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# Fresh Broccoli in Fortified Snack Pellets: Extrusion-Cooking Aspects and Physical Characteristics

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**Abstract:** The aim of the study was to obtain a new type of potato-based snack pellets fortified with fresh broccoli addition and to estimate their extrusion-cooking parameters (processing stability) and selected physical properties. In this work, fresh broccoli was added at varying levels (10, 20, and 30%) to potato-based pellets—a half-product for expanded ready-to-eat food snacks. The obtained results showed that the assessed variables: moisture content, screw speed, and amount of added fresh broccoli, have significantly affected the extrusion-cooking process and final product physical properties. Accordingly, increasing fresh broccoli by up to 30% induced higher efficiency of the extrusion-cooking process, lower energy consumption, a lower expansion index, lower bulk density values, and proper durability. Application of fresh broccoli may also significantly reduce water consumption during processing and save energy due to the omission of the vegetable drying step. We recommend the application of up to 30% fresh broccoli in newly developed extruded snack pellet formulations. Fresh broccoli, a valuable vegetable source of health-promoting substances, may be an attractive additive in snack pellet half-products with no negative effect on processing.

**Keywords:** extrusion-cooking; fresh broccoli; snack pellets; selected physical properties; processing parameters

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**Citation:** Mitrus, M.; Combrzyński, M.; Biernacka, B.; Wójtowicz, A.; Milanowski, M.; Kupryaniuk, K.; Gancarz, M.; Soja, J.; Różyło, R. Fresh Broccoli in Fortified Snack Pellets: Extrusion-Cooking Aspects and Physical Characteristics. *Appl. Sci.* **2023**, *13*, 8138. https://doi.org/10.3390/app13148138

Academic Editors: Urszula Pankiewicz, Ewelina Zielińska and Monika Sujka

Received: 19 June 2023
Revised: 9 July 2023
Accepted: 11 July 2023
Published: 13 July 2023

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## 1. Introduction

Broccoli, a member of the Brassica genus (*Brassica oleracea* L.), is a vegetable that is gaining popularity for human consumption. Broccoli is high in health-promoting substances such as vitamins, glucosinolates, phenolic compounds, and vital dietary minerals [1]. The majority of vitamins in broccoli are vitamin C, tocopherols, and folic acid [2]. Among the compounds contained, phenols, flavonoids, and hydroxycinnamic derivatives are the most abundant [3]. Studies conducted on 80 commercial broccoli samples showed fluctuations in vitamin C in the fresh weight on average in the range of 57.4 to 131.4 mg/100 g, while the concentration of kaempferol varied on average in the range of 0.2 to 13.2 mg/100 g, and the quercetin content was on average in the range of 0.03 to 10.8 mg/100 g. Moreover, overall phenolic activity in the fresh weight of broccoli was between 48.2 and 157.8 mg/100 g [4].

Consumption of broccoli contains compounds such as glucosinolates and cysteine s-methylsulfoxide, which in combination with other substances (including vitamins, minerals, and polyphenols), contribute to a variety of health advantages [5], including a reduced likelihood of cancer and autoimmune disorders [6–8].

The anticancer activity of broccoli consumption is due to the high presence of glucosinolates, which, when exposed to bacterial microflora, break down into isothiocyanins and indoles, chemicals responsible for protecting cells from oxidative stress [9]. In addition, broccoli's sulforaphane has been demonstrated to have anti-inflammatory and cancer-prevention properties [10,11]. Sulforaphane is synthesized from glucoraphan. All portions of this plant can be turned into nutritious foods for both the avoidance and treatment of certain ongoing diseases [12,13].

Processing vegetables, especially broccoli, results in the loss of important chemicals [14,15]. Indeed, high-pressure and regular cooking have been found to reduce total glucosinolates by 33% and 55%, respectively, as compared to raw broccoli [16]. Boiling in water causes antioxidant leaching, which increases with cooking time [17]. As a result, it is vital to investigate changes in component composition produced by various processing steps.

Extrusion-cooking is a method that can be applied in food manufacturing, packaging material production, and the alteration of various plant raw materials [18–21]. One food application is the production of various snacks. Broccoli can be employed in these items as a functional ingredient. So far, studies on maize extrudates using broccoli flour and olive paste have been conducted. The biochemical and sensory features of extrudates supplemented with these additives have been studied to assess the appropriate material moisture level and suitable extrusion setting. It has been demonstrated that by adopting suitable process conditions, acceptable extruded snacks, including broccoli powder and olive paste, may be created [22,23]. Other research has investigated the use of a laboratory twin-screw extruder to produce extruded snacks from rice flour with the addition of broccoli powder or fresh broccoli pomace. The results showed that the extruded snacks expanded less as the content of plant material in the recipe increased [24]. Snacks extruded from rice flour and high-protein quinoa flour enhanced with broccoli powder (4%) have demonstrated higher antioxidant capacity by way of the DPPH technique when compared to control snacks [25].

The objective of our research was to determine the best extrusion-cooking conditions for obtaining snack pellets fortified with fresh broccoli. The following variables were investigated: screw speed, moisture level, and fresh broccoli addition.

## 2. Materials and Methods

### 2.1. Materials

During our research, the following ingredients were used: organically grown fresh broccoli (supplier: ANREKO Andrzej Gębka, Jakubowice Konińskie, Poland), Superior Standard potato starch (from Przedsiębiorstwo Przemysłu Ziemniaczanego Bronisław S.A., Bronisław, Poland), potato flakes (supplier: Zakłady Przemysłu Ziemniaczanego w Lublinie, Lublin, Poland), potato grits (supplier: Zakłady Przemysłu Ziemniaczanego w Lublinie, Lublin, Poland), vegetable oil (manufacturer: Zakłady Tłuszczowe "Kruszwica", Kruszwica, Poland), sugar purchased at a Lidl store (Poland), salt purchased at a Lidl store (Poland).

### 2.2. Extrusion-Cooking of Snack Pellets

A potato-based composition (starch:grits:flakes ratio of 2:1:1) was prepared as a control sample and base recipe. Fresh broccoli was first crushed in a Germin cup blender (Berlinger, Germany) to a particle size less than 1 mm and was then added to the potato base in the amounts of 10%, 20%, and 30%, the mixture's moisture level being determined via a Radwag MA 50 R analyzer (Radwag, Radom, Poland). Next, the mixtures were moistened to obtain blend moisture levels of 32%, 34%, and 36% and sieved to ensure homogeneity of composition and moisture distribution. Here, the amount of added water was strongly dependent on the broccoli level: if 10% broccoli pulp was applied, the water amount varied from 220 to 297 mL per kg; for 20%, the needed additive water was between 132 and 203 mL

per kg; if 30% broccoli pulp was used, the water amount was minimal (17–81 mL per kg), respectively to each planned moisture level.

Afterwards, the samples were stored in a refrigerator for 24 h to standardize the samples.

An EXP-45-32 prototype single-screw extruder with L/D = 20 (Zamak Mercator, Skawina, Poland) was used during the extrusion-cooking process. During the tests, extruder screw speeds of 60, 80, and 100 rpm were applied. The pellets were extruded through the extruder die with a single flat opening (0.6 × 25 mm) into a ribbon shape and cut by a special knife system into square (25 × 25 mm) snack pellets (Figure 1).



**Figure 1.** Snack pellets with 20% addition of fresh broccoli—a half-product for further expansion.

A laboratory air dryer was used to remove moisture from the snack pellets to a moisture level between 8 and 10%. The pellets were packed in tightly closed containers and stored for further tests.

### *2.3. Extrusion-Cooking Process Efficiency and Energy Consumption*

The extrusion-cooking process was intended to evaluate the impact of process variables as well as the effect of the amount of fresh broccoli addition on process stability, efficiency, and the quality of the extrudates obtained.

Process efficiency was determined as the mass of pellets produced from each of the prepared mixtures during 30 s of processing [26]. The measurement was replicated three times for every mixture, and the mean was taken as the final result.

The energy consumption of the extrusion-cooking process was ascertained by calculating the Specific Mechanical Energy (SME) indicator by using the formula proposed by Matysiak et al. [27] in triplicate.

### *2.4. Quality of Pellets and Snacks*

The expansion index of the extruded pellets was assessed by dividing the thickness of the obtained pellets by the thickness of the opening in the extruder die [28]. The measurement was repeated five times, and the mean was taken as the final result.

The bulk density of the obtained extrudates was measured based on the ASAE standard [29]. The measurement was conducted in triplicate, and the mean was taken as the final result.

The durability of the snack pellets was determined by measuring their resistance to rotational forces within a closed chamber using the Pfost apparatus as a source of kinetic strength [29]. The arithmetic mean of the two measurements was taken as the final result.

### 2.5. Statistical analysis

Statistical analysis in the form of principal component analysis (PCA) was applied to establish the correlation between the degree of fresh broccoli addition and the parameters describing the obtained products. Principal component analysis and correlation determination were performed at the significance level $\alpha = 0.05$. The Statistica program (version 13.0, StatSoft Inc., Tulsa, OK, USA) was applied to obtain statistical analyses. The PCA data matrix for the statistical analysis of test results was composed of 8 columns and 36 rows. The appropriate number of principal components was determined using the Cattel criterion, considering an automatically scaled input matrix.

## 3. Results and Discussion

### 3.1. Effect of Variables on the Processing of Snack Pellets

Research has shown that extrusion enables the production of marketable snack pellets with a fresh broccoli addition. The introduction of fresh broccoli makes it possible to limit energy consumption due to the avoidance of vegetable drying and to limit the amount of water used to obtain the appropriate initial moisture level of material composition. We found that, as compared to control samples moistened to 32–36% (327–410 mL per kg), the addition of water was significantly limited if a greater amount of fresh broccoli pulp was applied in the recipe. Similar findings were confirmed previously in studies with various vegetables [20,30,31]. Thus, the applicability of developed products fortified with fresh broccoli pulp seems valuable not only from the point of view of production costs but also taking into consideration certain environmental benefits.

The snack pellets obtained had a smooth surface and a compact structure without visible pores or bubbles (Figure 1). Here, an increased amount of added broccoli was visible as small particles in the snack pellet's uniform gelatinized structure. This effect can be a valuable aspect for producers and consumers, as snack pellets with the highest amount of broccoli showed an appealing slight green tint coming from the vegetable's green color. Overall, the aforementioned attributes make extrusion-processed broccoli supplemented potato-based pellet very attractive as a half-product for further expansion by frying, microwaving, or hot air toasting.

During the tests, stable operation conditions of the extruder were observed without interruptions in the flow of the processed mass. The efficiency of the snack pellet extrusion-cooking process depended on the material moisture level and the screw speed, as well as the amount of fresh broccoli additive used. The results of processing characteristics such as efficiency and energy consumption are presented in Table 1. The outcome of such an investigation demonstrates that the efficiency of the pellet extrusion-cooking process was influenced by both the process parameters and the composition of the processed mixtures. Higher efficiency results were observed for all raw material mixtures with the addition of fresh broccoli in comparison to the process efficiency of the control sample without the addition of fresh broccoli. The lowest efficiency of the process (15.76 kg $h^{-1}$) was registered for the control samples without the fresh broccoli, produced using the lowest extruder screw speed and the highest moisture level of the mixture. The highest efficiency (36.92 kg $h^{-1}$) was noted during processing of samples with 10% fresh broccoli content, extruded at 34% moisture content, and the highest extruder screw speed.

We observed the highest processing efficiency if 10 and 20% of vegetables were used in the composition, while 30% of added broccoli slightly decreased process yield (yield, however, was still higher than for the control sample). A significant increase in the extrusion-cooking efficiency with an increase in the screw speed was noted for all the tested raw material mixtures ($r = 0.887$), regardless of the amount of fresh broccoli added. Similar trends during snack pellet extrusion-cooking were presented by Matysiak et al. [27], Lisiecka and Wójtowicz [30], Lisiecka and Wójtowicz [31], and Lisiecka et al. [32].

**Table 1.** Results of extrusion-cooking efficiency and energy consumption of snack pellets depend on broccoli addition level and applied processing variables (n = 3 ± SD).

| Fresh Broccoli Content [%] | Screw Speed [rpm] | Moisture Content [%] | Q [kg $h^{-1}$] | SME [kWh $kg^{-1}$] |
|---|---|---|---|---|
| 0 | 60 | 32 | 19.44 ± 0.42 | 0.037 ± 0.027 |
| | | 34 | 17.60 ± 0.14 | 0.053 ± 0.023 |
| | | 36 | 15.76 ± 0.28 | 0.014 ± 0.004 |
| | 80 | 32 | 25.28 ± 0.37 | 0.085 ± 0.003 |
| | | 34 | 21.28 ± 0.14 | 0.108 ± 0.034 |
| | | 36 | 23.16 ± 0.14 | 0.060 ± 0.005 |
| | 100 | 32 | 29.36 ± 0.28 | 0.124 ± 0.032 |
| | | 34 | 26.32 ± 0.14 | 0.025 ± 0.002 |
| | | 36 | 24.72 ± 0.24 | 0.064 ± 0.060 |
| 10 | 60 | 32 | 21.60 ± 0.63 | 0.055 ± 0.011 |
| | | 34 | 22.48 ± 0.28 | 0.066 ± 0.005 |
| | | 36 | 21.20 ± 0.84 | 0.076 ± 0.005 |
| | 80 | 32 | 28.16 ± 0.50 | 0.068 ± 0.005 |
| | | 34 | 26.64 ± 0.83 | 0.059 ± 0.004 |
| | | 36 | 27.20 ± 0.14 | 0.060 ± 0.005 |
| | 100 | 32 | 34.96 ± 0.28 | 0.079 ± 0.003 |
| | | 34 | 36.72 ± 1.20 | 0.024 ± 0.007 |
| | | 36 | 35.68 ± 0.73 | 0.029 ± 0.005 |
| 20 | 60 | 32 | 20.72 ± 1.18 | 0.085 ± 0.002 |
| | | 34 | 20.88 ± 0.48 | 0.048 ± 0.010 |
| | | 36 | 19.16 ± 0.50 | 0.074 ± 0.006 |
| | 80 | 32 | 28.72 ± 1.94 | 0.047 ± 0.004 |
| | | 34 | 28.48 ± 0.28 | 0.084 ± 0.003 |
| | | 36 | 25.28 ± 0.14 | 0.079 ± 0.005 |
| | 100 | 32 | 35.76 ± 0.83 | 0.028 ± 0.005 |
| | | 34 | 35.04 ± 0.42 | 0.055 ± 0.009 |
| | | 36 | 33.44 ± 0.28 | 0.073 ± 0.002 |
| 30 | 60 | 32 | 21.44 ± 0.28 | 0.072 ± 0.003 |
| | | 34 | 20.16 ± 0.24 | 0.073 ± 0.006 |
| | | 36 | 19.44 ± 0.48 | 0.080 ± 0.002 |
| | 80 | 32 | 26.72 ± 0.77 | 0.061 ± 0.006 |
| | | 34 | 26.64 ± 0.48 | 0.068 ± 0.006 |
| | | 36 | 26.56 ± 1.41 | 0.064 ± 0.005 |
| | 100 | 32 | 34.40 ± 0.37 | 0.056 ± 0.005 |
| | | 34 | 32.96 ± 0.97 | 0.055 ± 0.002 |
| | | 36 | 31.76 ± 0.37 | 0.048 ± 0.004 |

Q—processing efficiency; SME—Specific Mechanical Energy.

During snack pellet extrusion without broccoli, a negative effect of increasing the raw material moisture level on the process efficiency was observed. In contrast, the addition of 10% fresh broccoli to the raw material mixture stabilized the initial moisture effect on the process efficiency changes, with minute differences being found between samples obtained at the same screw speeds. During extrusion-cooking of mixtures with 20% and 30% fresh broccoli at the highest screw speeds (100 rpm), a decrease in the process efficiency with increased mixture moisture level was observed.

The extrusion-cooking process of snack pellets with the broccoli addition was characterized by relatively low energy consumption (Table 1). SME values ranged from 0.014 to 0.124 kWh $kg^{-1}$ for snack pellets extruded at varied processing parameters and fresh broccoli addition levels.

During snack pellet extrusion-cooking without fresh broccoli, SME increased with an increase in screw speed. In addition, the increase in raw material moisture level caused a reduction in the energy consumption of the process. For these mixtures, we noted

the highest and lowest energy consumption values during extrusion. Accordingly, the lowest SME result (0.014 kWh $kg^{-1}$) was recorded for the control sample without vegetable additive processed using the highest level of moisture content (36% at 60 rpm), and the highest SME result (0.124 kWh $kg^{-1}$) was recorded for the sample extruded using 32% of the mixture moisture level at 100 rpm.

We also saw that the influence of the fresh broccoli addition on the energy consumption changes during the pellet extrusion process was ambiguous. Following an increase in screw speed, an increase in extrusion energy consumption was observed for mixtures with a 10% fresh broccoli addition and a 32% moisture level. The opposite tendency was found if the initial moisture level was increased for similar broccoli content. For mixtures with a moisture level of 36%, a decrease in SME value was observed with an increase in screw speed. The increase in the moisture level of the mixture contributed (in the majority of cases) to a reduction in extrusion energy consumption in the case of the process carried out at screw speeds of 80 and 100 rpm.

During the extrusion-cooking of snack pellets with a 20% fresh broccoli content, SME value increased with an increase in raw material moisture level when processed at 100 rpm. A similar effect was observed by Lisiecka and Wójtowicz [31] for snack pellets with a fresh vegetable addition. The extrusion-cooking of snack pellets with 30% fresh broccoli was characterized by the most stable energy consumption during processing under variable conditions. Moreover, a slight decrease in energy consumption was observed if the initial moisture of raw materials increased if extruded at 100 rpm. Some research shows that the SME value can be influenced by the combined effects of moisture level, fiber content, and processing temperature [33–35].

### *3.2. Effect of Variables on Selected Physical Properties of Snack Pellets*

During the tests, we noted that the mixture recipe had an influence on the snack pellet expansion index. In general, increasing the amount of fresh broccoli in the recipe significantly reduced the value of the expansion index of extruded snack pellets (Table 2) with a high correlation coefficient ($r = -0.898$). Bisharat et al. [36] noted similar dependencies for extruded corn crisps with a broccoli powder addition. Lisiecka et al. [32] also reported a decrease in the rice snack expansion index with an increase of fresh vegetable pulp addition. In our work, the highest value of the expansion index (3.05) for control snack pellets without fresh broccoli addition was obtained using the speed of the extruder screw set at 60 rpm with the moisture level of the mixture at 34%. The lowest value of the expansion index (1.43) was seen for samples with an initial moisture content of 32%, processed with a screw speed of 100 rpm, and incorporating a fresh broccoli addition of 30%. Despite the relatively high values of the expansion index, the obtained snack pellets were characterized by a compact structure without visible pores or bubbles.

Generally, as the screw speed increased, we noted an increase in the expansion index values. Bisharat et al. [36] saw the same effect during extrusion-cooking of corn flour and broccoli powder mixtures. Therein, the effect was greatest in the case of recipes with a 10% fresh broccoli addition. We discovered that the increasing moisture content of raw material mixtures led to a higher value of the expansion index. In the specific scenario of the extrusion-cooking process involving mixtures containing 20% fresh broccoli addition at a screw speed of 100 rpm, we observed that as the moisture level of the raw material mixture increased, there was a reduction in snack pellet expansion index.

The analysis of the bulk density of snack pellets manufactured using various recipes and process parameters shows that in most cases, both the initial moisture level of the extruded mixtures and the speed of the extruder screw had substantial influence on the values of the tested feature (Table 2). The highest bulk density value (379 kg $m^{-3}$) was documented for control snack pellets obtained from mixtures without fresh broccoli addition, with a moisture level of 32% and an extrusion process conducted at 100 rpm of screw speed. In contrast, snack pellets derived from a mixture containing 20% fresh broccoli at an

initial moisture content of 36% and processed at a screw speed of 60 rpm demonstrated the lowest bulk density value—256 kg $m^{-3}$.

**Table 2.** Results of expansion index, bulk density, and durability measurements of snack pellets depend on broccoli addition level and applied processing variables ([1] n = 5, [2] n = 3 ± SD).

| Fresh Broccoli Content [%] | Screw Speed [rpm] | Moisture Content [%] | Expansion Index [1] [-] | Bulk Density [2] [kg $m^{-3}$] | Durability [2] [%] |
|---|---|---|---|---|---|
| 0 | 60 | 32 | 2.63 ± 0.09 | 318.28 ± 6.88 | 99.63 ± 0.03 |
| | | 34 | 3.05 ± 0.36 | 326.91 ± 4.24 | 99.75 ± 0.02 |
| | | 36 | 2.82 ± 0.35 | 286.56 ± 9.20 | 99.83 ± 0.04 |
| | 80 | 32 | 2.90 ± 0.42 | 335.57 ± 8.36 | 99.63 ± 0.05 |
| | | 34 | 2.85 ± 0.35 | 320.98 ± 4.69 | 99.65 ± 0.06 |
| | | 36 | 3.03 ± 0.25 | 344.14 ± 10.48 | 99.76 ± 0.03 |
| | 100 | 32 | 2.89 ± 0.38 | 367.66 ± 9.84 | 99.57 ± 0.05 |
| | | 34 | 2.95 ± 0.28 | 317.01 ± 7.72 | 99.75 ± 0.01 |
| | | 36 | 2.62 ± 0.39 | 267.05 ± 6.82 | 99.77 ± 0.02 |
| 10 | 60 | 32 | 2.31 ± 0.17 | 349.93 ± 10.56 | 99.61 ± 0.03 |
| | | 34 | 2.17 ± 0.23 | 373.53 ± 2.25 | 99.68 ± 0.05 |
| | | 36 | 2.15 ± 0.45 | 357.51 ± 4.48 | 99.59 ± 0.06 |
| | 80 | 32 | 1.87 ± 0.22 | 369.00 ± 6.37 | 99.57 ± 0.13 |
| | | 34 | 1.93 ± 0.16 | 313.03 ± 8.79 | 99.61 ± 0.16 |
| | | 36 | 2.18 ± 0.27 | 327.76 ± 8.70 | 99.58 ± 0.06 |
| | 100 | 32 | 2.01 ± 0.33 | 311.73 ± 7.13 | 99.63 ± 0.04 |
| | | 34 | 2.24 ± 0.40 | 318.74 ± 8.57 | 99.63 ± 0.08 |
| | | 36 | 1.91 ± 0.38 | 296.53 ± 7.31 | 99.56 ± 0.02 |
| 20 | 60 | 32 | 1.88 ± 0.26 | 310.05 ± 9.75 | 99.62 ± 0.09 |
| | | 34 | 1.90 ± 0.18 | 273.89 ± 7.81 | 99.58 ± 0.04 |
| | | 36 | 2.06 ± 0.13 | 257.20 ± 3.73 | 99.73 ± 0.04 |
| | 80 | 32 | 2.17 ± 0.20 | 287.30 ± 1.70 | 99.64 ± 0.02 |
| | | 34 | 1.72 ± 0.23 | 309.86 ± 5.28 | 99.67 ± 0.13 |
| | | 36 | 2.04 ± 0.25 | 290.26 ± 9.77 | 99.62 ± 0.03 |
| | 100 | 32 | 1.89 ± 0.30 | 294.87 ± 6.60 | 99.59 ± 0.03 |
| | | 34 | 1.83 ± 0.27 | 305.51 ± 2.89 | 99.83 ± 0.09 |
| | | 36 | 1.72 ± 0.19 | 328.11 ± 9.95 | 99.55 ± 0.03 |
| 30 | 60 | 32 | 1.83 ± 0.20 | 297.61 ± 6.89 | 99.63 ± 0.04 |
| | | 34 | 1.60 ± 0.07 | 295.72 ± 6.76 | 99.77 ± 0.04 |
| | | 36 | 1.71 ± 0.19 | 308.81 ± 9.27 | 99.57 ± 0.08 |
| | 80 | 32 | 1.64 ± 0.26 | 307.04 ± 2.15 | 99.46 ± 0.03 |
| | | 34 | 1.70 ± 0.19 | 298.76 ± 10.56 | 99.63 ± 0.05 |
| | | 36 | 1.76 ± 0.20 | 309.78 ± 7.07 | 99.51 ± 0.12 |
| | 100 | 32 | 1.43 ± 0.12 | 323.38 ± 4.94 | 99.04 ± 0.04 |
| | | 34 | 1.49 ± 0.10 | 332.03 ± 1.52 | 99.48 ± 0.05 |
| | | 36 | 1.74 ± 0.14 | 299.49 ± 7.82 | 99.48 ± 0.10 |

In the case of snack pellets with 10% fresh broccoli, the value of the bulk density decreased as the speed of the extruder screw increased. Lisiecka et al. [32] noted a similar outcome during extrusion-cooking of directly expanded rice snacks with fresh vegetable pulp addition. In general, for pellets with 20% and 30% broccoli, the bulk density values increased with the increase in the speed of the extruder screw. Lisiecka et al. [20] also saw a similar tendency for snack pellets with an onion addition.

We noted that snack pellets processed through extrusion-cooking were characterized by excellent durability (Table 2). Indeed, throughout the testing, we determined that the extrusion-cooking parameters did not have an important impact on the durability of the obtained pellets. We observed that adding fresh broccoli to snack pellets allows for lower values of durability, but the correlation was low (r = 0.448). The lowest durability (99.06%) was recorded in the case of snack pellets obtained from mixtures with 30% fresh broccoli, a

moisture level of 32%, and extruded at a screw speed of 100 rpm. In contrast, the highest value of durability (99.88%) was observed for pellets obtained from mixtures without fresh broccoli addition, with a moisture level of 36%, and extruded with a screw speed of 60 rpm. Nevertheless, our results show that developed snack pellets seem to be very stable during transportation or storage, and only less than 1% of snack pellets were crushed or broken under simulation in a Pfost apparatus.

To indicate dependencies between the tested properties, we applied PCA analysis. As an outcome, five new variables were obtained, and the initial three principal components illustrate 79.22% of the variability of the entire system, while the first two principal components present 59.22% of the total variability of the system (Figure 2a). The parameters located within the two red circles have the most significant influence on its volatility (Figure 2a). Expansion ratio, SME, and efficiency have a slightly smaller impact on system variability than those that have the greatest impact (bulk density of snack pellet and durability of snack pellet). We observed a strong positive correlation between the bulk density of extrudates and SME. The same relationship was obtained for the durability of snack pellets and their efficiency. In turn, a strong negative correlation was shown between the durability of snack pellets, process efficiency, and expansion ratio. There was no correlation between the bulk density of snack pellets and SME or other parameters.

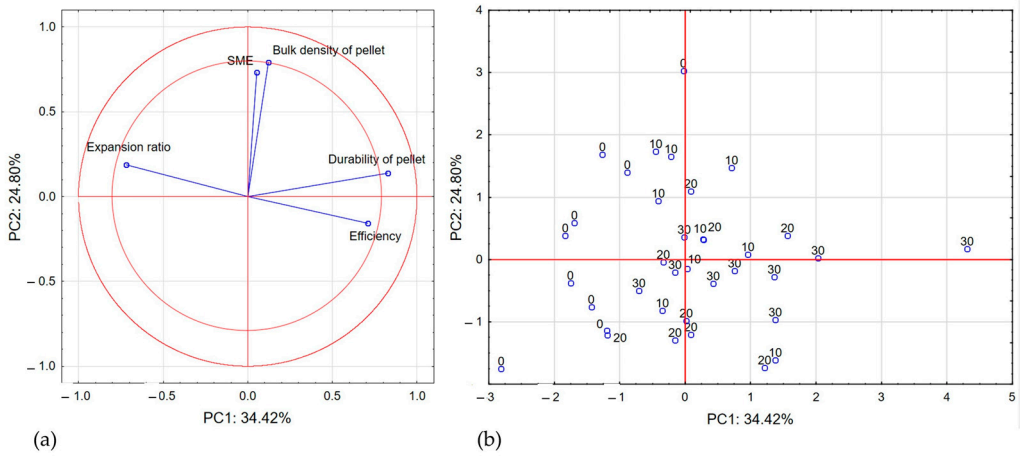



**Figure 2.** Loading plot (**a**) and score plot (**b**) of the principal component analysis (PC1 and PC2) carried out for the addition of fresh broccoli and tested parameters.

PCA analysis demonstrates that the first main component of PC1 describes the use of fresh broccoli as 34.42% of total variability (Figure 2b). Accordingly, positive PC1 principal component values describe the results of using a higher amount of fresh broccoli supplement, and negative PC1 principal component values describe the results of using no fresh broccoli supplement. The lack of fresh broccoli addition is characterized by the expansion ratio parameter, and the highest content of the additive correlates with the parameters of durability of snack pellets and process efficiency.

The first (PC1) and third (PC3) principal components reveal a similar relationship (Figure 3a,b). The first (PC1) and third (PC3) principal components describe 54.42% of the variability of the system. However, only three parameters in this system demonstrate the greatest influence on its variability. These are the expansion ratio, efficiency, and durability of snack pellets. Here, expansion ratio and durability of snack pellets are strongly negatively correlated, while efficiency and durability of snack pellets are positively correlated. In contrast, expansion ratio and efficiency are weakly and negatively correlated.

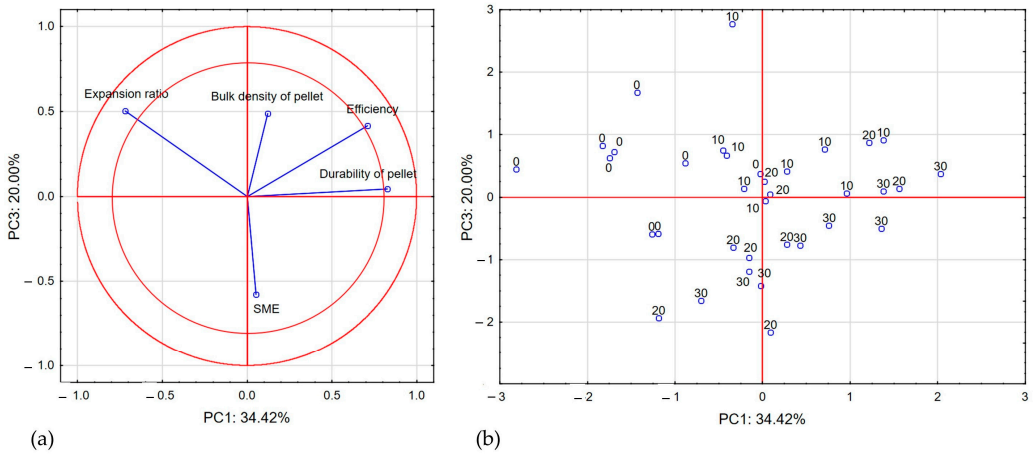



**Figure 3.** Loading plot (**a**) and score plot (**b**) of the principal component analysis (PC1 and PC3) carried out for the addition of broccoli and tested parameters.

Beyond the aforementioned, the expansion ratio parameter characterizes the lack of fresh broccoli addition, and the highest content of the additive correlates with the durability of snack pellets and less so with efficiency (Figure 3a,b). Raw material mixture moisture and extruder screw rotation had no effect on the obtained physical parameters, as was the case with the addition of fresh broccoli.

## 4. Conclusions

The extrusion-cooking process was conducted as an integral part of the LIDER X project, Contract No. LIDER/29/0158/L-10/18/NCBR/2019: "Development of a comprehensive technology of obtaining high-quality extruded snacks from plant and animal raw materials with a minimum degree of processing." The following conclusions were reached:

1. Higher extrusion-cooking process efficiency was observed for all raw material mixtures with the fresh broccoli addition. The control samples without the addition of fresh broccoli, processed at the lowest extruder screw speed and at the highest moisture level, showed the lowest process efficiency values;
2. The addition of fresh broccoli to the potato-based snack pellets processed by extrusion-cooking resulted in relatively low energy consumption. The energy consumption of the extrusion-cooking process for the new generation of fortified snack pellets was influenced differently by the screw speed and moisture level. During the extrusion of mixtures with 20% fresh broccoli content, we observed an increase in SME value along with an increase in the moisture level of the raw material mixtures. The extrusion of pellets with 30% fresh broccoli was characterized by stable energy consumption during processing;
3. In general, the increasing amount of fresh broccoli added to the processed mixtures reduces the value of the expansion index of the obtained snack pellets. We noted higher values of the expansion index as the screw speed and moisture level increased;
4. The extruded blend moisture content and the extruder screw speed had a significant impact on the bulk density values. Snack pellets with the addition of fresh broccoli showed reduced bulk density values;
5. We noted that the addition of fresh broccoli alone had an impact on the durability of snack pellets. Such an addition allowed for lower values of the tested feature;
6. Summarizing all the extrusion-cooking aspects and physical characteristics tested, the most functional snack pellets were obtained from a potato-based composition with 20% fresh broccoli addition, processed with 32% of the initial moisture level at 80 rpm screw speed.

**Author Contributions:** Conceptualization, M.C.; methodology, M.C., M.M. (Marcin Mitrus) and B.B.; software, M.G.; validation, R.R., M.M. (Marcin Mitrus), M.C., A.W. and J.S.; formal analysis M.M. (Marek Milanowski), M.C., M.G. and A.W.; investigation, M.C., B.B., M.M. (Marek Milanowski), K.K. and J.S.; resources, M.C. and R.R.; data curation, R.R., M.M. (Marek Milanowski), M.C., K.K. and M.G.; writing—original draft preparation, M.C., M.M. (Marcin Mitrus), B.B. and R.R.; writing—review and editing, M.C., A.W. and R.R; supervision, A.W. and R.R. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by The National Centre for Research and Development (NCBiR), grant number LIDER/29/0158/L-10/18/NCBR/2019, entitled "Development of a Comprehensive Technology of Obtaining High-Quality Extruded Snacks Based on Minimally Processed Vegetable and Animal Raw Materials".

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** All the data are contained within the article.

**Conflicts of Interest:** The authors declare no conflict of interest.

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