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Research on solid biofuels from cotton waste biomass – alternative for Tajikistan's energy sector development

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Abstract. An increasing awareness of the negative environmental cost associated with the combustion of fossil fuels and concerns over the geopolitical instability of the main oil producing regions is driving the development of renewable energy sources and biofuels. Use of solid biofuels made of different types of biomass became perspective alternative to conventional fuels in many countries. Such positive indicators as low cost of the final product that meets the quality of standards, not capital intensive production, possibility of producing briquettes/pellets from almost any agricultural waste or combination of raw materials are undoubted advantages of biomass based fuels. The main challenges for Tajikistan's energy sector, which is depended on energy imports, are: to increase energy supply through better exploitation of hydropower and other renewable energy sources such as wind, solar and primary biofuels. Within the agricultural sector of Tajikistan, which is highly agrarian country, cotton accounts for 60% of agricultural output. According to the Ministry of Agriculture of Tajikistan 199,400 hectares of lands have been allocated to cotton cultivation in the year of 2014. Plenty of unused cotton residual biomass could be effectively utilized for winter heating in rural areas. The main focus of the research was to investigate and assess physical, chemical and mechanical properties of pellets and briquettes produced form cotton waste biomass.

Key words: cotton residues, biofuel, standards, pellets, briquettes, quality assessment.

INTRODUCTION

Cotton (*Gossypium*) is one of the world major cultivated non-food crops (Kasimov, 2013) and the top consumed natural fibre (Esteve-Turrillas & de la Guardia, 2017). Thus, the global cotton production has continuously increased up to current estimates of about 25,000,000 t (Hamawand et al., 2016; Egbuta et al., 2017).

For Tajikistan cotton is an important dominant of an agricultural sector and the primary crop for its economy; with one-third of the total arable area, 75–90% of agricultural exports and significant portion of country's GDP (World Bank, 2012; Kasimov, 2013). According to TAJSTAT (2016) about 370,000 t of cotton was produced in 2015. Agricultural sector employs two-thirds of the Tajik population and cotton industry is the largest employer, which supports 75% of rural population (Boboyorov, 2012; MOA, 2012; Kasimov, 2013). Trends in the value of cotton output therefore have a major impact on overall sectors' growth and people well-being. Agriculture, in particular cotton production has made a powerful contribution to country's post-war economic recovery. However, Tajikistan still remains deeply poor (World Bank, 2012) and almost three-quarters of the extreme poor live in cotton growing areas (Boboyorov, 2012). According to Kasimov (2013) 'cotton has the potential to be an avenue for rural poverty reduction', but the current production, processing and marketing techniques being applied in Tajikistan do not develop the potential gains to be beneficial for local farmers. By MOA (2012) an important task of a present state policy programme for 2012–2020 is dedicated to improving cotton sector management. Resource-poor farming households all over the Tajikistan have a great level of self-sufficiency in food, fodder and fuel (Ruppen et al., 2016). Current energy situation, i.e. irregular supply of electricity and the lack of coal, which is also often expensive and of poor quality, forces reliance on scarce locally available resources (Mislimshoeva et al., 2014). Moreover, Tajikistan is characterized by harsh winters (World Bank, 2012; Mislimshoeva et al., 2014) and long heating period, which lasts from November to March or April (Ruppen et al., 2016). In many villages animal dung and firewood from fruit trees and cultivated vines are the main sources of energy for cooking and heating (Mislimshoeva et al., 2014; Ruppen et al., 2016).

Worldwide utilization of crop residues other than cotton for energy purposes has been an interesting subject for years (Mythili & Venkatachalam, 2013; Hamawand et al., 2016; Egbuta et al., 2017). Recently, the energy potential of cotton waste started to draw scientists' attention, too (Hamawand et al., 2016). Cotton cultivation results in tonnes of waste (Hamawand et al., 2016; Egbuta et al., 2017) and faces the producing countries to serious environmental issues (Eissa et al., 2013; Ranjithkumar et al., 2017). Cotton waste production was estimated to be 2.9–3.8 times larger than cotton production (Coates, 2000; Mythili & Venkatachalam, 2013). There are three types of wastes generated during growing and processing: post-harvest field trash (PHT), cotton gin trash (CGT) and seed meal after oil extraction (Egbuta et al., 2017); where PHT represents the biggest source of waste biomass (Hamawand et al., 2016). According to calculations about 5.2–5.6 t ha^{-1} of cotton waste is left in the field after harvesting and many growers usually burn it (Hamawand et al., 2016) or slash and leave on the field (Egbuta et al., 2017). However, PHT has little value as a soil amendment and tillage operations have high energy requirements and often degrade soil structure (Coates, 2000; Hamawand et al., 2016). Moreover, Li & Zhang (2016) observed allelopathic effects of naturally decomposed cotton stalks that caused autotoxicity, and much lower and unstable crop production in China. In contrast, Hamawand et al. (2016) published that PHT is important for minimising losses in soil carbon; it provides surface protection and has positive impacts on soil quality. Therefore, answering the question of how much PHT should be retained in the field and how much should be utilised for other purposes Sahoo et al. (2016) proved that 80% of PHT can be removed from the majority of the cotton land keeping the sustainability indicators within the limit. Additionally, by Hamawand et al. (2016) use of PHT as livestock feed is not suitable due to Endosulfan contamination and very poor feeding value.

For these reasons, PHT is considered as a negative value biomass (Coates, 2000), but it seems to be a good source of bioenergy (Hamawand et al., 2016). PHT can be processed to all kinds of biofuels: liquid, gaseous and solid, nevertheless, there are still little studies about it. According to Keshav et al. (2016) PHT is a promising feedstock for ethanol production due to high holocellulose content, but it is practically applicable only if technical issues associated with this process (especially pre-treatment) are solved (Hamawand et al., 2016; Ranjithkumar et al., 2017). Quality bio-oil can be produced from PHT by pyrolysis (Ji-lu et al., 2008; Hamawand et al., 2016); however, a number of barriers need to be overcome such as reducing the amount of char and energy required (Hamawand et al., 2016). By Iscia & Demirer (2007) PHT is a good source of biogas, per contra by Hamawand et al. (2016) the biogas production and conversion is low, and it seems to be non-feasible due to the little revenue generated. Several researches were focused on solid biofuels production: Chen et al. (2017) has studied chemical characteristics of cotton stalk briquettes; mechanical properties of briquettes produced by screw press were analysed by Eissa et al. (2013); research of Coates (2000) showed that cotton residues can be incorporated with pecan shells to manufacture commercially acceptable briquettes; Mythili & Venkatachalam (2013) concluded that PHT briquettes are well suited for the energy generation due to high gas production in gasifier; and Hamawand et al. (2016), Sahoo et al. (2016), Stavjarská (2016) stated that PHT can be feasible used to produce fuel pellets.

Thus, PHT presents available source of energy to cotton growers (Hamawand et al., 2016), but assumed high cost associated with harvesting the trash for other uses is considered as a major economic hurdle (Egbuta et al., 2017). However, Coates (2000) and Hamawand et al. (2016) have stated that the energy required to collect and process PHT into briquettes or pellets is a small percentage of the energy content of the residue itself. And, the complexity, capital and operating costs of such application are lower compering to other options (Hamawand et al., 2016). Therefore, today solid biofuels' production is the most viable solution of recycling PHT into useful products (Eissa et al., 2013). In addition, utilization of PHT as a bioenergy feedstock can offer new incentives to cotton growers (Sahoo et al., 2016); briquettes/pellets can be commercialized (Avelar et al., 2016). Still there is a lack of research in the area of cotton PHT utilization as solid biofuel and more studies are needed (Hamawand et al., 2016). The aim of this research is to determine the properties of both pellets and briquettes produced from cotton field residues originated from Tajikistan and to evaluate their quality through solid biofuels' standards.

MATERIALS AND METHODS

The cotton waste biomass used in the present research was brought from Tajikistan. The waste biomass (post-harvest trash) included different parts of the plant: predominantly stalks, some flowers/pods, roots, leaves and negligible amount of fibers.

Production of pellets and briquettes

Before densification the material was processed by two-steps crushing. For primary cutting up to 5 cm the shredder Murena (Bystroň) was used and the hammer mill 9FQ – 40C with screen holes' diameter of 6 mm was used for secondary crushing.

Production of pellets was carried out on pelletizing line Kovo Novak 200 with a size of matrix holes 6 mm and briquettes were produced by hydraulic briquette press Brikstar 50 with working pressure 18 MPa and diameter of pressing cylinder 65 mm.

Determination of pellets and briquettes properties was done by the methodology of International and European standards for solid biofuels. For further testing representative sample of waste cotton biomass was prepared according to EN 14780. Homogenized analytical sample was made by laboratory grinding knife mill Grindomix GM 100.

Moisture Content test (w) – determination of moisture content was carried out in accordance with EN ISO 18134-3 (2015) using laboratory dryer Memmert 100–800 and calculated by following formula (1):

$$w = \frac{m_2 - m_3}{m_2 - m_1} \cdot 100, \% \tag{1}$$

where m_1 – mass of empty crucible, g; m_2 – mass of crucible with sample before drying, g; m_3 – mass of crucible with sample after drying, g.

Ash Content test (AC) – measurement of ash content was performed in muffle furnace LAC by burning the sample in regulated temperatures with respect to EN ISO 18122 (2015). Formula for determination of ash content is (2):

$$AC = \frac{(m_3 - m_1)}{(m_2 - m_1)} \cdot 100 \cdot \frac{100}{100 - M_{ad}}, \% \tag{2}$$

where m_1 – mass of empty crucible, g; m_2 – mass of crucible with sample, g; m_3 – mass of crucible with ash, g; M_{ad} – water content in a sample expressed as a mass fraction, %.

Gross Calorific Value test (GCV) – determination of gross calorific value was carried out according to the standard EN 14918 (2009) using semi-automatic bomb calorimeter LECO AC-600 under compressed oxygen at temperature 22 °C. GCV was calculated by calorimeter taking into account heat capacity of calorimeter, weight of the material sample and different corrections.

Net Calorific Value (NCV) was calculated from GCV by the following Eq. (3):

$$NCV = GCV - 24.42 \cdot (w + 8.94 \cdot H_a), \text{ J g}^{-1} \tag{3}$$

where GCV – Gross calorific value, J g^{-1}; 24.42 – coefficient of 1% water in the sample at 25 °C (J g^{-1}); w – water content in the sample, %; 8.94 – coefficient for the conversion of hydrogen to water, H_a – hydrogen content in the sample, %.

Volatile Matter Content Test (VM) – volatile matter content was determined according to EN ISO 18123 (2015) by burning of material analytical sample for seven minutes at 900 °C in oxygen free environment in Muffle furnace ELSKLO MP5. Formula for calculation of volatile matter content is (4):

$$VM = \left[\frac{100(m_2 - m_3)}{m_2 - m_1} - M_{ad}\right] \cdot \left(\frac{100}{100 - M_{ad}}\right), \% \tag{4}$$

where m_1 – mass of empty crucible and lid, g; m_2 – mass of crucible with sample and lid before heating, g; m_3 – mass of crucible with sample and lid after heating, g; M_{ad} – moisture percentage by mass in the general analysis sample, %.

Durability Test (DU) – determination of mechanical durability of pellets was conducted by EN ISO 17831-1 (2015) using pellet tester and mechanical durability of briquettes was done by EN ISO 17831-2 (2015) in rotation drum. Mechanical durability of pellets and briquettes was further calculates as (5):

$$DU = \frac{m_A}{m_E} \cdot 100, \% \tag{5}$$

where m_A – sample weight after crumbling, g; m_e – sample weight before crumbling, g.

Carbon, Nitrogen, Hydrogen and Sulfur Content Test (C, H, N, S) – determination of C, H, N was carried out with the respect to International standard EN ISO 16948 (2015) and S content was determined according to EN ISO 16994 (2015). Elementary analyzer LECO CHN628 + S was used for these measurements.

Heavy Metals Content Test (Cr, Ni, Cu, Zn, As, Cd, Hg, Pb) – determination of heavy metals content was done according to standard EN ISO 16968 (2015). After required preparation of the sample solution the element contents were measured by inductively coupled plasma mass spectrometry using ICP-MS, Agilent 7700x.

RESULTS AND DISCUSSION

Quality of solid biofuels depends on a number of parameters (physical-mechanical and chemical properties). In the Table 1, all parameters assessed in this research are presented and compared to the standards of graded wooden and non-wooden biofuels (class A1).

From the Table 1 it is visible that pellets from cotton residues do not meet A1 class requirements of graded wood pellets, specifically due to high ash content and slightly lower $NCV_{a.r.}$ According to the same standard ash content for A2 class pellets is 1.2% and B class is 2.0%; $NCV_{w.b.}$ for A2 class is ≥ 16.5 and B class is ≥ 16.5. From above mentioned value it is seen that cotton pellets do not meet standard requirements of any class of graded wooden pellets. Also content of sulfur in cotton based pellets is higher than requirements of all the classes (class A2 ≤ 0.05 and class B ≤ 0.05) of graded wooden pellets. Nitrogen content in cotton pellets corresponds only to class B (EN ISO 17225-2, 2014). Beside ash content, NCV, S and N contents by all other parameters produced pellets achieved wood biomass quality. Comparing to non-wooden pellets standards, pellets from cotton biomass shows much better properties and fully fulfils A1 class requirements.

The same as pellets briquettes made of cotton fully correspond to the best A1 quality of non-wooden briquettes. In comparison with wood briquettes, cotton briquettes do not fulfill requirements of A1 class due to higher ash content and higher content of S and N. In contrast with cotton pellets, cotton based briquettes achieved the A1 class by NCV (see Table 1).

According to Coates (2000) and Hamawand et al. (2016) $GCV_{a.r.}$ of cotton stalks ranges from 17.1 to 18.1 MJ kg^{-1}, which is in correspondence with the present research results. $GCV_{d.b.}$ of cotton textile industry residues (CGT) published by Avelar et al. (2016) is 17.9 MJ kg^{-1} and $NCV_{d.b.}$ is 16.7 MJ kg^{-1}, i.e. the values are lower than the measured values. This can be explained by different composition of CGT. According to Egbuta et al. (2017) CGT contains of leaves, fibre, flowers, immature seeds, sticks and soil, and more attention was previously given to CGT utilization because it is centrally stockpiled at gins and collected with existing infrastructure. Comparing to another typical raw material used for solid biofuels production: $GCV_{d.b.}$ of cotton biomass is higher than the average calorific value of a mixture of wheat and rape straw 15.3 MJ kg^{-1} (Niedziółka et al., 2015), it is almost equal to the value of Miscanthus 19 MJ kg^{-1}, but lower than $GCV_{d.b.}$ of wood logging residues 19.7 MJ kg^{-1} (broad-leaf wood) and 20.5 MJ kg^{-1} (coniferous wood) (EN ISO 17225-1, 2014). In comparison, fossil non-renewable brown coal has $GCV_{d.b}$ 22.3 MJ kg^{-1} (Tsuchiya & Yoshida, 2017).

Table 1. Properties of pellets and briquettes based on cotton waste biomass

Parameters	Pellets	Briquettes	Standards for graded wooden*		Standards for graded non-wooden*	
			Pellets	Briquettes	Pellets	Briquettes
Moisture content ($w_{a.r.}$), %	6.7		≤ 10	≤ 12	≤ 12	≤ 12
Ash content ($AC_{d.b.}$), %	3.22		≤ 0.7	≤ 1.0	≤ 6	≤ 6
Gross calorific value ($GCV_{a.r.}$), MJ kg^{-1}	17.66		–	–	–	–
Gross calorific value ($GCV_{d.b.}$), MJ kg^{-1}	18.93		–	–	–	–
Net Calorific value ($NCV_{a.r.}$), MJ kg^{-1}	16.34		≥ 16.5	≥ 15.5	≥ 14.5	≥ 14.5
Net Calorific value ($NCV_{d.b.}$), MJ kg^{-1}	17.69		–	–	–	–
Volatile matter ($VM_{d.b.}$), %	88.4		–	–	–	–
Length (L), mm	30–40	55–65	$3.15 < L \leq 40$ $3.15 < L \leq 40$	–	$3.15 < L \leq 4\ 0$ $3.15 < L \leq 50$	–
Diameter (D), mm	6–8	65	6 ± 1 8 ± 1	–	$6 < D < 10$ $12 < D < 25$	–
Mechanical durability (DU), %	7.82	97.63	≥ 97.5	–	≥ 97.5	–
$C_{d.b.}$, %	8.56		–	–	–	–
$H_{d.b.}$, %	.69		–	–	–	–
$N_{d.b.}$, %	.90		≤ 0.3	≤ 0.3	≤ 1.5	≤ 1.5
$S_{d.b.}$, %	.13		≤ 0.04	≤0.04	≤ 0.20	≤ 0.20
$O_{d.b.}$, %	1.50		–	–	–	–
Chromium (Cr), mg kg^{-1}	.090		≤ 10	≤ 10	≤ 50	≤ 50
Nickel (Ni), mg kg^{-1}	.170		≤ 10	≤ 10	≤ 10	≤ 10
Copper (Cu), mg kg^{-1}	.080		≤ 10	≤ 10	≤ 20	≤ 20
Zinc (Zn), mg kg^{-1}	.890		≤ 100	≤ 100	≤ 100	≤ 100
Arsenic (As), mg kg^{-1}	.080		≤ 1	≤ 1	≤ 1	≤ 1
Cadmium (Cd), mg kg^{-1}	.009		≤ 0.5	≤ 0.5	≤ 0.5	≤ 0.5
Mercury (Hg), mg kg^{-1}	.002		≤ 0.1	≤ 0.1	≤ 0.1	≤ 0.1
Lead (Pb), mg kg^{-1}	.170		≤ 10	≤ 10	≤ 10	≤ 10

* – the values were obtained from international standards of graded wooden and non-wooden pellets and briquettes class A1 EN ISO 17225-2:2014; EN ISO 17225-3-2014; EN ISO 17225-6-2014 and EN ISO 17225-7:2014; all values vary according to the raw material and used compacting technology; a.r. – as received; d.b. – dry basis.

Table 1 also shows that ash content of cotton based pellets and briquettes is at least three times higher than ash content of graded wooden biofuels, but twice lower than required one for non-wooden pellets and briquettes. Avelar et al. (2016) have measured dry basis ash content of biofuels made of cotton residues 8.93%, which is much higher (three times) than ash content measured in this research, but textile industry residues were used in that case. For example, in comparison to ash content of rice straw 9.44% (Yang et al., 2016) or Pendopo brown coal 10.94% (Kim et al., 2000) content of ash in cotton wastes is significantly lower. According to Kim et al. (2000) high ash content causes high dust emissions and negatively affects combustion efficiency. Three other researches have presented very different values of cotton stalk waste's ash content (as received): 2.54% (Chen et al., 2017), 14.80% (Mythili & Venkatachalam, 2013) up to 17.3% (Hamawand et al., 2016). This difference can be probably explained by different origin of biomass (different soil conditions), different varieties or amounts of used defoliants.

High nitrogen and sulfur content in the fuel can negatively affect formation of harmful emissions, mainly nitrogen oxides (NO_x, principally NO) and sulfur oxide (SO_2) (Tumuluru et al., 2012). However, it was found several studies (Sun et al., 2008a; Sun et al., 2008b) dedicated to the combustion of poor cotton stalks, which have been considered the pollutant emissions of NO and SO_2 to be quite good (NO emission ranged from 110–153 ppm, SO_2 emission from 32–55 ppm, at 6% oxygen concentration; NO_2 emission were negligible – less than 1 ppm). Additionally, Sun et al. (2008b) observed a close linkage between the oxygen and NO emissions, so the emissions may be reduced by appropriate measures, e.g. air staging. Coates (2000) and Hamawand et al. (2016) have also published that cotton stalks are characterized by the highest burning efficiency and longest burn time in comparison with other residues such as corn stover and soybean.

Analysis of mechanical durability has showed that produced solid fuels are of high mechanical quality (see Table 1). Rajkumar & Venkatachalam (2013) have determined even better value of mechanical durability of briquettes made of cotton residues – 99.56%; in contrast Eissa et al. (2013) have measured slightly lower value – 97.06%. Durability of cotton pellets published by Stavjarská (2016) – 97.9% is almost equal to the present finding.

CONCLUSIONS

The research results showed that pellets and briquettes from cotton waste biomass (PHT) fully correspond to quality requirements for pellets and briquettes such non-wooden biofuels stated by standards. The standard requirements for graded wooden pellets and briquettes were not fulfilled due to higher ash content, higher nitrogen and sulphur content and slightly lower $NCV_{a.r.}$ (the last only for pellets). The contents of all other elements and heavy metals are within the limits. Moreover, pellets and briquettes produced from cotton waste biomass are characterized by high mechanical durability equal to A1 class wood pellets/briquettes. To summarize the results, PHT-based solid biofuels (both pellets and briquettes) showed very good quality.

According to the literature, cotton PHT is considerably lacking suitable utilization, furthermore accumulating large amounts of PHT has negative environmental impacts and generates social costs by insufficient or expensive disposal and difficulties in cultivation due to possible unfavourable effects on soil, etc. Taking into account positive fuels properties, sufficient energy content and abundance of waste biomass, especially in the country like Tajikistan where cotton is planted in a large scale, PHT utilization in form of solid biofuels can solve not only waste management and associated problems, but also significantly contribute to energy situation and sustainable development, primarily in rural areas. To conclude, cotton post-harvest residues (as also possibly in combination with gin trash) should be considered as an energy source/viable option for Tajik energy sector.

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