Evaluation of Physical-Mechanical Properties of Energy Plant Stems and Their Chaff

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Abstract. In this article characteristics of willow and topinambour stems used for energy generation are presented. The potential of energy plants grown in Lithuania is reviewed, the methods of plant converting to energy are presented, and different chopping mechanisms are reviewed. The article presents a methodology for evaluation of willow and topinambour stems, their bio-metrical properties and physical-mechanical properties of stem chaff. The experiment results were discussed. Experiments were made on manually cut willow and topinambour stems, which were chopped by drum, disc and screw type choppers. Bio-metrical properties of non-chopped willows and topinambour stems were determined, and the stem chaff physical-mechanical properties such as moisture content, density, angles of natural crumble and fall were evaluated and the investigation of chaff thinness was fulfilled.

Key words: Willow, topinambour stem, chopper, chaff, bio-metrical property, physical-mechanical property

INTRODUCTION

One of the most important renewable energy sources is the plant biomass used for power purposes. Plant biomass makes up about half of the alternative energy in the countries of the European Union (Communication from the commission, 2005). At present plant biomass used for power makes up approximately 90% of all the renewable energy used in Lithuania (Jasinskas, 2006). Growing of energy plants and their use as a fuel is important in Lithuania, because there are vast areas of unused land in Lithuania, in addition to poor land and that unsuitable for agriculture, where energy plantations could be established. Up to 10-15% of the agricultural land could be used for energy crops (Jasinskas et al., 2008 a, b).

Different kinds of grasses, such as reed fescue grass (*Festuca arundinacea Schreb*), awnless brome grass (*Bromus inermis Leyss*), reed canary grass (*Typhoides arundinacea* L.), flax (*Linum*), hemp (*Cannabis* L.), topinambour (*Helianthus tuberosus* L.), sunflower (*Helianthus* L.), etc. can be used for energy purposes (Jasinskas et al., 2008 b). Non-traditional grasses, such as elephant grass (*Miscanthus sinensis*) and sorgo (*Sorghum bicolor*) are grown in Scandinavian countries, Germany, Czech Republic and other countries (Jasinskas et al., 2008 a, b). Topinambour is popular in many countries, their roots can be used as food or for pharmaceuticals, and the stems can be utilized for the energy. The stems of these plants are similar to those of sunflowers, but the yield is greater. Topinambour is widely grown in Austria, France and USA, with 2.5 million ha grown (Jasinskas et al., 2008 a). These plants are grown in Lithuania, too.

Test data from Lithuania showed that topinambours have good perspectives for being used for energy purposes – for combustion and heat production. The stems of topinambours can reach 4m height and have approximately 15 t ha^{-1} of dry matter. The change in moisture content during their growth was determined as well as the uncut stems left in the field. In spring the moisture content of uncut stems is less than 20%, thus they need no additional drying. The bulk density of the chaff of topinambour stems ranged from 40 to 77 kg m^{-3}. The lower heating value of the dry mass ranged from 17,0 to 18,8 MJ kg^{-1} (Jasinskas, 2006). Self-propelled forage harvesting technique can be used for the harvesting and chopping of topinambour stems.

As the most important renewable energy sources, willow and other sorts of rotation energy plants – poplar, fast growing aspen, etc. can be used for energy purposes. Willows are widely used energy plants that offer great potential as a source of renewable energy, not adding to the production of greenhouse gases or acid rain.

Willows (*Salix viminalis*) can grow in the soil of different composition, in poor land and land unsuitable for agriculture, by the roadsides, on the slopes, etc. (Jasinskas, 2006; João Carlos et al., 2007). Producing willow as an energy crop contributes to sustainable development in:

- putting the land, and the farmers' skills and equipment, to good use;
- retaining jobs in rural areas;
- helping rural communities to remain viable.

Willow grows throughout the northern hemisphere, mainly in cold and wet areas, and a few species are native to the southern hemisphere. Willows:

- produce a lot of biomass in a short period, and are among the fastest growing woody species in northern Europe;
- can be grown with low inputs of agro-chemicals;
- are easily established from un-rooted cuttings;
- re-sprout vigorously after each harvest;
- offer large potential for genetic improvement;
- have an energy balance in the region of 20:1 (i.e., the energy obtained can be 20 times as much as the energy used to grow the crop);
- can be used as a vegetation filter during "bio-remediation" of waste water or contaminated land.

One hectare of a well-managed willow plantation can yield 10-12 tonnes of dry matter per year, with energy equivalent to about 5,000 liters of oil. As a rough guide, 1 kg of willow will yield about 1 kW h^{-1} of electrical output. A district heating scheme for the development of 100 houses would require about 25 hectares of willow coppice. A combined heat and power system with a 100 kW electrical output will use 50 ha of willow coppice harvested on a three year cycle. A power station generating 5 MW of electricity would need around 2,500 ha of willow (Jasinskas, 2006; Jasinskas & Scholz, 2008).

Willow for energy is normally grown as coppice. The plants are cut back at intervals near ground level, and allowed to re-grow as multiple shoots rather than a single stem. Willow coppice might be harvested up to six times, typically at intervals of 3-5 years. At the end of that time (perhaps 25 years), the stumps can be removed, and the land re-planted with agricultural crops or more coppice (Jasinskas & Scholz, 2008).

Most of the chopped material is used for energy needs. It is easy to chop willow during harvesting, but freshly-harvested chops tend to decompose in a store unless a drying system is installed. Alternatively, the crop can be harvested as long stalks and chopped shortly before use. The main types of short-rotation plant harvesting systems are able to (Jasinskas & Scholz, 2008):

- harvest and chop in one operation;
- harvest full length stalks or gather stalks into bundles or bales during harvest, to be chopped later.

Willow harvesting is normally restricted to the winter months (November -February in northern Europe) in the period after leaf fall and before leaf set. An extended harvest period from late September to June is possible, but may lead to:

- higher moisture content at harvest;
- lockage of harvesters by leaf material;
- eduction in long-term yield, as nutrients in leaves are not returned to the soil.

Willow for energy production has generally been harvested on a three-year cycle. Harvesting on a 2-year, 4-year or 5-year cycle can be considered, depending on the rate of crop growth and the demand for fuel. Stem thickness influences the type and quality of fuel produced: shorter harvesting cycles will produce thinner stems, with a high proportion of bark. Delayed harvesting results in stems with larger diameter, which need robust machinery (Jasinskas & Scholz, 2008).

Willow can be used to produce heat or electricity. Electricity is either used on site, or sold through a distribution grid. An engine or turbine driving a generator converts only 25-33% of the energy content of the fuel into electricity, the remainder is emitted as heat. Where this heat energy can be utilized in a combined-heat-and-power (CHP) system, the total efficiency can be increased to 85% or more (Jasinskas, 2006; Jasinskas & Scholz, 2008).

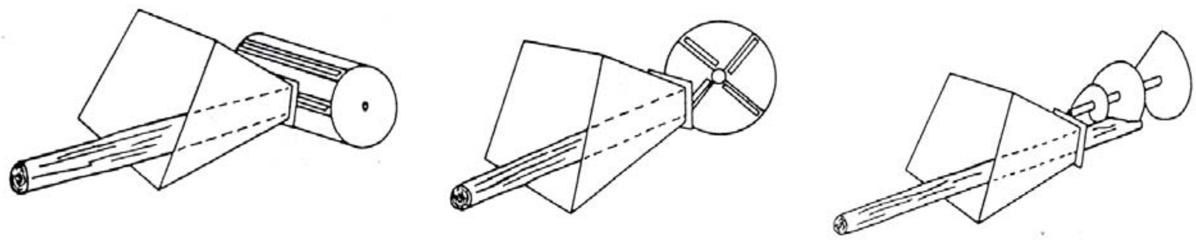
Willow is converted to energy using *thermo-chemical* processes (i.e., they involve both heat and chemical reactions). There are three methods for converting willow into energy:

- *combustion* is used for heating water or for raising steam for a turbine (Nadziakiewicz & Micha, 2003; Lund & Münster, 2003; Chagger et al., 1998);
- *gasification* produces a combustible gas that can be burned in a boiler, or used as a fuel for an engine or gas turbine (Schaumann, 2007; Marbe & Harvey, 2006; Jong et al., 2003; Bram et al., 2009);
- *pyrolysis* can be used to convert the crop into gas, oil or charcoal fuels (Sand et al., 2008).

Combustion technology is already well established. Gasification and pyrolisis are not new methods, but their utilization for energy generation from willows is still in the development stage. In the future Lithuania is going to carry out research in this field (Jasinskas & Scholz, 2008; Jasinskas & Zvicevičius, 2008).

In Lithuania, there are more than 70 larger wood waste fired boilers which can use willow chaff without major reconstruction of their design. According to their energy characteristics, wet (not dried) 50% moisture content willow chaff is not different from the chopped wood waste, which is already used in the regional boiler houses for heat production. If expressed in calorific value, one ton of willow chaff gives about 9 GJ, almost as much as one ton of peat briquettes. Thus, the yield per one hectare of willows is enough to produce approximately 40 MW h^{-1} of heat. It was calculated, that in order to provide bio-fuel for a 10 MW power boiler for a 6 month burning period (for one heating season), 18,720 tons of willow chaff must be prepared. To produce such a quantity of bio-fuel, willows should annually be planted on approximately 930 hectares (Jasinskas & Zvicevičius, 2008).

There are three basic chopper types, which can be used for willow stem chopping: a) the drum chopper, b) the disc chopper and c) the screw chopper (Fig. 1). The only difference is the way they produce the chips. All the choppers are equipped with a blower which conveys the chips into the container through a duct (Handbook for Energy Forestry, 1986; Olsson, 1993; Scholz et al., 2006).



a) b) c)

Fig. 1. Various types of energy plant chopping mechanisms: a) the drum chopper; b) the disc chopper; c) the screw chopper.

The drum chopper consists of a rotating drum with knives embedded in 2-4 longitudinal grooves in the curved surface. Like in the disc chopper, the knives pass a fixed anvil and the chip size is modified in the same way. As a result of the circular movement of the drum chopper, the cutting angle in relation to the fibre direction of the tree changes with the diameter of the stem. Consequently, the chips produced are less uniform than those from a disc chopper. These choppers are generally used for wood chopping, and they are best suited for chopping willow stems, too (Jasinskas & Scholz, 2008).

The disc chopper consists of a heavy rotating disc with rectangular grooves provided with knives running radially on the shaft. Normally, a disc chopper for fuel chips has 2-4 knives. When the disc is rotating, the knives pass an anvil. The chip size can be modified by adjusting the knives and the anvil. The chips produced by a disc chopper are fairly uniform as the cutting angle in relation to the fibre direction of the tree remains unchanged regardless of the thickness of the stem.

In a screw chopper, the chips are cut by a conical screw with a sharp peripheral edge. When the screw is rotated, it cuts into the tree while pulling the tree stem into the chopper. However, feed rollers are needed, too. The shape of the screw determines the size of the chips. Screw choppers can produce larger chips than disc choppers and drum choppers. Some types cut down the wood into chunks of 150 mm length. Chips from this type of chopper are usually wider as well (Olsson, 1993). However, such long and wide chips are not suitable for automatically feeding into the boiler. These choppers are generally used for chopping thick branches, and are best suited for chopping overgrown (5-6 years) willow stems. It is therefore appropriate to evaluate all three types of chopping mechanisms, to determine their operating parameters while chopping willows, and to assess the quality of chaff.

Recently, interest in willows grown for fuel in Lithuania has been increasing. Big boiler owners claim that willow chaff is suitable for wide use for bio-fuel and they can buy this bio-fuel in unlimited quantities. So, it is appropriate for Lithuanian farmers to expand the cultivation of willows.

In a review of the advantages of willows grown and used for fuel it is appropriate to analyze in-depth and estimate the plant cultivation, the plant harvesting and fuel preparation technologies and viable techniques, which could be used in Lithuanian climate.

The aim of this study was to determinate the biometric characteristics of different maturity willow and topinambour stems and their physical-mechanical properties that have an impact on their preparation and use for energy purposes, as well as the characteristics of willow and topinambour stem chaff prepared by different chopping mechanisms.

MATERIAL AND METHODS

Biometric indicators of energy plant stems

Biometric indicators of plant stems, such as size, mass dimensions, weight, moisture content, density, and yield were determined during the experiments carried out by Lithuanian researchers. The existing procedures were adopted (Jasinskas, 2002; DD CEN/TS 15149-1:2006). Each test was conducted in five replications.

Stem dimensions. Stem length and diameter of 20 field-grown willows (*Salix Wiminalis)* and topinambours (*Helianthus tuberosus* L.) were measured separately in the test. Stem length was measured with measuring tape (accuracy of reading 1 mm) and stem diameter with the Vernier callipers (accuracy of reading 0.1 mm). Measurements were made at:

- 100 mm from the ground level;
- 1,100 mm from the ground level.

Stem weight was determined with balance (accuracy of reading 0.1 g). The average weight of 20 stems and their diffusion confidence interval were calculated.

Stem moisture content was determined in the laboratory. Five stems of willow (*Salix Wiminalis)* and topinambour (*Helianthus tuberosus* L.) were separately chopped into pieces of 10 mm length. Mixing the chaff of each plant, five samples (200 g of mass each) were taken are weighed. Samples were dried for 24 hours at the temperature of 105°C. The dried samples were weighed and then the empty cups were weighed. The moisture content and average moisture content of each sample were calculated. The amount of the water mass M_v, the dry mass M_s, and the relative humidity w_s of the sample were calculated, too.

Evaluation of plant stem chaff physical-mechanical properties

Stem chopping and sample taking were carried out according to the methodology used in Denmark, Germany and Lithuania (Olsson, 1993; Scholz et al., 2006; Jasinskas, 2002). Freshly cut (53-54% moisture) willow and topinambour stems of 2nd and 3rd year growth were chopped. The chopped mass was supplied in bags, from which the chaff samples were taken for the determination of physical-mechanical properties.

Used choppers

Three types of choppers were used (Fig. 1) to chop the already cut energy plant stems:

- drum chopper;
- disc chopper;
- screw chopper.

Three year old stems of willow and topinambour grown in the Institute test plots were chopped with drum and disc choppers. Only three year old willow stems were chopped with screw chopper.

The chopped mass was supplied in bags, from which chaff samples were taken for determination of physical-mechanical properties. The average length of the chaff, the quality of stem chopping was defined (by two different methodologies), as well as the angle of fall and natural crumble. Comparing the physical-mechanical properties of stem chaff chopped with different choppers, the chopping machine operating parameters and their chopping quality can be described.

The average length of the chaff

The traditional chaff (no chips) fineness evaluation methodology was applied to assess the quality of large chaff (Scholz et al., 2006). Five different stem chaff samples were chosen. From each sample 20 pieces were taken and their length was measured with callipers. Then the mean of each sample was measured for the length of chopping fineness, and then the mean of all samples.

Methodology of chaff fineness evaluation

The plant stem chaff fineness used for fuel must be determined by refinement on the basis of boilers used in the combustion chamber, chaff transport equipment and storage requirements. Furnaces with the required fineness of chaff obtained high combustion efficiency. There was no problem with chaff transport to the furnaces and their supply from storages.

Three year old willow and topinambour stem chaff, chopped by two types of choppers – drum and disc chopper – were used in the experiment. The quality of stem chaff and chaff fineness was defined by two different methodologies:

- the Danish methodology was used to define the quality of stem chaff (Olsson, 1993);
- the EU countries use the stem chaff fractional composition determination methodology (Scholz et al., 2006; DD CEN/TS 15149-1:2006).

To apply the first methodology, four sieves with different hole diameters: round, diameter 45 mm, 7 mm, 5 mm, and oblong, width 8 mm, were used. The samples of the chopped mass (2-3 kg) were sifted through the sieves by driving the sieves in a circle horizontally, 10 times to the left and 10 times to the right. The mass left on the different sieves was weighed and percentages calculated.

The permissible values of separate fractions of chaff (chips) are given in Table 1 (according to the methodology used in Denmark, defining the fineness of chips used for fuel) (Olsson, 1993).

Table 1. Estimation of chaff chopping quality

Chaff	Quality of stem chopping (portion of the chopped stems on the sieve, %)				
	ø 45 mm	oblong, 8 mm	ø 7 mm	ø 5 mm	Dust
Fine	< 5%	< 25%	> 40%	< 20%	< 10%
Large	< 15%	< 40%	> 23%	< 15%	< 7%

A second methodology used for determining the fractional composition is based on European Standard (DD CEN/TS 15149-1:2006). About 5 kg of chaff sample was passed via 40 mm diameter sieves with round holes with diameters 63 mm, 45 mm, 16 mm, 8 mm and 3.15 mm. While screening each sample the sieve set was rotated 30 times within a semicircle in a horizontal plane. The mass remaining on sieves was weighed separately. The mass left on the different sieves was weighed and percentages were calculated. Each test was repeated 3 times.

The density of chaff mass

The density of chopped plant stems was determined in a special cylinder (with 5.7 dm^3 capacity) in three replications. The container was filled with the chaff by free filling without any pressure. After filling the container to its upper edge, the chaff was weighed and after estimating its moisture content, dry material density (d.m.) was calculated.

Chaff angles of crumble

Chaff fineness of plant stems used for fuel must be determined by refinement on the basis of boilers used in the combustion chamber, chaff transport equipment and storage requirements. Furnaces with the required fineness of chaff obtained high combustion efficiency. There was no problem with chaff transportation to the furnaces and their supply from storages.

In designing chaff transportation equipment to the furnaces and chaff dispensers and storage bunkers, it was important to determine the crumble angles: the angle of fall α_f and the angle of natural crumble α_n (Jasinskas, 2002). To determine the crumble angles the stand was used (Fig. 2).

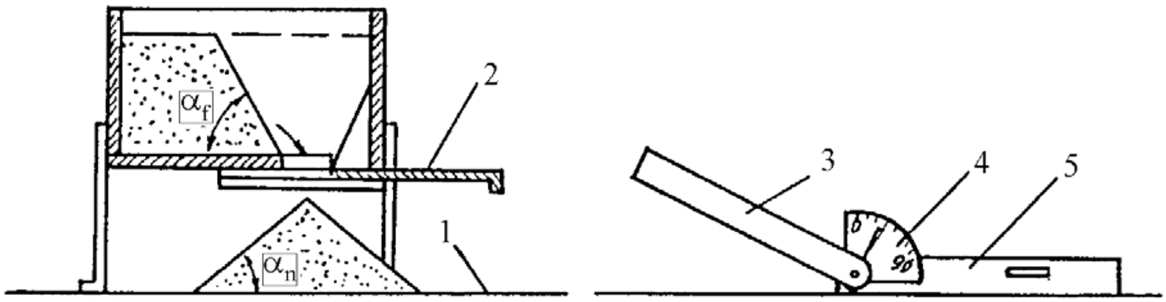


Fig. 2. Scheme of equipment for establishing the angle of fall α_f and the angle of natural crumble α_n: 1 – horizontal surface; 2 – valve; 3 – revolving ruler; 4 – protractor; 5 – ruler underneath with spirit-level.

A portion of chaff (5 kg mass) was poured into a rectangular container. After opening the valve, part of the chaff mass crumbled off. With the help of turned ruler and protractor the angles of crumble were measured:

- the angle of natural crumble α_n (on the horizontal plane);
- the angle of fall α_f (at the bottom of container).

Each test was replicated three times, and mean values of angles and their error values were calculated.

RESULTS AND DISCUSSION

Common biometric indicators of osier plant stems

Test results of biometric indicators of willow (*Salix Wiminalis*) (2nd and 3rd year growth) and topinambour (*Helianthus tuberosus* L.) stems grown in the test plot of AE Institute of Lithuanian Agricultural University are presented in Table 2. The table shows individual stem biometric characteristics, e.g., dimensions (length, thickness of stem in the lower part), weight, moisture content, density and yield.

Table 2. Biometric indicators of willow (*Salix Wiminalis)* (2nd and 3rd year growth) and topinambour (*Helianthus tuberosus* L.) stems

Indicator	Energy plants		
	Willow (Salix Wiminalis)		Topinambour (Helianthus tuberosus L.)
	2nd year growth	3rd year growth	
Stem height, cm	294.8±17.2	355.0±26.5	244.6±15.4
Stem thickness, mm	19.4±1.7	27.7±2.4	17.1±1.5
Stem mass, g	314.6±53.8	635.6±50.1	248.2±63.1
Stem moisture content , %	44.3±6.9	47.1±2.9	72.1±4.6
Stem density, $kg \cdot m^{-3}$ d.m.	149.4±17.3	152.2±15.3	87.2±10.9
Plant stem yield, $t \cdot ha^{-1}$	6.9±0.6	14.7±0.5	27.7±0.5
Plant stem yield, $t \cdot ha^{-1}$ d.m.	3.8±0.5	7.8±0.6	7.7±1.4

Research results of energy plant stem biometric indicators show that 2nd year willow plant stems grew up to 2.9 m height, 3rd year willow stems grew up to 3.5 m height and the average length of topinambour stems was 2.4 m, and 3rd year willow stem mass average was 2 times higher than that of the 2nd year and 2.6 times higher than the mass of topinambour stem.

Willow stem moisture content ranged within the limits of 44-47% and topinambour stems in the same phase of growth were much wetter with moisture content being about 72%. Topinambour stem density was significantly lower – only 87 kg m^{-3} d.m, while willow stem density was almost twice as much, being 149-152 kg m^{-3} d.m. This shows that the use of willow for fuel is much more efficient because they will burn longer, measured by calorific intake. However, the 3rd year growth of willow yield compared to topinambour stem yield (7.7 t ha^{-1} d.m.) was similar and reached 7.8 t ha^{-1} d.m. This can be explained by adverse weather conditions – a drastic lack of moisture, and no fertilizer supply for the plants. In the same area topinambour was cultivated for 3 years, it was well-rooted and a lot of additional vegetative shoots contributed to greater plant yield.

Evaluation of physical-mechanical properties of willow plant stem chaff

After measuring and calculating the average chaff length of willow and topinambour stems chopped with various coppers, it was determined that the finest chaff obtained while chopping with the smallest disc chopper was l_{vid}=8.6±2.1 mm (for willows), l_{vid}=7.9±1.8 mm (for topinambour). Much larger chaff obtained was chopped by drum chopper – lvid l_{vid}=17.5±3.4 mm (for willows), l_{vid}=14.6±3.5 mm (for topinambour). The largest willow chaff was received by chopping with screw chopper (l_{vid}=22.2±5.6 mm).

Quality assessment of willow and topinambour stem chaff in accordance with the methodology used in Denmark when a set of sieves with different size holes (specified in Table 1) was used, revealed that significantly larger chaff lengths were produced by chopping with drum chopper and screw chopper and more detailed and uniform willow chaff was produced by disc chopper (Table 3). However, the stem of the plant chopped by disc chopper produced a large quantity of dust – in topinambour chaff there was 22.1% of dust and in willow chaff there was 8.1% of dust (according to Table 1 the dust amount in large chips must comprise < 7%).

Larger chaff is obtained when chopped by drum chopper – the identification with 8 mm oblong holes accumulate 88.2% of willow chaff weight, and even 91.9% of topinambour chaff weight. As a result, these choppers are not recommended for the copping of willow and topinambour stems particularly. The chaff chopped with screw choppers was very large, the amount of dust in it being low, only 0.5% of weight, and the identification on sieves with 8 mm oblong holes accumulated even 74.1% of chaff weight (according to Table 1, the chaff may be < 40%).

Table 3. Plant chaff fractional composition (according to the Danish methodology)

Plant	Chopper type	Chopped stem mass left on sieve, %				
		Ø 45 mm	Oblong 8 mm	Ø 7 mm	Ø 3 mm	dust
Willow (3rd year growth)	Disc	0.06 ±0.19	26.42 ±22.24	28.47 ±10.90	36.91 ±8.83	8.14 ±2.91
	Drum	5.92 ±2.56	88.23 ±8.36	4.95 ±4.73	0.78 ±1.15	0.11 ±0.14
	Screw	20.00 ±6.48	74.15 ±5.87	4.31 ±0.32	1.00 ±0.43	0.52 ±0.28
Topinambour	Disc	0.29 ±0.47	36.65 ±30.65	15.54 ±11.36	25.43 ±11.97	22.06 ±8.45
	Drum	1.86 ±1.69	91.88 ±3.77	5.55 ±4.28	0.58 ±1.00	0.11 ±0.18

The assessment of the quality of willow and topinambour stem chaff in accordance with methodology of the EU countries, using a set of sieves with round holes of different diameter, disclosed that similar values were received if compared with the results obtained using the Danish methodology, because larger parts of the chaff were received by chopping with drum chopper and disc chipper chopped more uniformly and finest willow chaff was obtained (Table 4).

Table 4. Plant chaff fractional composition (according to the EU methodology)

Plant	Chopper type	Chopped stem mass left on sieve, %					
		Ø 63 mm	Ø 45 mm	Ø 16 mm	Ø 8 mm	Ø 3.15 mm	dust
Willow (3rd year growth)	Disc	0.98 ±0.40	0.74 ±0.11	69.24 ±5.67	22.76 ±5.66	5.90 ±0.99	0.39 ±0.129
	Drum	1.58 ±1.53	2.19 ±2.02	89.54 ±2.98	6.19 ±1.14	0.81 ±0.37	0.20 ±0.06
	Screw	10.17 ±6.25	7.57 ±2.31	76.06 ±6.67	4.88 ±0.78	1.08 ±0.37	0.25 ±0.16
Topinambour	Disc	2.45 ±2.70	7.84 ±13.07	69.28 ±9.91	14.81 ±7.25	5.12 ±0.93	0.41 ±0.08
	Drum	0.52 ±0.61	4.35 ±7.99	90.39 ±7.37	3,99 ±1.71	0.63 ±0.59	0.11 ±0.11

Chaff fineness was shown by accumulated chaff fraction on Ø 16 mm sieve: willow and topinambour stems were chopped by a drum chopper, 89.5% of willow chaff mass and 90.4% of topinambour chaff mass was left on this sieve; however, when these plants were chopped by disc chopper, much less chaff was left on this sieve – the total of 69.2% of willow mass and topinambour chaff mass.

Willow chaff chopped by screw chopper was also quite large – the chaff fraction part equals to 76.1% of chaff mass accumulated on Ø 16 mm sieve. In the chopped willow chaff, more than 10% particles were larger than 63 mm in length, which is not desirable for bio-fuel from high-quality chaff.

Table 5 presents results of chaff density and crumble angles in case of willow and topinambour stems chopped by drum, disc and screw choppers.

The density of willow stem chaff chopped by different types of choppers was evaluated. The angle of natural crumble varied from 44 to 50 degrees and angle of fall varied from 78 to 83 degrees. The angle of natural crumble of topinambour stem chaff chopped with different choppers varied from 45 to 52 degrees and the fall angle varied from 67 to 85 degrees.

The results in Table 5 show that the density of willow chaff chopped with drum and disc choppers varied from 116 to 157 kg m^{-3} d.m., and it was nearly two times greater than the density of topinambour stem chaff, i.e. from 58 to 67 kg m^{-3} d.m. The density of the chaff chopped by screw chopper was 98 kg m^{-3} d.m. This shows that the density of willow chaff prepared with screw chopper was the lowest and large storages will be needed to keep such chaff.

Table 5. Plant stem chaff density and crumble angles (chopped by drum, disc and screw choppers)

Plant	Chopper type	Chaff moisture content, %	Density, kg $\cdot m^{-3}$	Angle of fall, degrees	Angle of natural crumble, degrees
Willow (3rd year growth)	Disc	45.73	214.32±12.04 (116.31 d.m)	51±10.22	81±7.42
	Drum	45.73	289.31±10.68 (157.01 d.m)	44±6.62	78±6.44
	Screw	48.67	190.88±6.67 (97.98 d.m)	50±3.67	83±9.06
Topinambour	Disc	72.14	207.63±11.37 (57.84 d.m.)	45±9.18	85±9.18
	Drum	72.14	241.36±10.26 (67.24 d.m.)	52±13.78	67±5.3

In virtue of the results of the investigations, the storages and park sizes required for willow and topinambour stem chaff can be identified and calculated.

CONCLUSIONS

1. Biometric indicators of energy plant stems were investigated and the results showed that 2nd year growth willow (Salix Wiminalis) plant stems grew up to 2.9 m height, 3rd year growth willow stems grew up to 3.5 m height, and topinambour (Helianthus tuberosus L.) stem average length was 2.4 m, and 3rd year growth willow stem average mass was 2 times greater than that of the 2nd year growth and 2.6 times greater than that of the topinambour stem.

2. Willow stem moisture content ranged within the limits of 44-47% and topinambour stems in the same growth phase were much wetter, the moisture content being about 72%. Topinambour stem density was significantly lower – only

87 kg m^{-3} d.m., while willow stem density was almost twice as much, being 149-152 kg m^{-3} d.m. This shows that the use of willow for fuel is much more efficient and it will burn longer, measured by calorific intake.

3. The 3rd year growth willow yield compared to topinambour stem yield (7.7 t ha^{-1} d.m.) was similar and reached 7.8 t ha^{-1} d.m. This can be explained by adverse weather conditions – a significant lack of moisture and by the fact that the plants were not fertilized. In the same area, topinambour was cultivated for 3 years, it well-rooted and gave additional vegetative shoots, which contributed to greater plant yield.

4. The assessment of the quality of willow and topinambour stem chaff in accordance with the Danish methodology revealed that significantly larger chaff was produced when chopping stems with drum chopper and screw chopper, and more detailed and uniform willow chaff was produced when chopping with disc chopper (Table 3). However, the stem of the plant chopped by disk chopper produced a large amount of dust – topinambour chaff had 22.1% of dust and willow chaff had 8.1% (according to Table 1, the amount of dust in large chips may be < 7%).

5. Assessment of the fractional composition of willow and topinambour stem chaff in accordance with the EU countries' methodology disclosed the fineness of the chaff fraction accumulated on a Ø 16 mm sieve: 89.5% of willow and 90.4% of topinambour chaff was left on the sieve of stems chopped by drum chopper, and of plants chopped by disc chopper, much less chaff was left on the sieve: 69.2% willow and topinambour chaff mass of weight.

6. It was determined that willow chaff chopped by screw chopper was quite large – the chaff part accumulated on a Ø 16 mm sieve was 76.1% of chaff weight. This chopped mass had more than 10% of larger than 63 mm length particles, which is not desirable in case of high-quality chaff used as bio-fuel.

7. The chaff density of willow stem chopped by different types of choppers was evaluated. Angle of natural crumble varied from 44 to 50 degrees and the fall angle varied from 78 to 83 degrees. The angle of natural crumble of topinambour stem chaff chopped with different choppers varied from 45 to 52 degrees and the fall angle varied from 67 to 85 degrees.

8. It was determined that the density of willow chaff chopped with drum and disc choppers varied from 116 to 157 kg m^{-3} d.m. which was nearly two times greater than topinambour stem chaff density that varied from 58 to 67 kg m^{-3} d.m. The density of chaff chopped by screw chopper was 98 kg m^{-3} d.m. That shows that the chaff prepared with screw chopper had the lowest density and large storages will be needed to keep such chaff.

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