Ignacy NIEDZIÓŁKA [1], Mariusz SZYMANEK [1], Wojciech TANAŚ [1], Beata ZAKLIKA [1], Janusz ZARAJCZYK[2]
[1] Uniwersytet Przyrodniczy w Lublinie, Katedra Maszynoznawstwa Rolniczego
ul. Głęboka 28, 20-612 Lublin, Poland
[2] Uniwersytet Przyrodniczy w Lublinie, Katedra Maszyn Ogrodniczych i Leśnych
ul. Głęboka 28, 20-612 Lublin, Poland
e-mail: ignacy.niedziolka@up.lublin.pl

ANALYSIS OF QUALITATIVE PROPERTIES OF BRIQUETTES MADE FROM PLANT BIOMASS WITH A HYDRAULIC PISTON BRIQUETTE MACHINE

Summary

In connection with the depletion of fossil fuel resources and negative impact of their combustion products on the environment, there is a need to search for renewable energy sources. Biomass of plant origin that can be used e.g. for the production of solid biofuels in the form of briquettes or pellets is one such source. The article presents an analysis of qualitative characteristics of briquettes made from the selected plant materials using a hydraulic piston briquette machine. The study used the following materials: wheat straw, rape straw and camomile waste. During the briquetting process the adopted moisture of the crushed material was: 10.0; 13.0 and 16.0%, while the operating pressure of the briquetting piston: 6.0; 8.0 and 10.0 MPa. During the study the following values were determined: particle size distribution, length and mass of the produced briquettes as well as their specific density and mechanical strength. Depending on the briquetted raw material and studied factors, the specific density of the pellets and their mechanical strength increased with the increasing moisture and briquette machine's pressure. There was a statistically significant effect of the raw materials moisture and briquetting pressure on the qualitative properties of briquettes under study.
***Key words**: biomass, briquettes, qualitative properties, specific density, mechanical strength*

ANALIZA JAKOŚCIOWYCH CECH BRYKIETÓW WYTWORZONYCH Z BIOMASY ROŚLINNEJ W HYDRAULICZNEJ BRYKIECIARCE TŁOKOWEJ

Streszczenie

W związku z wyczerpywaniem się zasobów paliw kopalnych oraz negatywnym wpływem produktów ich spalania na środowisko naturalne, istnieje konieczność poszukiwania odnawialnych źródeł energii. Jednym z takich źródeł jest biomasa pochodzenia roślinnego, którą można wykorzystać m.in. do produkcji biopaliw stałych w postaci brykietów lub peletów. W artykule przedstawiono analizę jakościowych cech brykietów wytworzonych z wybranych surowców roślinnych w brykieciarce hydraulicznej tłokowej. Do badań wykorzystano następujące surowce: słomę pszenną, słomę rzepakową i odpady rumiankowe. Podczas procesu brykietowania przyjęta wilgotność rozdrobnionych surowców wynosiła: 10,0; 13,0 i 16,0%, natomiast ciśnienie robocze brykieciarki – 6,0; 8,0 i 10,0 MPa. W trakcie badań określano skład granulometryczny surowców oraz długość i masę wytworzonych brykietów, a także ich gęstość właściwą i trwałość mechaniczną. W zależności od rodzaju brykietowanych surowców i badanych czynników, gęstość właściwa brykietów i ich trwałość mechaniczna zwiększała się ze wzrostem wilgotności i ciśnienia roboczego brykieciarki. Stwierdzono statystycznie istotny wpływ wilgotności surowców i ciśnienia roboczego brykieciarki na analizowane cechy jakościowe brykietów.
***Słowa kluczowe**: biomasa, brykiety, cechy jakościowe, gęstość właściwa, trwałość mechaniczna*

1. Introduction

Traditional fuels, such as coal, lignite, oil and natural gas are being replaced by alternative energy sources. This is due to the limited resources of fossil fuels, problems connected with their use as well as their negative impact on the environment. Therefore, replacements of conventional fuels should be inexhaustible, inexpensive to obtain and, most importantly, environmentally neutral. Biomass, including the widely available raw materials of plant origin is one such source that meets the above-mentioned criteria [2, 5]. Among them, raw materials derived from field crops are used as well as by-products and waste produced in the food industry. Biomass includes also the wood waste produced in forestry, woodworking, pulp and paper industry or energy crops, such as e.g.: *Sida hermaphrodita* or *Miscanthus giganteus* [3]. Biomass use carries a number of advantages. These include lower emissions of combustion products relatively to the products of conventional fuels combustion, possibility of using local natural resources and production surplus as well as upgrading the energy security of the country [4, 18].

Plant materials produced on fields and grasslands such as straw and other plant residues have a high energy potential. In Poland, every year after securing the necessary amount of straw for agricultural purposes there is left approx. 10 million tonnes of raw material which can be obtained for energy purposes [5]. The use of raw, unprocessed straw is very difficult compared to other energy carriers. In addition, this raw material is available seasonally and it has a smaller calorific value. This is due to its wide range of moisture and low density. The reduction in volume of plant biomass can be accomplished e.g. by compaction, briquetting or pelleting [1, 7, 10]. The processing of plant materials significantly increases their density and calorific value, reduces the area of storage and transport costs and provides the ability to automate the process of combustion [11, 15, 16].

The briquetting of plant biomass takes place in the process of pressure agglomeration. The material crushed by both the external forces (compacting pressure) and the internal (intermolecular) ones takes the stable form. Briquettes may have a cylindrical shape, a cuboid one or that of a hexagonal prism. Both the shape and the dimensions of the briquettes are determined by the type of pressing unit in a particular briquetting device [8, 17, 19], whereas the density of agglomerates is influenced by factors related to the physical properties of the raw material. These include parameters such as: moisture content in the raw material, fineness, particle size distribution, coefficient of internal friction, etc. [19].

The optimum moisture of straw for energy purposes should be 15-20%. If the straw used to produce the agglomerate is too moist, the briquetting process is impaired, the resulting agglomerate is burnt and, most importantly, its calorific value is lower and the emission of pollutants in fumes higher [6, 17]. The applied amount of compaction pressure (piston unit pressure) is the second parameter which to a large extent influences both the briquetting process and the quality of obtained product. If the value of this parameter is mismatched to the type of compacted material, energy consumption may increase and the resulting agglomerate obtains unfavorable mechanical properties. The high quality of briquettes obtained in the process of compaction is evidenced by their specific density and mechanical strength [9, 11, 16]. The aesthetics of agglomerates also matters, if the briquettes are to be used as fuel for fireplaces.

The aim of the study was to analyze the qualitative properties of briquettes made from selected plant materials with a hydraulic piston briquette machine.

2. Material and methods

The study used the following raw materials of vegetable origin: wheat straw, rape straw and camomile waste. Thickened plant materials were derived from crops on a family farm in the Lublin province. The compressed straw cubes were pulverized using a universal hammer mill H 111/1 driven with the electric power engine of 7.5 kW equipped with sieves of 20 mm diameter mesh. For the production of briquettes the hydraulic piston briquette machine of the JUNIOR company Deta Poland type was used. During the briquetting, a single stroke of the material's feeder to the compression chamber was applied and the adopted three values of the operating pressure were: 6.0; 8.0 and 10.0 MPa. The assumed pressure values were obtained using the scaled knob.

The relative moisture of raw materials was determined by the laboratory weigh-drying device MAX 50/1 / WH RADWAG. Samples of wet biomass (approx. 5 g) were placed in the drying chamber of the device and then dried at 120°C up to the constant weight in accordance with the standard PN EN 15414-3: 2011 [12]. The display read the moisture value of the dried raw material. The briquetting of the plant materials was carried out at three moisture levels, i.e.: 10.0; 13.0 and 16.0%. For the sieve analysis of the raw materials samples were taken of 100 g (± 1 g) and then a laboratory shaker was used with a set of sieves of the following meshes: 3.15; 2.8; 2.0; 1.4; 1.0; 0.5; 0.25 mm. They were determined according to the PN-EN 15149-2: 2011 standard [13].

The measurements of physical properties of briquettes produced in the hydraulic piston briquette machine included: length, diameter and mass. For the measurement, briquette samples were taken of 1000 g (± 10 g) and they were obtained in 5 replications. The geometrical dimensions of the briquettes were determined by calipers with the accuracy of ± 0.1 mm, while their mass was determined with a laboratory balance with the accuracy of ± 0.1 g. The specific density of the briquettes was determined by the measurement of their physical properties performed in 5 replications and was calculated according to the formula (1):

$$\rho_w = \frac{4\cdot 10^6 \cdot m}{\pi \cdot d^2 \cdot l} \ (\mathrm{kg\cdot m^{-3}}) \quad (1)$$

where: ρ_w - density of the briquette ($\mathrm{kg\cdot m^{-3}}$),
m - mass of the briquette (g),
d - external diameter of the briquette (mm),
l - briquette length (mm).

The measurements of mechanical strength of briquettes were carried out on the test bench according to the PN-EN 15210-2: 2011 [14]. The rotational speed of the drum was 21 rev· $\mathrm{min^{-1}}$ (± 0.1 rev·$\mathrm{min^{-1}}$), testing time 5 minutes, sample mass 2000 g (± 100 g). After the strength test, the tested briquette samples were sifted on a sieve with the 31.5 mm mesh. The mechanical strength of the briquettes was determined according to the formula (2):

$$D_U = \frac{m_A}{m_E} \cdot 100 \ (\%) \quad (2)$$

where: D_U - mechanical strength of briquettes (%),
m_A - briquette mass after the strength test (g),
m_E - briquette mass before the strength test (g).

The obtained results of briquette density measurements were subjected to statistical analysis using the two-way analysis of variance and Tukey's test. In all the analyses, the level of significance $\alpha = 0.05$. For this purpose the statistical program SAS Enterprise Guide 5.1 was used. The obtained results are shown in the tables containing the medium densities of briquettes with the designation of a significant impact of the adopted factors on the studied properties.

3. Results and analysis

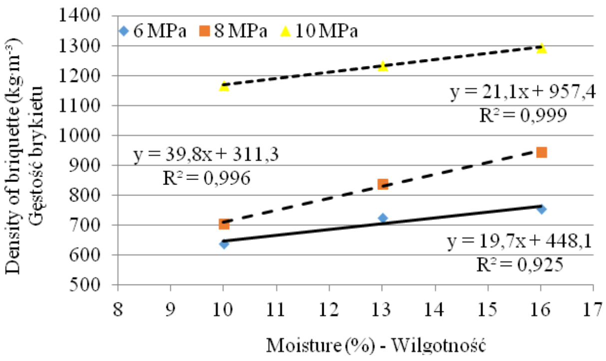
Table 1 lists the results of sieve analysis of particle size distribution of plant materials used for the production of briquettes. The length of the particles depended on the type of material and its sensitivity to crushing. The highest share of particles above 3.15 mm was observed for wheat straw (76.2%), significantly lower for rape straw (35.6%) and the lowest for camomile waste (19.5%). The lowest share of pulverized fraction (> 0.5 mm) was found for camomile waste (6.3%) and wheat straw (7.6%), and the highest for rape straw (11.3%).

Figure 1 shows the results of measurements of the density of briquettes made from wheat straw. For the assumed moisture contents the lowest density was observed for the briquettes produced at the pressure of 6 MPa (636-754 $\mathrm{kg\cdot m^{-3}}$), considerably higher at the pressure of 8 MPa (705-944 $\mathrm{kg\cdot m^{-3}}$) and the highest at the pressure of 10 MPa (1167-1293 $\mathrm{kg\cdot m^{-3}}$). The analysis of the data shows that with an increase in moisture and pressure, the density of the produced briquettes increased by approx. 18; 34 and 11%.

Table 1. Particle size distribution of plant materials used in the production of briquettes (%)
Tab. 1. Skład granulometryczny surowców roślinnych użytych do produkcji brykietów (%)

Meshes of sieve (mm) / Otwory sita Kind of material / Rodzaj materiału	3.15	2.8	2.0	1.4	1.0	0.5	0.25	0.0
Wheat straw Słoma pszenna	76.2	0.2	0.4	1.7	4.2	9.7	5.1	2.5
Rape straw Słoma rzepakowa	35.6	0.3	3.5	17.3	14.8	17.2	7.0	4.3
Camomile waste Odpady rumiankowe	19.5	0.3	0.6	7.2	24.6	41.5	5.3	1.0

Source: own work / Źródło: Opracowanie własne



Source: own work / Źródło: Opracowanie własne

Fig. 1. Density of briquettes produced from wheat straw depending on moisture content and the operating pressure of briquette machine
Rys. 1. Gęstość brykietów wytworzonych ze słomy pszennej, w zależności od wilgotności surowca i ciśnienia roboczego brykieciarki

There were no statistically significant differences between the density of briquettes produced at the moisture of 10% and the pressure of 8 MPa and the density of briquettes produced at the moisture of 13% and the pressure of 6 MPa (Table 2).

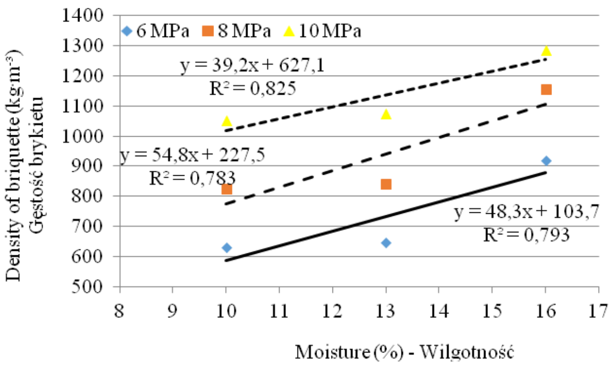
Table 2. Comparison of mean briquette densities for the adopted wheat straw compaction parameters
Tab. 2. Porównanie średnich gęstości brykietów dla przyjętych parametrów zagęszczania słomy pszennej

Moisture (%) Wilgotność	10.0	13.0	16.0	LSD NIR
Density ($kg \cdot m^{-3}$) Gęstość	835.9^{A}	932.1^{B}	997.1^{C}	
Pressure (MPa) Ciśnienie	6.0	8.0	10.0	24.6
Density ($kg \cdot m^{-3}$) Gęstość	704.5^{D}	829.4^{A}	1231.2^{E}	

$^{A, B, C}$ – averages indicated by the same letter do not differ significantly at the level $\alpha = 0.05$
$^{A, B, C}$ – średnie oznaczone tą samą literą nie różnią się istotnie przy poziomie $\alpha = 0,05$

Source: own work / Źródło: Opracowanie własne

Figure 2 presents the results of density measurements for the briquettes produced from rape straw. For the assumed moisture contents, the lowest density was observed in the briquettes produced at the pressure of 6 MPa (630-920 $kg \cdot m^{-3}$), slightly higher at the pressure of 8 MPa (826-1155 $kg \cdot m^{-3}$) and the highest at the pressure of 10 MPa (1051-1286 $kg \cdot m^{-3}$). The analysis of the data showed that with an increase in moisture and pressure the density of the produced briquettes increased by 46; 40 and 22%. There were no statistically significant differences between the density of briquettes produced with the moisture content of 10 and 13% for all the adopted compaction pressure values (Table 3).



Source: own work / Źródło: Opracowanie własne

Fig. 2. Density of briquettes produced from rape straw depending on moisture content and the operating pressure of briquette machine
Rys. 2. Gęstość brykietów wytworzonych ze słomy rzepakowej, w zależności od wilgotności surowca i ciśnienia roboczego brykieciarki

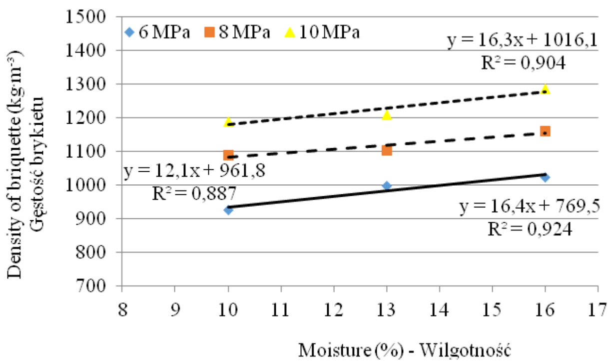
Table 3. Comparison of mean briquette densities for the adopted rape straw compaction parameters
Tab. 3. Porównanie średnich gęstości brykietów dla przyjętych parametrów zagęszczania słomy rzepakowej

Moisture (%) Wilgotność	10.0	13.0	16.0	LSD NIR
Density ($kg \cdot m^{-3}$) Gęstość	835.5^{A}	853.8^{A}	1120.4^{B}	
Pressure (MPa) Ciśnienie	6.0	8.0	10.0	25.4
Density ($kg \cdot m^{-3}$) Gęstość	732.3^{C}	940.3^{D}	1137.1^{B}	

$^{A, B, C}$ – averages indicated by the same letter do not differ significantly at the level $\alpha = 0.05$
$^{A, B, C}$ – średnie oznaczone tą samą literą nie różnią się istotnie przy poziomie $\alpha = 0,05$

Source: own work / Źródło: Opracowanie własne

Figure 3 presents the results of density measurements for the briquettes produced from camomile waste. For the assumed moisture contents, the lowest density was observed for the briquettes produced at the pressure of 6 MPa (926-1024 kg·m^{-3}), slightly higher at the pressure of 8 MPa (1090-1163 kg·m^{-3}) and the highest at the pressure of 10 MPa (1189-1287 kg·m^{-3}). The analysis of the data shows that with an increase in moisture and pressure, the density of produced briquettes increased by 10.6; 6.7 and 8.2%. There were no statistically significant differences between the densities of briquettes produced at the moisture of 10 and 13% and the pressure of 8 MPa and at the moisture of 10 and 13% and the pressure of 10 MPa, as well as the density of briquettes at the moisture of 13 and 16% and the pressure of 6 MPa (Table 4)



Source: own work / Źródło: Opracowanie własne

Fig. 3. Density of briquettes produced from camomile waste depending on moisture content and the operating pressure of briquette machine

Rys. 3. Gęstość brykietów wytworzonych z odpadów rumiankowych, w zależności od wilgotności surowca i ciśnienia roboczego brykieciarki

Table 4. Comparison of mean briquette densities for the adopted camomile waste compaction parameters

Tab. 4. Porównanie średnich gęstości brykietów dla przyjętych parametrów zagęszczania odpadów rumiankowych

Moisture (%) Wilgotność	10.0	13.0	16.0	LSD NIR
Density (kg·m^{-3}) Gęstość	1068.2^{A}	1104.5^{AB}	1157.9^{C}	
Pressure (MPa) Ciśnienie	6.0	8.0	10.0	38.1
Density (kg·m^{-3}) Gęstość	983.2^{D}	1118.9^{B}	1228.6^{E}	

$^{A, B, C}$ – averages indicated by the same letter do not differ significantly at the level α = 0.05

$^{A, B, C}$ *– średnie oznaczone tą samą literą nie różnią się istotnie przy poziomie α = 0,05*

Source: own work / Źródło: Opracowanie własne

Table 5 presents the results of studies on the mechanical strength of pellets depending on the type of raw materials, adopted moisture contents as well as the briquette machine operating pressure values.

For the adopted moisture and operating pressure values, the lowest mechanical strength was observed in the briquettes made from rape straw, much higher in the briquettes from wheat straw and the highest in the briquettes from camomile waste. The analysis of the obtained data showed that with the increase in moisture and operating pressure the mechanical strength of the produced briquettes increased from 3 percentage points for camomile waste to almost 5 percentage points for wheat straw and more than 8 percentage points for rape straw.

Table 5. Results of mechanical strength measurements of briquettes produced from the tested plant materials (%)

Tab. 5. Wyniki pomiarów trwałości mechanicznej brykietów wytworzonych z badanych surowców roślinnych (%)

Moisture (%) Wilgotność	Pressure (MPa) Ciśnienie	Wheat straw Słoma pszenna	Rape straw Słoma rzepakowa	Camomile waste Odpady rumiankowe
10.0	6.0	92.5	84.2	95.8
	8.0	94.1	86.3	96.3
	10.0	95.2	89.3	97.1
13.0	6.0	93.6	85.9	96.9
	8.0	94.8	87.1	97.3
	10.0	95.9	90.5	97.9
16.0	6.0	94.2	88.6	97.4
	8.0	96.5	90.4	98.1
	10.0	97.3	92.7	98.8

Source: own work / Źródło: Opracowanie własne

4. Conclusions

1. Depending on the type of used material as well as the adopted moisture and operating pressure values in the briquette machine, the produced briquettes differed significantly both in terms of specific density and mechanical strength.
2. The increase in the moisture content from 10 to 16% and in the operating pressure in the briquette machine from 6 to 10 MPa caused almost 1.5-fold increase in the density of briquettes made from camomile waste and more than 2-fold one for briquettes from wheat straw and rape straw.
3. The highest increase in the briquette density was observed for rape straw at the moisture of 10 and 16% and the pressure of 6 MPa (46%), the lowest one for camomile waste at the moisture of 10 and 16% and the pressure of 8 MPa (6.7%).
4. The mechanical strength of the briquettes was dependent on the type of compacted raw material, the moisture and the pressure in briquette machine. The lowest durability of briquettes was recorded in the case of rape straw compaction (84.2-92.7%) and the highest one for the briquettes from camomile waste (95.8-98.8%).
5. The analysis of the obtained study results showed that the improvement of qualitative properties of the produced briquettes was strongly dependent on such factors as the degree of fragmentation and particle size distribution of plant materials as well as their moisture content and operating pressure in the briquette machine.

5. References

[1] Adamczyk F., Frąckowiak P., Mielec K., Kośmicki Z.: Problematyka badawcza w procesie zagęszczania słomy przeznaczonej na opał. Journal of Research and Applications in Agricultural Engineering, 2005, 50(4), 5-8.

[2] Bielski S., Dubis B., Jankowski K.: Efektywność energetyczna produkcji i konwersji biomasy pszenżyta ozimego na biopaliwa. Przem. Chem., 2015, 94/10, 1798-1801.

[3] Dreszer K., Michałek R., Roszkowski A.: Energia odnawialna – możliwości jej pozyskiwania i wykorzystania w rolnictwie. Kraków: Wyd. PTIR, 2003. ISBN 83-9170-530-7.
[4] Gradziuk P.: Biopaliwa. Warszawa: Wieś Jutra Sp. z o.o., 2003, 114.
[5] Grzybek A., Gradziuk P., Kowalczyk K.: Słoma – energetyczne paliwo. Warszawa: Wieś Jutra Sp. z o.o., 2001. ISBN 83-88368-19-2.
[6] Hebda T., Złobecki A.: Wpływ wilgotności słomy na trwałość kinetyczną brykietów. Inżynieria Rolnicza, 2011, 6(131), 45-52.
[7] Hejft R. Ciśnieniowa aglomeracja materiałów roślinnych. Radom: Wyd. ITE, 2002. ISBN 83-7204-251-9.
[8] Hejft R., Obidziński S.: Pressure agglomeration of plant materials – pelleting and briquetting (Part II). Journal of Research and Applications in Agricultural Engineering, 2015, 60(1), 19-22.
[9] Kulig R., Skonecki S., Gawłowski S., Zdybel A., Łysiak G.: Oddziaływanie ciśnienia na efektywność zagęszczania trocin wybranego drewna miękkiego. Acta Sci. Pol., Technica Agraria, 2013, 12(1-2), 31-40.
[10] Niedziółka I., Szpryngiel M., Kraszkiewicz A., Kachel-Jakubowska M.: Ocena wydajności brykietowania oraz jakości brykietów wytworzonych z wybranych surowców roślinnych. Inżynieria Rolnicza, 2011, 6(131), 149-155.
[11] Niedziółka I., Szymanek M.: An estimation of physical properties of briquettes produced from plant biomass. Teka Komisji Motoryzacji i Energetyki Rolnictwa, 2010, Vol. X, 301-307.
[12] PN-EN 15414-3:2011. Oznaczanie zawartości wilgoci metodą suszarkową – Część 3: Wilgoć w ogólnej próbce analitycznej.
[13] PN-EN 15149-2:2011. Biopaliwa stałe – Oznaczanie rozkładu wielkości ziaren – Część 2: Metoda przesiewania wibracyjnego.
[14] PN-EN 15210-2:2011. Biopaliwa stałe – Oznaczanie wytrzymałości mechanicznej brykietów i peletów. Część 2: Brykiety.
[15] Panwar V., Prasad B., Wasewar K.: Biomass residue briquetting and characterization. J. Energy Eng., 2011, 137/2, 108-114.
[16] Praca zbiorowa pod red. J. Frączka. Optymalizacja procesu produkcji paliw kompaktowanych wytwarzanych z roślin energetycznych. Kraków: Wyd. PTIR, 2010. ISBN 978-83-930818-0-6.
[17] Sharma M. K., Gohil P., Sharma N.: Biomass briquette production: a propagation of non-convention technology and future of pollution free thermal energy sources. American Journal of Engineering Research (AJER), 2015, 04/02, 44-50.
[18] Szyszlak-Bargłowicz J., Piekarski W.: Charakterystyka biomasy jako paliwa [W:] Jackowska I. (red.) Biomasa jako źródło energii. Warszawa: Wieś Jutra Sp. z o.o., 2009, 29-38.
[19] Zawiślak K.: Wpływ kształtu powierzchni rolek wytłaczających na trwałość granulatu. Inżynieria Rolnicza, 2006, 7(82), 475-483.