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Management of selected fruit and vegetable pomace in fortified snack pellets through the single-screw extrusion-cooking under various process conditions

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ABSTRACT

Fruit and vegetable pomace, a by-product of the agri-food industry, creates environmental problems due to difficulties in its disposal. At the same time, pomace contains valuable bioactive compounds, making it suitable for reuse in food production. This study focused on the influence of extrusion-cooking parameters on process efficiency, energy consumption and physical characteristics of the snack pelletss enriched with fresh apple, chokeberry and pumpkin pomace. Extrudates were produced using a single-screw extruder-cooker with two plasticizing systems (L/D ratios 16 and 20). The highest efficiency (24.00 kg h^{-1}) was obtained with 20% apple pomace and an L/D 20. Energy consumption ranged between 0.005 and 0.189 kWh kg^{-1}. Pomace addition strongly affected the physical properties of the snacks. A sample containing 30% chokeberry pomace and processed with the L/D 20 system reached a water absorption index of 7.11 g g^{-1} and a water solubility index of 7.92%. Bulk density reached a maximum of 691.35 kg m^{-3} for the same configuration. The findings confirm that application of fresh fruit and vegetable pomace is possible following processing with proper plasticizing system and can improve extruded products quality while reducing waste. This supports sustainable practices in food processing by incorporating plant-based by-products into the development of extruded snack pellets.

Keywords: food by-products management, fruit and vegetable pomace, extrusion-cooking, processing parameters, physical properties.

INTRODUCTION

The modern agri-food industry faces a significant challenge related to the increasing volume of plant-based waste generated throughout the production process (Sarker et al., 2024). A substantial amount of raw materials used in food processing does not reach the consumer market but instead ends up as waste or low-value by-products (Maqsood et al., 2025; Dey et al., 2021). The problem has not only an economic dimension, but also an environmental one – inadequate management of organic waste contributes to increased greenhouse gas emissions and places a strain on local waste management systems (Taifouris et al., 2023; Rebolledo-Leiva et al., 2024). In addition, drying the pomace before further processing can generate additional energy consumption, increasing the negative impact on the environment. Therefore, developing strategies for the effective reuse of such by-products has become a necessity, aligning with the principles of a circular economy.

Among the by-products with considerable potential for valorization are fruits and vegetable pomace, produced during juice extraction, purée production and other processing operations. These residues are rich in dietary fibre, phenolic compounds, vitamins and other bioactive substances that can enhance the nutritional and functional properties of food products (Raczkowska and Serek, 2024; Ramzan et al., 2025). Of particular interest are apple, chokeberry and pumpkin pomace – readily available, low–cost materials with high contents of fiber and natural antioxidants.

Reusing this type of plant waste in food production can help reduce raw material losses, improve the nutritional profile of final products and increase their market value (Pakulska et al., 2024; Gil–Martín et al., 2022).

One of the most promising technological approaches for incorporating such by-products into food is the extrusion-cooking technology – an advanced, high-efficiency processing method widely used in the food industry (Cotacallapa-Sucapuca et al., 2021; Sule et al., 2024). Extrusion-cooking involves subjecting the feed material to high temperature, pressure and shear forces over a short residence time. These conditions induce physicochemical transformations, resulting in a final product with modified structure, texture and functional properties (Qui et al., 2024; Pismag et al., 2024). The method is extensively employed in the production of snacks, breakfast cereals, pasta, petfood and specialised nutritional products. An important advantage of extrusion-cooking is the ability to combine cooking and shaping in a single step, contributing to lower energy consumption and process simplification (Mironeasa et al., 2023). The design of plasticizing system in the extruder-cooker significantly affects both the course of the extrusion-cooking process and the characteristics of the final product. These systems differ primarily in the length-to-diameter (L/D) ratio of the screw, which influences the shear, pressure and residence time applied to the materials. A higher L/D ratio typically allows for the inclusion of additional functional barrel zones – such as mixing or degassing sections – thereby enabling more precise control over product transformation and quality (Lewko et al., 2024). The configuration of the screw system is therefore a critical factor in optimizing the processing of formulations enriched with fiber-rich by-products as plant pomace (Schmid et al., 2020).

Incorporating of fresh fruit and vegetable pomace into mixtures offers several benefits. It enriches the products with fiber and bioactive compounds, limits the water addition into raw materials composition, while enabling the valorization of materials that would otherwise be discarded (Gupta et al., 2024). The latest research has shown that such fresh additives can affect extrusion-cooking parameters (efficiency, energy consumption, and pressure) as well as physical and sensory characteristics of the extrudates including structure, expansion, bulk density and water absorption. It is possible to formulate the products that are both acceptable to consumers and environmentally sustainable, provided that there is adequate consideration of formulation and parameter optimisation (Soja et al., 2025).

Based on this information, the aim of this study was to evaluate the effect of extrusion-cooking parameters on process efficiency, energy consumption and selected physical properties of extruded food products enriched with fresh apple, chokeberries and pumpkin pomace. Particular focus in the study was placed on comparing the type and level of additives used when processed in different plasticizing systems, characterised by different screw L/D ratios. This was undertaken in order to assess the impact on the extrusion–cooking process and the quality attributes of the final products. In a broader sense, this work supports the implementation of sustainable and circular solutions in food production chain.

MATERIALS AND METHODS

Raw materials

In 2023, in the laboratories of the Department of Food Process Engineering at the University of Life Sciences in Lublin, research was conducted on the management of agri-food industry by-products in the production technology of extruded snack pellets. The main goal of the experiment was to evaluate the effect of the addition of selected fresh plant pomace on the extrusion-cooking process and the physical properties of the extrudates obtained. As part of the study, a comparative analysis of various plasticizing system configurations was carried out to evaluate the influence of system design on the development of product properties and the efficiency of the technological process.

Fresh plant pomace derived from apples, chokeberries and pumpkin was introduced into the raw material mixtures. The addition of these components was intended to assess the influence on technological parameters and the quality of the obtained snack pellets. At the same time, a control sample was prepared which served as a reference point for comparative analysis. The production process of snack pellets was based on the recipes developed for the study. The blends were composed of ingredients obtained from local suppliers, including high quality potato starch, potato flakes, rapeseed oil, beet sugar and salt. These raw material bases allowed for effective monitoring of the influence of the variables studied on the quality and course of the extrusion–cooking process.

At the beginning of the research phase, raw material compositions were developed according to the established recipes (Table 1). Plant–based pomace derived from apples, chokeberries and pumpkin, was introduced as a fresh pulp into each composition at three levels: 10, 20 and 30% by weight.

The concentrations were selected on the basis of previous own experience and analysis of available literature sources. The selected conditions were considered optimal in terms of potential for modifying technological and physicochemical properties of the product, while preserving sensory acceptability. Exceeding the 30% level could lead to process disturbances such as pressure and temperature instability, which would consequently reduce the quality of the obtained extrudates.

Prior to inclusion in the raw material mixtures, fresh fruit and vegetable pomace were finely ground using a Germin CY–329 cup blender (Germin Berlinger, Jarosław, Poland). This procedure made it possible to obtain a homogeneous fraction of plant material, which was crucial to ensure the structural integrity of the mixtures. Sample batches of 4.5 kg were then prepared, in which the proportions of base ingredients and plant additives were adjusted accordingly, depending on the assumed pomace content. To ensure an even distribution of the individual components and to minimise differences in moisture distribution, all mixtures were subjected to a sieving process (0.63 mm). They were then stored under refrigeration for 24 hours. This stage served to stabilise the system and equalise the moisture levels throughout the material, which was important to maintain the uniformity of the extrusion process.

Extrusion-cooking processing

Prior to the actual thermomechanical processing, the actual water content of the samples was determined. On this basis, the hydration process was carried out by mixing with tap water to 34% of feed moisture as the value considered optimal, in accordance with previous research results and the applicable technological conditions. This allowed proper preparation of the feedstock for the extrusion-cooking process, minimising the risk of technological disruption.

The production of extrudates with added fresh fruit and vegetable pomace was carried out using a single–screw extruder-cooker (EXP–45–32, Zamak Mercator, Skawina, Poland). The equipment comprised two plasticizing systems with different screw length-to-diameter (L/D) ratios: 16 and 20. This configuration enabled a comparison of the effect of screw design on process parameters and product quality. The extrusion-cooking process was conducted at different screw speeds (40, 60 and 80 rpm). The temperature in the barrel's heating zones ranged from 30 to 81 °C (Tables 2 and 3), thereby ensuring stable thermal conditions during processing. The plasticizing system with an L/D ratio of 20 contained an additional fourth section, which supported improved plasticization of the fibrous material. The extruded mass was shaped through a ring die with a slit thickness of 0.6 mm. A cutting unit, located in a close proximity to the die, was employed to cut the material into uniform pieces. The drying process of the extrudates was conducted in a laboratory shelf dryer at 40 °C for 12 hours, until moisture content reached 8.5–9.5%. After the drying process, the products were sealed in Ziplock bags and stored prior to further analysis.

Processing characteristics

Process efficiency (Q) was determined by measuring the mass of extrudate exiting the die at 30–second intervals. All processing conditions, including feed rate, were kept constant during

Table 1. Composition of the mixtures

Raw material	Control sample	10% pomace	20% pomace	30% pomace
Apple, chokeberry, pumpkin pomace (%)	0	10	20	30
Potato starch (%)	82	72	62	52
Potato flakes (%)	15	15	15	15
Rapeseed oil (%)	1	1	1	1
Sugar (%)	1	1	1	1
Salt (%)	1	1	1	1

Table 2. Temperature profile of individual extruder–cooker sections under processing of snack pellets with L/D 16 plastification system

Type of plant pomace	Content of the additive (%)	Screw speed (rpm)	Temperature of section I (°C)	Temperature of section II (°C)	Temperature of section III (°C)	Temperature of section IV (°C)
Control sample	0	40	31.40 ± 0.00	60.33 ± 0.67	75.63 ± 0.50	81.80 ± 1.91
		60	31.80 ± 0.20	61.80 ± 0.26	77.77 ± 0.31	80.40 ± 0.20
		80	32.37 ± 0.12	59.60 ± 1.01	76.93 ± 1.34	79.37 ± 0.71
Apple pomace	10	40	32.00 ± 0.10	58.80 ± 0.85	67.70 ± 0.26	73.40 ± 0.00
		60	32.50 ± 0.00	59.77 ± 0.64	68.13 ± 0.15	73.50 ± 0.00
		80	33.00 ± 0.00	59.73 ± 0.64	68.37 ± 0.15	73.50 ± 0.00
	20	40	33.83 ± 0.06	62.13 ± 0.75	66.90 ± 0.40	73.67 ± 0.06
		60	33.47 ± 0.06	60.83 ± 0.84	67.63 ± 0.31	73.83 ± 0.06
		80	33.30 ± 0.00	60.87 ± 0.25	67.63 ± 0.40	73.87 ± 0.12
	30	40	34.03 ± 0.06	60.23 ± 0.60	67.60 ± 0.46	73.53 ± 0.06
		60	34.47 ± 0.06	59.83 ± 0.84	67.60 ± 0.35	73.50 ± 0.10
		80	34.90 ± 0.00	60.47 ± 0.31	68.47 ± 0.45	73.57 ± 0.06
Chokeberry pomace	10	40	31.77 ± 0.06	60.47 ± 1.29	60.47 ± 1.29	73.63 ± 0.06
		60	31.80 ± 0.00	61.47 ± 0.51	61.47 ± 0.51	73.33 ± 0.15
		80	37.73 ± 0.12	59.10 ± 0.75	58.50 ± 0.62	72.80 ± 0.10
	20	40	31.70 ± 0.00	61.00 ± 0.20	65.50 ± 0.00	73.50 ± 0.10
		60	31.60 ± 0.06	60.40 ± 0.20	66.07 ± 0.15	73.10 ± 0.00
		80	31.73 ± 0.06	59.63 ± 0.81	67.63 ± 0.42	73.13 ± 0.06
	30	40	31.90 ± 0.00	60.77 ± 0.25	65.00 ± 0.10	72.83 ± 0.06
		60	31.90 ± 0.00	61.23 ± 0.50	64.67 ± 0.40	73.07 ± 0.06
		80	31.90 ± 0.00	59.07 ± 1.16	66.60 ± 1.21	73.37 ± 0.06
Pumpkin pomace	10	40	28.60 ± 0.10	58.63 ± 1.42	68.03 ± 0.31	73.37 ± 0.55
		60	29.27 ± 0.15	58.57 ± 1.23	68.07 ± 0.35	72.23 ± 0.06
		80	29.83 ± 0.12	58.67 ± 1.59	68.43 ± 0.25	72.83 ± 0.46
	20	40	31.47 ± 0.06	60.13 ± 1.10	67.87 ± 0.35	73.43 ± 0.06
		60	31.07 ± 0.06	60.40 ± 0.72	68.07 ± 0.35	73.43 ± 0.15
		80	30.50 ± 0.10	58.67 ± 1.40	68.30 ± 0.20	73.57 ± 0.06
	30	40	30.80 ± 0.17	60.27 ± 0.31	67.33 ± 0.35	73.07 ± 0.06
		60	30.60 ± 0.00	59.87 ± 0.98	67.67 ± 0.55	73.13 ± 0.06
		80	31.00 ± 0.10	59.33 ± 1.17	68.10 ± 0.40	73.00 ± 0.17

measurements. Each measurement was repeated three times and the mean value was used for final calculations. Time was recorded using a digital stopwatch and mass was measured with a precision balance (DS–788 Yakudo, Tokyo, Japan) with an accuracy of 0.001 kg. The procedure followed the method described by Kręcisz (2016) and allowed for reduced measurement error and improved result reliability:

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

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

Energy consumption was monitored continuously using a built-in wattmeter integrated into the extruder-cooker's standard control system. Energy consumption was assessed by analysing motor load, process efficiency, machine specifications and recorded operating parameters. On the basis of these data, the specific mechanical energy (SME) was calculated. Each value was determined as the average of three repetitions. The calculation followed the method described by Ryu and Ng (2001) and the measured values were converted into SME using the following formula:

$$SME = (n\,n_m{}^{-1})(O\,100^{-1})(P\,Q^{-1}) \tag{2}$$

Table 3. Temperature profile of individual extruder-cooker sections under processing of snack pellets with L/D 20 plastification system

Type of plant pomace	Content of the additive (%)	Screw speed (rpm)	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	30.50 ± 0.00	60.03 ± 0.15	64.90 ± 0.10	71.57 ± 0.06	72.67 ± 0.06
		60	30.70 ± 0.00	59.93 ± 0.25	64.90 ± 0.20	71.67 ± 0.06	72.97 ± 0.06
		80	30.97 ± 0.12	59.83 ± 0.55	64.90 ± 0.17	70.47 ± 0.31	69.67 ± 0.31
Apple pomace	10	40	33.13 ± 0.06	59.90 ± 0.17	64.83 ± 0.21	69.63 ± 0.15	70.77 ± 0.31
		60	33.13 ± 0.06	59.77 ± 0.58	64.67 ± 0.12	70.27 ± 0.06	72.53 ± 0.12
		80	33.10 ± 0.00	60.03 ± 0.06	65.07 ± 0.12	68.03 ± 0.06	70.00 ± 0.10
	20	40	33.10 ± 0.00	60.07 ± 0.06	64.83 ± 0.06	67.47 ± 0.06	69.93 ± 0.06
		60	33.10 ± 0.00	59.97 ± 0.06	64.80 ± 0.36	66.43 ± 0.06	66.50 ± 0.10
		80	33.00 ± 0.00	60.10 ± 0.00	64.77 ± 0.38	67.37 ± 0.15	69.23 ± 0.15
	30	40	32.93 ± 0.06	60.23 ± 0.50	64.97 ± 1.36	67.50 ± 0.00	69.63 ± 0.06
		60	32.90 ± 0.00	60.60 ± 0.46	63.47 ± 0.20	67.70 ± 0.00	69.90 ± 0.10
		80	32.90 ± 0.00	60.10 ± 0.10	66.43 ± 1.70	67.73 ± 0.06	70.13 ± 0.06
Chokeberry pomace	10	40	33.10 ± 0.00	59.73 ± 0.06	65.47 ± 0.06	66.00 ± 0.00	66.77 ± 0.06
		60	33.30 ± 0.00	60.20 ± 0.00	64.77 ± 0.06	66.80 ± 0.10	68.77 ± 0.15
		80	33.30 ± 0.00	59.90 ± 0.00	64.63 ± 0.06	66.80 ± 0.00	69.17 ± 0.06
	20	40	32.90 ± 0.00	60.37 ± 0.06	67.17 ± 0.06	66.43 ± 0.06	68.43 ± 0.06
		60	32.90 ± 0.00	61.07 ± 0.06	67.57 ± 0.06	66.57 ± 0.06	68.80 ± 0.00
		80	32.87 ± 0.06	59.60 ± 0.10	68.07 ± 0.15	66.50 ± 0.00	69.03 ± 0.06
	30	40	32.60 ± 0.00	59.57 ± 0.31	64.43 ± 0.25	66.40 ± 0.10	68.23 ± 0.06
		60	32.40 ± 0.00	59.97 ± 0.12	64.93 ± 0.06	66.30 ± 0.00	68.00 ± 0.00
		80	32.20 ± 0.00	59.90 ± 0.00	64.70 ± 0.00	66.30 ± 0.00	68.00 ± 0.00
Pumpkin pomace	10	40	32.27 ± 0.06	64.77 ± 0.50	70.07 ± 0.15	73.40 ± 0.10	75.27 ± 0.06
		60	31.90 ± 0.00	64.90 ± 0.17	69.93 ± 0.06	73.07 ± 0.06	75.07 ± 0.21
		80	33.07 ± 1.63	60.33 ± 0.35	65.67 ± 1.33	69.90 ± 1.39	71.00 ± 2.43
	20	40	33.40 ± 0.00	60.40 ± 0.10	65.50 ± 0.10	69.80 ± 0.00	71.67 ± 0.06
		60	33.47 ± 0.15	60.07 ± 0.06	65.63 ± 0.06	70.27 ± 0.12	72.07 ± 0.12
		80	33.80 ± 0.10	60.13 ± 0.06	64.80 ± 0.17	70.03 ± 0.06	71.67 ± 0.06
	30	40	33.13 ± 0.06	59.90 ± 0.00	65.00 ± 0.00	66.90 ± 0.10	69.73 ± 0.06
		60	33.20 ± 0.00	59.87 ± 0.06	64.93 ± 0.06	66.30 ± 0.00	68.70 ± 0.00
		80	33.20 ± 0.00	60.00 ± 0.00	64.93 ± 0.06	66.70 ± 0.00	68.90 ± 0.10

where: *SME* is the specific mechanical energy (kWh kg^{-1}), *n* is the screw speed (rpm), n_m is the maximum screw speed (rpm), *O* is the engine load expressed as a percentage of the nominal power *P* (kW), *Q* is the extrusion–cooking process efficiency (kg h^{-1}).

Physical properties of extrudates

Bulk density (BD) was calculated as the ratio of sample mass to sample volume. Mass was measured using a precision balance (DS–788 Yakudo, Tokyo, Japan) with an accuracy of 0.001 kg. Each portion was placed in a container with a fixed volume of 0.001 m^3. This parameter describes the relationship between product weight and spatial dimensions. To ensure result accuracy, the measurement was repeated three times, and the average value was used. The procedure followed the method proposed by Han et al. (2018):

$$BD = m\,V^{-1} \tag{3}$$

where: *BD* is the bulk density (kg m^{-3}), *m* is the mass of the sample (kg), *V* is the volume of the measuring vessel (m^3).

The water absorption index (WAI) was determined using a modified procedure described by

Estrada-Giron et al. (2015). For the analysis, 0.7 g of extrudate that had previously been ground was weighed out and placed in a cylindrical vessel. Thereafter, 7 mL of distilled water was added to the vessel. The mixture was stirred continuously for a period of 20 minutes, thereby facilitating optimal interaction between the water molecules and the hydrophilic components present within the sample. Following the rehydration step, the suspension was subjected to a centrifugation process at 15,000 rpm for a duration of 10 minutes, utilizing a Digicen 21 centrifuge (Labsystem, Krakow, Poland). Following centrifugation, the upper layer was meticulously extracted, while the residual gel precipitate was measured with a precision laboratory balance (WPS 210/C, Radwag, Radom, Poland) with a precision of 0.001g. The test was performed on each sample three times to enhance the accuracy and repeatability of the results. The final WAI value was calculated as the arithmetic mean of three independent replicates using a formula specific to this type of determination:

$$WAI = m_g \, m_s^{-1} \quad (4)$$

where: WAI is the water absorption index (g g^{-1}), m_g is the mass of formed gel (g), m_s is the mass of dry sample (g).

The water solubility index (WSI) was determined according to the procedure described by Estrada-Giron et al. (2015) using adapted laboratory conditions. After measuring the water absorption index (WAI), the supernatant obtained was exposed to a water evaporation process. This activity was carried out in an SLW 53 STD laboratory dryer (Pol–Eko Aparatura S.J., Wodzisław Śląski, Poland), at a temperature of 110 °C, until the water was completely removed. After drying process, the solid residue was precisely weighed using a laboratory balance WPS 210/C (Radwag, Radom, Poland), ensuring a measurement accuracy of 0.001 g. The WSI determination was carried out three times for each sample to increase the reliability of the results. The final value was calculated as the arithmetic mean of three independent measurements using the appropriate formula:

$$WSI = (m_V - m_{dV}) \, m_s^{-1} \, 100 \quad (5)$$

where: WSI is 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), m_s is the mass of the dry sample (g).

Statistical analysis

The Statistica 13.3 software was used to compile the results. A significance level of α = 0.05 was assumed. For statistical analysis, response surface methodology (RSM) was used for fitting polynomial models, where x was the screw speed and y was the various pomace addition level; also the quadratic equations of the tested characteristics were evaluated depending on the variables used in the experiment. The coefficient of determination R^2 was appointed.

RESULTS AND DISCUSSION

Characteristics of extrusion-cooking process

In the control samples (without pomace), the efficiency of the extrusion–cooking process increased along with screw speed. In the L/D 16 plasticizing system, the highest efficiency was 21.48 kg h^{-1} at 80 rpm, while in the L/D 20 system the maximum value reached 14.40 kg h^{-1} at the same speed. These results indicate that the shorter plasticizing system (L/D 16) provided higher process efficiency for the base mixture. For extrudates with an apple pomace, at a concentration of 10%, the L/D 16 system achieved efficiency ranging from 8.88 to 16.32 kg h^{-1}, increasing with rising screw speed (Figure 1a). For the same concentration, the L/D 20 system recorded lower values (Figure 1b), ranging from 7.68 to 15.12 kg h^{-1}. At a concentration of 20% apple pomace, a significant increase in efficiency was observed in the L/D 20 system, with a value of 24.0 kg h^{-1} at 40 rpm being the highest of all samples. For L/D 16 in the same concentration range, the maximum value did not exceed 13.68 kg h^{-1}. At 30% apple addition, the efficiency in the L/D 16 system was still high (up to 19.2 kg h^{-1}); while in L/D 20 it reached a maximum of 15.84 kg h^{-1}, suggesting limitations at high fiber saturation in the longer system. For chokeberry pomace, 10% addition resulted in lower values compared to apples – at L/D 16 the range was 6.96–16.80 kg h^{-1} and at L/D 20 it was 8.40–14.52 kg h^{-1} (Figure 1b and 1c, respectively). The highest results for chokeberry pomace were obtained at 20% addition, where 19.44 kg h^{-1} at 80 rpm was achieved at L/D

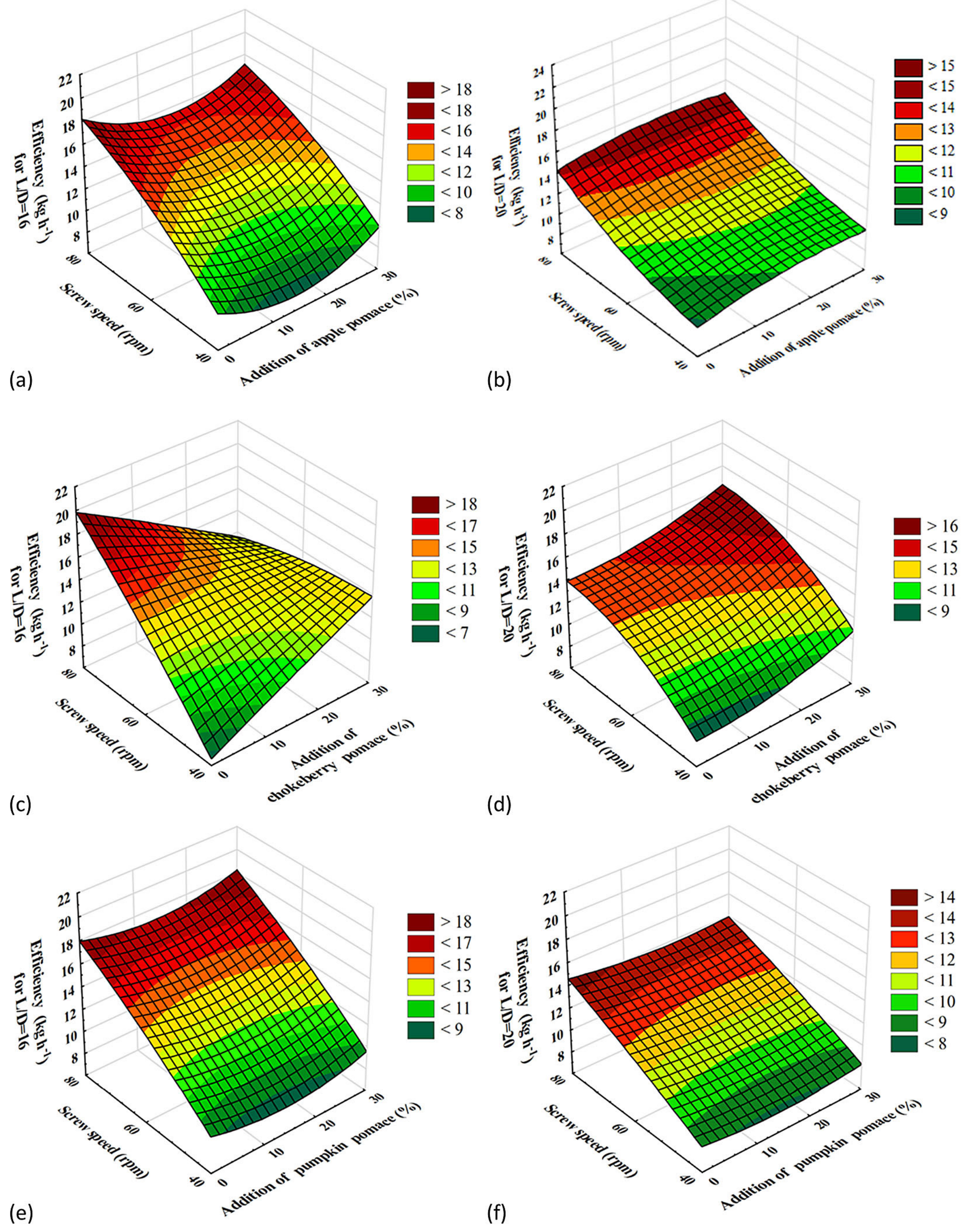

Figure 1. Effect of plant pomace addition and screw speed on the processing efficiency of snack pellets, for two plasticizing systems, (a) apple pomace addition with L/D 16, (b) apple pomace addition with L/D 20, (c) chokeberry pomace addition with L/D 16, (d) chokeberry pomace addition with L/D 20, (e) pumpkin pomace addition with L/D 16, (f) pumpkin pomace addition with L/D 20

16. For the system with L/D 20 ratio, the efficiency for this concentration was lower and did not exceed 14.40 kg h^{-1}. At 30% chokeberry pomace addition, the L/D 16 system showed a decrease in efficiency (down to 9.12 kg h^{-1}), while L/D 20 maintained relatively high values (up to 17.04 kg h^{-1}), which may indicate a better adaptation of this system to the structure of this raw material at high loadings. For extrudates with pumpkin pomace, the L/D 16 system provided significantly higher and more stable efficiency in all variants (Figure 1e). At 10% addition, values ranged from 9.12–17.16 kg h^{-1}, while at L/D 20 7.32–14.64 kg h^{-1}. For 20% pumpkin pomace addition, L/D 16 reached a maximum of 17.52 kg h^{-1}, while L/D 20 reached 14.88 kg h^{-1}. The highest efficiency for

pumpkin pomace were obtained at 30% concentration, where L/D 16 recorded as much as 19.44 kg h^{-1} at 80 rpm, one of the highest results. At L/D 20 for this concentration, values did not exceed 13.68 kg h^{-1} (Figure 1f).

Similar correlations for extrusion–cooking efficiency were presented by Lisiecka and Wójtowicz (2019) who found the highest values at lower vegetable additive concentrations and higher screw speed. In the conducted study, the maximum efficiency was achieved at 20% apple addition in the L/D 20 system, while further increases in pomace proportion led to a decrease efficiency. Although different additives and operating parameters were used in both cases, the common conclusion is that the type of raw material, its quantity and mechanical conditions play an important role in shaping the process efficiency. Similar relationships of extrusion–cooking process efficiency were observed by Lisiecka et al. (2021) who showed that an increase in screw speed contributed to the efficiency of snack production with the addition of fresh vegetable pulp, although this effect depended on the type of raw material. The highest efficiency was obtained with 7.5% onion addition and 120 rpm, while the lowest was obtained for 10% carrots at 80 rpm. The conducted study also found an increase in efficiency with screw speed, particularly in the L/D 16 system. At the same time, it showed that too high an additive concentration (30%) led to a decrease in efficiency, confirming that both the type and amount of vegetable raw material have a significant effect on extrusion–cooking efficiency.

For the control samples, the SME values ranged from 0.018–0.074 kWh kg^{-1} for the L/D 16 system and 0.025–0.067 kWh kg^{-1} for the L/D 20 system. Higher speed generally led to lower energy consumption, especially for the L/D 16 system. For the addition of apple pomace at 10% concentration, a pronounced increase in SME was noticed, especially at L/D 20, where values reached 0.189 kWh kg^{-1} (at 40 rpm). In L/D 16 system (Figure 2a), the highest values were also recorded at this speed (up to 0.093 kWh kg^{-1}), while at 60 and 80 rpm the SME even dropped to 0.009 kWh kg^{-1}. At 20% concentration of pomace, the L/D 20 system showed significant fluctuations (Figure 2b), from 0.019 to 0.183 kWh kg^{-1}, while L/D 16 was more stable (0.013–0.113 kWh kg^{-1}). At 30% apple pomace, the SME values in L/D 16 fluctuated around 0.023–0.047 kWh kg^{-1}, while in L/D 20 increased to 0.114 kWh kg^{-1} at 40 rpm. At 10% chokeberry pomace addition, the mixtures processed in L/D 16 system showed moderate energy consumption (0.012–0.122 kWh kg^{-1}) (Figure 2c), while L/D 20 presented scattered values ranging from 0.027 to 0.108 kWh kg^{-1} (Figure 2d). At 20%, the SME in L/D 16 remained at 0.005–0.065 kWh kg^{-1}, while in L/D 20 it varied between 0.016 and 0.025 kWh kg^{-1}. At a concentration of 30% for this additive, L/D 16 recorded a marked increase in SME at the highest speed (0.113 kWh kg^{-1}), while L/D 20 remained relatively energy efficient (minimum of 0.014 kWh kg^{-1} at 80 rpm). In the case of pumpkin pomace, as presented in Figure 2e and 2f, for 10% concentration SME was relatively low in the L/D 16 system (up to 0.092 kWh kg^{-1}), while in L/D 20 it peaked at up to 0.126 kWh kg^{-1} at 40 rpm. At 20% pumpkin addition, the L/D 20 generated extremely high energy consumption values of up to 0.139 kWh kg^{-1} (60 rpm), while the L/D 16 maintained a lower and more even level (0.012–0.054 kWh kg^{-1}). For 30% pumpkin, the SME values in L/D 16 were stable (0.016–0.048 kWh kg^{-1}), while L/D 20 saw a rapid growth to as much as 0.151 kWh kg^{-1}.

In the Kantrong et al. (2018) study, an increase in screw speed and changes in mixture composition were found to increase SME values, which is consistent with the authors' observations. In both cases, it was noted that intensification of mechanical parameters led to higher energy requirements. In addition, both Kantrong et al. (2018) and the presented study showed that the amount of plant raw material addition influenced SME – an increase in SME resulted in an initial increase in the energy intensity of the process, which was associated with higher mass resistance during transport and plasticisation in the extruder–cooker. Both studies confirm that SME is a sensitive indicator of technological change and can effectively reflect the impact of recipe modifications and machine settings. In the study of Soja et al. (2025) a noticeable relationship was observed between pomace additive concentration, screw speed and L/D system configuration and specific mechanical energy consumption (SME) values. As in the presented study, the lowest SME values were found at higher speeds (80 rpm), while the highest values were found at lower speeds (40 rpm) and higher additive concentration, especially in the L/D configuration of 20. In both cases, it was shown that increasing the screw speed could effectively reduce material flow resistance and thus lower energy consumption.

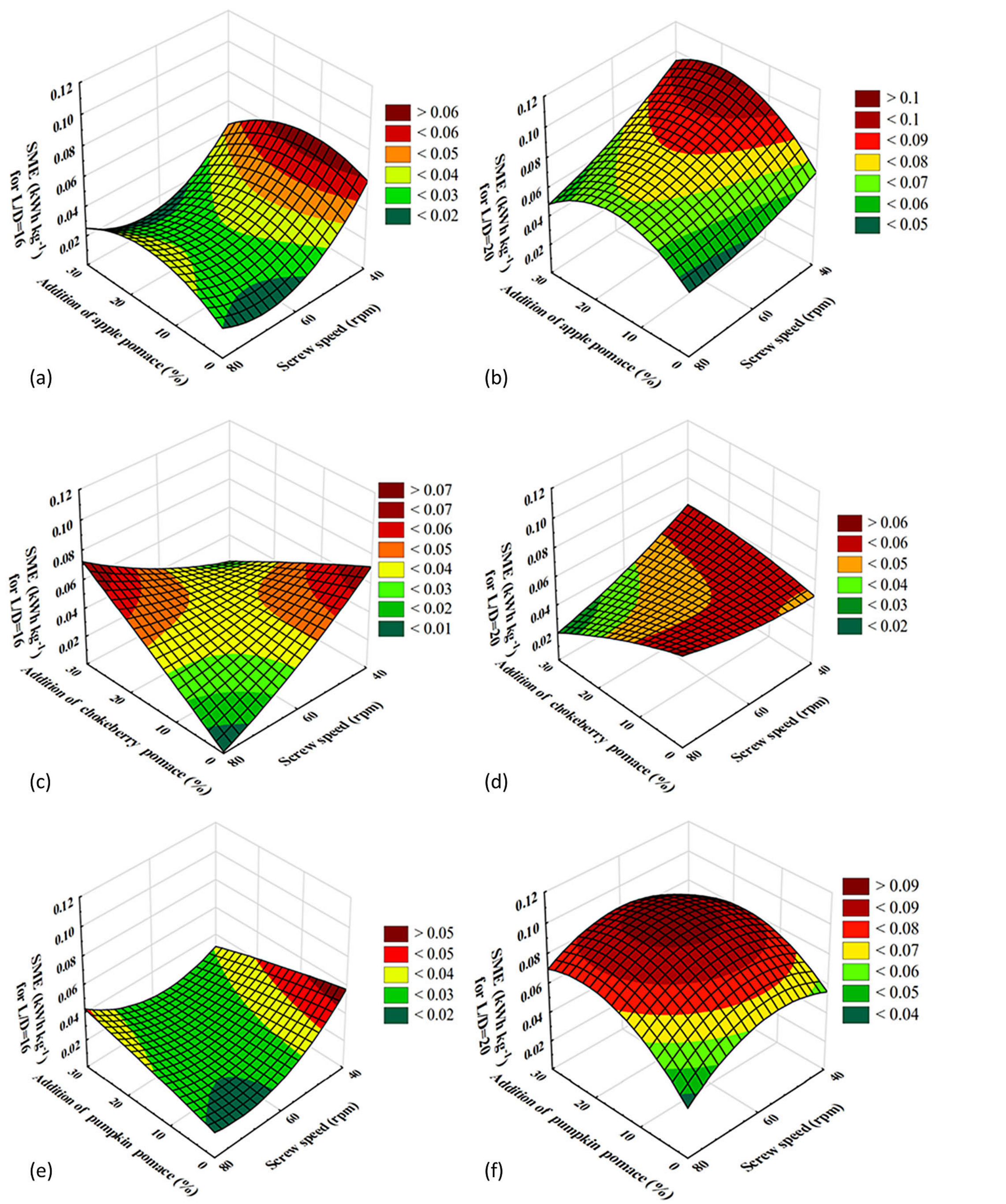

Figure 2. Effect of plant pomace addition and screw speed on the energy consumption during snack pellet processing for two plasticizing systems, (a) apple pomace addition with L/D 16, (b) apple pomace addition with L/D 20, (c) chokeberry pomace addition with L/D 16, (d) chokeberry pomace addition with L/D 20, (e) pumpkin pomace addition with L/D 16, (f) pumpkin pomace addition with L/D 20.

Moreover, the observations on the effect of the length of the plasticisation zone are consistent, with the L/D 20 configuration being associated with higher SME at lower speeds due to higher friction and longer residence time of the material in the cylinder. As speeds increased, these differences decreased and the process was more energy efficient. In both Soja et al. (2025) study and the present study, it was noted that the highest SME occurred at lower additive concentrations, and that further increases could lead to lower energy efficiency – which could be the result of changes in flow structure and lower mass compaction. Both studies confirm that SME is strongly dependent on the interaction between additive, screw geometry and machine parameters.

The comparison of the results clearly shows that both changes in raw material composition and the process configurations used affect generation efficiency and energy requirements, as is well illustrated by the relationships shown in Table 4.

Physical properties of extruded snack pellets with pomace addition

In the control samples, the bulk density values at L/D 16 system ranged from 399.52 to 407.41 kg m^{-3}, while at L/D 20 were slightly higher, ranging from 402.68 to 408.26 kg m^{-3}. The highest recorded value was observed at L/D 20 and 60 rpm, which may indicate enhanced compression within the extended plasticizing system under conditions of medium processing intensity. For the extrudates with the addition of apple pomace, a systematic increase in bulk density was noticeable compared to the control sample. At 10% addition, values reached a maximum of 458.23 kg m^{-3} (L/D 16) and 527.87 kg m^{-3} (L/D 20) as presented in Figure 3a and 3b, respectively. As the concentration increased to 20%, the density decreased slightly – to approximately 430.12 kg m^{-3} (L/D 16) and 510.08 kg m^{-3} (L/D 20). Further increases to 30% resulted in a further decrease in density, reaching a minimum of 416.19 kg m^{-3} at L/D 16 and 504.12 kg m^{-3} at L/D 20. This trend suggests that a moderate addition of apple pomace improves the spatial structure, but an excess may destabilise it. The extrudates with chokeberry pomace showed the highest density values among the additives analysed (Figure 3c and 3d). At 10% additive, L/D 16 generated values up to 578.45 kg m^{-3} and L/D 20 up to 690.25 kg m^{-3}. Even at a concentration of 20%, the density in both systems remained high (up to 545.25 kg m^{-3} and 655.78 kg m^{-3}, respectively). For the samples with 30% addition, a decrease in density was observed (min. 461.11 kg m^{-3} in L/D 16 and 584.45 kg m^{-3} in L/D 20), but it still remained significantly higher than for the other groups. The high content of fiber and peel can affect the density of the material. The extrudates enriched with pumpkin pomace also showed an increase in density compared to the control sample, although less pronounced than for apples and chokeberry pomace. At 10% addition, the maximum density reached 553.58 kg m^{-3} (L/D 16, Figure 3e) and 589.86 kg m^{-3} (L/D 20, Figure 3f). As the concentration increased to 20%, a gentle decrease to 474.27 and 566.54 kg m^{-3} was observed, respectively. The lowest bulk density values for pumpkin pomace occurred at 30% addition and 80 rpm – 425.77 kg m^{-3} at L/D

Table 4. Response surface fitting models describing the processing efficiency (Q) and energy consumption (SME) during the extrusion-cooking process as a function of plant pomace addition and screw speed for two plasticizing systems (L/D 16 and 20).

L/D	Additive	Property	Model equation	R^2
16	Apple pomace	Q (kg h^{-1})	$-6.1942-0.221x + 0.4693y + 0.0099x^2-0.0014xy-0.0021y^2$	0.899
		SME (kWh kg^{-1})	$0.2803 + 0.0009x - 0.0078y - 7.1111^{E-5}x^2 + 1.7333^{E-5} xy + 5.6875^{E-5}y^2$	0.696
	Chokeberry pomace	Q (kg h^{-1})	$-10.364 + 0.7656x + 0.4706y - 0.0003x^2 - 0.0129xy -0.0012y^2$	0.688
		SME (kWh kg^{-1})	$0.1818 - 0.0056x - 0.0033y - 3.8889^{E-6}x^2 + 0.0001xy + 1.2708^{E-5}y^2$	0.695
	Pumpkin pomace	Q (kg h^{-1})	$-2.6118 - 0.1316x + 0.3363y + 0.0048x^2 - 4.5^{E-5}xy-0.001y^2$	0.891
		SME (kWh kg^{-1})	$0.2195 - 0.0024x - 0.0056y - 4.4444^{E-6}x^2 + 4.2333^{E-5}xy + 3.8542^{E-5}y^2$	0.705
20	Apple pomace	Q (kg h^{-1})	$9.599 + 0.1461x - 0.0974y - 0.0028x^2 - 0.0006xy + 0.0019y^2$	0.769
		SME (kWh kg^{-1})	$0.124 + 0.0047x - 0.002y - 9.7222^{E-5}x^2 - 2.0417^{E-5}xy + 1.1979^{E-5}y^2$	0.813
	Chokeberry pomace	Q (kg h^{-1})	$-7.9853 - 0.0089x + 0.5394y + 0.0032x^2 - 6^{E-5}xy-0.0033y^2$	0.932
		SME (kWh kg^{-1})	$0.0619 + 0.0027x - 0.0007y - 1.3611^{E-5}x^2 - 4.6583^{E-5}xy + 8.8542^{E-6}y^2$	0.878
	Pumpkin pomace	Q (kg h^{-1})	$0.5853 - 0.0408x + 0.2089y + 0.0021x^2 - 0.0006xy -0.0004y^2$	0.941
		SME (kWh kg^{-1})	$-0.0612 + 0.0022x + 0.0046y - 8.1944^{E-5}x^2 + 1.7917^{E-5}xy-4.2396^{E-5}y^2$	0.836

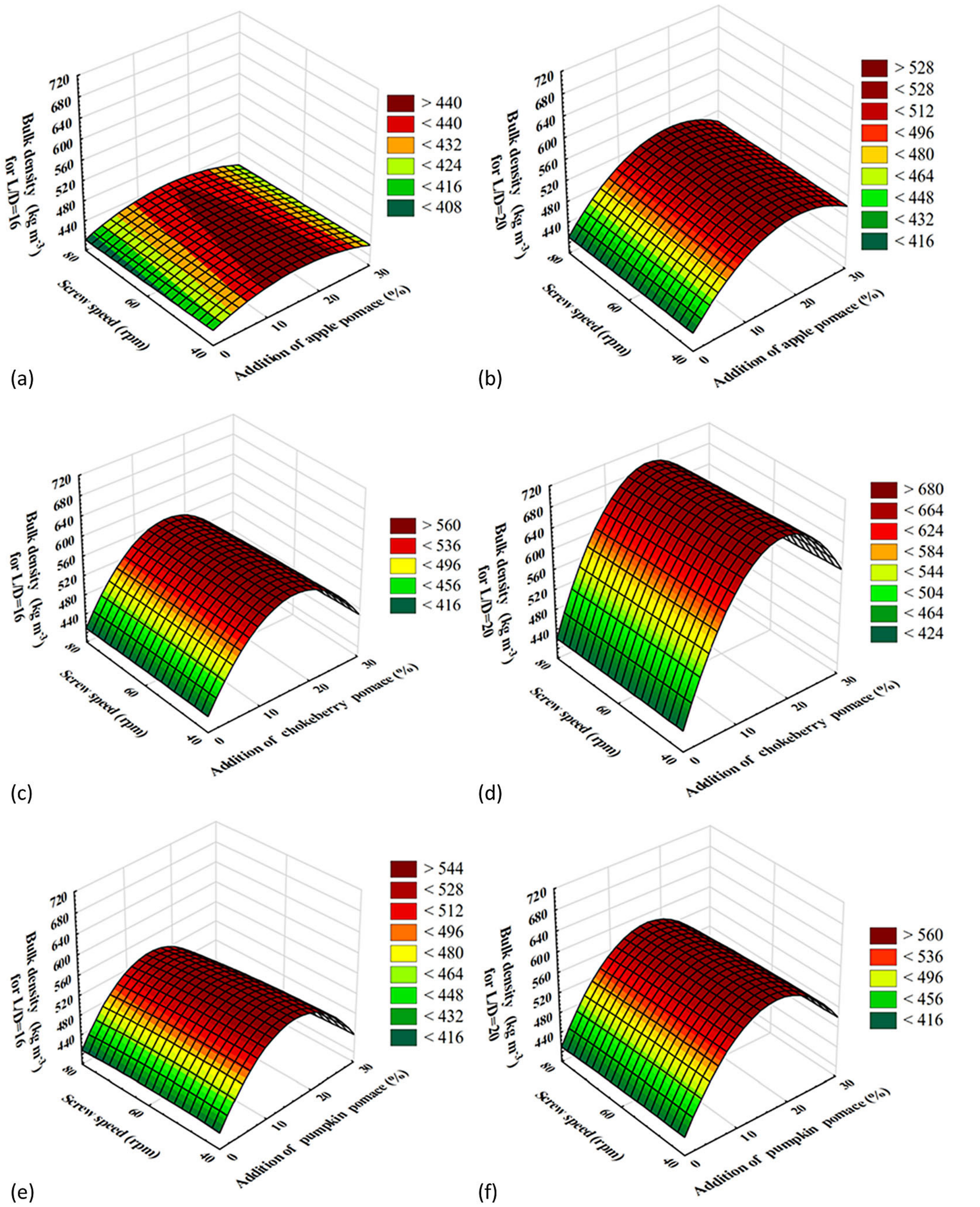

Figure 3. Effect of plant pomace addition and screw speed on the bulk density of snack pellets, for two plasticizing systems, (a) apple pomace addition with L/D 16, (b) apple pomace addition with L/D 20, (c) chokeberry pomace addition with L/D 16, (d) chokeberry pomace addition with L/D 20, (e) pumpkin pomace addition with L/D 16, (f) pumpkin pomace addition with L/D 20

16 and 489.95 kg m^{-3} at L/D 20, indicating a loosening of the structure due to an excess of insoluble components (Figure 3e and 3f, respectively).

The study presented by Dushkova et al. (2024) showed that an increase in the addition of chokeberry pomace led to an increase in the bulk density of the extrudates, particularly at higher moisture levels. Although the moisture content was constant in the conducted study (34%), it was also observed that a higher proportion of pomace – especially from chokeberry – resulted in a major increase in density, confirming the general trend indicated by Dushkova et al. (2024). These authors also noted that screw speed had a minor effect on density. In the obtained results, the effect of speed was also limited, but some differences depending on the configuration of the L/D system were noted – for example, for chokeberry pomace, density values were higher in the L/D 20 system than in the L/D 16 system regardless of speed. This may suggest that, as reported by Dushkova et al. (2024), the effect of changes in screw speed on density is secondary to the effect of raw material composition.

Potter et al. (2013) showed that the addition of fruit powder in all formulation variants led to a significant increase in bulk density compared to the control sample, with no significant differences observed between the different types of fruit. A similar relationship was noted in the conducted study – each type of pomace (apple, chokeberry, pumpkin) contributed to an increase in bulk density relative to the control sample, regardless of the type of raw material. This confirms that the pomace addition of a plant component with a high fiber content and a structure that is less susceptible to expansion increases the density of the finished product, regardless of the origin.

In the L/D 16 system, the water absorption index was in the range 4.14–4.34 g g^{-1}, while in the L/D 20 system it was slightly higher, reaching a maximum of 4.64 g g^{-1} at 80 rpm. The increase in speed caused a slight increase in WAI, which may be due to a more intensive breakdown of the starchy structure. For the extrudates with apple pomace addition (Figure 4a and 4b), at a concentration of 10%, WAI values remained similar or slightly higher than in the control sample (4.12–4.26 g g^{-1} in L/D 16 and 4.46–4.52 g g^{-1} in L/D 20). However, an increase in the additive concentration to 20% led to a marked decrease in WAI – especially in the L/D 16 system, where values even fell to 3.11 g g^{-1}. For 30% apple addition, WAI decreased further and reached a minimum of 2.51 g g^{-1} (L/D 16), which may suggest a reduction in absorption capacity due to depletion in hydrophilic components. A different trend was observed for chokeberry pomace. Already at 10% addition, there was an increase in WAI compared to the reference sample. Values reached 4.54 g g^{-1} (L/D 16) and 4.42 g g^{-1} (L/D 20) but at 20% addition differences were significant. The WAI of snack pellets increased to 4.91 g g^{-1} when processed with L/D 16 but decreased to 4.29 g g^{-1}, when L/D 20 was used, as presented in Figure 4c and 4d. The highest WAI values throughout the study were obtained for 30% additive – as much as 6.01 g g^{-1} in the L/D 16 system at 80 rpm. Such an increase may be related to the presence of specific pectin and fiber fractions in the chokeberry pomace, which are characterised by high absorbability. Pumpkin pomace application also significantly increased WAI relative to the control sample, especially at lower concentrations. At 10% additive in the L/D 16 system (Figure 4e), values reached 5.65 g g^{-1}, and at L/D 20 (Figure 4f), even 6.25 g g^{-1}. Increasing the proportion of additive to 20%, resulted in a major decrease in values – to between 3.98 and 4.38 g g^{-1}. For 30% pumpkin, the WAI decreased even further – in the L/D 16 system to 3.12 g g^{-1} and in L/D 20 to 3.45 g g^{-1}, which may be related to the presence of less reactive structural fractions.

In the study of Blejan et al. (2025) there was a marked decrease in WAI values with an increase in the proportion of bilberry pomace in the corn extrudates. All variants with additives had significantly lower water absorption than the control sample, which was explained by reduced starch gelatinisation in the presence of pectin and lipids. Similar correlations were observed in the conducted study – for apple and pumpkin additives, an increase in concentration resulted in a gradual decrease in WAI, particularly pronounced at 30% of raw material. This confirms that fruit and vegetable additives can reduce water binding capacity by affecting starch transformation during extrusion–cooking process.

In the study of Drożdż et al. (2019) a decrease in WAI from 6.5 to 4.6 g g^{-1} was observed with an increase in the addition of blackcurrant pomace, what confirms the trends also seen in this experiment. In the considered case, increasing the proportion of apple, chokeberry and pumpkin pomace also resulted in a decrease in WAI, especially at a 30% addition. Both in the study of Drożdż et al. (2019) and in the presented results, no significant differences were found between the types of pomace used. This indicates a similar effect of fiber and compounds limiting starch gelatinisation.

The WSI values of extrudates without additives processed in L/D 16 system were in the range 5.45–5.82%, while slightly higher values of up to 6.65% were recorded at L/D 20, confirming the beneficial effect of a longer residence time of the material in the plasticising system on the development of soluble fractions. In the case of apple pomace, the incorporation of 10% resulted in a significant increase in WSI, reaching a maximum of 6.75% (L/D 16) and 6.47% (L/D 20) as reported in Figure 5a and 5b, respectively. It was demonstrated that higher concentrations

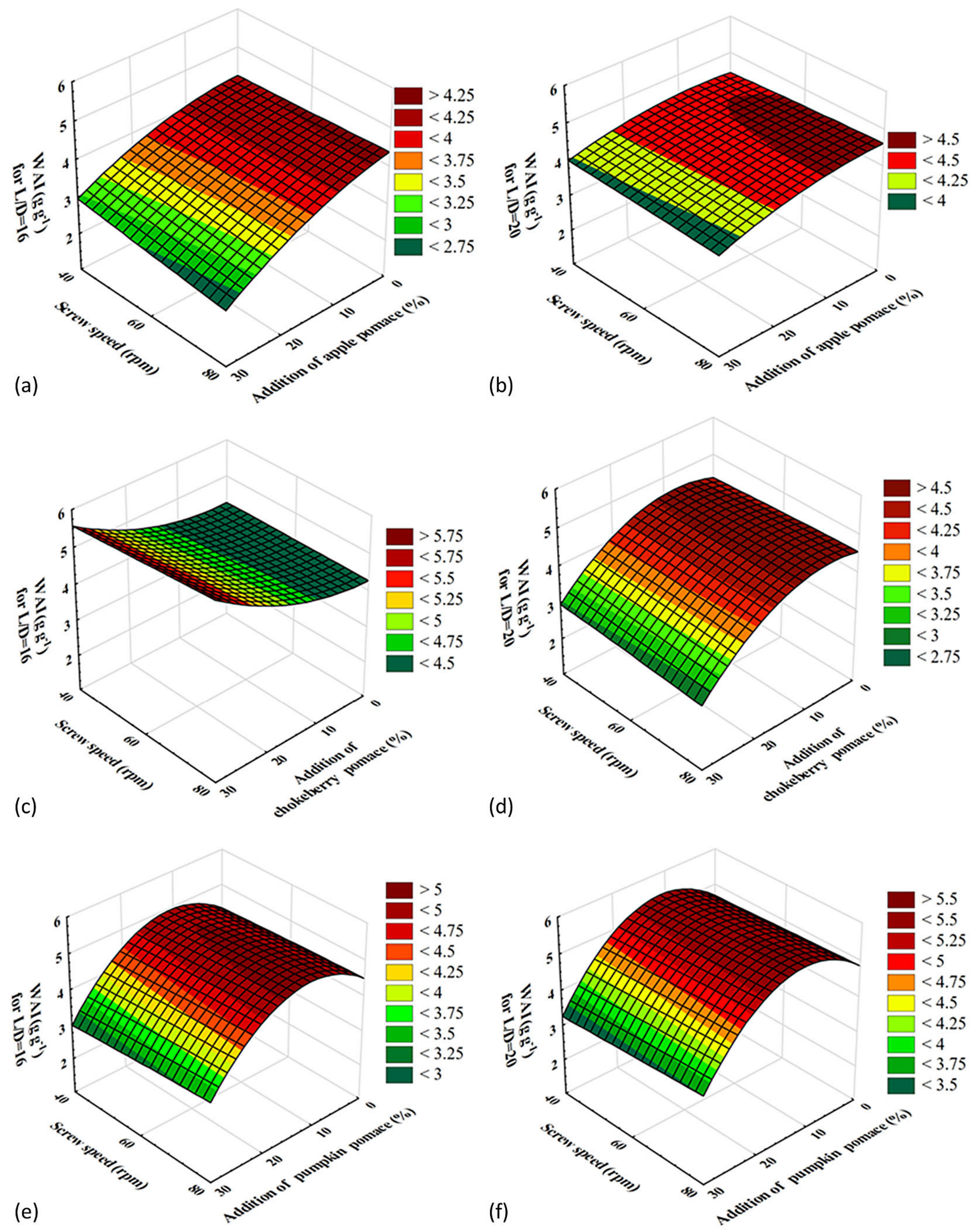

Figure 4. Effect of plant pomace addition and screw speed on the water absorption index of snack pellets, for two plasticizing systems, (a) apple pomace addition with L/D 16, (b) apple pomace addition with L/D 20, (c) chokeberry pomace addition with L/D 16, (d) chokeberry pomace addition with L/D 20, (e) pumpkin pomace addition with L/D 16, (f) pumpkin pomace addition with L/D 20

(20%) resulted in further increases, particularly in the L/D 16 system, where 7.32% was achieved at 80 rpm. The highest values for apple were observed at a concentration of 30%, reaching 7.52% (L/D 16) and 7.34% (L/D 20). This finding suggests that apple pomace significantly contributes to the development of the soluble fraction, likely as a result of the presence of organic acids and fructooligosaccharides. For the extrudates enriched with chokeberry pomace, the WSI values increased less rapidly. At 10% addition, WSI ranged between 4.92 and 5.11% (L/D 16, Figure 5c) and between 5.41 and 5.67% (L/D 20, Figure 5d). More pronounced changes were only observed at 30%, where the WSI was 6.98% (L/D 16) and 7.92% (L/D

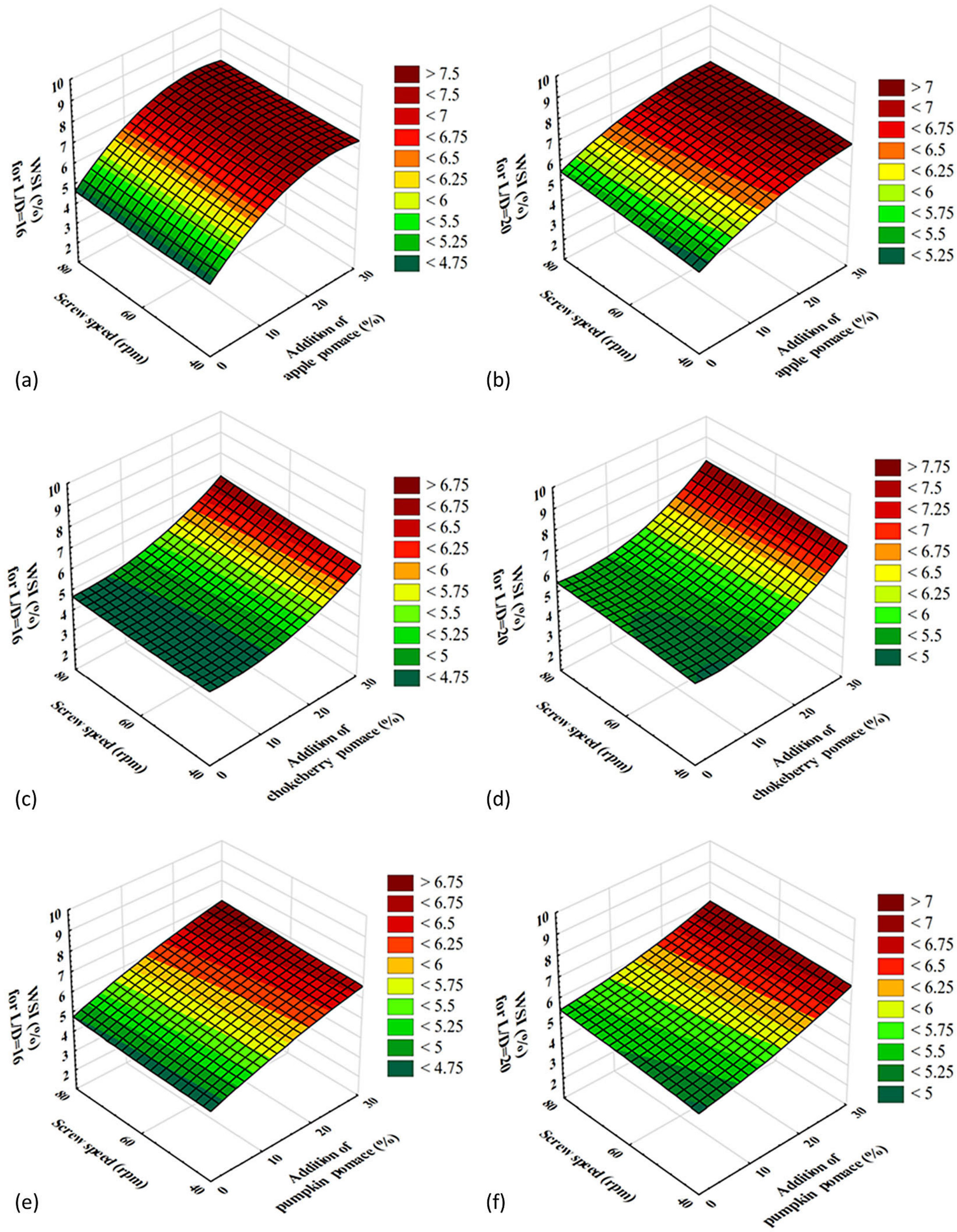

Figure 5. Effect of plant pomace addition and screw speed on the water solubility index of snack pellets, for two plasticizing systems, (a) apple pomace addition with L/D 16, (b) apple pomace addition with L/D 20, (c) chokeberry pomace addition with L/D 16, (d) chokeberry pomace addition with L/D 20, (e) pumpkin pomace addition with L/D 16, (f) pumpkin pomace addition with L/D 20

20), the highest value of all samples. The soluble fractions present in the chokeberry, including anthocyanins, may have contributed to this increase. In the case of pumpkin addition, the highest increase in WSI was already recorded at 10%: up to 5.93% in L/D 16 and 5.71% in L/D 20. Further increases in concentration up to 20% resulted in moderate increases – up to 6.15% (L/D 16) and 6.28% (L/D 20). The highest values for pumpkin pomace were achieved at 30% addition – up to 7.05% and 7.20% respectively, indicating good solubility of the pumpkin components, albeit less than in chokeberry (Figure 5e and 5f, respectively).

Table 5. Response surface fitting models describing the bulk density (BD), water absorption index (WAI) and water solubility index (WSI) of snack pellets as a function of plant pomace addition and screw speed for two plasticizing systems (L/D 16 and 20)

L/D	Additive	Property	Model equation	R^2
16	Apple pomace	BD (kg m^{-3})	$419.9363 + 4.6092x - 0.307y - 0.1395x^2 - 0.0007xy + 0.0011y^2$	0.918
		WAI (g g^{-1})	$4.2139 - 0.0165x + 0.0019y + 0.0016x^2 + 0.0003xy - 1.5625^{E-5}y^2$	0.977
		WSI (%)	$4.7778 -0.0271x - 0.0083y + 0.0026x^2 + 0 .0003xy + 8.5417^{E-5}y^2$	0.936
	Chokeberry pomace	BD (kg m^{-3})	$405.1082 + 19.9435x + 0.3316y - 0.59x^2 - 0.0103xy - 0.0035y^2$	0.898
		WAI (g g^{-1})	$4.2139 - 0.0165x + 0.0019y + 0.0016x^2 + 0.0003xy - 1.5625^{E-5}y^2$	0.880
		WSI (%)	$4.7778 - 0.0271x - 0.0083y + 0.0026x^2 + 0.0003xy + 8.5417^{E-5}y^2$	0.917
	Pumpkin pomace	BD (kg m^{-3})	$379.2641 + 17.6344x + 1.2924y - 0.5371x^2-0.0185xy - 0.0117y^2$	0.887
		WAI (g g^{-1})	$4.0342 + 0.1105x + 0.0089y - 0.0053x^2 + 0.0001xy - 4.1667^{E-5}y^2$	0.899
		WSI (%)	$4.5251 + 0.0872x - 0.0022y -0.0008x^2 + 0.0002xy + 5.9375^{E-5}y^2$	0.786
20	Apple pomace	BD (kg m^{-3})	$412.2249 + 12.0426x + 0.1168y - 0.3093x^2 + 0.002xy - 0.0017y^2$	0.899
		WAI (g g^{-1})	$4.0502 + 0.0624x + 0.0098y - 0.0032x^2 - 0.0003xy-4.5833^{E-5}y^2$	0.836
		WSI (%)	$4.1333 - 0.022x + 0.027y + 0.0037x^2 - 0.0001xy - 0.0001y^2$	0.884
	Chokeberry pomace	BD (kg m^{-3})	$417.406 + 31.0789x + 0.1761y - 0.8341x^2 - 0.0136xy - 0.0016y^2$	0.799
		WAI (g g^{-1})	$4.0502 + 0.0624x + 0.0098y - 0.0032x^2 - 0.0003xy - 4.5833^{E-5}y^2$	0.889
		WSI (%)	$4.1333 - 0.022x + 0.027y + 0.0037x^2 - 0.0001xy - 0.0001y^2$	0.893
	Pumpkin pomace	BD (kg m^{-3})	$402.2073 + 20.8603x + 0.5839y - 0.5918x^2 - 0.0084xy - 0.0061y^2$	0.879
		WAI (g g^{-1})	$4.5104 + 0.1267x + 0.0044y - 0.0059x^2 + 6.5833^{E-5}xy - 3.125^{E-6}y^2$	0.947
		WSI (%)	$4.1715 + 0.0463x + 0.0222y + 0.001x^2 - 0.0003xy - 8.3333^{E-5}y^2$	0.924

The study of Schmid et al. (2021) showed that WSI values increased along with the intensity of thermomechanical processing, which was associated with degradation of the material structure and release of soluble fractions. In contrast, Selani et al. (2014) observed a decrease in WSI in extrudates with pineapple pomace, which was explained by the high content of insoluble fiber and the limited amount of starch in the blend. In the conducted study, WSI values increased markedly with both increasing additive concentration and screw velocity, which may reflect the predominance of easily soluble components such as simple sugars and soluble fiber fractions. The observed differences suggest that the direction of WSI changes depends primarily on the characteristics of the additive used and the process flow – the more low–molecular–weight ingredients and the more intensive the technological conditions, the higher the solubility of the finished product.

The obtained results confirmed that the choice of additive and processing conditions shaped the physical properties of the extrudates, including bulk density and water absorption and solubility, as shown in Table 5.

In the study of Sharifi et al. (2021) an increase in WSI from 44.99% to 48.44% was observed with an increase in the proportion of soy flour in the recipe, which indicates more intensive decomposition of macromolecules during extrusion-cooking. A similar trend was observed in this experiment – WSI also increased along with the proportion of fruit and vegetable pomace, reaching values above 9%, which indicates an increased release of soluble components. In both cases, the addition of protein or fiber components promoted an increase in WSI, emphasising the importance of raw material composition in modifying the functional properties of extrudates.

CONCLUSIONS

The present research has demonstrated the efficacy of utilising fruit and vegetable pomace as valuable components in mixtures for the production of food extrudates with beneficial functional properties and thus the possibility to reduce pomace as a waste product. The impact of these additives was found to vary depending on the type of pomace used, the proportion incorporated into the mixture and the configuration of the plasticizing system during processing. The highest process efficiency was observed with the use of 20% apple pomace in an L/D 20 system, whereas the extrudates enriched with pumpkin in an L/D 16 system exhibited the most stable processing behaviour. It was found that SME consumption was the lowest in the case of chokeberry pomace addition, particularly at low screw speed. Furthermore, it was demonstrated that higher concentrations of apple and pumpkin pomace in the extended plasticizing system led to increased energy consumption. This is due to more difficult material transport and increased viscosity. When analysing bulk density of snack pellets with addition of pomace, the highest values were obtained in the samples with chokeberry pomace, especially when using the L/D 20 system. The WAI and WSI of enriched snack pellets reached the highest values with 30% chokeberry pomace addition. In contrast, for the snack pellets containing pumpkin and apple pomace, a decrease in WAI was observed at higher levels of addition. The findings indicate that the selection of an appropriate type of fruit or vegetable pomace, the proportion of these additives and the type of plasticizing system are pivotal in the design of enriched extrudates. These factors significantly impact both the process and the properties of the finished product. The observed changes can be attributed to variations in the composition and behaviour of the raw materials during the intensive thermomechanical processing.

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