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Assessment of unconventional bioenergy plant chopping, milling and pelleting quality indicators and physical-mechanical properties

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Abstract. This paper provides the research results of techniques for solid biofuel preparation, while usage of chopping (chipping), milling and pressing (pelleting) of the unconventional bioenergy plants – elephant grass (*Miscanthus x giganteus*), fibrous hemp (*Futura 75*) and fibrous nettle. These energy plants were grown in the experimental fields of the Institute of Agriculture, Aleksandras Stulginskis University and Lithuanian Research Centre for Agriculture and Forestry. It was approved as the methodology for solid biofuel preparation of unconventional bioenergy plants, and was selected as the technique for plant chopping, milling, pressing, and the technique for determination of plant chaff, mill and pellet quality. There are presented results of the experimental research. There were determined the unconventional bioenergy plant stems, chaff and mill chopping quality, in justification of the use of the drum chopping and hummer milling equipment for prepared chaff and mill fractional composition. The quality of stem chaff and mill fineness was defined according to the most widely used methodology approved by the EU countries. There were determined physical-mechanical properties of these unconventional bioenergy plant chaff, mill and pellets – plant moisture content, bulk density, natural slope and failure angles.

Key words: elephant grass, hemp, nettle, stems, chaff, mill, pellets, moisture content, bulk density, fractional composition.

INTRODUCTION

Plant biomass (biomass – is an eco-friendly local fuel: wood, straws, energy crops) is one of the most important renewable energy sources in Lithuania and already makes quite a large contribution to local fuel usage. Compared with traditional energy sources and even some kinds of renewable energy, biomass has many advantages due to relatively low costs, less dependence on short weather changes, the promotion of regional economic structures' development and alternative sources of income for farmers. As a renewable energy source unconventional energy plants can be grown:

hemp, nettle and elephant grass (*Miscanthus x giganteus*). These plants grow well in Lithuanian climatic conditions.

Hemp (Latin – *Cannabis*) – is a plant belonging to the hemp family (Zaltauskas et al., 2001; Jankauskiene & Gruzdeviene, 2010). Hemp is one of the oldest cultivated plants. There are three main types of hemp: Seeder hemp (*Cannabis sativa*), Indian hemp (*Cannabis indica*) and Rubbish hemp (*Cannabis ruderalis*). Hemp originated in Central Asia (Hadders, 1997; Jasinskas & Vrubliauskas, 2000).

In Lithuania hemp has been cultivated since ancient times. The dry hemp yield per hectare often exceeds 15 tonnes – it is almost twice more than the yield of willow mass grown for fuel (Scholz et al., 2006; Burbulis et al., 2012). Cultivating oily types of hemps, after getting in the harvest, straws can be burned in boiler-houses. Hemp is not climate-demanding, although they grow better in milder and wetter climate areas.

Researches were carried out for hemp preparation and use for energy purposes. It was found out that hemp is very promising as a biofuel stock. Comparing hemp with other agricultural plants' parts suitable for biomass (canola, wheat straws), during burning hemp releases the biggest amount of energy (18.5 MJ) and leaves the least ashes (about 1.2%). When growing hemp the soil is not impoverished, but it is even enriched by restoring removed nutrients in the form of leaves and roots. Therefore, these plants are irreplaceable in crop rotation. In addition, having heavy metal absorbtion properties, hemp can be used to bring back to agriculture use contaminated and abandoned fields (Jasinskas & Scholz, 2008).

The next unconventional energy plant is the Nettle (Latin *urtica*) – it is from the urticarial family of plants. The plant has stinging and plain hair. Three kinds of nettle grow in Lithuania: hemp *(urtica cannabina*), the great (*urtica dioica*) and poignant (*urtica urens*) (Gruzdeviene et al., 2008; Jankauskiene & Gruzdeviene, 2010). The nettle is a perennial plant that can grow for a long time in a suitable place. The nettle plant contains a high-quality fibre, similar to flax or hemp fibre The use of nettle is quite wide – they are useful for man from the roots to the very top: dried nettle leaves and juice are used in medical preparations, the fibre is used in vessels and tendons production. For the production of cosmetic soaps, shampoos, lotions, creamy nettle leaves are necessary, young plants of nettle are suitable for food, and the whole plant is good for chlorophyll in industry, for fodder in husbandry (Jankauskiene et al., 2006; Friedman et al., 2008). The possibilities are being discussed to use nettle for biofuel production, because these plants grow well without fertilisation in Lithuanian moderate and heavy soils.

The next unconventional energy plant is Elephant grass – it is a perennial herbaceous plant of the Poaceae family, Miscanthus genus, with glossy, sloping leaves, sometimes growing even up to 4 m in height (Christian et. al., 1997; Aleksynas, 2004). Main advantages of this tall, long-lived plant: it has great potential to convert solar energy, accumulates relatively high biomass yield during photosynthesis. It is very important because they grow in arid and barren soils, which are unsuitable for most other plants. The use of their biomass is very wide, because they are like a potential source of energy with low nitrogen oxide emissions, like a stock for lignin cellulose production, more than other plants they accumulate a higher concentration of fibre than nitrogen.

Elephant grass naturally grows in African and South Asian tropics and subtropics, in the East Asian climate zone, etc. It came to Europe as an ornamental plant (Christian et. al., 1997). The biomass yield of elephant grass is highly dependent on soil moisture, and crop watering almost every year brings extra yield. Under favourable conditions and sufficient moisture in the soil, elephant grass is capable to produce up to 25 t ha^{-1} of dry mass. The stems of these plants for fuel in the same area can be grown for 20–25 years. To granulate the stems, simple herb mills are used. Such dry granulated mass can be immediately used in boiler-houses. Also elephant grass can be used as raw material in biogas powerhouses, and elephant grass gives probably the biggest methane gas production (Doom, 1994).

As the growing experience and scientific research in Germany showed, one of the most limiting factors of elephant grass yield is water. Water transpiration rate of elephant grass is 2.2–2.5, compared to wheat 1.1–1.9, potatoes 1.45–2.1. It is estimated that the water demand for 10 t ha^{-1} dry mass yield is about 250 mm of rainfall. According to the amount of rainfall, Lithuania has favourable conditions for elephant grass. Elephant grass, especially older crops, provide themselves with all the nutrients, so additional fertilising is not necessary (Jasinskas & Scholz, 2008).

The possibilities of elephant grass and fibre plants' utilisation and usage for energy purposes in Lithuania has been poorly investigated, researches have been carried out in the Lithuanian Institute of Agriculture and Lithuanian Institute of Engineering, Aleksandras Stulginskis University.

The aim of this work – to investigate the technical means of elephant grass and fibre plants mass preparation for biofuel, to assess quality indicators of these unconventional energy plants' chopping, milling and pelleting, to determine the basic physical mechanical properties of plant biomass prepared for fuel.

MATERIALS AND METHODS

Three non-traditional plants have been investigated: hemp, nettle and elephant grass. At first biometric features of the plants were established. Each plant's stem length and diameter were measured separately. After that, each stem was weighed on the scales and its density determined. The moisture of plants was determined in the laboratory using standard methodology. Each investigation was repeated five times.

The granulation quality of plants' stems used for fuel has to correspond to the requirements of burning chambers used in boiler-houses, chopped transportation equipment and storages. In furnaces using required thinness chips, a high burning efficiency is produced, the chopped transportation to furnaces and supply from storages does not bring any problems.

The investigated hemp, nettle and elephant grass stems were first chopped by harvester's *Maral 125* drum chopper (Fig. 1), which shredding drum's 1 rate of revolutions 913 min^{-1}, the 7 conveyor's driver roller rate of revolutions 8 is replaced by a power's rate converter 5, the number of blades 8. The theoretical length of the chopper depends on the drive drum 8 rate of revolutions. The electric motor 4 turns the chopper's gears. During the research the minimum theoretical length of chopper l_{teor} = 11.80 mm and the maximum l_{teor} = 36.75 mm were chosen.

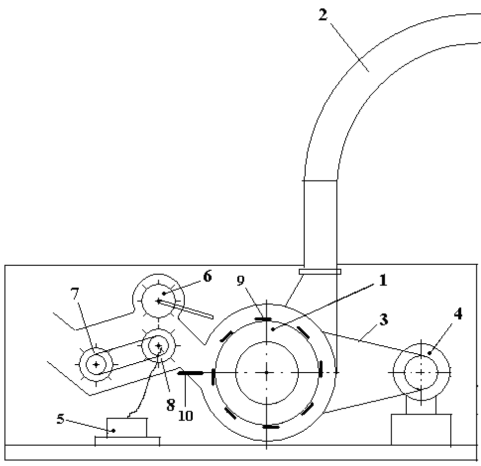

Figure 1. Harvester's *Maral – 125* drum chopper's scheme: 1 – chopping drum; 2 – pneumatic transporter for the chopped mass 3 – belt gear; 4 – electric motor; 5 – electric power rate transducer; 6 – upper drum for plants pressing; 7 – transporter; 8 – lower drum for plants pressing; 9 – knives; 10 – counter-knife plate.

The fractional composition of the plant granulated with drum chopper was determined using the system which is widespread in (EU DD CEN/TS 15149-1:2006), using the vibratory device and sieves with different diameter of holes (Fig. 2). 400 mm diameter sieves were used, where sieves with a round pore are put one on top of the other (in order from the top sieve) 63 mm, 45 mm, 16 mm, 8 mm, 3.15 mm and 1 mm diameter. Screening a 5 kg sample with a special sieve shaker, the set of sieves are being rotated in a semicircle for 3 minutes in the horizontal plane. The rest of the mass on the sieve is weighed and each fraction's part in percentage is calculated. Each experiment is repeated 5 times.

Figure 2. The stand for determination of chaff and flour fraction composition: vibratory device and sieves with the different diameter of holes.

To prepare the mass for pellet production, it needs to be granulated into the form of flour. The mill Retsch SM 200 was used for that (Fig. 3). The granulating quality was determined in a similar way to granulating plants with a drum cracker, the fractional composition of which mass was determined using sieves with different diameter holes (see Fig. 2).

Figure 3. The mill Retsch SM 200.

Granulation technology and the equipment depend on the stock, its fractional composition and humidity. A small capacity granulator (up to 150–200 kg h^{-1}) with the horizontal array was used in the investigations (Fig. 4). Finally, to 1–4 mm particles the biostock is granulated after drying, because it is easier to do that technically, since when the mass moisture decreases, the plasticity of biomass also decreases. Before granulation plant mass has to be chopped very finely, and about 40–50% of particles size should be to 1 mm.

Figure 4. Small capacity granulator with the horizontal array.

Conditioning operation is performed before the biomass goes into the granulator. During the conditioning operation the biomass is thoroughly mixed, gradually absorbing water. This ensures the stock's homogeneity and the similarity of made pellets. An important task of the conditioning operation is to wet the biostock, if it is too dry for granulation.

The formation of pellets is performed in the granulator (pellet production press), evenly supplying it with wet flour. The granulated biomass is moved in rollers through 8mm diameter matrix holes, from which pressed pellets break themselves off and go into a specific bunker, where they are kept to firm.

These physical mechanical properties of granulated plants and pellet were determined: moisture, bulk density, friction properties. Relative moisture of granulated mass and granules is determined in a chemical laboratory. Wet substance is obtained by weighing the sample. Water content in material, dry material content, absolute moisture content is calculated. The density of granulated mass and granules is determined by filling 5 dm^3 cylindrical vessel and weighing plant mass in it. The friction characteristics are determined by evaluating flow corners, using a special laboratory stand (Jasinskas et al., 2011). All investigations are repeated 5 times, the average values and tolerances are calculated.

RESULTS AND DISCUSSION

Tests were made with unconventional (non-traditional) energy plants (Hemp, Nettles and Miscanthus). Firstly, the biometrical indexes of these plant's stems were determined (Table 1).

Table 1. Biometrical indexes of unconventional bioenergy plant's stems

Indicators	Unconventional bioenergy plants		
	Fibrous hemp *Futura 75*	Fibrous nettle	Miscanthus
Stem length, mm	2601 ± 333.1	2267 ± 196.3	2747 ± 151.6
Stem diameter on the distance 0.1 mm from the soil surface, mm	8.1 ± 1.0	6.9 ± 1.0	9.3 ± 1.3
Stem mass, g	18.7 ± 4.4	22.1 ± 8.1	60.1 ± 18.2
Stem moisture content, %	9.0 ± 1.3	12.3 ± 1.3	14.9 ± 1.6

Note: The Hemp and Nettles stems, used for the test, were dry, bundles were kept in a barn and dried naturally.

Single stem test results shown that the length of all 3 types of plants stems' is similar and it depends on the way plants were cut, kept and desiccated, and, also, on the accurateness when selecting plants for comparison. The observed stems moisture content is shown in Table 1. From the data it is obvious that Miscanthus provide the highest amount of dry mass – the medium weight of a Miscanthus stem is 60.1 ± 18.2 g, hemp – 18.7 ± 4.4 g, and nettle – 22.1 ± 8.1 g.

It indicates that given the right growing conditions, the Miscanthus can provide more dry substance than any other plant. The moisture content of stem match with the required plant stems conditioned humidity (18–20%), hemp medium humidity is 9.0%, nettle – 12.3%, and Miscanthus – 14.9%.

By using sieves with different diameter perforation, the remaining mass quantum was determined. Plants' chaff factional composition (%) dependence on sieves perforation diameter (mm) is shown in Fig. 5, Fig. 6 and Fig. 7.

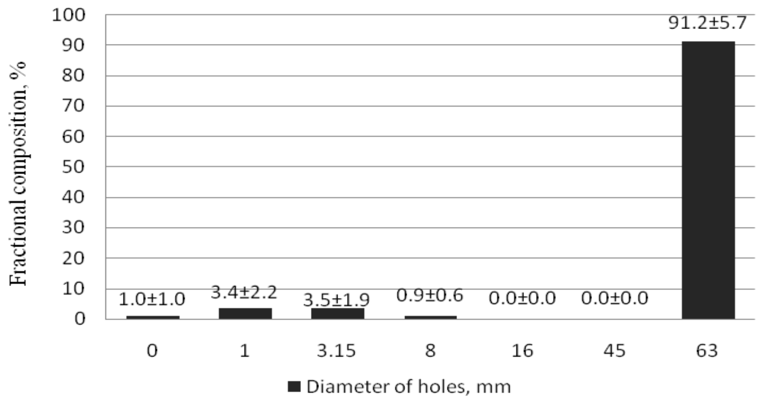

Figure 5. Fibrous hemp (*Futura 75*) chaff fractional composition (%) dependence on sieves perforation diameter (mm).

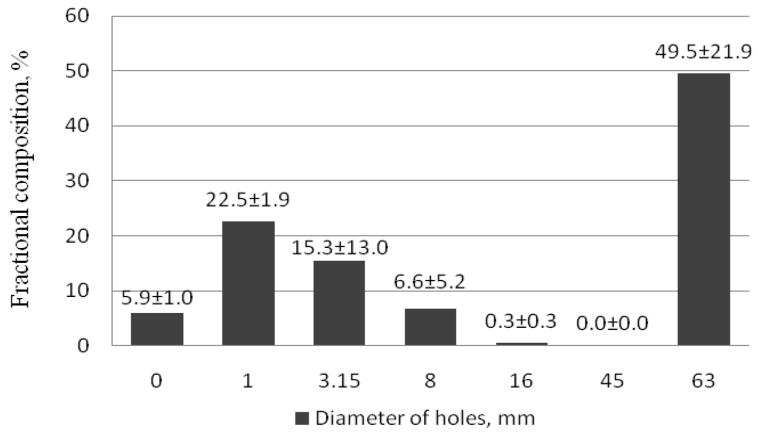

Figure 6. Fibrous nettle chaff fractional composition (%) dependence on sieves perforation diameter (mm).

After evaluation of plants' stems chaff factional composition, according to EU methods, when using sieves with different diameter perforation, it was noticed that when chaff's theoretical length varies from 11.8 mm to 36.75 mm, the maximum chaff faction of cannabis and nettles collects on the sieve with circle 63 mm diameter perforation: hemp – 91.2 ± 5.7%, nettles – 49.5 ± 21.9%, and Miscanthus on 8 mm diameter perforation sieve – 62.7 ± 23.2%.

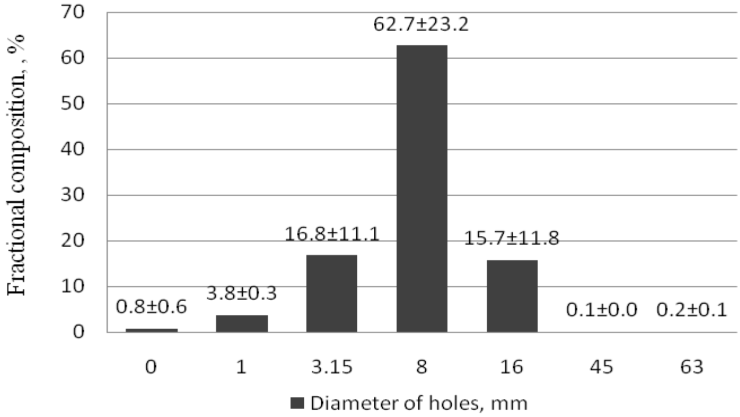

Figure 7. Miscanthus chaff fractional composition (%) dependence on sieves perforation diameter (mm).

For the preparation of chaff for pellets production, it was broken up in the form of mill using a hammer mill. Fractional composition of prepared mill (%) dependence on sieves perforation diameter (mm) is presented in Fig. 8, Fig. 9 and Fig. 10.

When preparing chaff for granule production it was pulverised with a grinding mill to a powdery consistence. After evaluation of factional powder composition from the chart we can see that the biggest hemp powder fraction has collected on 0.5 mm perforation diameter sieve – 77.4 ± 0.6% factional part.

The largest faction of nettles was found on 2 mm diameter perforation sieve – 44.4 ± 1.9%, little less on 1 mm diameter perforation sieve – 25.1 ± 0.6% and on 0.63 mm diameter perforation sieve –22.6 ± 2.9%. The Miscanthus factional powder composition was very similar to the nettles: the biggest part was noticed on 0.63 mm diameter perforation sieve – 46.4 ± 0.6%, a bit less on 2 mm diameter perforation sieve – 31.0 ± 0.0%.

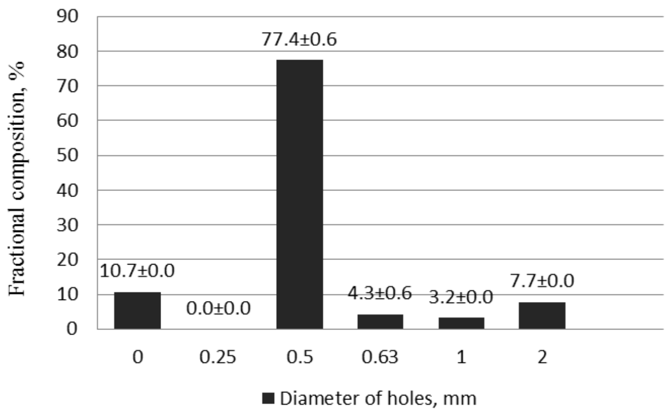

Figure 8. Fibrous hemp (*Futura 75*) mill fractional composition (%) dependence on sieves perforation diameter (mm).

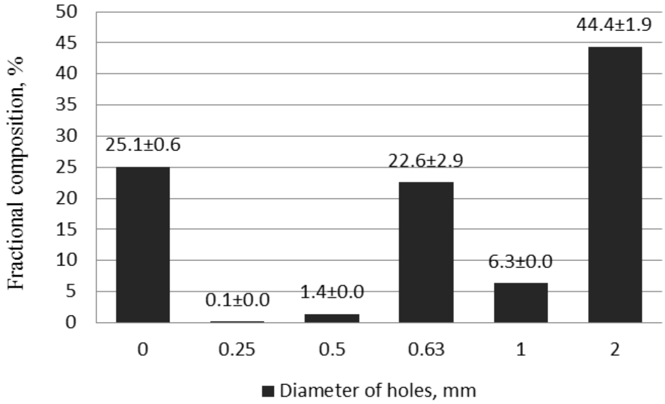

Figure 9. Fibrous nettle mill fractional composition (%) dependence on sieves perforation diameter (mm).

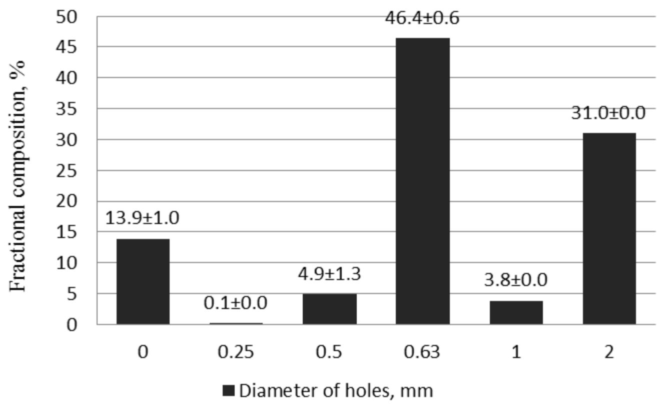

Figure 10. Miscanthus mill fractional composition (%) dependence on sieves perforation diameter (mm).

The physical-mechanical characteristics of the plant stems chaff, chopped with forage harvester-thresher *Maral 125*, were defined: moisture content, density, inrush and natural slope failure angles are shown in Table 2.

Table 2. The physical-mechanical characteristics of the plant stems chaff

Plant species	Chaff moisture content, %	Plant chaff parameters			Frictional angles	
		Mass, g	Volume, m^3	Density, kg m^{-3}	Natural slope angle α_n, degree	Inrush failure angle α_{gr}, degree
Fibrous hemp 'Futura 75'	9.0	372.3	0.012	31.0 ± 1,3 (28.2 DM)	66.8 ± 5.1	–
Fibrous nettle	12.3	1185.7	0.012	98.8 ± 4.9 (86.6 DM)	57.1 ± 2.1	–
Miscanthus	14.9	586.2	0.012	48.9 ± 2.3 (41.6 DM)	44.2 ± 1.3	73.3 ± 1.8

From data, shown in Table 2 it is obvious that the medium density with allowed bias of the hemp chaff chopped with the harvester-thresher *Maral 125* is 31.0 ± 1.3 kg m^{-3}, nettles – 98.8 ± 4.9 kg m^{-3}, and Miscanthus – 48.9 ± 2.3 kg m^{-3}. The largest stem mass amount was collected from nettles (86.6 kg m^{-3} DM), the least – from hemp (28.2 kg m^{-3} DM).

The largest natural slope angle medium with allowed bias, was from hemp (66.8 ± 5.1 degree), the least – from Miscanthus (44.2 ± 1.3 degree). There was determined the failure angle of Miscanthus (73.3 ± 1.8 degree), failure angles of hemp and nettles was not possible to determine exactly, due to their specific fibre properties.

The physical-mechanical characteristics of the plant chaff chopped with disintegrator *Retsch SM 200* shown in Table 3. Fibrous hemps powder density – 101 kg m^{-3} DM, fibrous nettles powder – 127 kg m^{-3} DM, Miscanthus – 111 kg m^{-3} DM. Natural slope angles: nettles – 38.5 ± 1.0 degrees, Miscanthus – 39.8 ± 1.5 degrees. Failure angles: nettles – 64.4 ± 1.8 degrees, Miscanthus – 62.5 ± 1.5.

Table 3. The physical-mechanical characteristics of the plant stems mill

Plant species	Mill moisture content, %	Plant mill parameters			Frictional angles	
		Mass, g	Volume, m^3	Density, kg m^{-3}	Natural slope angle α_n, degree	Inrush failure angle α_{gr}, degree
Fibrous hemp 'Futura 75'	0.1	336.6	0.0033	102.0 ± 7.0 (101.0 DM)	–	–
Fibrous nettle	0.4	420.9	0.0033	128.0 ± 1.0 (127.0 DM)	38.5 ± 1.0	64.4 ± 1.8
Miscanthus	1.1	369.4	0.0033	112.0 ± 3.0 (111.0 DM)	39.8 ± 1.5	62.5 ± 1.5

Prepared pellets physical-mechanical characteristics presented in Table 4.

Table 4. The physical-mechanical characteristics of prepared pellets

Plant species	Pellets moisture content, %	Pellets parameters			Frictional angles	
		Mass, g	Volume, m^3	Density, kg m^{-3}	Natural slope angle α_n, degree	Inrush failure angle α_{gr}, degree
Fibrous hemp 'Futura 75'	6.4	368.6	0.0009	409.6 ± 23.0 (385.0 DM)	–	–
Fibrous nettle	8.3	412.4	0.0009	457.0 ± 15.0 (419.0 DM)	55.8 ± 2.6	35.0 ± 1.8
Miscanthus	7.1	464.0	0.0009	514.0 ± 1.0 (478.0 DM)	56.1 ± 1.3	32.6 ± 1.8

From the data in this chart it is obvious that pellets of hemp density are only 385 kg m^{-3} DM, pellets of nettles density – 419 kg m^{-3} DM, and very similar the pellets of Miscanthus density – 478 kg m^{-3} DM. The angles of pellets' natural slope: nettles – 55.8 ± 2.6 degrees, Miscanthus – 56.1 ± 1.3 degrees. Failure angles: nettles – 35.0 ± 1.8 degrees, and Miscanthus – 32.6 ± 1.8 degrees.

Main conclusion of this research work is – fibre hemp preparation for burning is complicated due to the specific hemp fibre properties. Fibre nettle and Miscanthus preparation for the biofuel process is less complicated, requires less time and are about 15–17% lower power consumptive.

It has been estimated that while using the investigated low-power granulators with a horizontal array, when biomass moisture content was reduced of 15%, the total biofuel preparation energy consumption with usage of this granulator was 3.5–3.9 MJ kg^{-1}.

CONCLUSIONS

1. According to cannabis', nettles' and Miscanthus' stem biometrical index it can be concluded that Miscanthus provide the highest amount of dried mass – the stem medium weight is 60.1 ± 18.2 g, hemp just – 18.7 ± 4.4 g, and nettle – 22.1 ± 8.1 g. The moisture content of all 3 plant stems matches with the required plant stems conditioned humidity (18–20%).
2. Evaluating the quality of plant stem chaff that were chopped by harvester-thresher *Maral 125* it was noticed that the largest hemps and nettles chaff faction collects on the sieve with circle 63 mm diameter perforation: hemp – 91.2 ± 5.7%, nettle – 49.5 ± 21.9%, and Miscanthus – on 8 mm diameter perforation sieve – 62.7 ± 23.2%. Least (or nothing at all) hemps and nettles on 16 and 45 mm diameter perforation sieves, and Miscanthus on the 45 and 63 mm diameter perforation sieves.
3. After the evaluation of plants' chaff that were chopped with hammer disintegrator *Retsch SM 200* it was noticed that the largest part of hemp powder faction collected on 0.5 mm diameter perforation sieve (77.4 ± 0.6%), and on 0.25 mm diameter perforation sieve there was left nothing. The largest part of nettles' powder faction was noticed on 2 mm diameter perforation sieve (44.4 ± 1.9%), also, very similar part collected on 0 mm diameter perforation sieve (25.1 ± 0.6%), and on 0.63 mm diameter perforation sieve (22.6 ± 2.9%). The Miscanthus' powder faction collected very similarly like the nettles: the largest part was noticed on 0.63 mm diameter perforation sieve – 46.4 ± 0.6%, little less on 2 mm diameter perforation sieve – 31.0%.
4. The bulk density of unconventional energy plants was established. Bulk density of plants, chopped by the forage harvester-thresher *Maral 125*: hemps – 28.2 kg m^{-3} DM, nettles – 86.6 kg m^{-3} DM and Miscanthus – 41.6 kg m^{-3} DM. Bulk density of plants, chopped with hammer disintegrator *Retsch SM 200*: smallest amount of hemp – 101 kg m^{-3} DM, about 1.3 times bigger of nettle – 127 kg m^{-3} DM and Miscanthus – 111 kg m^{-3} DM. Prepared pellets bulk density: hemp pellets – 385 kg m^{-3} DM, nettle pellets – 419 kg m^{-3} DM and Miscanthus – 478 kg m^{-3} DM.
5. It was found that fibre hemp preparation for burning – chopping, milling and pelleting is complicated due to the specific hemp fibre properties. Fibre nettle and Miscanthus preparation for the biofuel process is less complicated, and crushing and pressing of these plants requires less time and about 15–17% less power.

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