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Analysis of the extrusion-cooking process and selected physical properties of snack pellets with the addition of fresh kale**

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A b s t r a c t. The aim of the study was to evaluate selected properties of potato snack pellets fortified with fresh kale addition. Varying levels of fresh kale (10, 20 and 30%) were added in order to obtain a new type of fortified snack pellet as a semi-finished product for further expansion and their effects on processing stability as well as on selected physical properties were defined. The results showed that the applied variables (moisture content, screw speed and the addition of fresh kale) significantly affected the extrusion-cooking process and also certain selected physical properties of the snack pellets. Furthermore, increasing the addition of fresh kale up to 20 and 30% in the fortified snack pellets changed some of these properties (lower energy consumption, higher efficiency of the extrusion-cooking process, higher expansion index, lower bulk density of the pellets, lower durability). The application of up to 30% fresh kale in the newly developed extruded snack pellet formulations is recommended.

K e y w o r d s: extrusion-cooking, fresh kale, snack pellets, selected physical properties, processing parameters

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INTRODUCTION

Over the last few years, rapid technological development in food manufacturing has resulted in more and more attention being focused on the extrusion-cooking process (Oluwole *et al*., 2013). Extrusion-cooking is a type of high temperature short time (HTST) pressure and thermal treatment (Oniszczuk *et al*., 2019; Lisiecka *et al*., 2021b). During the process, raw materials, most often those of plant origin, are processed in an extruder in order to obtain products with pre-configured physical and chemical characteristics (Combrzyński and Özmen, 2021; Wójtowicz, 2018). The use of this type of equipment with a flexible and modifiable plasticizing system enabled the development of a new range of extruded products (Offiah *et al.,* 2019).

Even though extrusion-cooking basically seems to be a relatively simple process, adjusting and controlling the various in-process parameters may be very challenging. Among the basic factors influencing the physical and chemical properties of extruded mixes, are the following: the temperature in the individual extruder sections, the screw length and diameter ratio, the type of die used, and the type of raw materials included in the processed mix. When designing new products, the appropriate selection of ingredients in the raw material mixes is paramount. With regard to extrusion-cooking, the content of protein, starch, fibre, and fat is important as an excessive amount of any ingredient may cause process instability. These and other factors have a significant impact on the variety of extruded products produced; they also allow for the production of products with specific physical and chemical characteristics, which are, of course, intended to attract the interest of potential consumers (Pęksa, 2007).

Recent years have witnessed profound changes in the food market (Kantrong *et al.*, 2022; Wójtowicz *et al.,* 2019). Consumers expect to have access to easily digestible, convenient, and fortified foodstuffs that do not require an excessive preparation time. These products include snack pellets. They are obtained using the extrusion-cooking process, during which they take shape under increased pressure and temperature conditions, then they expand in oil or in hot air after the drying process (Trela and Mościcki, 2007).

The development of innovative raw material mixes based on various types of fruit and vegetables with a high degree of health enhancement potential allows for the manufacture of products with the desired physical and chemical properties (Pardhi *et al.*, 2019). A key factor in the extrusion-cooking process is energy consumption. The use of fresh fruit and vegetables can reduce the demand for water and energy consumption, as well as stabilizing the process as such (Ruiz-Gutiérrez *et al.,* 2018).

Kale (*Brassica oleracea* L. var. *Sabellica* L.) is ranked among the foods which are widely known as superfood vegetables. It contains polyphenolic compounds, such as quercetin and kaempferol in abundance. It is a rich source of vitamin K, vitamin C, carotenoids (β-carotene, lutein, zeaxanthin), and calcium. Like broccoli and other cruciferous vegetables, it contains sulforaphane. Kale is also an excellent source of iron and contains folic acid. It is a leafy plant with a relatively compact structure and jagged leaves. It can be obtained as a whole plant but also shredded and packaged, or deep-frozen. When used in the extrusion-cooking process, fresh kale should be properly fragmented into a semi-liquid structure. The addition of the right amount of kale to a recipe mix enhances the production capacity while reducing the power and water consumption of the extruder. This can be attributed to the physical and chemical properties of the plant, *i.e.* the high content of water and dietary fibre (Lisiecka and Wójtowicz, 2020; Flaczyk *et al.,* 2014). Functional additives, such as fruit and vegetables with a high antioxidant potential, which includes kale, are raw materials that are sensitive to high temperatures. As a consequence, their thermal treatment and the time that it is applied for determine the ultimate content of polyphenolic compounds. In summary, optimal conditions for the extrusion-cooking process must be created, which will be directly translated into the quality of the finished product and furthermore, will help to preserve the most valuable nutrients (Mazzeo *et al.,* 2011). Pressure and thermal treatment may lead to the release of many biological compounds, thus increasing their bioavailability (Bąk-Sypień *et al.,* 2017).

The aim of the study was to determine the course of the extrusion-cooking of snack pellets with the addition of kale depending on the applied variables (moisture content, screw speed and the addition of fresh kale). Next, certain selected physical properties of snack pellets were analysed.

MATERIALS AND METHODS

The description and evaluation of the extrusion-cooking of snack pellets with the addition of fresh kale which included tests concerning certain selected physical properties were performed in the laboratories of the Department of Process Engineering, in the University of Life Sciences in Lublin, in 2021.

The production of the snack pellets was based on pre-prepared recipes. They included the following raw materials:

– organically grown fresh kale (supplier: ANREKO Andrzej Gębka, Poland);

– SUPERIOR STANDARD potato starch (from Przedsiębiorstwo Przemysłu Ziemniaczanego Bronisław S.A., Poland);

– potato flakes (supplier: Zakłady Przemysłu Ziemniaczanego w Lublinie, Poland);

– potato grits (supplier: Zakłady Przemysłu Ziemniaczanego w Lublinie, Poland);

– vegetable oil (manufacturer: Zakłady Tłuszczowe „Kruszwica”, Poland);

– beet sugar purchased at a Lidl store (Poland);

– table salt purchased at a Lidl store (Poland).

During the first stage, the mixtures were prepared based on the recipes provided (Table 1).

The addition of fresh kale was planned at a level of 10, 20 and 30% by weight. Fresh kale was crushed in a Germin cup blender (Berlinger, Germany). Each of the 3 kg mixtures had appropriately modified proportions, depending on the amount of the plant additive used. In order to distribute

Table 1. Prepared mixes for extrusion-cooking process of snack pellets

Fresh kale	Potato			Vegetable oil	Beet sugar	Table salt
	starch	flakes	grits			
(%)						
0	71	12.5	12.5	2	1	1
10	61					
20	51					
30	41					

the ingredients evenly and stabilize the moisture content, the samples were sieved. Next, the samples were stored in a refrigerator for 24 h in order to stabilize the ingredient mixing process. In the following stage, their moisture contents were tested. The samples were then moistened until the desired value was reached in each case.

Before the extrusion-cooking process was initiated, samples were collected from the previously prepared mixtures stored for 24 h. Their moisture contents were measured using a Radwag MA 50 R moisture analyser (Radwag, Poland). Next, the samples were moistened to obtain moisture content values of 32, 34, and 36%. The mixtures were then sieved to make their composition and moisture level more homogeneous.

The extrusion-cooking process was performed in a single-screw extruder with an L/D ratio of 20 (length of the working part to the diameter of the screw). Next, tests were carried out at variable extruder screw speeds of 60, 80 and 100 rpm. These processing parameters were pre-selected for the initial trials with the use of various raw materials being regarded as optimal to obtain the appropriate structure of snack pellets and ensuring the stability of the production process. In Table S1 the effect of the variable processing conditions on the acceptability of the snack pellets as determined using preliminary tests is shown. The properties assessed to determine the degree of acceptability involved the material flow, structure, shape, surface structure, colour stability and also the presence of steam bubbles inside the snacks. More information is provided in the Supplementary Material section (Table S1).

The loose, moistened mixture was fed through the hopper to the extruder machine. The actual production of the snacks was carried out in the Zamak Mercator EXP-45-32 prototype single-screw extruder. The machine used was equipped with an additional compression and mixing section (L/D=4) which allowed for the attainment of a total length barrel L/D=20 and the more effective processing of raw materials. This design allowed for the intensive cooling of the processed material to be performed to avoid water evaporation and the formation of steam bubbles inside the structure of the pellets. The dough was forced through the extruder die (single flat opening 0.6 x 25 mm) into a ribbon shape. Next, the extrudate was routed through a system of rollers with a cooled cutting system, where the knives cut the dough to a size of 25×25 mm. The snack pellet formed was evenly spread on metal meshes and placed in a laboratory dryer in order to reduce the moisture content of the finished product. After being properly dried in the laboratory dryer to a moisture content of 8 to 10% (Fig. 1), the snack pellets were then placed in tightly closed containers. Throughout the subsequent research phases, samples were taken from the containers for testing purposes.

The study of the extrusion-cooking process was intended to determine the impact of (i) process variables, (ii) raw material mixes, and (iii) the addition of fresh kale on

Fig. 1. Snack pellets with the addition of 10% kale.

process stability, efficiency, and the quality of the obtained extrudates. The process efficiency was determined on the basis of the mass of each of the prepared mixtures which was determined directly after leaving the die every 30 s with constant processing conditions and feed rate for each sample. The time measurement was carried out using an electronic stopwatch; the pellet mass was measured using the WPS 210 scale. The process efficiency was calculated using the formula proposed by Alavi *et al.* (1999):

$$Q = \frac{m}{t}, \tag{1}$$

where: Q – process efficiency (kg h^{-1}), m – mass of feed extrudate (kg), t – measurement time (h).

The measurement was repeated three times for each mixture. The arithmetic mean of the measurements was adopted as the result.

During the extrusion-cooking process, the temperature in the individual extruder sections was recorded. The temperature was measured with an accuracy of 0.1°C. The measurement was performed using sensors placed in five extruder sections. The temperature of the extrudate leaving the extruder die was controlled using a pyrometer.

The measurement of the active power of the extruder was recorded using a measuring system installed in the machine. The value of the energy intensity was converted into the Specific Mechanical Energy (SME) using the formula provided by Matysiak *et al.* (2018):

$$SME = \frac{n}{n_m}\ \frac{O}{100}\ \frac{P}{Q}, \tag{2}$$

where: SME – specific mechanical energy (kWh kg^{-1}), n – extruder rotational speed measured with a tachometer (s^{-1}), n_m – extruder nominal speed measured with a tachometer (s^{-1}), O – extruder motor load versus maximum load (%), P – nominal power indicated by the control panel (kW), Q – process efficiency described above (kg h^{-1}).

The expansion index for the extruded snack pellets is equivalent to the ratio of the diameter of the obtained pellets to the diameter of the extruder die. The measurement was repeated five times. The arithmetic mean of the measurements was adopted as the final result. The expansion index was determined using the formula proposed by Wójtowicz *et al.* (2013):

$$X = \frac{d}{D}, \quad (3)$$

where: X – value of the expansion index (-), d – pellet snack diameter (mm), D – extruder die diameter (mm).

The bulk density of the obtained extrudates was measured on the basis of the BN-87/9135-09 standard and the literature on the subject (ASAE Standard, 1989). The measurement was repeated three times. The arithmetic mean of the measurements was adopted as the final result; the following formula was used:

$$\rho = \frac{m_u}{V}, \quad (4)$$

where: ρ – bulk density (kg m^{-3}), m_u – prepared sample mass (kg), V – vessel volume (m^3).

An analysis of the moisture level of the raw material mixtures and the finished products was carried out using the dryer method. The measurement of the moisture level using this method is aligned with the PN-EN ISO 712:2012 standard. In order to obtain the moisture results specified in the recipes, the mixtures were adequately moistened before being fed into the extruder based on the following formula (Jurga, 1985):

$$x = \frac{M\,(W_c - W_m)}{100 - W_c}, \quad (5)$$

where: x – amount of water required to moisten the raw material mixture (kg), M – material mass (kg), W_c – mixture moisture level specified in the recipe (%), W_m – actual mixture moisture (%).

The measurements were repeated three times for each sample. The arithmetic mean of the individual results were adopted as the final result. The results were rounded to 0.1%.

Durability was measured twice using the Pfost apparatus as a source of kinetic strength during rotation in a closed chamber. For that purpose, a 100 g sample was placed inside the apparatus chamber and rotated for 10 minutes. The weight of the uncrushed sample was subsequently determined in relation to the weight of the initial sample. Durability was confirmed using the formula:

$$D = \frac{m_u}{m_s}\,100, \quad (6)$$

where: D – durability (%), m_u – mass of pellets after tumbling (g), m_s – mass of pellets before tumbling (g).

Statistica software (v. 12.0, StatSoft Inc., Tulsa, OK, USA) was used to conduct the statistical analyses. The RSM with a squares approximation was used to investigate the dependence of the process-specific results on variable process parameters. A principal component analysis (PCA), an analysis of variance (ANOVA), and a determination of correlation were performed at the significance level of $\alpha = 0.05$. The PCA was used to determine the relationship between the addition of kale (%), the screw rotation (rpm) and the moisture (%), the durability of the pellets, expansion index, pellet bulk density, extrusion-cooking efficiency, SME and pellet temperature. The PCA data matrix for the statistical analysis of the results had nine columns and 108 rows. The input matrix was scaled up automatically. The optimal number of the principal components obtained in the analysis was established using Cattell's criterion.

RESULTS AND DISCUSSION

After the process of composing the raw material mixtures and testing their original moisture level, was complete all compositions were moistened according to the adopted methodology formula in order to achieve the desired moisture range. It was noted that the original moisture content of the mixtures increased with the growing addition of kale to the material. The mixtures with a 30% addition of kale (max. 26.6%) showed the highest moisture content, the lowest one was observed in the control mixtures (min. 13.9%). Ultimately, the moisture levels of the raw material mixtures after moistening fell within the range of 32 to 36%, as specified in the methodology.

When the top speed of the extruder screw was applied, the highest moisture level of the pellets produced was observed. This may be attributed to the greater degree of starch gelatinization which occurs during the extrusion-cooking process. In other words, the water trapped inside the pellets was not effectively removed at the pellet cooling stage. When the amount of water added in the recipe is increased, a higher level of moisture in the pellets was also reported. The observed relationships align with the results achieved by Matysiak (2019) who studied the impact of the extrusion-cooking parameters on the quality of the extruded pellets. The higher addition of kale also caused an increase in the moisture content of the pellets after production. The highest moisture content was reported in pellets with a 30% addition of kale, this occurred when the moisture content of the raw material mixture was 36% and the screw speed was set to 100 rpm (18.9%). In his research, Zambrano *et al.* (2022) also demonstrated the significant impact of the initial moisture content of mixtures. It had a substantial impact on the pellet microstructure, thus affecting the volume and the thickness of the pellet walls. They recorded the highest values for mixtures with the lowest water content (27%).

The following charts (Fig. 2) show the results of extrusion-cooking efficiency measurements performed during the production of snack pellets. The results depend on the pellet moisture content, the speed of the extruder screw, and the amount of kale additive.

The efficiency of the extrusion-cooking of the snack pellets using mixtures with different additions of kale and moisture contents exhibited varied results depending on the recipe used and the extruder screw speed. The main factor enhancing the process efficiency was the faster rotation of

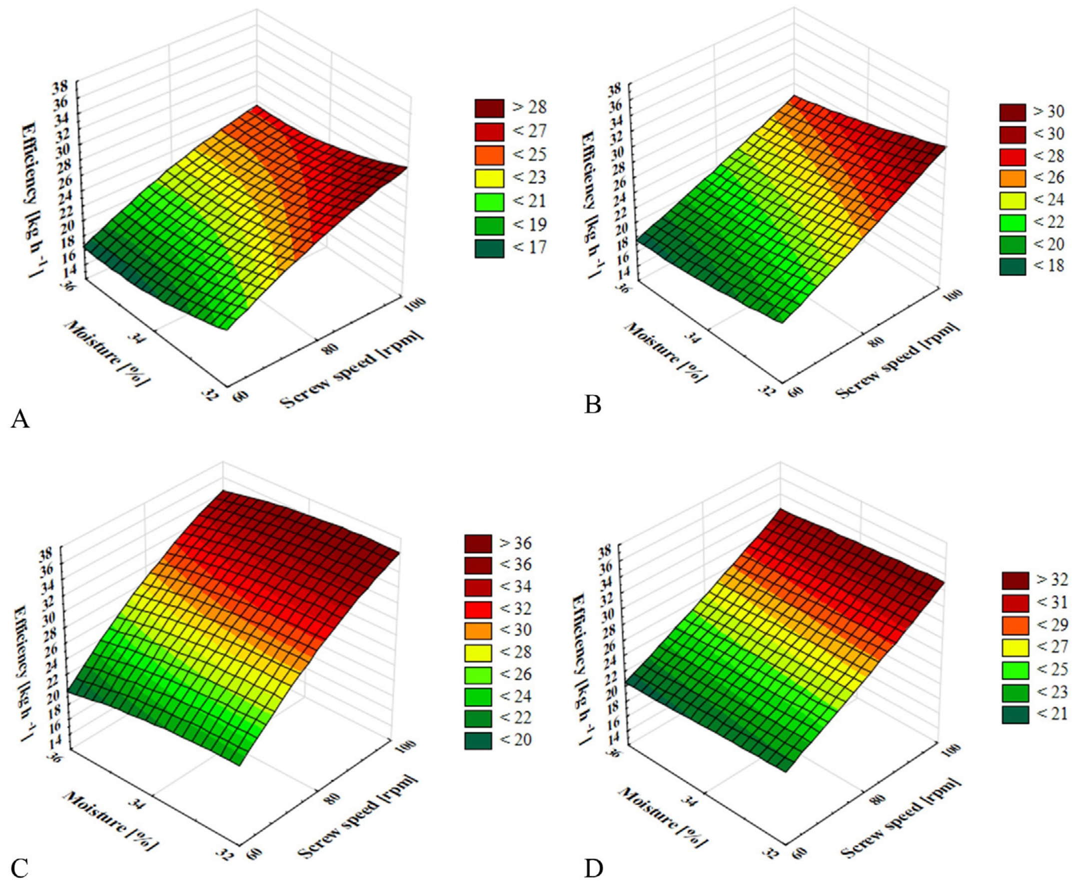

Fig. 2. Efficiency of the extrusion-cooking process for snack pellets with and without kale addition, depending on the moisture content and screw speed: A – without kale, B – 10% kale addition, C – 20% kale addition, D – 30% kale addition.

the screw and the lower moisture content of the processed raw material mixture. The higher screw speed and the lower water content of the mixture meant a faster material flow through the device and a greater efficiency of product extrusion on the die. Matysiak *et al*. (2018) demonstrated a similar trend. It was the speed of the extruder screw that influenced the efficiency of the extrusion of the starch-based pellets. Depending on the type of vegetables added to the mix, this efficiency may fluctuate due to the physical and chemical composition of the additive. However, in most cases, the efficiency of the extrusion-cooking process increases along with the higher screw speeds. During the extrusion of maize snacks, Lisiecka and Wójtowicz (2019) reported an efficiency level of 32-34 kg h^{-1}. In the case of all mixtures, production at the top rotational speeds of the extruder screw leads to the highest efficiency level of extrusion-cooking. When extruding a control sample (without kale) at a higher moisture content, the production process revealed a lower efficiency level. For raw material mixes with added kale, for the most part the mixtures with a 32% moisture content had a higher level of efficiency. The highest process efficiency occurred at a level of 36.96 kg h^{-1} and was recorded for a sample with a kale addition amounting to 20% of the total mass, for which the highest screw speed (100 rpm) was used at a moisture level of 32%, and the lowest (17.28 kg h^{-1}) for a mixture where the addition of kale was 10%, at 60 rpm and a 36% moisture content. Kręcisz *et al.* (2015) observed a similar relationship in her research. She noted that the higher the moisture level of the mixtures, the lower the efficiency of maize and rice extrusion: a drop from 24 to 18 kg h^{-1}.

The addition of kale in the amount of 20 and 30%, as compared to the pellets produced without it, resulted in a higher level of efficiency of extrusion-cooking. When kale was added to the raw material mixture in the amount of 10% it caused no significant changes in efficiency as compared to the blank samples. The top level of efficiency of the extrusion-cooking process was reported in mixtures moistened to a level of 32%. The processed material did not stick to the screw coils during processing, therefore it did not reduce the material flow, which was the case when the extruding samples had a higher degree of moistening.

During the extrusion-cooking process, the temperature was monitored in five sections using the internal system of the device. The temperature along the entire cylinder ranged from 48.0 to 65.8°C. The highest temperatures achieved for all mixtures were observed in the second section (64.1-65.8°C), while the lowest were noted in the first one (48.0-53.8°C). The temperatures of the subsequent sections of the extruder (section 3, section 4, section 5) were gradually lowered in order to stabilize the material inside. In addition, the temperature was also controlled after the material left the die.

Through analysing the data produced by the process it was established that a higher screw speed, despite the operation of the cooling system present in the extruder, was in most cases reported to cause a minor increase in temperature across all sections of the device. Despite the temperature differences, the stability of the process was maintained at a similar level and was considered appropriate.

The temperatures of the pellets leaving the die, both with and without the addition of kale, remained at a similar level. Minor temperature fluctuations depended mainly on the moisture content of the processed mix. The temperature decreased along with increases in the level of moistening of the processed raw material. The highest product temperature (80.5°C) was observed for the sample with a 20% addition of kale and an initial moisture content of 34%, it was processed at 100 rpm; the lowest temperature (64.9°C) was recorded for the sample with a 10% addition of kale and an initial moisture content of 36%, it was processed at 80 rpm. The addition of 20% kale to the raw material mixture generated a higher temperature of the product leaving the die as compared with pellets obtained from a control mixture sample without kale. During the extrusion-cooking of the mixtures with the addition of 30% kale, a clear drop in the temperature of the final product was recorded. The processing of the raw material mixtures with a higher moisture content caused a decrease in temperature in successive sections of the extruder, as the higher amount of water in the processed material created a cooling effect inside the extruder. It also caused a lowering of the temperature of the final product leaving the die.

The graphs below (Fig. 3) show the energy intensity results of the extrusion-cooking process.

The parameter that had the most substantial influence over the energy intensity of the extruder operation was the applied screw speed. The higher the speed, the greater the energy consumption during snack pellet extrusion-cooking. This process parameter also changed significantly depending on the moisture content of the processed raw material mixture and the addition of kale. For the control samples, i.e. the mixtures without kale, the highest energy intensity of the process was recorded for mixtures with a moisture content of 32% (0.1336 kWh kg^{-1}) processed at a screw speed of 100 rpm. The lowest SME value was observed

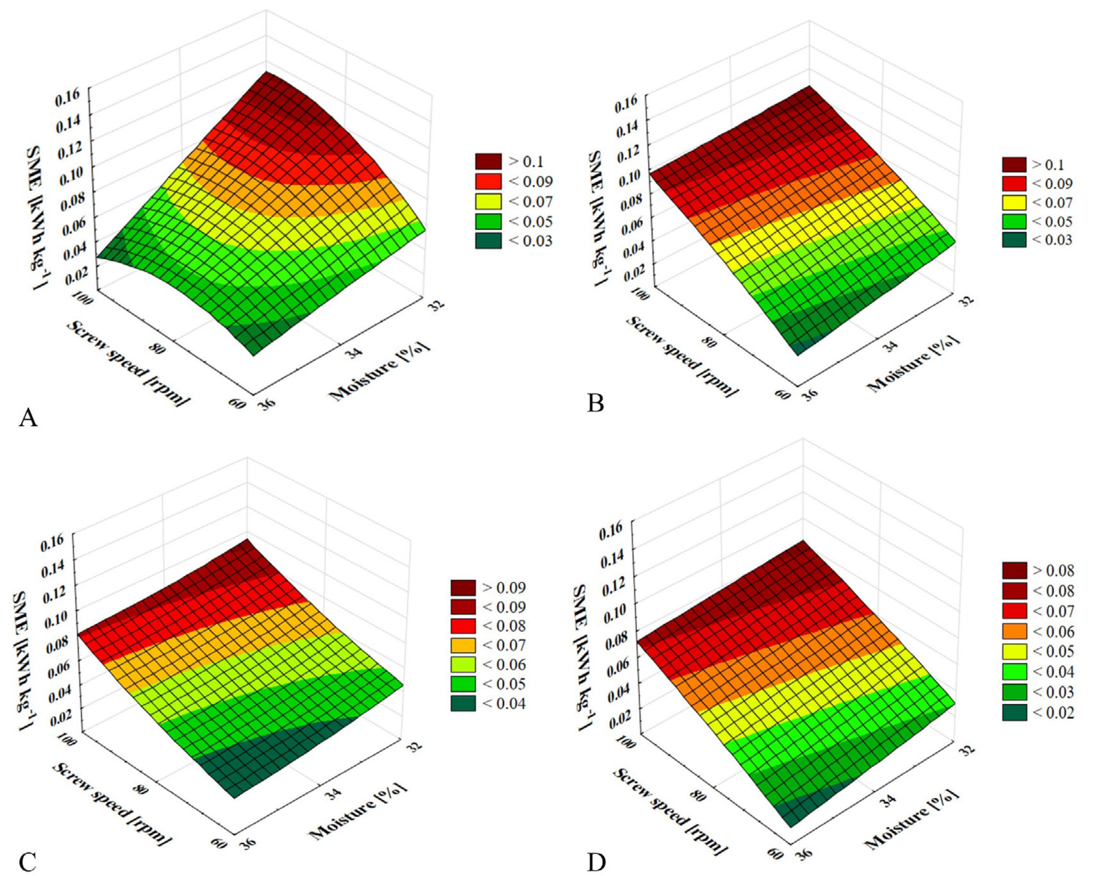

Fig. 3. SME of the extrusion-cooking process for snack pellets with and without kale addition, depending on the moisture content and the screw speed: A – without kale, B – 10% kale addition, C – 20% kale addition, D – 30% kale addition.

in samples with a 30% addition of kale, this was obtained from a mixture with a moisture content of 36% processed at 60 rpm (0.0096 kWh kg^{-1}). When kale was added to the raw material mixture, the energy consumption of the process decreased as compared to the control samples. This may have been due to the higher content of fibre in the samples with kale. As a filler, it facilitated the movement of the material through the cylinder, thus reducing the requirements for electrical power during the production of this type of snack pellet.

For the mixtures with the addition of kale, higher SME values were also noted along with higher extruder screw speeds. In addition, the consumption of energy during extrusion was also higher for mixtures with a lower level of moisture content. Trela and Mościcki (2007) and Singh *et al.* (2014) made similar observations. They demonstrated that an increase in the moisture content of the raw material mixtures determined the power consumption during pellet production. The samples processed with a higher moisture content required less power in the extrusion-cooking process as compared to the mixtures with a lower moisture content. Singh *et al.* (2014) also noted that the higher moisture content of the mixtures reduced the SME value. This is due to the occurrence of the lubrication effect in the extruder cylinder. It reduces the demand for the energy required to process and transport the material to the die. The results match the conclusions drawn by Delgado-Nieblas *et al.* (2012). They noted that the SME value increased along with the decreasing moisture content. Also, the higher moisture level of the mixture reduces friction during the processing of the raw material in the extruder cylinder.

The charts below (Fig. 4) show the results of the measurements of the expansion index of the pellets obtained from the extruder die.

During the tests, the influence on the pellet expansion index of the type of recipe used to make the raw material mixture was observed. The reported differences not only depended on the presence of kale but also on its percentage content in the mixtures. The highest values of the expansion index were recorded in pellets with 20% kale (1.96). This was the case in the pellets obtained from the mixtures with a 36% moisture content when applying 100 rpm in the extrusion-cooking process. The lowest average values were reported in samples with a 10% kale addition and an initial moisture content of 36% extruded at 80 rpm and in control samples with an initial moisture content of 36% and

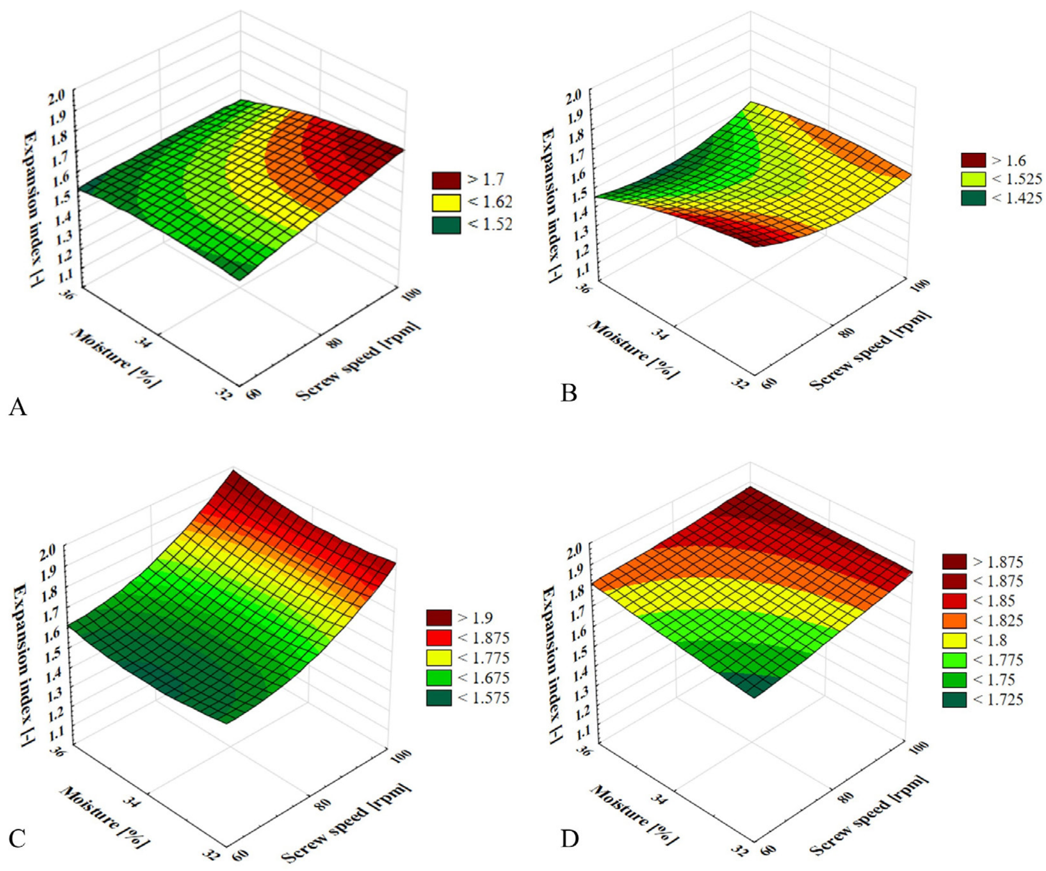

Fig. 4. Results of the analysis of the expansion index of the snack pellets with and without kale addition, depending on the moisture content and screw speed: A – without kale, B – 10% kale addition, C – 20% kale addition, D – 30% kale addition.

processed at 100 rpm (1.27 and 1.43, respectively). The increasing amount of kale in the pellets was confirmed to have increased the expansion index. This may have been due to the higher fibre content in such pellets, which made the process of pellet expansion in the die less problematic. In the vast majority of the tested samples with a 20 and 30% kale addition, the pellets made from mixtures with the highest moisture content of 36% exhibited the highest expansion index.

The speed of the extruder screw applied during the production of the pellets had a greater impact on the expansion index of the obtained extrudates. Matysiak (2019) observed the opposite trend when studying snack pellets. While researching third generation extrudates, the authors (Neder-Suárez *et al.,* 2021) demonstrated the positive effect of a higher screw speed and of the reduced initial moisture content of the mixtures on the pellet expansion index. A lower moisture content raised the internal pressure, which contributed to starch dispersion in the polymer phase, thus leading to an increase in product expansion. In the case of maize crisps, Wójtowicz *et al.* (2012) observed a lower expansion index coupled with an increase in the percentage addition of flax to corn snacks. They showed that the crisps without flax returned the highest value of 5. A proportional increase in the addition of flax at 2.5% reduced the expansion index by 5-10% as compared with the previous value.

Figure 5 shows the results of the analysis using the RSM with a squares approximation, this was obtained after matching the results of the bulk density measurements of the extruded pellets to the model. The results show different moisture contents depending on the screw speeds and fresh kale addition.

An analysis of the bulk density of the pellets produced using various recipes and process parameters shows that, in most cases, the degree of moisture content of the various mixtures before the extrusion-cooking process and the speed of the extruder screw had a significant impact on the value of the tested property. In tests where the amount of added kale was 0, 10 and 30%, an evident increase in the bulk density of the pellets was noted along with the falling moisture content of the raw material mixture processed by extrusion. The highest value of bulk density (379 kg m^{-3}) was recorded for a control sample produced at a 32% moisture content of the raw material mixture processed at 100 rpm. By contrast, the lowest measured value of the studied parameter (194 kg m^{-3}) was recorded in pellets obtained from the raw material mixture with the addition of 30%

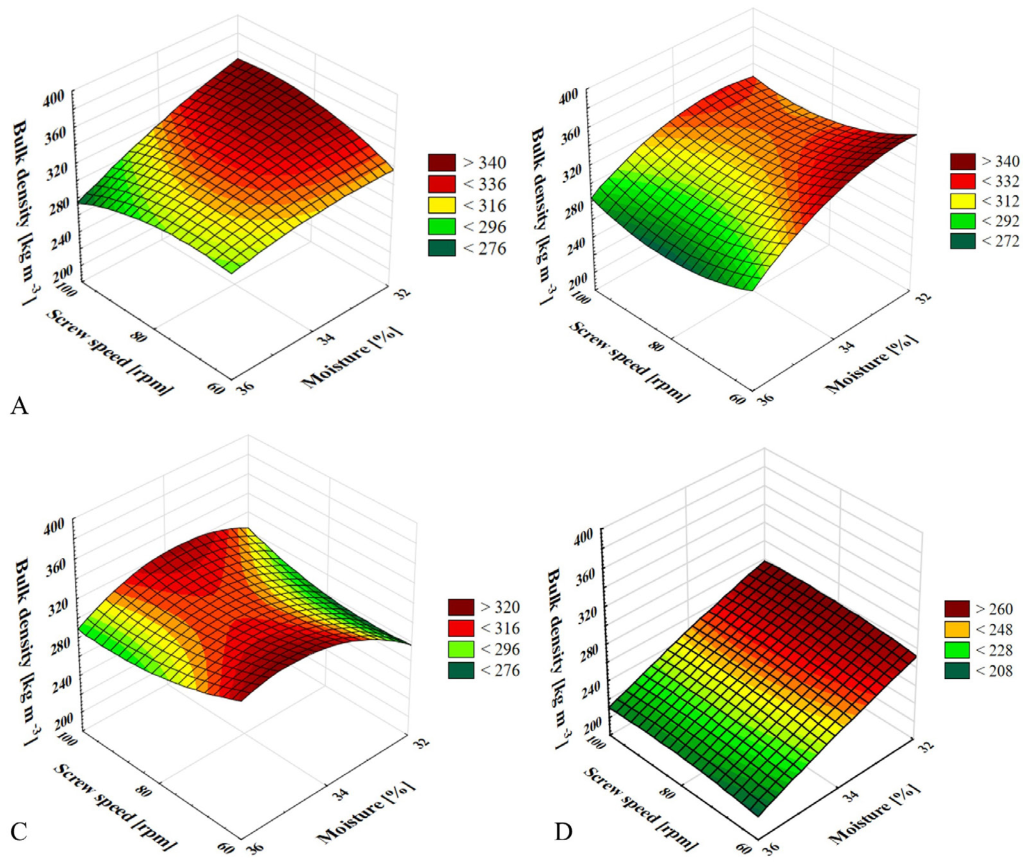

Fig. 5. Results of the measurement of the bulk density of snack pellets with and without kale addition, depending on the moisture content and screw speed: A – without kale, B – 10% kale addition, C – 20% kale addition, D – 30% kale addition.

kale and an initial moisture content of 36%, processed at 100 rpm. In the case of mixtures with 20% kale, the highest average values were recorded for samples with a moisture content of 34% (348 kg m^{-3}). For this amount of kale addition, the screw speed had no significant effect on the result. In general, the higher addition of kale to the raw material mixture reduced the bulk density of the obtained pellets.

Trela and Mościcki (2007) confirmed the impact of the moisture content of the mixture and the screw speed on the bulk density of pellets. They showed how the pellet density increased along with the higher screw speed and lower moisture content of the processed raw material mixtures. In their research with maize pellets, Lee *et al.* (2000) obtained the highest bulk density level for one of the lowest moisture content levels (10%). A slight increase in the moisture content of mixtures above 10% caused a large decrease in bulk density. They justified their observations by referring to the limited water vapour pressure inside the pellet, which limited its swelling and expansion, thus lowering the bulk density value. Lisiecka *et al.* (2021a) also confirmed the increased bulk density of the pellets with an increase in the screw speed.

Lisiecka and Wójtowicz (2021) reported that the bulk density of potato-based pellets ranged from 340.6 to 466.5 kg m^{-3} when processed with a single screw extruder with a configuration of L/D=18. This means that the results obtained for the elongated extruder barrel L/D=20 allowed for the attainment of a lower bulk density of potato pellets. Snack pellets supplemented with fresh beetroot from 2.5 up to 30% showed a bulk density which ranged from 299.2 to 361.3 kg m^{-3}. Lisiecka *et al.* (2021b) determined the bulk density of onion and leek supplemented snack pellets up to a moisture content of 30% and processed with L/D=18 and they found that the bulk density varied from 216.6 to 391.6 kg m^{-3}. Much lower values for snack pellets supplemented with fresh kale were obtained when an elongation plasticizing unit was applied during the experiment (they ranged from 194 to 348 kg m^{-3}).

In the case of pellets produced without kale, it was observed that the higher extruder screw speeds resulted in a higher degree of durability for the samples extruded at levels of moisture of 32% and 34% (Fig. 6A). The highest level of durability (99.85%) was observed in a sample extruded at a level of moisture of 36% and a screw speed of 60 rpm.

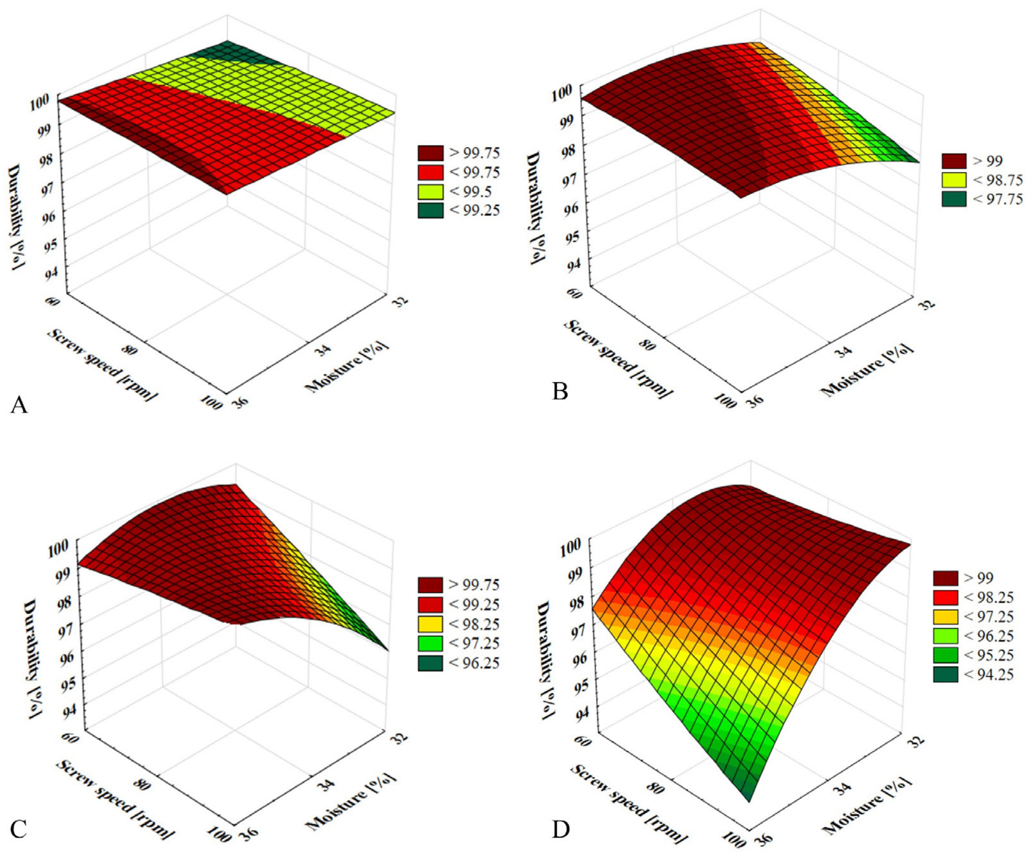

Fig. 6. Results of the measurement of the durability of snack pellets with and without added kale, depending on the moisture content and screw speed: A – without kale, B – 10% kale addition, C – 20% kale addition, D – 30% kale addition.

With the addition of kale at a level of 10 and 20%, a significant decrease in durability was recorded for samples extruded at 80 and 100 rpm (Fig. 6B and C). In the case of pellets with kale at 10 and 20%, across the entire range of screw speeds tested, the highest level of strength was reported in samples subjected to extrusion at a level of moisture of 36%. For pellets with kale at 30%, a much lower level of durability was noted in samples with a 36% level of moisture across the entire range of applied screw speeds (Fig. 6D). The lowest durability level (92.65%) was recorded for one sample produced using the highest values of process variables. In the case of pellets with this share of the additive, the peak strength across the entire range of applied screw speeds was seen in samples with a 32% level of hydration.

The first two components reflect 67.9% of the variability of the entire data set. The parameters falling within the two red circles have the greatest impact on the variability of the system (*i.e.* all of them, except for the pellet bulk density and the pellet temperature, Fig. 7). The durability of the pellets is negatively correlated with the pellet bulk density but the pellet bulk density has less influence on system variability than the durability of the pellets. There is also a positive and weak correlation between the expansion index and the durability of the pellets. There is a weak and negative correlation between the durability of the pellets and the SME. A 0% addition of kale has the greatest effect on the pellet bulk density (Figs 7 and 8). For a 30% addition of kale, a substantial effect on the durability of the pellets was confirmed (Figs 7 and 8).

The PCA shows a first principal component (PC1) at 37.20% and a PC 2 value at 29.90% which refers to the use of kale addition (blue arrow). The pellet bulk density refers

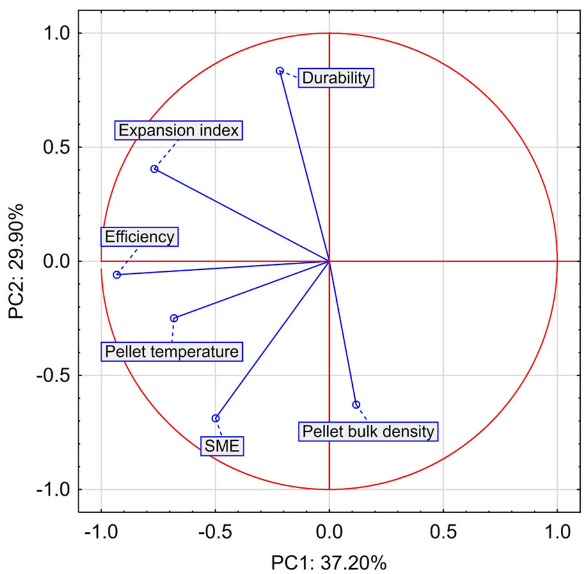

Fig. 7. Projection of variables onto the factors plane.

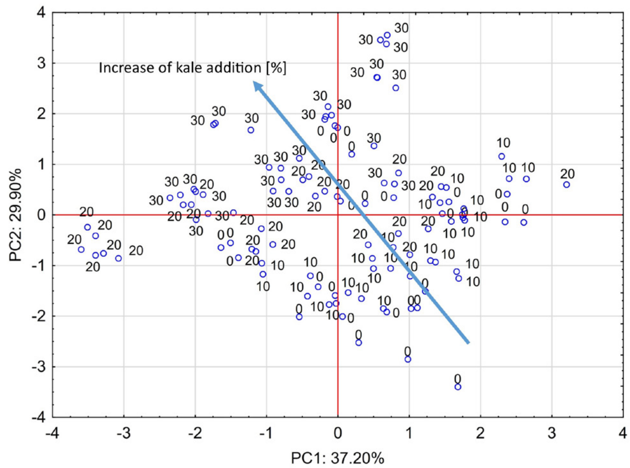

Fig. 8. Projection of cases on the factors plane.

to the product without the additive (Figs 7 and 8). The negative values of PC1 and the positive values of PC2 describe the product with a 30% addition of kale and the parameters that it affects.

CONCLUSIONS

The extrusion-cooking process of a new range of snack pellets was carried out using the Zamak Mercator EXP-45-32 prototype single-screw extruder. Research conducted on the extrusion-cooking of snack pellets with the addition of fresh kale was used to develop preliminary technological guidelines that will allow for the lab results to be applied on an industrial scale. Selected physical properties of the obtained snack pellets were studied. The study focused on the effect of the conditions applied and the sequence of the extrusion-cooking process used on the quality of the pellets obtained (semi-finished products). The process was carried out as a 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 drawn from the research conducted and a thorough analysis of the measured effects of the extrusion-cooking process parameters and the raw material recipes used:

1. High-quality snacks were obtained owing to the design of the appropriate recipe mixtures and the use of fresh kale as an additive in the amount of 10 to 30%. The composition of the raw material mixtures and the applied extrusion-cooking parameters allowed for the manufacture of a finished product with a high production potential. The extrusion-cooking process did not lead to any adverse results, which additionally confirms the applicability and the implementability of the research results.

2. The appropriately low moisture content of the mixtures – approx. 32% – and the high speed of the extruder screw (100 rpm) increased the efficiency of the extrusion-cooking process even with the relatively high energy intensity of the manufacturing process.

3. A higher moisture content of the processed recipes and a higher percentage share of fresh kale content in the raw material mixtures created a lower unit demand for energy during the extrusion-cooking process.

4. With an increase in the amount of water in the raw material mixtures and a lower share of fresh kale in the recipes, the expansion index of the obtained products decreased.

5. More fresh kale in the raw material mixtures resulted in a higher level of moisture and a lower rotational speed of the extruder screw during production which reduced the bulk density of the pellets obtained in the extrusion-cooking process.

6. The addition of fresh kale to the raw material mixtures up to a value of 20% resulted in a lower moisture content and a higher screw speed which allowed for the attainment of a lower durability of snack pellets.

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

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