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Energy potential of densified biomass from maize straw in form of pellets and briquettes

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Abstract. The aim of the study was the evaluation and comparison of energy potential of briquettes and pellets produced from the maize straw and woody biomass based on various diameters of pellets. By experimental measurements a calorific value and ash content was observed. Calorific value was measured by laboratory calorimeter IKA C 6000 (IKA® Works, Inc., USA) and laboratory combustion chamber Lindberg/Blue M (Thermo Fisher Scientific, Inc., USA). Individual calorific values and ash content was observed and subsequently confronted to obtain differences with replication. The analysis showed that calorific value of pellets with diameter 6 mm ranged from 16.99 MJ kg^{-1} to 17.80 MJ kg^{-1}. Calorific value of pellets with 8 mm diameter ranged from 16.63 MJ kg^{-1} to 17.20 MJ kg^{-1}. However, compared calorific value of briquettes ranged from 14.99 MJ kg^{-1} to 15.66 MJ kg^{-1}. Further analysis showed that ash content of samples varied as well and it's even affected by diameter of pellets. While ash content of pellets with diameter 6 mm was observed as 4.9% of total volume in case of pellets with 8 mm it was observed at value 5.5%. Briquettes produced from maize straw have ash content at value 5.4%. In contrary, ash content of woody biomass was significantly higher, 11% of volume, specifically. At the basis of observed parameters it can be concluded that maize straw densified in form of briquettes and pellets have a great energy potential which is comparable and competitive with currently used materials for production of briquettes and pellets.

Key words: biomass, maize straw, briquettes, pellets, calorific value, ash content.

INTRODUCTION

From the perspective of the combustion of biomass its properties are essential where the main indicators of quality are values such as moisture content in biomass, chemical content of biomass, volatile matter content and calorific value (Maga & Piszalka, 2006). The usable biomass comes from a variety of plants and includes a wide range of chemicals and even though its energy content is in the most cases similar. As it was reported by Maga & Piszczalka (2006) and Pepich (2006) energy production from biomass has a great potential in the frame of agriculture and similar fields even in case of Slovakia (Table 1). Calorific value of dry biomass is typically in the range from 15 to 19 MJ kg^{-1}. The heat produced from biomass materials can be obtained directly by combustion or indirectly, e.g. by cooling of the engines combusting the biogas or by electricity generation. In the case of direct way of energy production it means the combustion of plant or woody biomass. And in combination with more currently advanced energy source devices defined by increased thermal efficiency it means less bio fuel requirements for the same amount of energy produced (Piszczalka & Jobbágy, 2011). The harvest of energy crops can be realized by different technologies. An annual willow or grass crops can be harvested by using machinery which is designed for harvest of the maize (Urbanovičová, 2011). Chopped biomass can be used for additional purposes such as production of the briquettes. The particle fractions are one of the most important features of chopped biomass (Lisowski et al., 2010). However, the harvest of crops has a high energy demands and therefore it is inevitable to optimize the whole harvest process (Lisowski et al., 2009).

Table 1. Energy potential of biomass in Slovakia (adopted from Maga & Piszczalka (2006) and Pepich (2006))

Type of biomass	Total amount	Energy potential, PJ
Biomass from agriculture for combustion	2,031 Mt	28.6
Woody biomass	1,810 Mt	16.9
Wood processing industry	1,410 Mt	18.1
Mouldings in the production of bio fuels	0.1 Mt	1.8
Purpose-grown biomass for energy production by combustion	$100\times10^{-3}\times$ha	10.6
Total	-	76

PJ – Peta joules; Mt – Mega tons; ha – hectare.

Biomass is an ideal renewable energy with advantages of abundance resources and neutral in the greenhouse gas circulation (Krištof et al., 2011; Fei et al., 2014). Maize is one of the agricultural crops, which have wide use from the view of phytomass production and is considered as the third millennium crop. Alcohol, oil and biogas, also plastics, thermal insulation and other materials can be produced from maize, even electric energy by means of biogas cogeneration. Maize is primarily an economically profitable crop (Križan et al., 2017). Considering combustion the characteristics of biomass are important whereas the main indicators of quality are values of water content in biofuel, chemical composition of combustible fuel, content of volatile matter, biofuel heat value (Findura et al., 2006; Maga & Piszczalka, 2006; Jobbágy et al., 2011). Maize stalks have a heat value of 14.4 MJ kg^{-1} at moisture level of 10%, at the volumetric weight of 100 kg m^{-3} in packages. However, straw, Miscanthus, maize, and horse manure were reviewed in terms of fuel characteristics by Carvalho et al. (2008; 2013) with conclusion that all the fuels showed problems with ash lumping and slag formation.

At the same time it needs to be noted that treatment of biomass is required for its use improvement. Moreover, biomass material pressing at very high pressure is a working process, which we refer to as compaction in the final phase (Pepich, 2006). Traditional multi-operational maize straw harvesting is performed in the following steps, which are defined by primary method of the grain maize harvesting, it means what type of machine was used to harvest maize crop (Jandačka & Mikulík, 2008). Grain harvest is performed by conventional combine harvesters with adapter for grain maize harvesting with crushing maize stalks under combine-harvester. After that, maize straw crushing is performed. This is followed by maize straw and stubble grinding by means of hammer and knife mulching machine (Birrell, 2006; Collection of Laws, 2010).

The aim of the study was the evaluation and comparison of energy potential of briquettes and pellets produced from the maize straw and woody biomass based on various diameters of pellets. By experimental measurements a calorific value and ash content was observed.

MATERIALS AND METHODS

Since the aim of the study was to compare pellets and briquettes produced from maize straw (residues) with regards to its physical and mechanical properties in relationship with differences in diameters. Therefore, by experimental measurements was observed calorific value and ash content as a main criterion. Various laboratory devices were employed in measurements, e.g. laboratory calorimeter control unit (Fig. 1) and laboratory combustion furnace.

Figure 1. Calorimeter IKA C 6000 control unit (IKA® Works, Inc., USA).

The experimental field was selected in accordance of sufficient experimental sampling grid needed with area of 120 ha (N 48.069135, E 17.959389). From selected area were collected samples in regular grid by manual harvest. Ten sampling points were selected with average area represented by 1 m^2, from which the whole maize were collected at the end of maturity before field harvest. Subsequently, a maize cob were removed and only leafs and stalks were utilized in pellets and briquettes production while their represents the maize residues left on the field after harvest of maize. Obtained residue mixture of leafs and stalks were shredded and crushed in order to produced an appropriate particle size of this elements which can be utilized in pellets and briquettes production. This mixture were then densified in form of briquettes by employment of automatic briquetting press BrikStar MAGNUM (BRIKLIS – Slovakia, Inc., Slovakia) which operates in pressure range from 12 to 18 MPa. Produced briquettes were then analysed in order to determination of its calorific value by employment of calorimeter device IKA C 6000 (IKA® Works, Inc., USA). For each sample of produced briquettes were conducted ten replications. Subsequently, ash content of individual samples were determined by employment of laboratory combustion chamber Lindberg/Blue M (Thermo Fisher Scientific Inc., USA), The same methodologies were followed in case of production and analysis of pellets produced from maize residues however two types of pressing matrices were utilized. Those matrices differ in diameter of its holes (6 mm and 8 mm) and pelletizing press was used (UDKL 120, TIANYUYOUDO, Shandong, China).

The production pellets and briquettes was conducted according following standards: DIN 51900, BS 1016 part 5 1977, ASTN D3286-91, ASTM D240-87, ASTM E711-87, ISO 1928-1976, ASTM D 1989-91 and BSI. In case of determination of the calorific value and ash content of produced briquettes were followed standards STN ISO 1928 – Calorific value of biological materials and STN ISO 1171 – Ash content of biological materials.

RESULTS AND DISCUSSION

According to Frei (2013) lignin is a plant component with important implications for various agricultural disciplines. It confers rigidity to cell walls, and is therefore associated with tolerance to abiotic and biotic stresses and the mechanical stability of plants. In animal nutrition, lignin is considered an anti-nutritive component of forages as it cannot be readily fermented by rumen microbes. In terms of energy yield from biomass, the role of lignin depends on the conversion process. It contains more gross energy than other cell wall components and therefore confers enhanced heat value in thermo chemical processes such as direct combustion.

Our study as well as in those conducted by Kaliyan et al. (2009) and Kaliyan & Morey (2010) confirmed that highly dense, strong, and durable briquettes and pellets from corn stover and switch grass could be produced without adding chemical binders (i.e., additives) by activating (softening) the natural binders such as water-soluble carbohydrates, lignin, protein, starch, and fat in the biomass materials by providing moisture and temperature in the range of glass transition of the biomass materials. Moreover, the same study as well as those conducted by Urbanovičová et al. (2017) has proved that the roll press briquetting appears to be a promising low-cost, low-energy, high-capacity densification approach for commercial production of the biomass briquettes.

The energy potential analysis reveal that in case of produced pellets with diameter of 6 mm the average calorific value was obtained at level 17,381.6 kJ kg^{-1} while in case of pellets with diameter of 8 mm was observed lower average value at level 17,041.7 kJ kg^{-1}. From this point of view it can be concluded that the lower diameter of utilized holes matrices leads to increase of the pellets densities which was then transformed into the increased energy potential. In comparison with the average calorific value of produced briquettes the significantly lower value (15,402.8 kJ kg^{-1}). This phenomenon can be explained by conclusion that in briquetting process do not secure comparable densification of utilized material while its energy potential was observed at level 15,402.8 kJ kg^{-1} while in case of pellets were about 11.38 and 9.61% lower than in case of pellets with diameters of 6 and 8 mm (Table 2).

Wongsiriamnuay & Tippayawong (2015) has reported that the compact density increased with pressure and temperature to around 950–1,100% higher than the residue density. The relaxed density was stable at 60–80°C, but at 30 °C, it was found to decrease from 800–1,000 kg m^{-3} to 660–700 kg m^{-3}. The durability index was observed to improve with increasing pressure and temperature by 30–60% and 70–90%, respectively. This corresponded well with the lignin glass transition temperatures being in the range of 60–80 °C at moderate pressure values between 150 MPa and 250 MPa. Pellet density was also found to increase with increasing compression pressure and temperature. Pellet density was three times higher than bulk density and similar to the particle density. Heating the feed materials during compression decreased the compaction pressure from 250 MPa to 150 MPa, resulting in the formation of pellets with a higher durability index and more stable relaxed density.

Moreover, Brunerová et al. (2017) concluded that utilization of Poppy waste material (by extension, all tested waste materials utilization) for briquette production can be recommended, however, with necessary improvements related to their mechanical parameters. It can be recommended using of extremely high briquetting pressure (> 60 MPa) or using of external additives, for example wood dust or chips (with high level of lignin), to improve mechanical properties of briquettes. Overall evaluation of all obtained results proved satisfactory level of chemical quality and high energy potential of all investigated materials but low level of their mechanical quality (Brunerová et al., 2017).

Table 2. Comparison of calorific values and ash content of selected diameters of pellets and briquettes

n	Calorific value, kJ kg^{-1}			Ash content, %		
	Pellets, 6 mm	Pellets, 8 mm	Briquettes	Pellets, 6 mm	Pellets, 8 mm	Briquettes
1	17,303	17,092	15,531	1.026	1.007	1.012
2	17,221	16,638	15,516	1.024	1.010	1.017
3	17,502	16,889	15,307	1.030	1.003	1.013
4	16,991	17,110	15,446	1.025	1.012	1.009
5	17,150	17,087	15,293	1.027	1.006	1.006
6	17,207	17,200	15,662	1.023	1.007	1.012
7	17,449	17,128	14,994	1.027	1.008	1.016
8	17,783	16,993	15,334	1.025	1.015	1.011
9	17,801	17,105	15,405	1.028	1.019	1.014
10	17,409	17,175	15,540	1.024	1.009	1.011
Mean	17,381.6	17,041.7	15,402.8	1.026	1.010	1.012

In order to maintain a high operating comfort for end users in the residential heating sector, high ash content must be avoided. On the one hand because of the demand of emptying the ash box at periodical intervals, on the other hand because of the increasing danger of slag and deposit formation in the furnace as well as due to the rising dust emissions. The ash content of pellets could be higher, however, if the pellets are used in medium and large-scale applications due to the higher robustness as well as to the more sophisticated combustion and process control technology applied for such plants (Obernberger & Thek, 2004; Niedziółka et al., 2015).

The ash content analysis reveal that in the case of pellets with diameter 6 mm the average value of ash content was recorded at level of 1.026% while in case of pellets with diameter of 8 mm was observed lower average value at level 1.010%. In comparison with ash content of produced briquettes it was observed at value 1.012% which means the difference about 0.014% in case of pellets with diameter of 6 mm. Moreover, in comparison of the briquettes and pellets with diameter of 8 mm there were observed significantly greater energy potential of pellets however in the case of ash content the difference were at minimum 0.002% (Fig. 2).

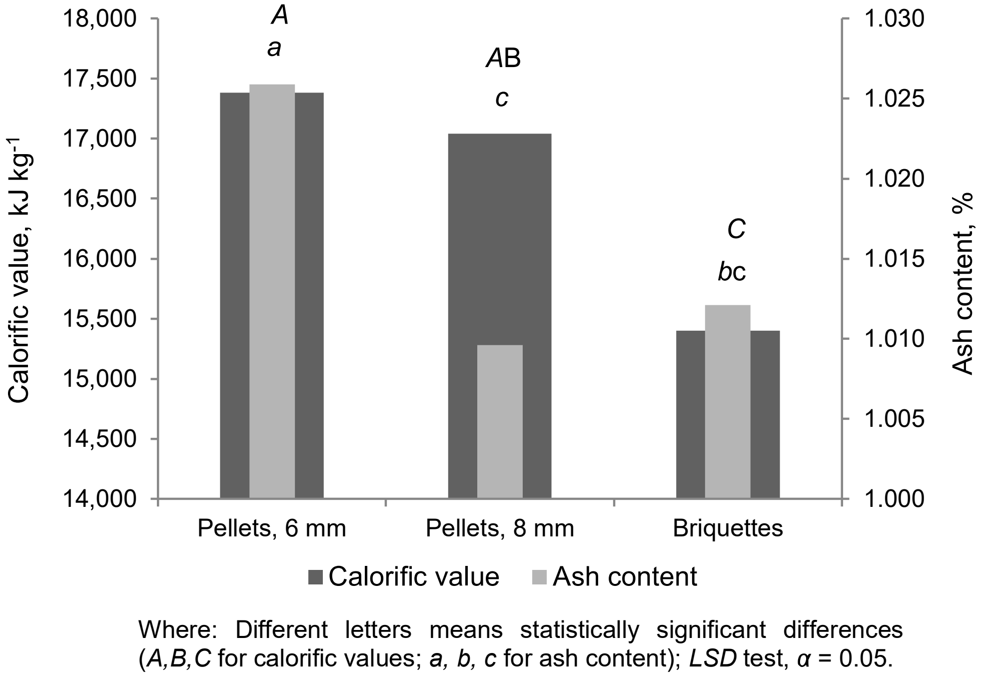

Figure 2. Comparison of calorific values and ash content of selected diameters of pellets and briquettes (according statistics: *LSD* test, $\alpha = 0.05$; $n = 10$).

In comparison of pellets with the different diameters were energy potential recorded at minimum however in the case of ash content of individual pellets was observed difference about 0.016%. This phenomenon support the previous assumption that with decreasing diameter of pellets with no difference in the pressing condition it leads to increased and more efficient densification of pressed material and therefore to increased energy potential and increased ash content of selected pellets.

On the other hand the differences may be caused by the different composition of maize biomass used in densification process. According to Zhang et al. (2012) and Fei et al. (2014), corn residues (cobs, leaves and stalks) are abundantly available renewable materials that can be used as an energy source in gasification and combustion systems. Proper understanding of the physical properties of these materials is necessary for their use in thermo chemical conversion processes. It was observed that the leaves had an increasing trend of particle size distribution between the particle sizes 0.106 and 0.925 mm. The average particle sizes for the cobs, leaves and stalks were 0.56, 0.70 and 0.49 mm, respectively. The average bulk density was 282.38, 81.61 and 127.32 kg m^{-3} for the corn cobs, leaves and stalks, respectively. The average porosity was 67.93, 86.06 and 58.51% for the corn cobs, leaves and stalks, respectively. A positive relationship between the average particle size and the porosity was observed for the corn residues. The differences in the physical properties among the corn residues (cobs, leaves and stalks) observed in the study are due to variations in the compositions and structures of these materials (Zhang et al., 2012).

The study of Witters et al. (2012) examines the renewable energy production of crops used for phytoremediation. Cultivation of crops for energy purposes on such land offers the opportunity to come up with an approach that efficiently uses contaminated agricultural land and that can be beneficial for both farmer and society. Performing a Life Cycle Analysis (LCA), it was examined the energy and CO_2 abatement potential of willow (*Salix spp.*), silage maize (*Zea mays L.*), and rapeseed (*Brassica napus L.*) originating from contaminated land. Taking into account the marginal impact of the metals in the biomass on the energy conversion efficiency and on the potential use of the biomass and its rest products after conversion, digestion of silage maize with combustion of the contaminated digestate shows the best energetic and CO_2 abating perspectives. The replacement of cokes based electricity by willow is more efficient in CO_2 abatement than willow used in a Combined Heat and Power (CHP) unit, despite lower net energy production in the former option. Willow reaches the same energy production and same CO_2 abatement per hectare per year as silage maize when its biomass yield is respectively 13 and 8.7 Mg dm ha^{-1} y^{-1}.

However, Meyer-Aurich et al. (2012) conducted a study to observe the impact of uncertainties on greenhouse gas mitigation potential of biogas production from agricultural resources. Their analysis demonstrates the variability of the mitigation effect due to uncertainties with technical and environmental processes, which are difficult to control. Uncertainties due to fertilizer induced N_2O emissions from the soil had the biggest impact on the mitigation effect of biogas use when the digestate is stored gas-tight. Otherwise, the uncertainty of emissions from the digestate dominates the variability of GHG emissions of the whole process. Moderate effects are caused by the biogas yield from feedstock, methane leakage, the electrical efficiency of the combined heat and power unit (CHP), and nitrate leaching. A minor impact can be expected from fertilizer volatilization and from the power consumption of the biogas plant.

In addition, Prade et al. (2012) in their comprehensive study focused on energy balances for biogas and solid bio fuel production from industrial hemp. This study evaluated and compared net energy yields (NEY) and energy output-to-input ratios ($R_{O/I}$) for production of heat, power and vehicle fuel from industrial hemp. Four scenarios for hemp biomass were compared; (I) combined heat and power (CHP) from spring-harvested baled hemp, (II) heat from spring-harvested briquetted hemp, and (III) CHP and (IV) vehicle fuel from autumn-harvested chopped and ensiled hemp processed to biogas in an anaerobic digestion process. The results were compared with those of other energy crops. Calculations were based on conditions in the agricultural area along the Swedish west and south coast. There was little difference in total energy input up to storage, but large differences in the individual steps involved. Further processing to final energy product differed greatly. Total energy ratio was best for combustion scenarios (I) and (II) ($R_{O/I}$ of 6.8 and 5.1, respectively). The biogas scenarios (III) and (IV) both had low $R_{O/I}$ (2.7 and 2.6, respectively). They suffer from higher energy inputs and lower conversion efficiencies but give high quality products, i.e. electricity and vehicle fuel. It was concluded that the main competitors for hemp are maize and sugar beets for biogas production and the perennial crops willow, reed canary grass and miscanthus for solid biofuel production. Hemp is an above-average energy crop with a large potential for yield improvements (Prade et al., 2012).

CONCLUSIONS

In this study was observed the energy potential and related ash content of sampled briquettes and pellets produced from maize residues (leafs and stalks, cobs not included) and following comparison of individual differences. The analysis of individual samples reveals that energy potential of pellets with diameter 6 mm ranged from 16.99 MJ kg^{-1} to 17.80 MJ kg^{-1}. In case of pellets with diameter 8 mm it was observed in range from 16.63 MJ kg^{-1} to 17.20 MJ kg^{-1}. The energy potential of compared briquettes produced from the same material mixture was significantly lower and ranged from 14.99 MJ kg^{-1} to 15.66 MJ kg^{-1}. Further analysis has shown that the differences were also in the recorded ash content of briquettes and pellets moreover the differences were observed also in case of pellets in relation with their different diameters. At the basis of this information it can be concluded that maize residues in form of briquettes and pellets has a great energy potential which is comparable with currently used materials for production of briquettes and pellets. Taken together, utilization of all present waste materials is highly recommended, as well as all kinds of waste materials (especially the biological ones) in attempt to keep the main key factors of proper waste management.

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