

Effect of extrusion-cooking conditions on the physical properties of Jerusalem artichoke straw

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Abstract. The paper presents the effect of extrusion-cooking conditions (moisture content and screw speed) on the physical properties of extruded Jerusalem artichoke straw. A single screw extruder was used for straw processing. Shredded Jerusalem artichoke straw moistened to 30, 40, and 50% was subjected to an extrusion-cooking process at various screw speeds (70, 90, and 110 rpm). Selected physical properties and pasting profile were tested. Significant differences were observed depending on the moisture content of the samples and the various screw speed on their physical properties. Notably, increased moisture content lowered the specific mechanical energy, increased processing efficiency, water solubility, peak viscosity and breakdown. The maximum efficiency and the highest breakdown was observed for the sample with 50% moisture content processed at an extruder screw speed of 90 rpm. The sample obtained at 30% moisture and at 90 rpm was characterized by the lowest efficiency and hot paste viscosity, and the highest specific mechanical energy. The results showed that the extrusion-cooking process yielded desirable changes to the structure of the analysed lignocellulosic biomass.

Keywords: pretreatment, lignocellulosic biomass, physical properties, extrusion-cooking, Jerusalem artichoke straw

INTRODUCTION

In the last decade, rapid climate changes have been observed worldwide due to the increased emissions of greenhouse gasses produced, to a large extent, by conventional systems of power and heat generation (Pilarska *et al.*, 2014). Most European governments recognize the need to change the directions of their current energy policies. There has been a notable turn towards renewable sources of ener-

gy as well as a growing interest in new, low-emission and more environmentally friendly technologies of energy production (Kozłowski *et al.*, 2019a). Third generation peak biogas plants, which produce electrical energy in a specific time period when the requirement is urgent (*e.g.* between 6 a.m. and 9 p.m.), are a good example of such technologies. The location of the biogas plant as well as its nominal power is highly dependent on the available access to substrates. Typically, such facilities are located in the vicinity of large farms which provide a source of liquid and solid manure, as well as agri-food industry facilities, distilleries, or breweries, whose waste output can be fully utilized for the purposes of biogas production (Kozłowski *et al.*, 2019b; Guerrieri *et al.*, 2019). The use of such waste can often significantly reduce the costs of its utilization, additionally, the obtained digestate can be used as a natural fertilizer rich in nitrogen, phosphorus, and potassium. Agricultural biogas plants typically utilize corn, beet, and grass silage (Przybył *et al.*, 2017). The price of corn silage has grown significantly in recent years (from approx. EUR 12 to EUR 30 for Mg⁻¹ fresh matter (FM)) while governmental financial support has proven largely insufficient, hence investors are constantly on the lookout for potential new, more cost effective sources of substrates (Dach *et al.*, 2014).

Agriculture continues to generate large quantities of unutilized organic waste in the form of so-called lignocellulosic biomass. This includes cereal, maize and rape straw, hay, as well as a wide range of other plants with consider-

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able energetic potential (Cieřlik *et al.*, 2016; Oniszczuk *et al.*, 2016; Maj *et al.*, 2019). The large quantities of biomass refuse coupled with the difficulty of finding ways to effectively utilize it, have encouraged the development of technologies capable of allowing its use in energy production. Biogas plants are a prime example of the effective utilization of organic waste by using it to produce heat and power. The process of methane fermentation conducted in such facilities is capable of handling waste materials that could potentially pose a threat to ecosystems (Wandera *et al.*, 2018). One of the plants recognized for its high energy potential is Jerusalem artichoke (*Helianthus tuberosus*), also known as sunchoke, which is characterized by significant production value and multi-directional processing usability. It is a fast-growing plant with high net calorific value, resistant to disease and pests, and with relatively low soil-quality requirements (Kowalczyk-Juřko, 2016).

However, the effective use of lignocellulosic biomass is problematic and difficult. In order to improve the speed and efficiency of the methane fermentation process, first lignocellulosic material has to be pretreated in order to disintegrate lignin and release cellulose and hemicelluloses (Kumar *et al.*, 2009). Therefore, extensive research is currently being conducted with the aim of developing adequate methods for such pretreatment. As follows from the literature results, the inclusion of a pretreatment stage can improve the efficiency of biogas production by over 90% for raw materials such as grass, maize straw, or wood. Several distinct methods of lignocellulosic biomass pretreatment can be distinguished, including chemical, biological, mechanical, and extrusion-cooking (Robak and Balcerek, 2017; Kupryaniuk *et al.*, 2020). It is impossible to identify the most effective method because the results are strongly dependent on the particular type of lignocellulosic biomass used in the given process. Each of the methods corresponds to specific technological processes which are employed at later stages. Indeed, production facilities often employ a combination of several methods to further enhance the efficiency of subsequent treatment. At the same time, although this approach improves the effectiveness of technological processes, it can also entail higher overall energy consumption and extend the time required for effective pretreatment. The decision to employ a given pretreatment method must be economically viable, which necessitates striking a viable compromise between the necessary expenditures and the ultimate profitability of production (Gizińska-Górna *et al.*, 2016).

One such pretreatment method involves the process of extrusion-cooking, which is commonly used when processing food or feeds. The process is fast, simple, continuous, and highly efficient; it entails the thermal and mechanical treatment of raw plant materials (Witaszek *et al.*, 2015). Under the influence of high temperatures (up to 200°C), pressures (up to 20 MPa), and shearing forces, the physicochemical properties of the material placed in the

extruder change, including protein denaturization, starch gelatinization, as well as the inactivation of enzymes, microorganisms, and many antinutrients. After leaving the extrusion die, the plasticized material undergoes the rapid expansion and evaporation of intracellular water, which yields a honeycomb-like structure and facilitates effective refinement (Kaur, 2015). The extrusion-cooking process utilizes single- and twin-screw extruders, with the time spent by the mass inside the machine being dependant on its specific design, the efficiency of the plasticizing system, and the rotational speed of the extruder screw – it can range from several seconds to a few minutes. The parameters of the process, including screw speed, extrusion temperature, screw configuration, and raw material moisture content, all have a significant impact on treatment efficiency and can affect the degree to which cellulose complexes are disintegrated. When lignocellulosic complexes are disintegrated, enzymes are provided with easier access to cellulose (Karunanithy *et al.*, 2012).

The aim of the study was to investigate the effect of extrusion-cooking conditions (moisture content and screw speed) on the physical properties of Jerusalem artichoke extruded straw.

MATERIAL AND METHODS

The Jerusalem artichoke used in the study was harvested from the experimental field maintained by the University of Life Sciences in Lublin, from a 2019 cultivation. The straw was ground with a hammer shredder to reduce particle size to less than 5 mm, and moistened to obtain three experimental moisture content levels (30, 40, and 50%) by spraying with a suitable amount of water. Subsequently, the material was mixed using a laboratory drum mixer. Before processing, the material was stored in sealed bags for a period of 24 h to unify the migration of water. Afterwards, the samples were mixed again. The effective mixing duration was 10 min.

The raw material moisture content was determined using the oven-drying method. Prepared weighing vessels containing finely ground 2 g samples (weighed with a 0.001 g accuracy – 1/3 of the dish height) were placed inside the laboratory oven drier (POL-EKO, SLW 53 STD, Wodzisław Ślaski, Poland) heated to 130°C and dried for 1 h. After removal and cooling, the samples were weighed. The moisture content was calculated from the following equation:

$$W = \frac{a-b}{a-c} 100, \quad (1)$$

where: W – is the material's moisture content (%), a – is the weight of the vessel containing the material prior to drying (g), b – is the weight of the vessel containing the material after drying (g), c – is the mass of the empty vessel (g). The measurements were conducted in triplicate.

The study was performed using a single screw extrusion-cooker type TS-45 (Polish design) with the length to diameter ratio $L/D=12$ equipped with a plasticizing system with a modified recirculation section in the final part of the screw, and a forming die with an 8 mm hole diameter. Extrudates were produced at extruder screw speeds of 70, 90, and 110 rpm. The extrusion-cooking process temperature was set in the extruder sections at 80°C in the feeding zone, at 120°C in the transport zone and 150°C in the compression zone, respectively, and maintained at a constant level during processing. The processing temperature was measured with thermocouples installed along the barrel; the results were recorded. The rotational speed of the screw was monitored using a DM-2234B Laser electronic tachometer (Transfer Multisort Elektronik Ltd., Łódź, Poland). Ground straw without extrusion served as a control sample.

The processing efficiency (Q , kg h⁻¹) was determined by measuring the mass of the extrudate obtained in a given time for all the raw materials and adopted process parameters. The measurements were conducted in triplicate for each study series with the mean results adopted as final. The extrusion-cooking process efficiency was determined as:

$$Q = \frac{m}{t}, \quad (2)$$

where: m – is the weight of extrudate obtained during the measurement (kg), t – is the measurement time (h).

Energy consumption, expressed as specific mechanical energy (SME , kWh kg⁻¹) was calculated by taking into account the engine load, the extruder working parameters and the process efficiency of each test according to the formula (Combrzyński *et al.*, 2020):

$$SME = \frac{n}{n_m} \frac{O}{100} \frac{P}{Q}, \quad (3)$$

where: n – is screw rotation (rpm), n_m – is the screw rating rotation (rpm), O – is the engine load compared to the maximum (%), P – is rated power (kW), Q – is process efficiency (kg h⁻¹). The final results were the means from the results obtained in triplicate.

The water absorption index (WAI) and the water solubility index (WSI) were used to evaluate the extrusion-cooking intensity in accordance with the method described by Bouasla *et al.* (2017). For this purpose, 7 mL of distilled water was added to 0.7 g of the ground extruded sample. The sample was mixed, and then centrifuged for 10 min at 15 000 rpm. The centrifuged samples were filtered, and the remains, after gel formation, were dried in an air oven at 130°C until completely dry. The WAI was calculated as the mass of gel formed per constant dry weight of the sample, and the WSI was calculated as the amount of residue dissolved in the supernatant after drying. All measurements were performed in triplicate.

Density measurements were performed according to Wójtowicz *et al.* (2017) by placing the analysed material into a measuring cylinder; the excess material was struck off and the cylinder filled with sample was weighed with a 0.01 g accuracy. Based on the result, the apparent density (ρ_u , kg m⁻³) was calculated as:

$$\rho_u = \frac{m_u}{v}, \quad (4)$$

where: m_u – is the weight of the sample (kg), v – is the dish volume (m³). The measurement was conducted in triplicate.

The study of pasting properties was conducted to indirectly assess the changes taking place in the processed material during extrusion. The tests of raw and extruded straw were determined using a Brabender Micro Visco-Amylo-Graph (Brabender, Germany) following the method described by Bouasla *et al.* (2016) and Wójtowicz *et al.* (2017) with slight modification. 5 g of the ground extrudate was dispersed in 100 mL of distilled water. The pasting properties were evaluated at a constant speed (250 rpm) and sensitivity (235 cmg). Measurements were performed within the following profile: heating from 30 to 93°C with a temperature gradient of 7.5°C min⁻¹, holding at 93°C for 5 min, cooling from 93 to 50°C with a temperature gradient of 7.5°C min⁻¹, holding at 50°C for 1 min. Brabender Viscograph software (version 4.1.1) was used to determine the pasting properties. The measurements were conducted twice.

The results obtained were analysed using Statistica 13.3 software (StatSoft, Poland) to examine the effects of the initial moisture content and the screw rpm applied with ANOVA. Pearson's correlation coefficients were evaluated and an analysis of variance was conducted at a confidence level of 95% ($\alpha = 0.05$); the significance of the observed differences was assessed using Duncan's range test.

RESULTS AND DISCUSSION

The rotational screw speed of the extruder and the initial moisture content of the material had a significant impact on the extrusion-cooking process itself and on the results of subsequent measurements. Table 1 presents the values of obtained selected physical properties of control and extruded Jerusalem artichoke straw samples in relation to the processing variables.

The material moisture content had a crucial influence on the processing efficiency results. The lowest value (7.20 kg h⁻¹) was recorded for samples processed at 30% moisture content and an extruder screw speed of 90 rpm. The highest (18.24 kg h⁻¹) – for samples extruded at 50% moisture and 90 rpm. Higher efficiency was reported by Ding *et al.* (2006) when extruding wheat-based snacks at moisture content levels of 14-22%. In the case of the extruded wheat snacks, the processing efficiency reached was between 20 and 32 kg h⁻¹.

Table 1. Selected physical properties of the control and extruded Jerusalem artichoke straw relative to the processing variables

Sample	Moisture (%)	Screw speed (rpm)	Q (kg h ⁻¹)	SME (kWh kg ⁻¹)	WAI (g g ⁻¹)	WSI (%)	ρ_u (kg m ⁻³)
Control					6.74 ^c	6.67 ^c	142.26 ^{ab}
M1R1		70	10.92 ^{ab}	0.284 ^a	3.06 ^a	1.76 ^a	239.29 ^c
M1R2	30	90	7.20 ^a	0.690 ^c	3.18 ^a	3.99 ^{ab}	172.58 ^{bc}
M1R3		110	14.80 ^b	0.572 ^{bc}	3.43 ^a	2.61 ^a	128.42 ^a
M2R1		70	10.80 ^{ab}	0.246 ^a	4.41 ^{ab}	3.08 ^{ab}	168.68 ^{bc}
M2R2	40	90	16.80 ^{bc}	0.267 ^a	3.54 ^a	4.03 ^{ab}	174.84 ^{bc}
M2R3		110	14.04 ^b	0.447 ^b	4.68 ^{ab}	7.02 ^c	156.93 ^b
M3R1		70	10.92 ^{ab}	0.219 ^a	3.81 ^a	6.68 ^c	129.39 ^a
M3R2	50	90	18.24 ^c	0.220 ^a	3.58 ^a	5.22 ^{bc}	150.54 ^b
M3R3		110	17.04 ^{bc}	0.354 ^{ab}	4.05 ^{ab}	4.51 ^b	142.99 ^{ab}

M – moisture, R – rotation, Q – process efficiency, SME – specific mechanical energy, WAI – water absorption index, WSI – water solubility index, ρ_u – apparent density, ^{a-c} – means followed by similar letters in columns do not differ significantly at $\alpha = 0.05$.

Table 2. Correlation matrix between processing variables and the physical and pasting properties of extruded Jerusalem artichoke straw

	Moisture	Screw speed	Q	SME	WAI	WSI	ρ_u	IV	PV	HPV	CPV	FV	BD
Q	0.521	0.520											
SME	-0.644*	0.534	-0.378										
WAI	0.176	0.435	0.305	-0.020									
WSI	0.658*	0.214	0.175	-0.139	0.217								
ρ_u	-0.505	-0.469	-0.330	-0.124	-0.143	-0.551							
IV	0.843*	0.281	0.727*	-0.540	0.531	0.587	-0.419						
PV	0.868*	0.299	0.763*	-0.521	0.480	0.545	-0.405	0.976*					
HPV	0.609*	0.500	0.511	-0.131	0.344	0.295	-0.311	0.637*	0.684*				
CPV	0.637*	0.264	0.314	-0.260	0.532	0.303	-0.298	0.683*	0.675*	0.890*			
FV	0.620*	0.434	0.374	-0.138	0.510	0.427	-0.317	0.702*	0.698*	0.945*	0.961*		
BD	0.854*	0.232	0.754*	-0.562	0.470	0.556	-0.392	0.971*	0.987*	0.561	0.574	0.589	
SB	0.302	-0.313	-0.213	-0.367	0.532	0.061	0.025	0.331	0.246	0.279	0.677*	0.499	0.218

Q – process efficiency, SME – specific mechanical energy, WAI – water absorption index, WSI – water solubility index, ρ_u – apparent density, IV – initial viscosity, PV – peak viscosity, HPV – hot paste viscosity, CPV – cold paste viscosity, FV – final viscosity, BD – breakdown, SB – setback, *significant effect at $\alpha \leq 0.05$.

The process energy consumption results presented in Table 1 were adversely affected to a significant extent by the moisture content (Table 2). It was observed that the SME decreased with higher moisture content, while increasing the screw speed increased energy consumption only in the case for samples moistened at 30 and 40%. For samples moistened at 50%, the difference was not significant. The highest SME value (0.690 kWh kg⁻¹) was obtained for the sample processed at 30% moisture content and a screw speed of 90 rpm. The extrudates production process at 50% moisture and at 70 rpm was characterized by the lowest

values of SME (0.22 kWh kg⁻¹). As the degree of moisture content increases, the demand for energy decreases. In the case of raw material moistened up to 50%, water behaved as a lubricant, the friction and shear forces during the extrusion process were lower, and this directly translates into lower energy consumption, regardless of the rotational speed of the extruder screw. Slight differences in energy demand in the case of samples with 50% initial moisture content may indicate that the extruder works as a heated screw conveyor, and the extrusion process takes place to a limited extent.

The obtained results were higher compared to those reported by Hjorth *et al.* (2011) for extruded straw maize. It should also be mentioned that the study was conducted using a readapted device produced in the 1980s and equipped with a Shrage engine with an efficiency of 0.55-0.97, depending on the nominal revolutions of the engine: 650-1950 rpm. The outdated engine construction significantly impacted the measurement results obtained. Modern engines installed in industrial extruders are characterized by significantly higher efficiency, which naturally has a bearing on the energy efficiency of the entire production process. The *SME* values obtained using laboratory equipment should be treated as rough estimates applicable to the TS-45 extruder, as such they merely illustrate the correlation between the type of raw materials used and the conditions of the extrusion-cooking process. It should be noted that a different energy consumption profile will be observed when using a new, more modern production unit (an industrial extruder) characterized by a considerably higher efficiency.

In terms of the water absorption index (WAI) the maximum value (4.68 g g^{-1}), recorded for a sample extruded at 40% moisture content and with an extruder screw speed of 110 rpm, was significantly lower than that in the control untreated material (6.74 g g^{-1}) (Table 1). The lowest WAI (3.06 g g^{-1}) was obtained for the sample processed at 30% moisture and at the lowest screw speed. It was observed that in the case of a 30% moisture level, the WAI slightly increased with increasing screw speed. In the case of higher moisture level, there was a partial increase followed by a decrease in the WAI values observed but the differences between samples were insignificant. Wani and Kumar (2016) studied extrudates from oats and fenugreek beans processed at 17% moisture content, and reported the result of 5.86 g g^{-1} , which is higher than the result obtained for Jerusalem artichoke straw. A higher WAI value was only obtained for the untreated Jerusalem artichoke straw as the control sample (6.74 g g^{-1}). No significant correlation was found between WAI and the processing variables.

The initial moisture content influenced the water solubility index (WSI) more intensively than the rotational screw speed of the extruder ($r = 0.685$). In the case of 30% moisture content, increasing the screw speed resulted in a partial increase, followed by a decrease in the WSI value but the differences were insignificant. At 40% moisture content, it was observed that WSI increased with growing rpm, while in the case of 50% moisture content, WSI decreased (Table 1). The highest value (7.02%) was recorded for the sample extruded at 40% moisture content and at a screw speed of 110 rpm. This value was slightly but insignificantly higher than that obtained with the control untreated straw (6.74%) which has a limited ability to absorb and hold water due to the high content of insoluble fibrous fractions. Extrusion-cooking in proper conditions may increase the water absorption ability of the sample. The lowest result

(1.76%) was observed for the sample processed at 70 rpm with 30% initial moisture because limited access to water at a low moisture content and low mechanical shearing using low rpm were insufficient to change the internal structure of the material significantly. Higher WSI values (8.28%) were previously reported for the extrusion of corn grits with the 5% addition of propylene glycol (Ekielski *et al.*, 2018).

Only in the case of samples extruded at 30% moisture and a screw speed of 110 rpm (the lowest value of 128.42 kg m^{-3}) and at 50% moisture and 70 rpm (129.39 kg m^{-3}) were the recorded values of bulk density lower than those of the control, in all other cases the values recorded were higher but without significant differences (Table 1). The highest ρ_u (239.29 kg m^{-3}) was recorded for samples pretreated with an initial moisture content of 30% at the lowest rpm due to the incomplete transformation of components. Compared to corn porridge with the addition of linseed pomace (Makowska, 2013), it was observed that the densities of the control sample without an additive and extrudates with 25% additive would achieve twice the value recorded for extruded Jerusalem artichoke straw, which may be connected with the structure of straw which is different from that of the flour components.

The pasting characteristics of extrudates may serve as a measure of component processing intensity relative to the process variables employed in extrusion-cooking (Deepa and Hebbar, 2017; Hagenimana *et al.*, 2006; Koh and Singh, 2009). The pasting profiles of the selected samples of extruded Jerusalem artichoke straw are presented in Figs 1 and 2, relative to the initial moisture level and screw rpm used in the experiment.

For the control (non-extruded) sample, an initial increase in viscosity was observed while the suspension was heated to 93°C . This may provide evidence of the enhanced absorption of water by the unprocessed straw and the presence of starch undergoing gelatinization during heating. While the sample was maintained at a temperature of 93°C , the suspension viscosity was observed to gradually decrease, which may suggest a partial disintegration of lignocellulose during heating and, possible dissolution of the substrates (including sugars) in water. As the suspension temperature decreased, the viscosity increased once more, which may suggest the formation of a viscous structure by the lignocellulosic material after cooling.

In the case of the extruded straw, we observed a considerable reduction or complete absence of an increase in viscosity during the initial heating stage of the suspension. This suggests that significant physicochemical changes have occurred during the extrusion-cooking of the straw, which ultimately led to the breakdown of a considerable part of the lignocellulose, possibly down to simple sugars which do not undergo gelatinization. A similar behaviour was observed for extruded starch (Mitrus *et al.*, 2017) and extruded bean (de la Rosa-Millan *et al.*, 2019). At the heating up stage and maintenance of the temperature at 93°C ,

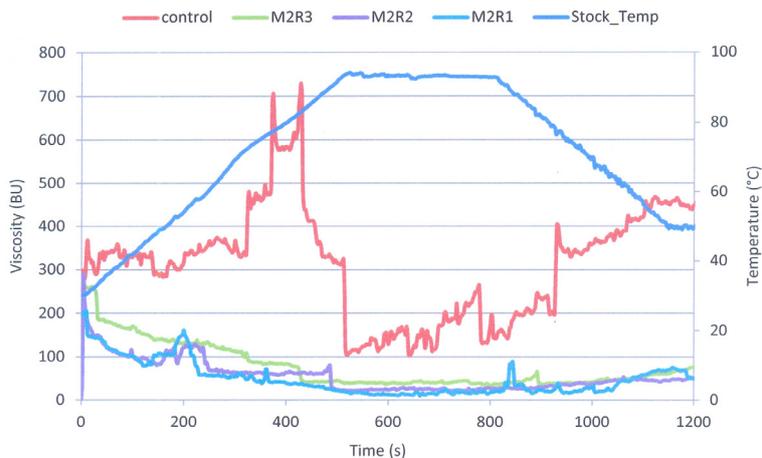


Fig. 1. Pasting profile of the control and extruded Jerusalem artichoke straw moistened at 40% and processed at various screw speeds.

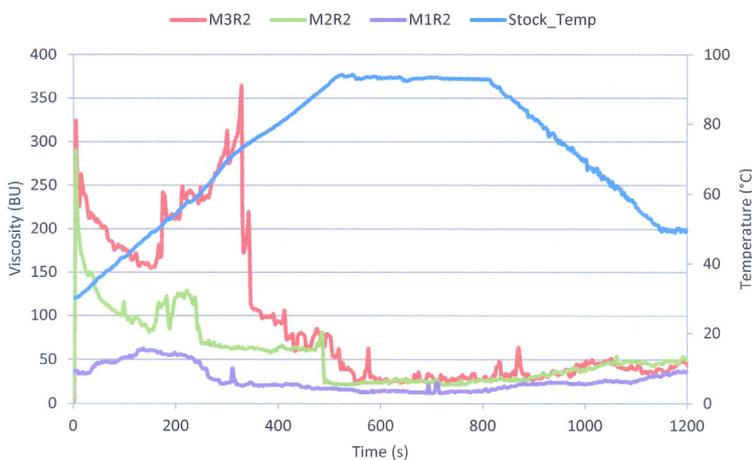


Fig. 2. Pasting profile of extruded Jerusalem artichoke straw processed at 90 rpm at various moisture levels.

Table 3. Pasting characteristics of the control and extruded Jerusalem artichoke straw relative to the processing variables

Sample	Moisture (%)	Screw speed (rpm)	IV (BU)	PV (BU)	HPV (BU)	CPV (BU)	FV (BU)	BD (BU)	SB (BU)
Control			337 ^c	710 ^c	187 ^c	442 ^c	443 ^c	523 ^c	256 ^c
M1R1	30	70	40 ^a	48 ^a	16 ^a	25 ^a	24 ^a	32 ^a	18 ^{ab}
M1R2		90	45 ^a	61 ^a	16 ^a	30 ^a	37 ^{ab}	46 ^a	15 ^{ab}
M1R3		110	77 ^a	77 ^a	16 ^a	21 ^a	21 ^a	61 ^a	6 ^a
M2R1	40	70	198 ^{ab}	201 ^{ab}	17 ^a	68 ^b	50 ^{ab}	184 ^{ab}	51 ^b
M2R2		90	276 ^{bc}	276 ^b	25 ^{ab}	45 ^{ab}	50 ^{ab}	251 ^b	19 ^{ab}
M2R3		110	254 ^b	255 ^b	34 ^b	59 ^{ab}	74 ^b	221 ^b	25 ^{ab}
M3R1	50	70	195 ^{ab}	195 ^{ab}	26 ^{ab}	52 ^{ab}	52 ^{ab}	169 ^{ab}	26 ^{ab}
M3R2		90	274 ^{bc}	353 ^{bc}	30 ^b	38 ^a	41 ^{ab}	323 ^{bc}	8 ^a
M3R3		110	307 ^{bc}	361 ^{bc}	87 ^{bc}	121 ^{bc}	129 ^{bc}	273 ^b	34 ^b

M – moisture, R – rotation, IV – initial viscosity, PV – peak viscosity, HPV – hot paste viscosity, CPV – cold paste viscosity, FV – final viscosity, BD – breakdown, SB – setback, ^{a-c} – means followed by similar letters in columns do not differ significantly at $\alpha = 0.05$.

a decrease in the suspension's viscosity was observed, which may indicate that the components obtained from lignocellulose disintegration were dissolved in water (Figs 1 and 2). While cooling the suspension, we observed only a slight increase in viscosity, which provides evidence of the considerably reduced extent of lignocellulosic structure reformation. In general, it may be concluded that the use of higher extruder screw speeds resulted in less intensive changes to the extruded straw, as shown by the higher viscosities of the obtained suspensions. As the screw speed increased, the straw spent less overall time inside the extruder, which meant a shorter processing time and less intensive physicochemical changes.

Various straw moisture contents prior to extrusion as well as variable screw speeds positively correlated with all the tested pasting characteristics, with the exception of SB, but an insignificant correlation between the screw speed and pasting characteristics has been noted (Table 2). This suggests that the moisture level is more responsible for the intensity of the extrusion-cooking processing of straw, and influences the extensive physicochemical changes to the extruded material. As a result, such samples produced at a low screw speed and with low initial moisture material whose water suspensions were tested, are characterized by a lower viscosity, this is probably due to the insufficient pretreatment of the extruded straw.

The maximum viscosity recorded during the heating stage (PV) was 710 BU for raw straw and varied from 48 to 361 BU for extruded samples, as shown in Table 3. The highest value was recorded for the control sample, while the remaining results were half of the value of the control sample or lower. A high degree of correlation (Table 3) was found between PV and IV ($r = 0.976$).

Both, IV and PV were significantly correlated with the initial moisture content of Jerusalem artichoke straw ($r = 0.843$ and 0.868 , respectively). HPV was positively and highly correlated with the CPV and FV values ($r = 0.890$ and 0.945 , respectively). The cold paste viscosity (CPV) varied from 21 to 121 BU for extruded straw, but the highest CPV value was recorded for the control of the untreated sample – nearly four times the results obtained for extruded samples. The lowest values of FV (21-30 BU) were recorded for the extrudates processed at 30% moisture whereas for untreated material FV was 443 BU – over 10 times more than those of the extruded samples. The breakdown (BD) varied from 32 to 323 BU. The lowest values were recorded for the extrudate processed at 30% moisture and 70 rpm. The pasting properties which were evidently influenced by the moisture level included: CPV, FV, and BD. The changes in extruder screw speed had a clear impact on HPV (hot paste viscosity) only at 40 and 50% moisture levels, whereas at 30% moisture content the obtained results remained roughly unchanged. The values of SB reached 6-34 BU and the results were not observably affected by either moisture level or extruder screw speed with the highest value being

observed for the untreated sample (256 BU). The extruder screw speed had no clear effect on the values obtained from the measurements. Significant correlations between Q and the variable pasting properties were observed, including IV ($r = 0.727$), PV ($r = 0.763$), and BD ($r = 0.754$).

CONCLUSIONS

1. Maximum processing efficiency (18.24 kg h^{-1}) was observed for the sample processed at 50% moisture level and an extruder screw speed of 90 rpm.
2. The extrudates production process at 50% moisture and at 70 rpm was characterized by the lowest values of specific mechanical energy (0.22 kWh kg^{-1}).
3. The sample processed at 30% moisture and 90 rpm was characterized by the lowest efficiency (7.20 kg h^{-1}) and highest specific mechanical energy ($0.690 \text{ kWh kg}^{-1}$).
4. The material processed at 40% moisture content and an extruded screw speed of 110 rpm was characterized by the highest WSI (7.02%), while in the case of WAI (4.68 g g^{-1}), only the control sample yielded a higher WAI result (6.74 g g^{-1}).
5. The sample extruded at a 30% moisture level and a screw speed of 70 rpm was characterized by the lowest WSI (1.76%) and highest density (239.29 kg m^{-3}).
6. In terms of the pasting properties of extruded straw, the control sample yielded significantly higher results relative to those obtained for the extruded material. The results were significantly influenced by the moisture level.
7. The optimum extrusion-cooking conditions for the pretreatment of Jerusalem artichoke straw were a moisture content that reached 40% and a screw speed that was set to 110 rpm.

Conflict of interest: The Authors do not declare any conflict of interest.

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