

## THE PRODUCTION EFFICIENCY AND SPECIFIC ENERGY CONSUMPTION DURING PROCESSING OF CORN EXTRUDATES WITH FRESH VEGETABLES ADDITION

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### ABSTRACT

The aim of the work was to determine the influence of screw speed and variable amounts of fresh vegetable additives on selected aspects of extrusion-cooking of corn-vegetable blends. Corn grit as a basic component was supplemented with a fresh pulp of beetroot, carrot, leek and onion in amounts of 2.5-10% in the recipe. The extrusion-cooking was carried out using a single-screw extruder in the temperature range 120-145°C and extrudates were formed into directly expanded snacks. Two indicators were measured: the production efficiency ( $Q$ ) and the specific mechanical energy ( $SME$ ) consumption. As a result of the findings it was noted that the rotational speed of the extruder's screw showed a greater impact on both production efficiency and  $SME$  as compared to the variable amounts of applied additives. A tendency to increased efficiency and specific mechanical energy consumption was observed along with the increase of screw speed during processing. The highest production efficiency was observed if fresh leek and onion were used as additives and the highest extrusion speed screw was applied. The largest specific energy consumption was noted during the extrusion-cooking of blends containing fresh carrot and onion addition at high screw speed.

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## Introduction

Vegetables are very important sources of vitamins, micro- and macroelements as well as fiber in a daily diet. Consumption of fresh or minimally treated vegetables may avoid civilization diseases, such as cancer, cardiovascular disease or others. However, widespread dissemination of this knowledge does not increase the consumption of fruit and vegetables (Rekhy et al., 2017; Ocean et al., 2019). The most typical long-term preservation for vegetables is freezing, but it being an extremely power-consuming process (Korotkiy et al., 2016). Moreover, the findings for frozen vegetables demonstrate that transformation from its natural

state into frozen ones lead to negative products evaluations by consumer (Connell et al., 2018). While among the drying methods, lyophilization shows best effects for vegetable properties. However, this method is time and energy consuming (Yu et al., 2018). The most appropriate trend seems to be limiting treatment and using or eating the fresh or blanched vegetables to avoid losses of the valuable components and to keep its natural colour, flavour and texture.

Extrusion-cooking – a process using the high pressure and short time treatment - is the technology which creates the possibility of typical products' fortification, like e.g. snacks, with nutrient-rich ingredients (Wójtowicz, 2018). Extrusion-cooking have a lot of advantages, for example wide range of extrudates shapes, destruction of undesirable antinutritional factors, enhance the digestibility and makes it possible to achieve the desired texture (Shah et al., 2016). One of the most important classification of single screw extruders is the classification due to the L/D ratio (ratio of screw length to its diameter). L/D=9-11 is typically used for pasta press, 12-15 for high-pressure extruders, 15-30 for low-shear extruders, 15-25 for high-shear extruders and 3-5 for collet-type extruders to produce snacks (Harper, 1981; Mercier et al., 1989). From the literature it can be found that the specific energy consumption of the extrusion-cooking process in the case of single screw extrusion is dependent on the raw materials used, moisture content and screw speed applied. However, it should be noticed that the extrusion process is preceded by other processes, which may include grinding, mixing, moistening or steaming, that may influence on the total specific energy consumption of processing (Marks, 2010; Matysiak et al., 2018).

The most commonly used raw materials for ready to eat extrudates are cereals or pseudo-cereals, mainly corn, rice or wheat, rich in carbohydrates, enabling formation of a porous structure of the extruded snacks. However, these types of basic raw materials are not rich enough in nutrition compounds (Pełsa et al., 2016). So, it is possible to improve the nutritional value of extrudates by the addition of various components such as vegetables, fruits, herbs, etc. These additives are mainly used in a powdered state, but there is limited information about processing of extrudates supplemented with fresh vegetable additives. So, some tests have been made to check the possibility of using fresh vegetable pulps as valuable additives which haven't been air-dried or freeze-dried before the extrusion, what result in reducing the total energy requirements of the whole production process.

## **Objective, scope and methods of research**

The objective of the research was to evaluate the production efficiency and the specific energy consumption during processing of snacks with the single-screw extrusion-cooking. The main assumption was to obtain ready to eat corn snacks with possibly the largest amounts of fresh vegetables and to assess some aspects of the production process as the production efficiency and specific energy consumption.

The recipe of extrudates was based on corn grits (supplied by Lubella Sp. z o.o. Sp. K., Lublin, Poland) and vegetable additives, such as beetroot, carrot, leek and onion (commercially available on the market). Corn grit (as a control sample) and blends with variable amount of additives as replacement of the corresponding amount of the base ingredient in the recipe were prepared. Two independent variables were used in the experiment: the content of vegetable additives (2.5, 5.0, 7.5 and 10.0% as a replacement of corn grits in the recipe)

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and the speed screw (80, 100 and 120 rpm) during processing. In the first step, fresh vegetables were cleaned with tap water, removed from inedible parts, drained, cut into small pieces and then ground using a laboratory grinder (Grindomix GM 200, Retsch, Germany). In the next step, the ground additives were mixed with corn grits and left to rest for 2 h to equilibrate the moisture content brought by the fresh additives in the mixture. The moisture content of corn was 13.0% and for prepared blends ranged at 15.1%-20.8%, 14.2%-21.0%, 14.4%-20.0% and 14.3%-18.6% if beetroot, carrot, leek and onion were added, respectively. Extrusion-cooking was done using a TS-45 single-screw extruder-cooker (Z.M.Ch. Metalchem, Gliwice, Poland) with a ratio of the screw length to its diameter of L/D=12 at variable screw speeds with a 3 mm circular forming die. The temperature in the first, second and third section of the extruder was set at 120°C-145°C-130°C, respectively. Just after leaving a forming die the extrudates were cut with a rotary cutting knife for 30 mm long crisps. After forming, the snacks were cooled down to ambient temperature and collected as ready for direct consumption. Moreover, final extrudates characterized with the moisture content not exceeding 13% and the water activity below 0.56.

Evaluation of the extrusion-cooking efficiency ( $Q$ ), as a ratio of the extrudate mass obtained in a time unit, was determined according to the formula proposed by Matysiak et al. (2018):

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

where:

- $Q$  – production efficiency,
- $m$  – mass of the obtained snacks, (kg)
- $t$  – measurement time, (h)

Specific mechanical energy ( $SME$ ) as a power consumption was determined according to the formula presented by Kręcisiz et al. (2016):

$$SME = \frac{n \cdot P \cdot O}{n_{max} \cdot 100 \cdot Q} \text{ (kWh kg}^{-1}\text{)} \quad (2)$$

where:

- $SME$  – specific mechanical energy,
- $n$  – screw rotations, (rpm)
- $P$  – electric power, (kW)
- $O$  – engine load, (%)
- $n_{max}$  – maximum screw rotations, (rpm)
- $Q$  – production efficiency, (kg h<sup>-1</sup>)

Statistical analysis was carried out using a Statistica 13.3 software (StatSoft, USA). The data were analyzed with the response surface (RSM) models and plots to analyze interactions of two independent factors, additionally regression equations and regression coefficients have been found. A second-order polynomial model (Eq. 3) was defined to fit the responses:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} (X_1)^2 + \beta_{12} X_1 X_2 + \beta_{22} (X_2)^2 \quad (3)$$

where:  $Y$  is the response obtained by the fitted model and  $\beta_0$  is the model intercept.  $\beta_1, \beta_2$  are the linear coefficients,  $\beta_{12}$  is the interaction coefficient, and  $\beta_{11}, \beta_{22}$  are the quadratic coefficients. An analysis of variance was carried out with ANOVA at the level of confidence  $\alpha=0.05$ .

## Results and analysis

The results of the extrusion-cooking production efficiency during processing of corn extrudates with addition of different vegetables under various screw speed is presented in Fig. 1. An increased process output was noticed for all the tested samples with increased the rotation screw speed. Due to the effect of additive amount it have been found some differences and increasing efficiencies were observed for extrudates supplemented with beetroot (Fig. 1a), leek (Fig. 1c) and onion up to 5.0% (Fig. 1d). Further supplementation with beetroot, leek and onion affected slight decrease in processing output.

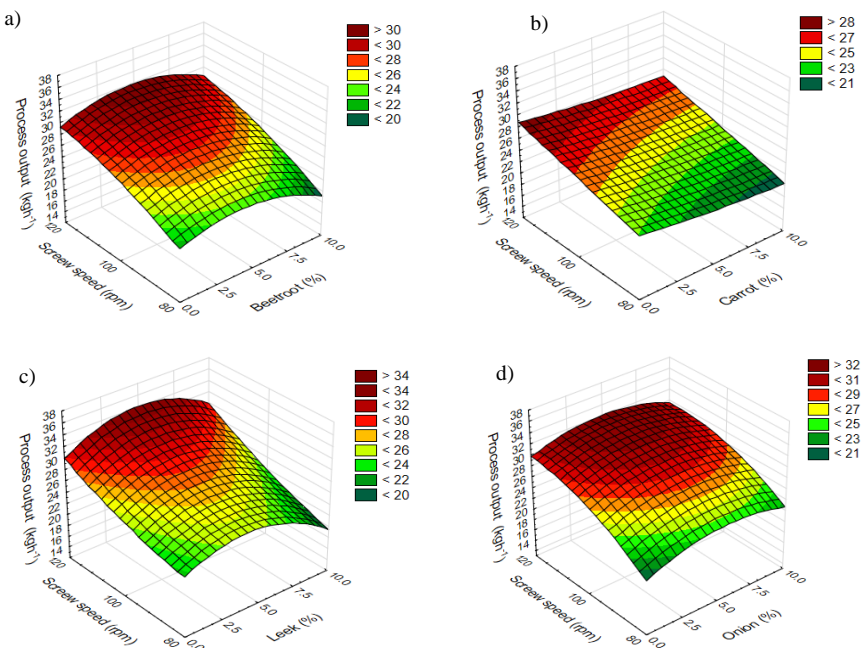


Figure 1. Production efficiency results during the extrusion-cooking of corn extrudates with addition various vegetables: a) beetroot, b) carrot, c) leek, d) onion

When a carrot was used as an additive, the constant decrease of efficiency was observed during processing of supplemented extrudates (Fig. 1b), also for this additive the lowest efficiency was observed along with the amount of vegetable additive as well as the screw

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speed applied. During the production of corn instant grits with using various screw speeds of single screw extruder, Kręcis (2016) found similar tendency to increasing processing efficiency in respect to increased screw speed. Similar relationships have been observed by Kręcis et al. (2015) for corn-rice instant grits produced with using screw speeds of 80,100 and 120 rpm, however, the results showed that blends with higher rice flour content characterized with higher process efficiency.

The highest production efficiency (above 34 kg h<sup>-1</sup>) was observed for corn extrudates with addition of 2.5 and 5.0% of leek and for snacks with 5.0% of beetroot and onion produced with applying the 120 rpm of screw speed. With the highest content of fresh vegetables, the production efficiency decreased what would be the effect of the increased moisture content of processed blends. The lowest production efficiency (19.2 kg h<sup>-1</sup>) was observed for corn-beetroot extrudates with 10.0% of additive with using a screw speed of 80 rpm. High determination coefficients characterized good model fitting due to the production efficiency if beetroot, carrot and leek were found in the experiment (Table 1). The analysis of variance (Table 2) showed that the content of vegetable additives had a significant effect on production efficiency only for corn extrudates with addition of beetroot ( $p=0.000$ ,  $r=0.93$ ) and leek ( $p=0.043$ ,  $r=0.97$ ), which, moreover, characterized similar responses from RSM plots. In the same time, the screw speed had a significant effect on production efficiency of corn-based blends with beetroot ( $p=0.000$ ,  $r=0.93$ ), carrot ( $p=0.000$ ,  $r=0.91$ ) and onion ( $p=0.000$ ,  $r=0.88$ ). The most significant effect, due to the highest value of F-test, according to the effect of the amount of additive was observed if beetroot was applied as additive, but if the effect of screw speed was analyzed, the most significant effect was found for corn-carrot blends.

Table 1.  
*Multiple regression equations and determination coefficients of production efficiency and specific energy consumption models for various additives in extruded blends*

Additive	Dependent variable	Regression equation	R <sup>2</sup>
Beetroot	$Q$	$Q = -19.5806 + 0.69CA + 0.7236SS - 0.1207CA^2 + 0.0036CA \cdot SS - 0.0026SS^2$	0.86
	$SME$	$SME = 0.2657 - 0.003CA - 0.0012SS + 0.0008CA^2 - 5.93E^{-5}CA \cdot SS + 9.89E^{-6}SS^2$	0.71
Carrot	$Q$	$Q = 10.3063 - 0.5266CA + 0.168SS + 0.0155CA^2 + 0.0014CA \cdot SS - 0.0001SS^2$	0.82
	$SME$	$SME = 0.1168 + 0.0027CA + 0.0015SS - 3.0735E^{-5}CA^2 - 2.78E^{-5}CA \cdot SS - 1.94E^{-6}SS^2$	0.59
Leek	$Q$	$Q = 30.008 + 0.7184CA - 0.2748SS - 0.1664CA^2 + 0.0079CA \cdot SS + 0.0023SS^2$	0.94
	$SME$	$SME = -0.0225 + 0.0028CA + 0.0045SS + 0.001CA^2 - 0.0001CA \cdot SS - 1.7321E^{-5}SS^2$	0.59
Onion	$Q$	$Q = -44.1897 + 1.5022CA + 1.2132SS - 0.0997CA^2 - 0.0043CA \cdot SS - 0.005SS^2$	0.77
	$SME$	$SME = 0.5777 - 0.0073CA - 0.0077SS + 0.0002CA^2 + 2.61E^{-5}CA \cdot SS + 4.26E^{-5}SS^2$	0.66

$Q$  – process efficiency;  $SME$  – specific energy consumption;  $CA$  – content of the additive;  $SS$  – screw speed

Fig. 2 presents the effect of processing variable conditions on specific mechanical energy requirements during the extrusion-cooking of various corn-based extrudates. The specific energy consumption during the extrusion-cooking relates to the thermo-mechanical starch

conversion. Therefore, in the case of higher *SME* it can be manifested better starch gelatinization of expanded products (Pardhi et al., 2019).

With the increased rotation screw speed, it has been noticed an increased *SME* during processing of extrudates with fresh beetroot (Fig. 2a), carrot (Fig. 2b) and onion (Fig. 2d). The range of *SME* varied from 0.21 to 0.27 kWh kg<sup>-1</sup>. The lowest specific energy consumption was observed during processing of blends with 7.5% and 10.0% of onion and at screw speeds of 80 and 100 rpm. Low *SME* values were observed also if beetroot and leek were added in amounts of 5.0 and 7.5% in the recipe. The greatest values were noted for corn extrudates without additives which means that addition of fresh vegetables reduced the energy requirements during the extrusion-cooking. This phenomenon is probably because of the higher initial moisture content of blends, what is reducing the mechanical shearing intensity and thus the specific energy consumption during processing. Wherein, the content of vegetable additive had an insignificant effect on *SME* only for snack with onion, it was noted that screw speed had significant effect on *SME* of corn snacks with almost all additives used, except of leek (Table 2).

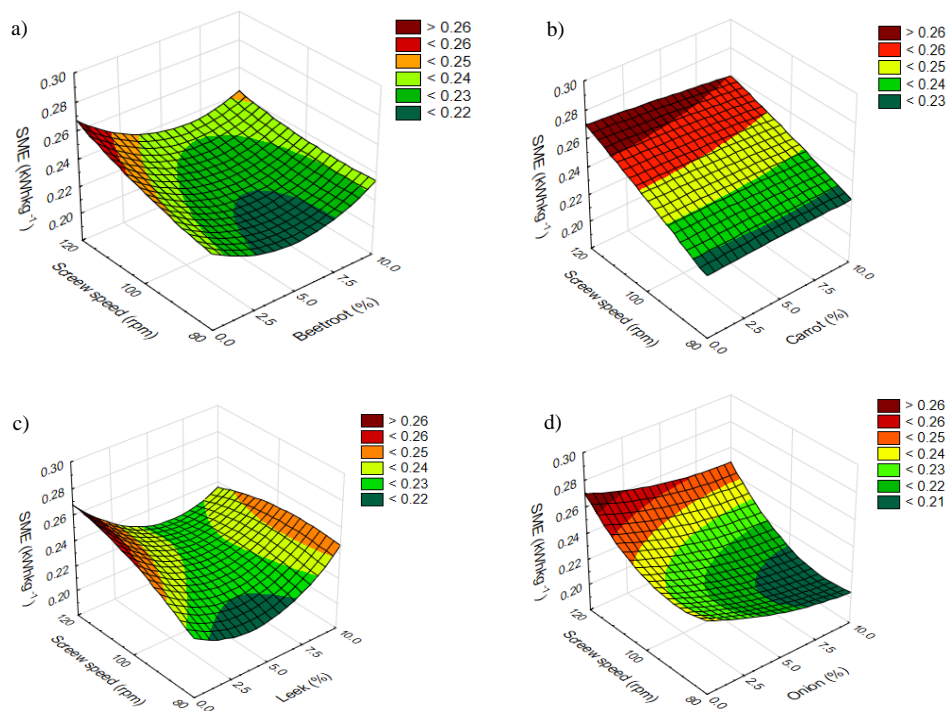


Figure 2. The effect of processing variable conditions on specific mechanical energy during the extrusion-cooking of corn extrudates with addition of fresh vegetables: a) beetroot, b) carrot, c) leek, d) onion

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Similar observations were reported by Ali et al. (2016a) for the extruded maize-chickpea flour mixture and the obtained values of *SME* ranged from 0.10 to 0.23 kWh kg<sup>-1</sup>. Other researchers (Baik et al., 2004) have noted that the growth of *SME* was caused by the fact that more energy is supplied in the aim to obtain higher screw rotations. What is more, the screw speed causes an increase in *SME* input attributed to the increase in shear rate with increased screw speed (Altan et al., 2008). The results presented by Singha and Muthukumarappan (2017) for extrudates with addition of apple pomace (from 0 to 20%) ranged from 0.05 to 0.16 kWh kg<sup>-1</sup>. They observed that *SME* decreased with increased level of apple pomace up to a certain extent. This relationship was assigned progressively by the decreasing of starch content. During the extrusion-cooking of maize–mung bean flour mixture values of *SME* reported by Ali et al. (2016b) were between 0.14 and 0.25 kWh kg<sup>-1</sup>. The greatest value of *SME* was noted in this research for samples processed at low feed moisture, low barrel temperature and high screw speed. Considering the F-test results, in most cases the rotational speed of the extruder's screw had a greater impact on *SME* during snacks processing than the content of vegetable additives (Table 2). However, Matysiak et al. (2018) reported that for the tested extruded snack pellets moistened up to 32-34% the rotational speed ranged 20-60 rpm had a smaller influence on *SME* as compared with the moisture content.

Table 2.

*Results of analysis of variance of the effects of processing conditions on process efficiency and specific energy consumption during the extrusion-cooking*

Independent variable	Additive	Dependent variable	Sum of square effect	df effect	Mean square effect	Sum of square error	df error	Mean square error	F-test	p
Content of the additive (%)	beetroot	<i>Q</i>	404.610	4	101.15	292.90	40	7.322	13.814	0.000*
		<i>SME</i>	0.005	4	0.001	0.009	40	0.0002	5.678	0.001*
	carrot	<i>Q</i>	66.812	4	16.703	310.51	40	7.603	2.151	0.092
		<i>SME</i>	0.006	4	0.001	0.017	40	0.0004	3.365	0.018*
	leek	<i>Q</i>	167.380	4	41.845	614.95	40	15.370	2.722	0.043*
		<i>SME</i>	0.005	4	0.002	0.101	40	0.0003	5.062	0.002*
	onion	<i>Q</i>	106.540	4	26.635	614.07	40	15.350	1.735	0.161
		<i>SME</i>	0.006	4	0.001	0.027	40	0.0007	2.094	0.099
Screw speed (rpm)	beetroot	<i>Q</i>	485.708	2	242.850	211.81	42	5.043	48.156	0.000*
		<i>SME</i>	0.004	2	0.002	0.010	42	0.002	8.416	0.001*
	carrot	<i>Q</i>	274.340	2	137.170	102.98	42	2.452	55.950	0.000*
		<i>SME</i>	0.012	2	0.006	0.012	42	0.0003	20.180	0.000*
	leek	<i>Q</i>	537.660	2	268.830	244.66	42	5.825	46.150	0.000*
		<i>SME</i>	0.002	2	0.001	0.013	42	0.0003	2.851	0.069
	onion	<i>Q</i>	498.790	2	249.400	221.82	42	5.281	47.220	0.000*
		<i>SME</i>	0.016	2	0.008	0.018	42	0.0004	18.560	0.000*

\* significant effect at  $\alpha=0.05$

## Conclusions

With regard to the obtained results, the following conclusions were established:

1. The most efficient production was the extrusion-cooking of corn extrudates with the addition of fresh leek and onion at the highest rotation screw speed.
2. The lowest specific energy consumption was observed during the extrusion-cooking of corn-onion blends, especially at low screw speed.
3. Generally, values of F-test showed the higher effects of the extruder's screw speed on production efficiency and *SME* as compared to the content of fresh vegetables in corn-based blends.

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## WYDAJNOŚĆ PROCESU I JEDNOSTKOWE ZAPOTRZEBOWANIE ENERGII MECHANICZNEJ PODCZAS WYTWARZANIA EKSTRUDATÓW KUKURYDZIANYCH Z DODATKIEM ŚWIEŻYCH WARZYW

**Streszczenie.** Celem pracy było określenie wpływu prędkości ślimaka i zmiennych ilości świeżych dodatków warzywnych na wybrane aspekty ekstruzji mieszanek kukurydziano-warzywnych. Grys kukurydziany jako podstawowy składnik uzupełniono dodatkiem pulpy ze świeżych buraków, marchwi, pora i cebuli w ilości 2,5-10,0% receptury. Ekstruzję prowadzono z zastosowaniem jednoślindakowego ekstrudera w zakresie temperatury 120-145°C, zaś ekstrudaty formowano do postaci bezpośrednio ekspandowanych przekąsek. Badano dwa wskaźniki: wydajność produkcji ( $Q$ ) i specyficzne zapotrzebowanie energii mechanicznej ( $SME$ ). W wyniku przeprowadzonych badań zauważono, że prędkość obrotowa ślimaka ekstrudera wykazała większy wpływ zarówno na wydajność procesu, jak i na  $SME$  w porównaniu ze zmienną ilością zastosowanych dodatków. Zaobserwowano tendencję do zwiększonej wydajności i zapotrzebowania energii mechanicznej wraz ze wzrostem prędkości obrotowej ślimaka podczas ekstruzji. Najwyższą wydajność procesu zaobserwowano, gdy jako dodatki zastosowano świeży por i cebulę, zaś ekstruzję prowadzono przy zastosowaniu najwyższej prędkości ślimaka. Największe jednostkowe zapotrzebowanie energii odnotowano podczas ekstruzji mieszanek zawierających dodatek świeżej marchwi i cebuli przy wysokich obrotach ślimaka ekstrudera.

**Słowa kluczowe:** kukurydza, ekstruzja, warzywa, wydajność,  $SME$