*. In this case, higher density comes with lower energy use. There are also some weak positive links. *SME* and *WSI* increase slightly together. A similar connection was seen between *WSI* and efficiency and also between efficiency and bulk density. No link was found between *WAI* and the other two parameters—bulk density and *SME*. These do not affect each other in this system.

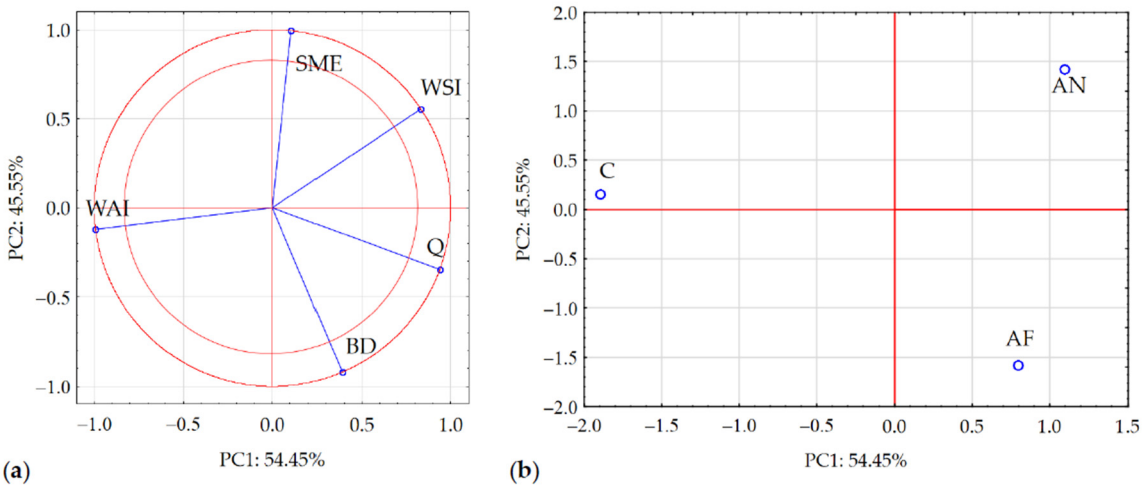


Figure 6. Loading plot (**a**) and score plot (**b**) of the principal component analysis (PC1 and PC2). The plot shows the position of tested parameters on the PC1 and PC2 axes (**a**) and the placement of additive types on the same axes (**b**), which makes it easier to see the influence of each parameter and additive type on the results.

The PCA also shows (Figure 6a,b) that the flaxseed pomace additive is strongly and positively correlated with *SME* and *WSI*, and the nigella seed pomace additive is strongly and positively correlated with bulk density and efficiency. In turn, the lack of additive is strongly and positively correlated with *WAI*. The PCA shows that the first principal component, PC1, distinguishes between the lack of the additive (negative PC1 values) and the use of the additive derived from seed pomace (Figure 6b) by 54.45%. Positive values of the PC1 principal component describe the results for the lack of the additive. The second principal component, PC2, distinguishes between the use of the Flaxseed pomace additive (negative PC2 values) and the use of the Nigella seed pomace additive (positive PC2 values) by 45.55%.

PCA carried out for different amounts of additive showed that the first two main components, PC1 and PC2, explain 85.95% of the system's variability. This means that most of the changes in the data can be described using just these two components. The loading plot (Figure 7a) shows that the parameters relating to the two red circles have the strongest influence on the system. These include all the tested parameters. A strong positive correlation was observed between efficiency and *WSI*, meaning both values increased together. A strong but negative correlation exists between efficiency, *WSI* values, and *WAI* parameters, and between the bulk density and *SME* parameters. There is no correlation between bulk density and efficiency and *WSI*, between *SME* and *WSI* and efficiency, or between *SME* and *WAI*.

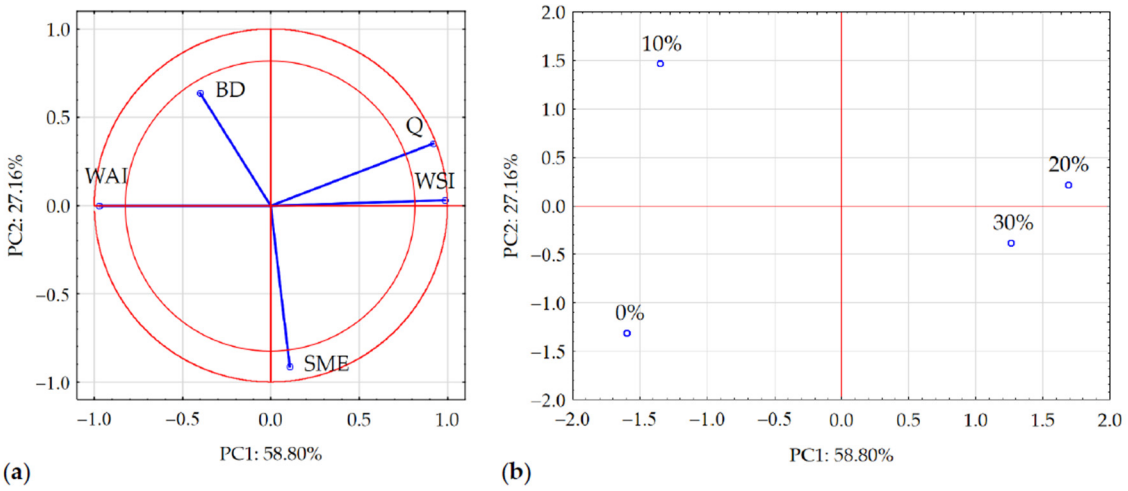


Figure 7. Loading plot (**a**) and score plot (**b**) of the principal component analysis (PC1 and PC2). The plot shows the position of tested parameters on the PC1 and PC2 axes (**a**) and the placement of additive quantity on the same axes (**b**), which helps to understand the influence of each parameter and additive level on the results.

The PCA also shows (Figure 7b) that PC1 describes the differences in the amount of the additive that affects the tested parameters, 58.80%. Positive PC1 values describe 20% and 30% of the additive, and negative PC1 values describe the lack of additive or lower additive values. PC2 distinguishes the lack of additive and the addition of 10% of the component in 27.18% of cases. The analysis shows (Figure 7a,b) that the *SME* parameter is positively correlated with the lack of additive, while the bulk density and *WAI* parameters are most strongly correlated with the 10% additive. The efficiency and *WSI* parameters are strongly and positively correlated with additions of 20% and 30%.

PCA for screw speed showed that the first two main components, PC1 and PC2, explained 100% of the system's variability. This means that all important changes in the data are covered by these two components. In this case, all tested parameters have a strong effect on the system (Figure 8a). Bulk density, *WAI*, *WSI*, and efficiency show a strong positive correlation, meaning values increase together. *SME* shows a strong negative correlation with the other tested parameters, which means that higher *SME* is linked with lower values of the remaining parameters.

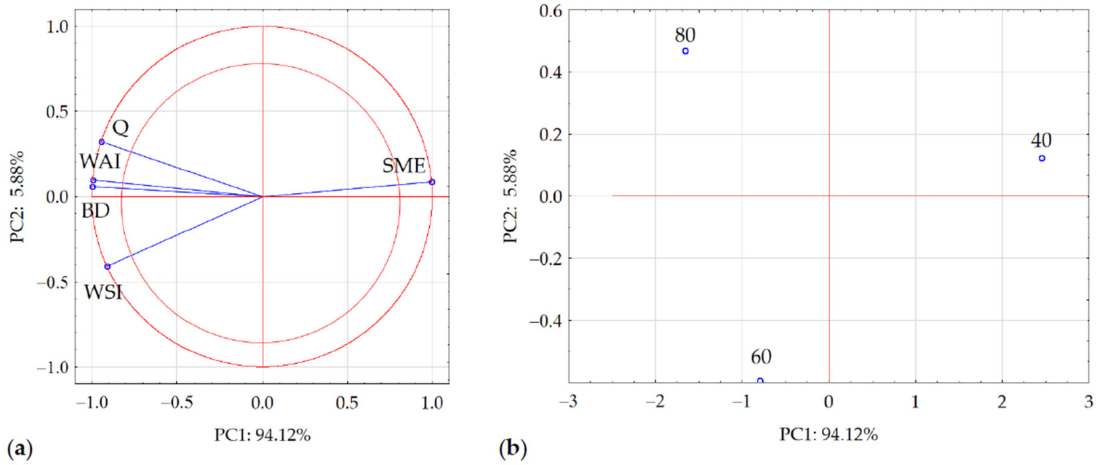


Figure 8. Loading plot (**a**) and score plot (**b**) of the principal component analysis (PC1 and PC2). The plot shows the position of tested parameters on the PC1 and PC2 axes (**a**) and the placement of screw speed values on the same axes (**b**), which helps to understand the influence of each parameter and screw speed setting on the results.

The PCA performed shows (Figure 8b) that the main component PC1 differentiates low and high screw speed values by as much as 94.12%. Positive PC1 values indicate lower screw speed values (40 rpm) and negative values indicate higher screw speed values (60 and 80 rpm). The second main component, PC2, differentiates between higher screw speed values (60 and 80 rpm) by 5.88%. The analysis shows (Figure 8a,b) that the *SME* parameter is strongly and positively correlated with the lower screw speed value (40 rpm). There is a clear correlation between 60 rpm and 80 rpm screw speed and the tested parameters: bulk density, *WAI*, *WSI*, and efficiency.

PCA for L/D ratio showed that the first two main components, PC1 and PC2, explain 98.48% of the system's variability. This means that nearly all changes in the data are described by these two components. In this case, all tested parameters strongly affect the system (Figure 9a). Bulk density, *WSI*, and efficiency are strongly and positively correlated, which means higher values of one are linked with higher values of the others. A strong but negative correlation exists between bulk density, *WSI* and *WAI*. A weak negative correlation occurs between efficiency and *WAI* and between efficiency and *SME*, and a weak positive correlation exists between *WSI*, bulk density, and efficiency.

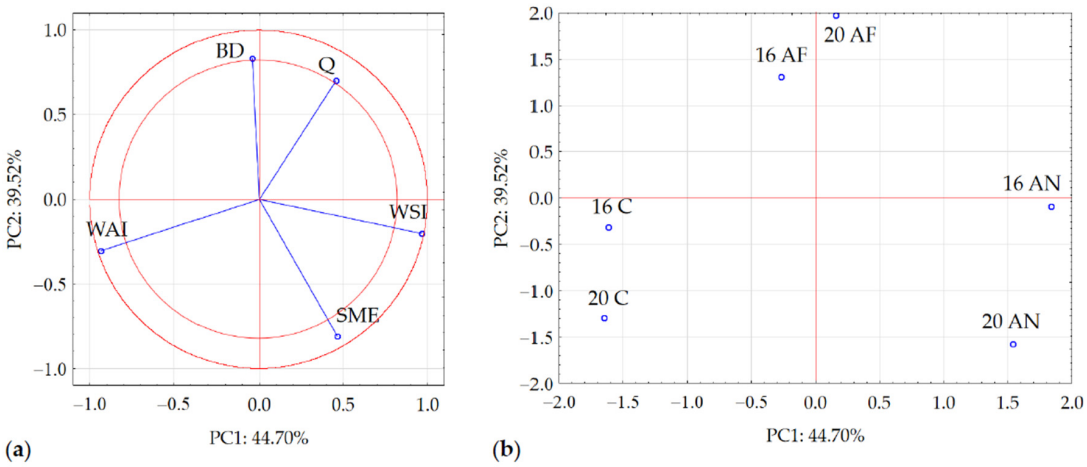


Figure 9. Loading plot (**a**) and score plot (**b**) of the principal component analysis (PC1 and PC2). The plot shows the position of tested parameters on the PC1 and PC2 axes (**a**) and the placement of L/D ratio values on the same axes (**b**), which helps to see the influence of each parameter and L/D setting on the results.

The conducted PCA shows (Figure 9b) that PC1 differentiates L/D dependency by as much as 67.45% for the use of the additive and the lack of use of the additive. Positive PC1 values indicate the use of flaxseed pomace and Nigella seed pomace additives, and negative values indicate the lack of use of additives. The PC2 differentiates L/D dependency values (16 and 20) by 31.03%. The analysis shows (Figure 9a,b) that the *SME* parameter is strongly and positively correlated with a higher L/D dependency value, and the efficiency parameter is strongly and positively correlated with a lower L/D dependency value with the additive.

4. Conclusions

1. An increase in screw speed to 60 and 80 rpm led to a higher extrusion-cooking efficiency for both L/D 16 and L/D 20 configurations, particularly at higher pomace concentrations. However, L/D 16 exhibited rising efficiency compared to L/D 20, especially at a higher screw speed (60 and 80 rpm). At higher pomace concentrations, a decline in efficiency was observed, likely due to flow difficulties caused by the increased amount of added material. Therefore, the extrusion-cooking process was more efficient at lower pomace concentrations and higher screw speeds.

These variations may result from the interaction between fiber-rich pomace particles and the starch structure, which affects the rheological behavior and flow resistance during processing.

2. *SME* values increased with a higher screw speed at 60 and 80 rpm, indicating greater energy consumption at higher rotational speeds, particularly at higher pomace concentrations. For L/D 16, *SME* was generally lower compared to L/D 20, especially at higher speed, suggesting that L/D 16 may be more energy-efficient in certain conditions. The addition of nigella seed pomace and flaxseed pomace contributed to higher *SME* values, particularly at lower screw speeds, highlighting differences in energy efficiency depending on the type of pomace used. At higher pomace concentrations (20% and 30%), *SME* showed greater variability, with a tendency to increase at 40 rpm and decrease at 80 rpm. This suggests that higher pomace levels alter the energy demand of the extrusion-cooking process, potentially due to changes in material flow and processing resistance. This can be explained by differences in the composition of the pomace, especially fat and fiber content, which influence friction, torque, and energy transfer during extrusion-cooking process.
3. Bulk density analysis showed that the control sample maintained stable values with a slight increase as screw speed became larger. In the case of nigella seed pomace, the changes were irregular—at 10% concentration, bulk density increased, while at 20% a decrease was observed, followed by another increase at 30%. On the other hand, flaxseed pomace demonstrated a more consistent trend, with bulk density gradually increasing along with higher concentrations and screw speed, indicating better compressibility during the extrusion-cooking process. A comparison to different plasticizing system revealed higher bulk density values for L/D 20, which suggests improved material compression in the longer screw system. Irregular changes in bulk density, especially for nigella seed pomace, may stem from variable hydration behavior and structural interference caused by the heterogeneous nature of the pomace components.
4. The analysis of water absorption capacity (water absorption index) showed that the control sample exhibited a gradual increase in *WAI* with higher screw speeds, likely due to more intense starch gelatinization caused by the higher temperatures generated during extrusion. At a low concentration (10%), the addition of nigella seed pomace led to an increase in *WAI*, while at higher concentrations (20% and 30%), a significant decrease was observed. This suggests that a greater amount of this additive limits water absorption capacity. For flaxseed pomace, *WAI* values decreased progressively with increasing concentrations, which may be attributed to the greater presence of fats and fiber, reducing water retention. A comparison between L/D 16 and L/D 20 revealed higher *WAI* values for L/D 20, indicating that a longer screw zone enhances the moisture absorption capacity of the samples, possibly due to the extended contact time with water during extrusion-cooking process. The decreasing trend in *WAI* at higher pomace levels may be attributed to the presence of non-starch polysaccharides and lipids, which can limit water penetration and reduce starch gelatinization.
5. The analysis of the water solubility index showed that the control sample had moderate values, with a minor increase as screw speed increased. For nigella seed pomace, a significant rise in *WSI* was observed at higher concentrations (20% and 30%), indicating more intense starch degradation and an increase in water-soluble components. For flaxseed pomace, *WSI* values increased at 10% and 20% concentrations, but at 30% a decline was noted. This may be due to the higher presence of insoluble components, such as fiber and fats, which reduce solubility. A comparison of *WSI* values between L/D 16 and L/D 20 showed that *WSI* was generally higher for L/D 20, suggesting

that a longer screw zone promoted more intense starch degradation, leading to an increased number of water-soluble components. The observed fluctuations in *WSI* likely reflect complex interactions between starch degradation, lipid binding, and insoluble fiber content, which together influence the solubilization of extrudate components.

6. Based on the findings, it can be recommended that the L/D 16 configuration, in combination with a higher screw speed (60–80 rpm) and moderate pomace concentrations (10–20%), provides a favorable balance between energy consumption and product quality. For applications requiring higher water absorption (e.g., instant foods), L/D 20 may offer advantages due to extended processing time. Additionally, flaxseed pomace demonstrated more predictable behavior than nigella pomace, making it a potentially more reliable additive in extrusion applications.
7. Future research could investigate the effect of varying moisture content on the processing behavior of blends containing oilseed pomace, as moisture is a critical factor influencing extrusion-cooking dynamics and final product quality. Additionally, sensory acceptability of snacks obtained from the expansion of the produced extruded pellets should be evaluated to assess consumer preferences. This analysis would provide valuable insights into the commercial potential and market readiness of these products. These directions would help bridge the gap between technological development and real-world application.
8. The results of this study highlight the potential for utilizing oilseed pomace as a functional ingredient in the production of sustainable snack pellets. The incorporation of by-products such as flaxseed and nigella pomace into starch-based mixtures offers opportunities to enhance the nutritional profile of extruded products while supporting waste valorization strategies. Tested process configurations demonstrate that, with proper optimization of screw speed, L/D ratio and pomace concentration, it is possible to balance energy efficiency with desirable product attributes. These findings may serve as a foundation for industrial-scale implementation, particularly in the development of high-fiber, clean-label, or upcycled snack products that align with current consumer and sustainability trends.

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