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Impact of Various Kinds of Straw and Other Raw Materials on Physical Characteristics of Pellets

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1. Introduction

Due to climate change and growing problems associated with the emission of excessive amounts of CO_2, not to mention the ubiquitous occurrence of smog in large cities, limitation of the use of fossil fuels is becoming a necessity. Replacing fossil fuels by energy produced from renewable energy sources such as biomass can significantly reduce greenhouse gas emissions, hence renewable energy sources are considered to be very important for the protection of the environment and the future of society (Piecuch 2010, Blaschke et al. 2013, Kuntal & Sudipta 2014, Malowaniec 2016). Sustainable energy systems will have to rely on the rational use of energy from renewable sources (Callejón-Ferre et al. 2011, Ibrahim et al. 2008, Hlavatá et. al 2014).

The energy use of biomass in heating devices favours refuse-derived fuels (RDF) with specified technical characteristics. However, due to better combustion process and easier handling of boilers, users of these fuels prefer the wood based ones. Also, automation of fuel supply to boilers results in pellets gaining bigger popularity than briquettes (Williams et al. 2012, Sypuła et. al 2010, Lisowski et. Al 2015, Wzorek & Krupa-Żuczek 2015). At the biomass market no chips or sawdust wood with low prices are available, and hence other types of biomass and commonly available agricultural or fodder by-products that could replace those in deficit are searched for in order to be used in pellet production. Such materials may consist of waste from agricultural production and processing of plant products such as – straw of cereals, rapeseed and soya bean, or industrial waste known as rapeseed cake and soya bean hulls and spelt hulls (Caryalho et al. 2013, Ståhl & Berghel 2011). It is assumed that on average 1 tonne of rapeseed seeds yields approximately 650 kg of rapeseed cake or about 600 kg of post-extraction meal (Firrisa et al. 2014). According to the conducted studies rapeseed cake has appropriate parameters for power industry, as their net calorific value is approximately 19.8 $MJ \cdot kg^{-1}$ (Mc Kendry 2002, Ståhl & Berghel 2011). Also the results for mechanical strength of the pellets produced from rapeseed cake or with admixture thereof were characterised by high parameters, which are within the accepted quality standards (96.5%) (Ståhl & Berghel 2011).

The production of soya bean in the world is estimated to approximately 160 million tonnes. Assuming that hulls make up around 14% of it, a yearly average production of hulls equals to 22 million tonnes (Firrisa et al. 2014). Oil and microcrystalline cellulose, to name just a few, in large quantities obtained from soya beans are very important products for pharmaceutical, food and cosmetic industries (Uesu et al. 2000). Soya bean meal is the most important source of protein used in livestock feeding. During processing of soya bean hulls are obtained as waste product, which may be used for power production purposes, for example by using it in pellet production.

Pellets are produced in the process of pressure agglomeration, in which the pulverised material under the external forces (solidifying pressure) and internal ones (intermolecular forces and bonds) takes the permanent shape with specified geometric dimensions (Adapa et al. 2004, Theerarattananoon et al. 2011). Depending on the die used the end product are pellets of cylindrical shape with a diameter between 6 and 25 mm and length of up to few cm (Shawa et al. 2009). However, the process of pressure agglomeration of biomass entails many technical and operating difficulties related to high variability of physical and chemical properties of the materials that were subject to granulation (Adapa et al. 2004). Keeping in mind the above issues an examination was conducted on the feasibility of pelleting cereal and rapeseed straw in compound with rapeseed cake and soya bean and spelt hulls. The physical characteristics of the obtained pellets and their possible use as solid biofuel were assessed.

2. Materials and methods

For the production of pellets rye straw, wheat straw, rapeseed straw and rapeseed cake, soya bean hulls and spelt hulls were used. The composition and mass fraction of the used kinds of straw and individual compounds are presented in Table 1. The particular ash content and average size of particle was presented in Table 2 in raw material. Prior to pelletizing the straw was initially pulverised using universal hammer crusher, driven by an electric motor with the power of 7.5 kW and fitted with 2 sieves with holes 20 mm in diameter. The final fragmentation of the straw was done by blade crusher, driven by an electric motor with the power of 5.5 kW and fitted with a sieve with holes 8 mm in diameter. All others raw materials used for the production of pellets were in pulverised form. For agglomeration of the plant raw materials a flat die pelleting machine with rotating compression rollers was used. It was driven by an electric motor with the power of 7.5 kW. The diameter of the holes in the pelleting machine die was 8 mm, and the length to diameter ratio (L/D) was 3.125.

Moisture content of raw materials and pellets was determined using a laboratory oven with forced air circulation. Samples of raw materials or pellets were placed in the oven and then dried at 105°C until reaching constant mass, in accordance with BS EN ISO 17225-6:2014 standard. Rapeseed straw, wheat straw and rye straw were moistened until the moisture content was equal to 18%.

The net calorific value of the produced pellets was calculated on the basis of the heat of combustion measured by calorimetric method using isoperibolic calorimeter, according to BS EN 14918:2009 standard. The ash content was measured after pellet sample ashing, at the final temperature of 550°C, according to BS EN 14775:2009 standard.

Measurements of the geometrical characteristics of the pellets produced in flat die pelleting machine included: diameter, length, and mass. Random samples of 20 pieces of pellets were collected for the measurements. The geometric measurements of the pellets were made using a calliper with measurement accuracy of ±1 mm, and their mass – using laboratory scales with measurement accuracy of ±0.1 g.

Table 1. Types of plant raw materials and the produced pellets
Tabela 1. Rodzaje surowców roślinnych i wytworzonych peletów

Type of straw	Straw mass fraction [%]	Other compounds	Additive mass fraction [%]	Pellet designation
Rye straw	50	Rapeseed cake	50	A
Wheat straw	50	Rapeseed cake	50	B
Rapeseed straw	50	Rapeseed cake	50	C
Rye straw	50	Soya bean hulls	50	D
Wheat straw	50	Soya bean hulls	50	E
Rapeseed straw	50	Soya bean hulls	50	F
Rapeseed straw	50	Rapeseed cake	25	G
		Spelt hulls	25	
Rapeseed straw	50	Soya bean hulls	25	H
		Spelt hulls	25	
Rapeseed straw	25	Rapeseed cake	50	I
		Spelt hulls	25	
Rapeseed straw	25	Soya bean hulls	50	J
		Spelt hulls	25	

Table 2. Average particle size and ash content in raw material
Tabela 2. Średni rozmiar cząstek i zawartość popiołu w surowcu

Raw material	Average particle size [mm]	Ash content [%]
Rye straw	1.71	3.69
Wheat straw	1.97	4.71
Rapeseed straw	1.38	4.85
Rapeseed cake	0.90	5.49
Soya bean hulls	1.29	4.44
Spelt hulls	3.30	4.62

Particle density of the pellets was determined on the basis of measurements of their physical characteristics including geometric dimensions and mass, and was calculated according to the BS EN 15150:2011 standard. Bulk density of pellets was determined on the basis of measurements of their mass and volume according to BS EN

15103:2009 standard. After the pellets were poured into measurement container with capacity of 5 dm^3 and their excess was removed with a straight edge, they were weighed on laboratory scales and the density was calculated.

Measurements of mechanical strength of the pellets were carried out on a test bench in accordance to BS EN ISO 17831-1:2015 standard. The rotational speed of the drum was 50 $rpm \cdot min^{-1}$ (± 0.1 $rpm \cdot min^{-1}$), the duration time of the measurement was 10 min, and the mass of the sample was 500 g (±10 g). After mechanical strength test the tested sample of pellets was sieved on a sieve with holes 1 mm smaller in diameter than the diameter of the pellet.

Crushing testing consisted of placing a pellet sample between work plates of a measuring head and then running a crushing test at a constant speed of 50 $mm \cdot min^{-1}$ until the point when a rupture or destruction of the structure of the sample occurred. The measurement of the pellet cutting strength was conducted using a blade set at 45° angle. On the basis of the obtained crushing and cutting strength curves for tested samples their respective values were specified. The tests were performed using TA.XT Plus TEXTURE ANALYZER.

Results of the measurements of the physical and energetic characteristics of the raw materials and pellets were statistically analysed using the one-way analysis of variance processed in STATISTICA 10.0 software. The significance of the differences between the means was defined using Tukey's test at the significance level of $\alpha = 0.05$.

3. Research results

The results of the determination of the moisture content, net calorific value and ash content in the produced pellets are shown in Table 3. The moisture content during the pelletizing process depended on the composition of the compound, and the differences were caused by various amounts of particular types of the raw materials (Table 3). The moisture content during the pelletizing process ranged between 9.0% and 13.65%. In similar conditions other authors were pelletizing barley straw using the moisture content within the limits of 9-17%. While the best quality pellets made from barley straw were obtained for moisture content between 19% and 23% (Serrano et al. 2011). Considering the produced pellets the highest ash content was measured for pellet from sample C – 5.17%, and the lowest for pellet from sample D – 4.06%, made of rye straw and rapeseed cake. When comparing these data with the data on the ash content in wheat straw (8.32%) or barley straw (10.72%), which was obtained by other authors in the course of research on pellets making (Mani et al. 2006), this content is low. According to the ISO standard 17225-6:2014, the ash content for cereal straw pellets should not be above 6%. The ash content of the biomass pellets due to the ash content in the raw material. Higher ash content may indicate contamination of raw material. Most are pollution from accidental admixture substrate storage area. The ash content of the presented pellets was below 6% which results from the ash content in the raw material (Table 2).

Table 3. Characteristics of the produced pellets
Tabela 3. Charakterystyka produkowanych peletów

Pellet designation	Moisture content of mixtures before pelleting [%]	Pellets moisture content [%]	Calorific value [MJ·kg^{-1}]	Ash content [%]
A	11.25	8.39	17.67	4.59
B	11.25	8.88	16.97	5.10
C	11.25	7.31	17.08	5.17
D	13.65	8.39	17.89	4.06
E	13.65	8.88	17.23	4.57
F	13.65	9.58	16.74	4.64
G	12.7	11.45	15.85	4.95
H	13.8	10.00	15.89	4.69
I	9.3	9.18	16.59	5.11
J	9.0	8.73	17.10	4.39

The net calorific value of the produced pellets varied to a small extent. The difference between the highest net calorific value and the lowest one was 2.04%. The lowest net calorific value was measured for pellets marked as G sample, made of rapeseed straw, rapeseed cake and spelt hulls (15.85 MJ·kg^{-1}), and the highest – for pellets from sample D, made of rye straw and soya bean hulls (17.89 MJ·kg^{-1}). In accordance with ISO standard 17225-6:2014, net calorific value of pellet should be within a range of 16.5-19.0 MJ·kg^{-1}. All tested pellets, with the exception of the samples marked as G and H, complied with the specified standard. While only the pellets from sample G did not meet the established in the standard level of moisture content below 10%. In the so far conducted studies the net calorific value of pellets made exclusively of wheat straw, rapeseed straw, or corn straw, as well as of compounds thereof was investigated. The highest net calorific value was obtained for the pellets made of rapeseed straw and corn straw, and it was equal to 16.22 $MJ \cdot kg^{-1}$ (Niedziółka et al. 2015). Also, a research on the net calorific value of pellets made of buckwheat hulls with admixture of potato pulp was performed. The highest net calorific value was measured in the case of buckwheat pellet. It equalled to 18.89 $MJ \cdot kg^{-1}$. With the increasing amount of potato pulp compound the net calorific value of pellets was decreasing, to reach the value of 17.95 $MJ \cdot kg^{-1}$, in the case of 30% pulp content (Obidziński et al. 2016).

Figure 1 depicts the specific density of the pellets. Statistical analysis of the results showed that the pellets used in the research, despite being varied in terms of the raw material composition, did not significantly differ in terms of the specific density. Also the change of the initial moisture content, which ranged between 9% (for compound J) to 13.65% (in the case of compounds D, E and F) had no effect on the density of the pellets. However, in studies on the impact of varied moisture content of hay (within a range between 28 and 44%) on the specific density of the produced pellets certain dependence was ascertained – with the increase of the moisture content the specific density of pellets decreased.

At the same time, statistically significant differences were obtained in the bulk density of the examined pellets (Fig. 2). The lowest bulk density was determined for pellets of sample G, which were made of rapeseed straw, spelt hulls and rapeseed cake. Despite the fact that composition of the pellet compound have no impact on its specific density, statistically significant differences in the bulk density resulted from varying lengths of the pellets (Fig. 3).

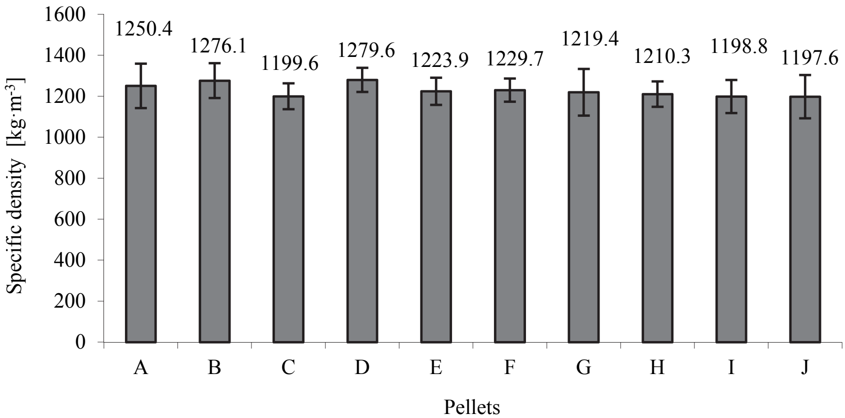

Fig. 1. Average specific density of the pellets with standard deviation
Rys. 1. Średnia gęstość właściwa peletów wraz z odchyleniem standardowym

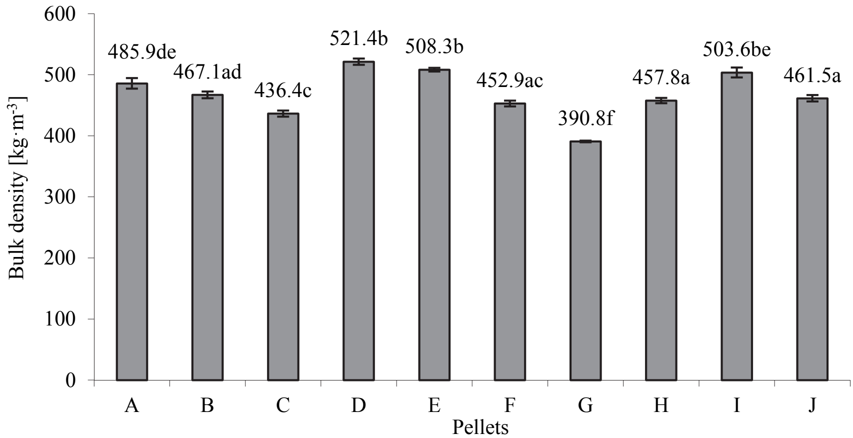

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Fig. 2. Average bulk density of the pellets with standard deviation
Rys. 2. Średnia gęstość nasypowa peletów wraz z odchyleniem standardowym

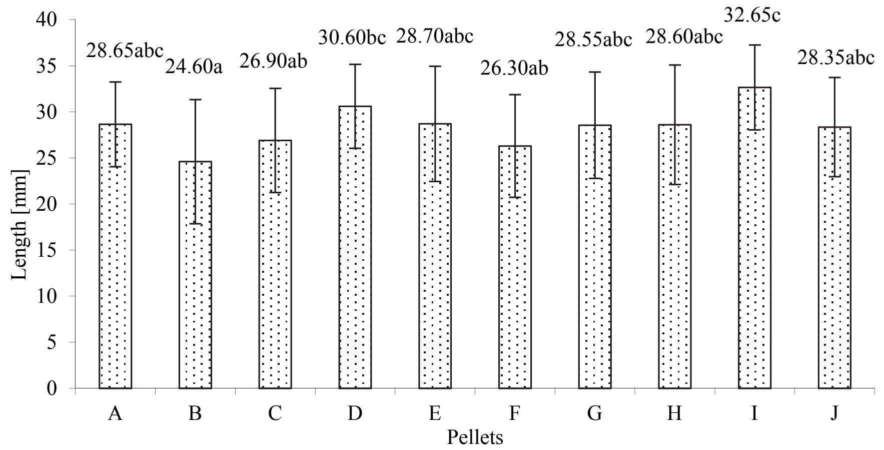

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Fig. 3. Average length of the pellets with standard deviation
Rys. 3. Średnia długość peletów wraz z odchyleniem standardowym

In the obtained results of the length measurements large standard deviation was observed, which testifies to high dimensional large of the pellets. The statistical differences was observed between B and I and C and I pellets. Varied length of the pellets resulted also in the varied mass of pellets. The statistical differences was observed also between pellets B and I, D and B. This was identified during mass measurement of the individual pellets (Fig. 4). According to the European Norms bulk density should be above 500 kg·m^{-3} (García-Maraver et al. 2011). Out of the tested pellets only the ones obtained from soya bean hulls and rye straw (sample D), wheat straw and soya bean hulls (sample E), and pellets of sample I made of rapeseed straw and spelt straw on the base of rapeseed cake complied with the specified standards. In so far completed studies on pellets made of different raw materials their bulk density was measured. Pellets were made of bamboo with addition of pine or rice straw, or of various kinds of straw (Liu et al. 2013, Liu et al. 2016). The bulk density of bamboo pellets increased with the increasing share of pine chips or rice straw admixture. After adding pine chips the bulk density of the pellet increased from 540 to 600 kg·m^{-3} (Liu et al. 2013, Liu et al. 2016). On the other hand, the bulk density of pellets made of straw was varied, depending on the straw kind or the composition of used compounds. The highest bulk density characterised pellets made of corn straw and it was equal to 566.9 kg·m^{-3}, while the ones made of wheat straw had the bulk density of only 407.7 kg·m^{-3} (Niedziółka et al. 2015).

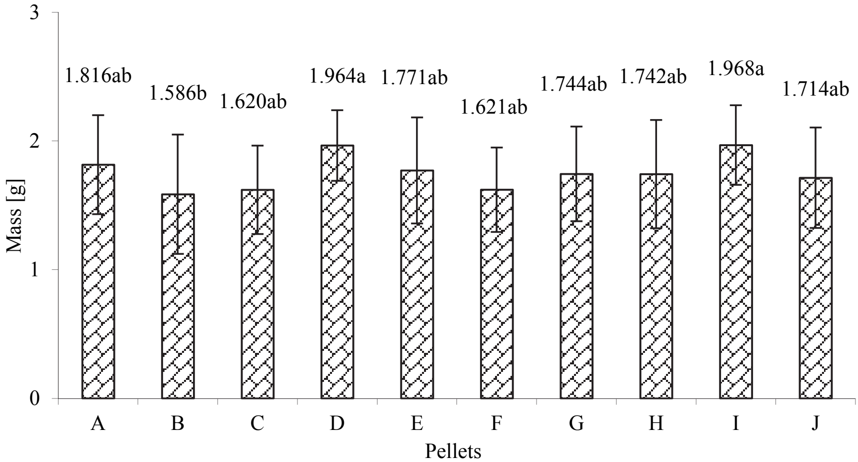

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Fig. 4. Average mass of the pellets with standard deviation
Rys. 4. Średnia masa peletów wraz z odchyleniem standardowym

The mechanical strength of the obtained pellets varied depending on the composition of their compound (Fig. 5). The highest strength characterised the pellets from sample I (95.9%) made of rapeseed straw, rapeseed cake and spelt hulls, while the lowest mechanical strength (85.4%) was determined in the case of the pellets from sample C, which were made of rapeseed straw and rapeseed cake. Statistically significant differences in the mechanical strength of pellets were observed after adding rapeseed cake to various kinds of straw. Pellets with rye straw in their compound (sample A) were characterised by greater mechanical strength (91.7%) than those with wheat straw composition (sample B – 87.7%), or rapeseed straw one (sample C – 85.4%). After introduction of soya bean hulls in the place of rapeseed cake the mechanical strength of pellets increased and amounted to 93.6% for compounds with rye straw (sample D), 94.0% for mixtures with wheat straw (sample E), and 90.2% for ones with rapeseed straw (sample F). In the research conducted by Liu et al. (2013) mechanical strength of pellets made of bamboo and rice straw (at a ratio of 2:3) was 99%. The mechanical strength of pellets made of straw ranged between 96.1% in the case of rapeseed straw to 97.7% in the case of compound of wheat and corn straw (Niedziółka et al. 2015). Additionally, an examination was made on the mechanical strength of pellets made of wheat straw depending on the degree of straw pulverization. On the basis of the results obtained, it was ascertained that the increased particle size caused increased mechanical strength of pellets made of wheat straw (Kashaninejad et al. 2014).

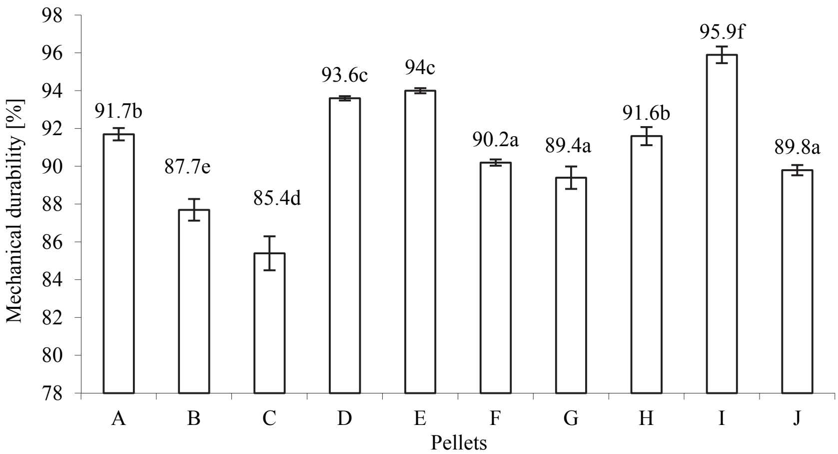

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Fig. 5. Average mechanical durability of the pellets with standard deviation
Rys. 5. Średnia wytrzymałość mechaniczna peletów wraz z odchyleniem standardowym

The pellet crushing strength determined in accordance with the agreed methodology varied for individual components (Fig. 6). Large differences in the results attest biological diversity of the material. The most resistant to compressive force turned out to be pellets from samples A, G, and I with 50% of rye straw or rapeseed cake, and the pellets with spelt hulls constituting 25% of the compound, which boosted the pellets compressive strength, and without soya bean hulls, which, in turn, lowered the compressive strength of the pellets. Research carried out by other authors on pellets compressive strength show that the highest resistance characterises the pellets made of rye straw and corn straw, somewhat smaller – the pellets made of rapeseed straw, and the lowest – ones made of wheat straw (Starek et al. 2014). In a research on the impact of size fraction of wheat bran on the compressive strength it was ascertained that the greatest resistance distinguish the pellets made of bran with the size of 0.5-1 mm. In turn, the pellets made of bran of the size of 1 to 2 mm had the lowest resistance (Zawiślak et al. 2014).

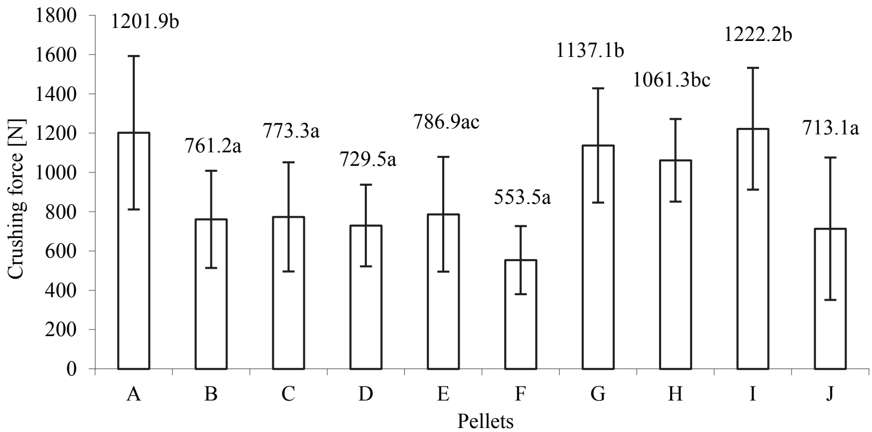

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Fig. 6. Average value of crushing force of the pellets with standard deviation
Rys. 6. Średnia wartość siły zgniatania peletów wraz z odchyleniem standardowym

The results of the cutting test of the produced pellets are presented on Figure 7. Similarly to the case of crushing strength measurement, there was a large variation in the results. The results for the pellet from sample I, which was characterised by the highest cutting strength, proved to be statistically significant. The pellets from I sample also had the highest resistance to crushing. Cutting tests performed by other researchers on pellets made of pine and poplar sawdust showed dependence on the moisture content during the process of compaction. In accordance to the obtained results, the increased initial moisture content in the sawdust decreased the cutting strength of the pellets (Millili & Schwartz 2008).

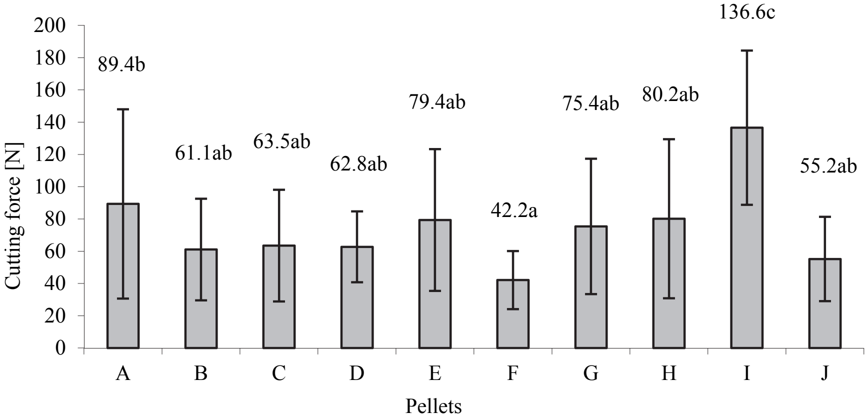

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Fig. 7. Average value of cutting force of the pellets with standard deviation
Rys. 7. Średnia wartość siły cięcia peletów wraz z odchyleniem standardowym

The effect of used different kinds of straw on the quality of the pellet was processed by statistical software Statistica 10.0, using the one-way analysis of variance (ANOVA) and Tukey's test. The results of statistical analysis for the individual parameters are displayed in Table 4. Statistically, varied raw material composition of the pellets did not affect the specific density thereof. Statistically significant differences were obtained for bulk density, length, mass, mechanical strength, as well as crushing and cutting. In conclusion, it can be inferred that the raw material composition has an impact on the evaluated physical parameters of pellets.

Table 4. Analysis of variance (ANOVA)
Tabela 4. Analiza wariancji (ANOVA)

Source variables	SS	df	MS	F value	Probability
Specific density [kg·m^{-3}]	132466.9	9	14718.54	2.01617	0.039
Bulk density [kg·m^{-3}]	40171.83	9	4463.536	98.4473	0.00
Length [mm]	884.38	9	98.26444	3.12253	0.0015
Mass [g]	3.196023	9	0.355114	2.54857	0.0087
Mechanical durability [%]	261.5939	9	29.06599	135.528	0.00
Crushing force [N]	10180415	9	1131157	14.0318	0.00
Cutting force [N]	119843.0	9	13315.89	8.57085	0.00

4. Conclusions

On the basis of the carried out studies on the influence of different raw materials used for production of pellets it was attested that statistically they do not affect the specific density of the pellets. However, there are differences in the bulk density of the pellets. Only three of the samples comply with European Norms regarding the pellet bulk density (samples: D, E and I). Further testing is necessary, in order to increase bulk density through the introduction of other raw materials. The pellet from sample I had the highest mechanical strength. It was made of rapeseed straw, rapeseed cake and spelt hulls. The same pellet had the highest crushing and cutting strength. When assessing the resistance to crushing and cutting it was concluded that there are significant statistical differences depending on the kind of straw and other raw materials used for pellet production. In terms of the analysed parameters pellet from sample G, made of rapeseed straw, soya bean hulls and spelt hulls, was the lowest rated one. The pellet from this sample had the lowest net calorific value, high moisture content, low bulk density, and low mechanical strength. Among the evaluated samples the highest rated were pellets from sample D, made of rye straw and soya bean hulls, which had the highest net calorific value of 17.89 $MJ \cdot kg^{-1}$, and complied with European standards in terms of bulk density, moisture content, and high mechanical strength.

References

Adapa, P.K., Tabil, L.G., Schoenau, G.J. & Sokhansanj, S. (2004). Pelleting characteristics of fractionated sun-cured and dehydrated alfalfa grinds. *Applied Engineering in Agriculture, (20)6,* 813-820.

Blaschke, T., Biberacher, M., Gadocha, S. & Schardinger, I. (2013). Energy landscapes: meeting energy demands and human aspirations. *Biomass Bioenergy, 55,* 3-16.

Callejón-Ferre, A.J., Velázquez-Martí, B., López-Martínez, J.A. & Manzano-Agügliaro, F. (2011). Greenhouse crop residues: energy potential and models for the prediction of their higher heating value. *Renewable & Sustainable. Energy Reviews, 15,* 948-955.

Caryalho, L., Wopierika, E., Pointner, C., Lundgren, J., Verma, V.K., Haslinger, W. & Schmidl C. (2013). Performance of a pellet boiler fired with agricultural fuels. *Applied Energy, 104,* 286-296.

Firrisa, M.T., van Duren, I. & Voinov, A. (2014). Energy efficiency for rapeseed biodiesel production in different farming systems. *Energy Efficiency, 7(1),* 79-95.

García-Maraver, V., Popov, V. & Zamorano, M. (2011). A review of European standards for pellet quality. *Renew. Energy, 36,* 3537-3540.

Hlavatá M., Čablíková L., Čablík V., Nowak A.K., Wzorek Z., Gorazda K., Serwatka K. (2014). Comparison of biomass and fossil fuels (Porównanie biomasy i paliw kopalnych). *Przemysł Chemiczny*, *6*, 93, 893-896.

Ibrahim, H., Ilinca, A. & Perron, J. (2008). Energy storage systems – characteristics and comparisons. *Renewable & Sustainable Energy Reviews, 12(5),* 1221-1250.

ISO 17225-6:2014. Solid biofuels – Fuel specifications and classes – Part 6: Graded non-woody pellets.

Kashaninejad, M., Tabil, L.G. & Knox, R. (2014). Effect of compressive load and particle size on compression characteristics of selected varieties of wheat straw grinds. *Biomass Bioenergy, 60,* 1-7.

Kuntal, J. & Sudipta, D. (2014). Biomass integrated gasification combined cogeneration with or without CO_2 capture – A comparative thermodynamic study. *Renew. Energy, 72*, 243-252.

Liu, Z., Liu, X., Fei, B., Jiang, Z., Cai, Z. & Yu, Y. (2013). The properties of pellets from mixing bamboo and rice straw. *Renew. Energy, 55,* 1-5.

Liu, Z., Mia, B., Jianga, Z., Fei, B., Cai, Z. & Liu, X. (2016). Improved bulk density of bamboo pellets as biomass for energy production. *Renew. Energy, 86,* 1-7.

Lisowski A., Grela M., Sypuła M., Świętochowski A., Dąbrowska-Salwin M., Stepień W., Korupczyński R. (2015). Pellets and briquettes from fruit trees wood. *Ann. Warsaw Univ. of Life Sci. – SGGW. Agricult. 66*, 127-136.

Malowaniec B. **(**2016**)**. European low-power renewable energy devices (Europejskie urządzenia małej mocy wykorzystujące odnawialne źródła energii). *Przemysł Chemiczny, 3*, 95, 512-518.

Mani, S., Tabil, L.G. & Sokhansanj, S. (2006). Effects of compressive force. particle size and moisture content on mechanical properties of biomass pellets from grasses. *Biomass Bioenergy, 30,* 648-654.

Mc Kendry, P. (2002). Energy production from biomass (part 1): overview of biomass. *Bioresource Technology, 83,* 37-46.

Millili, G.P. & Schwartz, J.B. (2008). The strength of microcrystalline cellulose pellets: The effect of granulating with water/ethanol mixtures. *Journal Drug Development and Industrial Pharmacy, 16(8),* 1411-1426.

Niedziółka, I., Szpryngiel, M., Kachel-Jakubowska, M., Kraszkiewicz, A., Zawiślak, K., Sobczak, P. & Nadulski, R. (2015). Assessment of the energetic and mechanical properties of pellets produced from agricultural biomass. *Renew. Energy, 76,* 312-317.

Obidziński, S., Piekut, J. & Dec, D. (2016). The influence of potato pulp content on the properties of pellets from buckwheat hulls. *Renew. Energy, 87,* 289-297.

Piecuch, T. (2010). Termiczna utylizacja odpadów. *Rocznik Ochrona Środowiska, 2*, 11-37.

Serrano, C., Monedero, E., Lapuerta, M. & Portero, H. (2011). Effect of moisture content. particle size and pine addition on quality parameters of barley straw pellets. *Fuel Process. Technology, 92,* 699-706.

Shawa, M.D., Karunakaranb, C. & Tabila, L.G. (2009). Physicochemical characteristics of densified untreated and steam exploded poplar wood and wheat straw grinds. *Biosystems Engineering, 103(2),* 198-207.

Ståhl, M. & Berghel, J. (2011). Energy efficient pilot-scale production of wood fuel pellets made from a raw material mix including sawdust and rapeseed cake. *Biomass and Bioenergy, 35(12),* 4849-4854.

Starek, A., Kośko, M., Zarajczyk, J., Kowalczuk, J., Tatarczak, J., Zawiślak, K., Sobczak, P., Mazur, J. & Szmigielski, M. (2014). Wpływ rodzaju surowca i parametrów roboczych granulatora nowej konstrukcji na odporność peletów na ściskanie. *Zeszyty Problemowe Postępów Nauk Rolniczych, 578,* 121-129.

Sypuła, M., Lisowski, A., Chlebowski, J., Nowakowski, T., Strużyk, A. (2010). Bulk density of chopped material of energetic plants. *Annals of Warsaw University of Life Sciences – SGGW. Agricult., 56*, 29-37.

Theerarattananoon, K., Xu, F. & Wilson, J. (2011). Physical properties of pellets made from sorghum stalk, corn stover, wheat straw, and big bluestem. *Industrial Crops and Products, 33(2),* 325-332.

Uesu, N.Y., Winkler, E.A.G. & Hechenleitner, A.A. (2000). Microcrystalline cellulose from soybean husk: effects of solvent treatments on its properties as acetylsalicylic acid carrier. *International Journal of Pharmaceutics, 206,* 85-96.

Williams, A., Jones, J.M., Ma, L. & Pourkashanian, M. (2012). Pollutants from the combustion of solid biomass fuels. *Progress in Energy and Combustion Science, 38(2),* 113-137.

Wzorek, Z., Krupa-Żuczek, K. (2015). Biomass from cultivation of sunflower and wheat as substitute of conventional fuels (Biomasa z uprawy słonecznika oraz pszenicy jako substytut paliw konwencjonalnych). *Przemysł Chemiczny, 8* , 94, 1344-1346.

Zawiślak, K., Sobczak, P., Panasiewicz, M., Mazur, J., Nadulski, R. & Starek, A. (2014). Wpływ wielkości frakcji otrąb pszennych na jakość granulatu. *Inżynieria Przetwórstwa Spożywczego, 3(4),* 25-28.

Wpływ rodzajów słomy i dodatków pochodzenia roślinnego na fizyczne cechy peletów

Streszczenie

W pracy przedstawiono wyniki badań nad peletowaniem różnych rodzajów słomy z dodatkiem makuchu rzepakowego, łuski sojowej i łuski orkiszowej. Uzyskane pelety poddano ocenie jakościowej badając: wytrzymałość mechaniczną peletów, siłę cięcia i zgniatania oraz podstawowe właściwości fizyczne. Otrzymane wyniki porównano z normą jakościową ISO 17225-6:2014 oceniając ich przydatność dla przemysłu. Wyniki opracowano statystycznie stwierdzając zależności wpływu dodatków i słomy na badane parametry.

Z badań wynika, że wilgotność mieszanek w procesie peletowania mieściła się w przedziale od 9,0 do 13,65%, a peletów – 7,31-11,45%. Wartość opałowa otrzymanych peletów była zróżnicowana w niewielkim stopniu (15,85-17,89 $MJ \cdot kg^{-1}$). Najmniejsza zawartość popiołu wyniosła dla peletu wytworzonego ze słomy żytniej i łuski sojowej (4,06%), a największa dla peletu ze słomy rzepakowej i makuchu rzepakowego (5,17%). Rodzaj słomy wraz z zastosowanymi dodatkami nie wpłynął na gęstość właściwą peletów. Otrzymano natomiast zróżnicowanie w gęstości nasypowej. Pelety uzyskane ze słomy rzepakowej z dodatkiem łuski orkiszowej i makuchu rzepakowego posiadały najniższą gęstość nasypową (380,9 $kg{\cdot}m^{-3}$). Tylko pelety uzyskane ze słomy żytniej i łuski sojowej, słomy pszennej i łuski sojowej oraz pelety uzyskane ze słomy rzepakowej i łuski orkiszowej na bazie makuchu rzepakowego posiadały gęstość nasypową powyżej 500 $kg{\cdot}m^{-3}$.

Najwyższą wytrzymałość mechaniczną posiadały pelety, wytworzone ze słomy rzepakowej z dodatkiem makuchu rzepakowego i łuski orkiszowej (95,9%), dla których uzyskano również najwyższą odporność na ściskanie (1222,2 N) oraz siłę cięcia (136,6 N). Pod względem analizowanych parametrów najniżej oceniono pelety, wykonane ze słomy rzepakowej z dodatkiem makuchu rzepakowego i łuski orkiszowej. Posiadały one najniższą wartość opałową (15,85 $MJ \cdot kg^{-1}$), wysoką wilgotność (11,45%), małą gęstość usypową (390,8 $kg{\cdot}m^{-3}$) oraz wytrzymałość mechaniczną (89,4%). Najkorzystniejsze z ocenianych peletów okazały się pelety, ze słomy żytniej i łuski sojowej o najwyższej wartości opałowej 17,89 $MJ \cdot kg^{-1}$.

Abstract

The paper presents the results of a research on pelletizing different kinds of straw with admixture of rapeseed cake, soya bean hulls and spelt hulls. Obtained pellets were qualitatively assessed by examining: mechanical strength of the pellets, cutting and crushing strength, and basic physical characteristics. The results were compared with the ISO 17225-6:2014 quality standard in order to assess their suitability for industry. The results were statistically processed to determine the effects the particular admixtures and straw kinds had on the test parameters.

The research testifies that moisture content of mixtures during the pelletizing process ranged between 9.0 and 13.65%, however pellets – 7.31-11.45%. The net calorific value of the produced pellets varied to a small extent (15.85-17.89 MJ·kg^{-1}). The lowest ash content was measured for pellet made of rye straw and soya bean hulls (4.06%), and the highest for pellet made of rapeseed straw and rapeseed cake (5.17%). The various kinds of straw with applied compounds do not affect the specific density of the pellets. However, the obtained bulk density varied. The pellets obtained from rapeseed straw with spelt hulls and rapeseed cake compounds had the lowest bulk density (380.9 kg·m^{-3}). Only the pellets made of soya bean hulls and rye straw, wheat straw and soya bean hulls, and the ones made of rapeseed straw and spelt hulls and based on rapeseed cake had bulk density > 500 kg·m^{-3}.

The highest mechanical strength was measured for the pellets made of rapeseed straw with admixture of rapeseed cake and spelt hulls (95.9%), for which also the highest crushing strength (1222.2 N) and cutting strength (136.6 N) were obtained. Considering the analysed parameters, the pellets made of rapeseed straw with rapeseed cake and spelt hulls admixture received the lowest ratings. They were characterised by the lowest net calorific value (15.85 MJ·kg^{-1}), high moisture content (11.45%), low bulk density (390.8 kg·m^{-3}) and low mechanical strength (89.4%). Out of the examined pellets, the one made of rye straw and soy bean hulls had the highest net calorific value of 17.89 MJ·kg^{-1} and received the highest ratings.

Słowa kluczowe:
biomasa roślinna, pelety, cechy fizyczne i energetyczne

Keywords:
plant biomass, pellets, energetic and physical properties