

Size of plant material particles designed for biogas production

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Abstract: *Size of plant material particles designed for biogas production.* This study aimed at development of chopped material characteristics of energy plants harvested at two phases of growth for the production of biogas. The plant material harvested in late June (I term) was characterized by a higher moisture content (76.3%) than that harvested in late July (big bluestem, switchgrass) or in early October (other plants, 62.7%); however, no relationship was found with the particle size, because for Jerusalem artichokes *Helianthus tuberosus*, giant knotweed *Polygonum sachalinense*, Virginia mallow *Sida hermaphrodita*, big bluestem *Andropogon gerardii* and switchgrass *Panicum virgatum* it decreased in the range from 10.40–5.39 mm to 6.86–4.71 mm, and for *Miscanthus × giganteus* and *Spartina pectinata* it increased from 6.24 and 5.08 mm to 6.36 and 5.54 mm, respectively. Cumulative distributions were approximated by a RRSB model and verified by statistical tests.

Key words: energy plants, size of particles, biogas

INTRODUCTION

Energy plant material can be one of raw materials subjected to biological processes; therefore, timely harvesting of material, its breaking up and ensilage is an important problem to be solved. Ensilage

of plant material enables to protect it for a longer period. If this process is carried out properly, the obtained raw material is uniform and of good quality. This silage characteristics can be achieved if several important conditions are fulfilled: type of material, phase of plant harvesting, moisture content, size distribution, compaction and protection of a silo. Some of these factors are related to each other. Breaking uniformity of material depends on its type and moisture content; at the same time it affects compaction [Nowakowski and Ślesiński 2012]. Moisture content is strictly related to the plant development phase and its type, and it varies along a plant height [Kasprzycka 2010, Chlebowski 2012d, Lisowski et al. 2012, Nowakowski 2012a, b, d].

The requirements about particle size distribution of ground biomass designed for silage and further methane-producing fermentation are far more rigorous than that related to feed. The substrate designed for biogas production should be characterized by particle size 4–8 mm [Sałagan et al. 2012], and their specific surface should be as big as

possible. Good breaking up effects can be achieved by proper selection of technical parameters of the flywheel or drum cutters. Dimensions of particles are affected by feeding speed of the material through withdrawing-compacting rolls as well as by drum rotational speed of drum or disk and by number of knives of the chopping unit [Chlebowski 2012a, b, c, Nowakowski 2012c]. Additional elements that assist in breaking up of plant material are used in the cutters. These are: bottom plates, corrugated vanes of beater, radial slats, re-cutting grits and compacting-grinding rolls [Chlebowski 2012f]. The least chaff length available in currently produced machines can amount to even 3.5 mm; however, the longer chaff of 15–20 mm is recommended for the rumen [Shaver 2002]. Under optimal conditions of flywheel cutter operation there was obtained the chaff of maize plants of dimensions 7.8 ± 0.4 mm [Lisowski et al. 2010] and the chips and chaff of energy plants of average dimension 9–11 mm [Lisowski et al. 2008b].

As it is evident from analysis on the chaff particle dimensions of maize plants designed for biogas, that this parameter ranged from 10 to 15 mm. Sorghum plants are most often broken up into longer fragments up to 20 mm, although some researchers recommend a range of 20–40 mm. Some other plants, including the energy plants, are broken up into bigger parts (up to 40 mm). The highest biogas output was obtained from silage cut into particles of dimensions 10–15 mm, the least output was found from particles 0.5–3 mm [Sałagan et al. 2012]. It proves some diversification of researchers' experiments, but they all agree that the careful breaking up of a

substrate for silage designed for biogas is needed.

Another important problem in breaking up of the material is connected with methods for evaluation of particles' dimensions, most often characterized by the following parameters: mean value and standard deviation as well as the type of distribution of particles' dimensions. In analysis of ground plant material the following distributions can be most useful: Gates-Gaudin-Schuhmann, modified Gaudin-Meloy, Rosin-Rammler-Sperling-Bennett, log-normal and modified Beta [Ahmed and Drzymala 2005, Bitra et al. 2008, Lisowski et al. 2010].

As it is evident from analysis on the subject, there is sufficient amount of investigation results on distributions of particles' dimensions for ground maize, alfalfa, grass [Schwab 2002, Zhang 2002], as well as wood chips [Bitra et al. 2008]. In available references there is far less information on a ground biomass of energy plants designed for biogas production; in just recent years it becomes a subject of wider interests of scientists and practitioners.

These investigations aimed at elaboration of characteristics of the ground biomass of selected energy plants, harvested in two growth phases and designed for silage and subsequent biogas production.

MATERIAL AND METHODS

Investigations were carried out for plant shoots of: miscanthus *Miscanthus × giganteus*, Virginia mallow *Sida hermaphrodita*, *Spartina pectinata*, giant knotweed *Polygonum sachalinense*,

switchgrass *Panicum virgatum*, big bluestem *Andropogon gerardii* and Jerusalem artichokes *Helianthus tuberosus*. The material was collected on plots of Experimental Station in Skierniewice of WULS. Plants were harvested in two terms: late June (I term) and late July (only big bluestem and switchgrass) and early October 2011 (II term). Plants were cut at height about 0.10 ± 0.03 m from the ground with the use of internal combustion motor cutter.

Basic investigations were carried out on a stand designed and based on trailed forage harvester Z 374 equipped with chopping unit, cooperating with tractor Ursus 1234 of engine power 85 kW [Lisowski et al. 2010]. The chopping unit was equipped with a smooth bottom plate and straight plate of the thrower with sharp edge of attack; the working clearance between these elements amounted to 8 mm. At angular disk velocity 104.7 s^{-1} and 10 knives and feeding speed of withdrawing-compacting rolls $0.82 \text{ m}\cdot\text{s}^{-1}$, there was obtained the cutting frequency 167 Hz and theoretical length of material particles 4.9 mm.

Plant samples of 15 kg were weighed on a decimal balance with accuracy 0.2 kg and placed on 4 m length of belt conveyor that was moving with speed $1 \text{ m}\cdot\text{s}^{-1}$; it transported the whole shoots to forage harvester header in the form of windrow pick-up.

To maintain repeatability of samples, the angular speed of tractor power take off (PTO) was monitored with a tachometer with digital display (accuracy $\pm 0.1 \text{ s}^{-1}$).

Material moisture content was determined by drying-weighing method according to S358.2 ASABE Stand-

ard [2011b]. Three averaged material samples of each plant were weighed on a balance RADWAG WPS 600/C with accuracy 0.01 g, and then dried to a constant weight at temperature $103 \pm 2^\circ\text{C}$ in laboratory drier SLW 115 for 24 hours.

In evaluation of distribution of cut plant material particle dimensions there was used a sieve separator [Lisowski et al. 2008a, b] as well as the research methodic according to ASABE Standard S424.1 [ASABE Standards 2011a]. In measurements there were used 3–5 averaged and not compacted samples of volume 10 dm^3 for each plant. The sifting time (120 s) was controlled with a stop-watch; particular fractions of particles were weighed on electronic balance RADWAG WSP 600/C with accuracy 0.01 g.

The characteristics of particle dimensions were made for the forage harvester working parameters (knife disk angular speed 104.7 s^{-1} , 10 knives, material feeding $3.75 \text{ kg}\cdot\text{s}^{-1}$ or $13.5 \text{ t}\cdot\text{h}^{-1}$). Particular research methodic and dependences for determination of parameters of distribution and Rosin-Rammler-Serling-Bennett model are included in the works of Lisowski et al. [2008b, 2009a, b].

Statistical analysis was carried out with the use of a standard statistical package Statistica v.10.

RESULTS AND DISCUSSION

Basing on carried out analysis of two-factor variance (type of plant, harvest term) it was found, that average angular speed of tractor PTO at idle running did not differ between the harvest terms ($F_{v1=1, v2=51} = 1.520$, at critical signifi-

cance level $p = 0.2240$), but it was diversified between plants ($F_{v1=6, v2=51} = 6.88$, $p < 0.0001$). The interaction of type of plant and harvest term influenced statistically the differences in PTO angular speed at idle running ($F_{v1=6, v2=51} = 3.58$, $p = 0.0049$). Mean value of PTO angular speed during chopping of plants harvested in the first term amounted to 106.8 s^{-1} , and in the second term – 107.3 s^{-1} ; difference amounted to 0.5 s^{-1} only (0.5% of spread). The maximal difference (4.6 s^{-1}) occurred between the PTO angular speed value for switchgrass (109.8 s^{-1}) and giant knotweed (105.2 s^{-1}) harvested in the second term. It is evident that the maximal relative error did not exceed 4.4%. In spite of the results of variance analysis one can recognize, that an assumption of the same value of PTO angular speed at idle running for all types of plants harvested in both terms was justified; it proved repeatability of the measuring samples.

Although plants were harvested in the same growth phases, they differed in moisture content in consideration of their type and different structure of tissues, thus, investigating of this parameter is justified. The results of variance analysis proved, that these differences were statistically significant. Material moisture content differed not only between plants ($F_{v1=6, v2=52} = 7.22$,

$p < 0.0001$), but also between harvest terms ($F_{v1=1, v2=52} = 173.34$, $p < 0.0001$). Plant material moisture content in the first term amounted on the average to 76.3%, in the second term it was substantially lower and amounted to 62.7%. In the first harvest term a highest moisture content (85.1%) was found for Jerusalem artichokes, the least value (70.7%) was found for spartina (Table 1). In the second harvest term a highest moisture content (71.3%) was found for giant knotweed, where the least drop in moisture content was found in relations to the first harvest term (difference 3.6%). The least moisture content was found for Virginia mallow (51.15%), together with the highest drop in moisture between the harvest terms (difference 24.0%). A substantial drop in moisture content was also found for Jerusalem artichokes (23.2%).

Values of geometric mean of particle dimensions – x_g , dimensionless standard deviation – s_g , and standard deviation expressed in units (mm) – s_{gw} differ statistically and significantly between plants and harvest terms (Table 2). A very strong interaction between these factors was found also.

Among these three parameters, the most important is geometric mean of particle dimensions (x_g) for the chopped plant material; generally, it was higher in the first harvest term (7.00 mm) than

TABLE 1. Moisture content expressed in percentage value of chopped energy plant material harvested in late June (I harvest term) and in early October (II harvest term)

Harvest term	<i>Miscanthus × giganteus</i>	<i>Polygonum sachalinense</i>	<i>Spartina pectinata</i>	<i>Sida hermaphrodita</i>	<i>Andropogon gerardii</i>	<i>Helianthus tuberosus</i>	<i>Panicum virgatum</i>
I	77.8	74.9	70.7	75.1	76.4	85.1	74.0
II	57.4	71.3	60.7	51.1	66.9	61.9	66.1

Source: Own results of the authors.

TABLE 2. Results of variance analysis on geometric mean of particle dimensions (x_g), dimensionless standard deviation (s_g) and standard deviation (s_{gw}) for geometric dimension of chopped shoots for the factors: type of plant, harvest term

Source	Geometric mean of particle dimension, x_g		Dimensionless standard deviation, s_g		Standard deviation, s_{gw}	
	F	p-value	F	p-value	F	p-value
A: plant	261.03	<0.0001	31.63	<0.0001	182.65	<0.0001
B: harvest term	162.54	<0.0001	200.14	<0.0001	8.13	0.0065
Interaction A × B	51.21	<0.0001	21.20	<0.0001	8.75	<0.0001

F – Fisher-Snedecor test; p-value – statistical significance level.
Source: Own results of the authors.

in the second (6.16 mm). The course of changes in x_g value (Fig. 1) point out, that this overall result was highly influenced by dimensions of Jerusalem artichokes particles, since x_g values in the first and second harvest terms amounted to 10.4 and 6.9 mm, respectively (shortening by 51.8%). Similar dynamic of drop in geometric mean value of parti-

cle dimensions was found for Virginia mallow, big bluestem and switchgrass: (13.8–15.9%), and least value was found for giant knotweed (6.4%). Different characteristics were found for a chopped material of miscanthus and spartina; the geometric mean of particle dimensions increase from 6.24 to 6.36 mm (by 1.9%) and from 5.08 to 5.54 mm (by

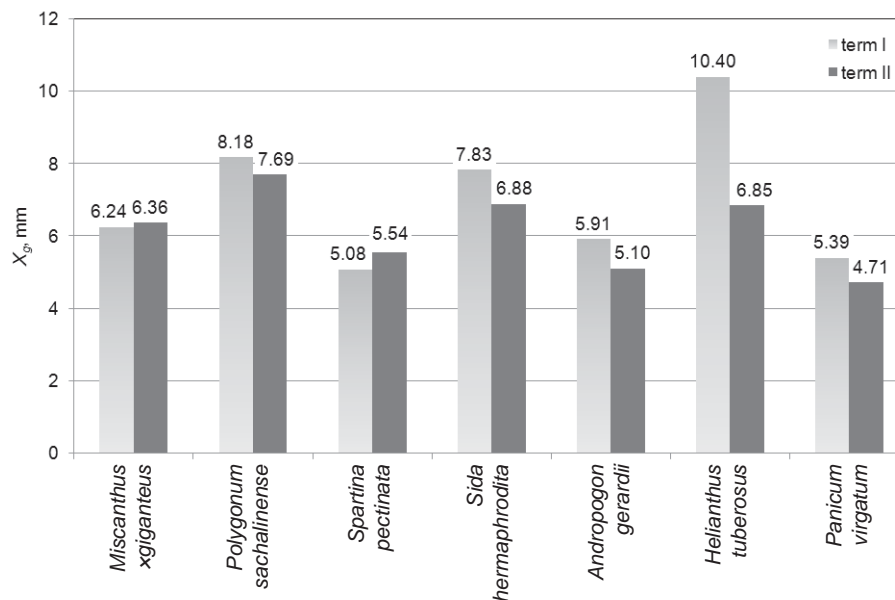


FIGURE 1. Change in geometric mean value of particle dimensions x_g of chopped material of energy plants harvested in late June (I harvest term) and in late July (big bluestem, switchgrass) and in early October (II harvest term) – based on authors' research results

9.0%), respectively. Probably, these differences result from biometric features of the plant choots, diameter of their stems, share of leaves and structure of tissues, since there is no mathematical relation between x_g values and the change in plant material moisture content. It points out at the need of further investigations to explain the changes found.

The parameters of Rosin-Rammler-Sperling-Bennett (RRSB) n and x_{50} for each distribution of particle dimensions are presented in Table 3. They are characterized by a highly statistical evaluation of significance. Values of Fisher-Snedecor test and of determination coefficients testify to good fitting of RRSB model to real distributions of particle dimensions. The RRSB model can be used in prediction of cumulated particle dimension distributions for the plant material

chopped in forage harvesters that operate under conditions determined in research methodically. A hypothetical dimension of sieve mesh diagonal that will sift out 50% of chopped plant material mixture (x_{50}) will correspond to geometric mean values of particle dimensions (x_g), suitable for a sieve mesh diagonal to sift out 63.2% of the mixture.

Therefore, considering the recommendations [Sałagan et al. 2012] on particle dimensions of 4–8 mm for the chopped material designed for methane-producing fermentation for biogas production one can find, that cutting of investigated energy plants (with exception of Jerusalem artichokes harvested in the first term) in the forage harvester equipped with chopping unit, at disk angular speed 104.7 s^{-1} , 10 knives and feeding speed of withdrawing-compact-

TABLE 3. Coefficients of Rosin-Rammler-Sperling-Bennett model for particle dimension distribution for chopped material of plants harvested in two terms

Plant	I harvest term				Plant	II harvest term			
	n	x_{50} [mm]	F	R^2 [%]		n	x_{50} [mm]	F	R^2 [%]
<i>Panicum virgatum</i>	1.54	4.40	1,060	97.4	<i>Panicum virgatum</i>	1.40	3.78	1,058	97.4
<i>Spartina pectinata</i>	1.46	4.12	1,093	97.5	<i>Andropogon gerardii</i>	1.54	4.29	839	96.8
<i>Andropogon gerardii</i>	1.71	5.10	752	96.4	<i>Spartina pectinata</i>	1.47	4.74	578	97.3
<i>Miscanthus × giganteus</i>	1.68	5.19	1,077	97.5	<i>Miscanthus × giganteus</i>	1.40	5.00	1,834	99.1
<i>Sida hermaphrodita</i>	1.88	7.04	963	97.2	<i>Helianthus tuberosus</i>	1.46	5.44	1,738	99.1
<i>Polygonum sachalinense</i>	1.76	7.88	378	93.1	<i>Sida hermaphrodita</i>	1.51	5.56	1,600	99.0
<i>Helianthus tuberosus</i>	2.44	10.04	230	90.9	<i>Polygonum sachalinense</i>	1.60	6.33	1,430	98.9

n – characteristic constant of material as a measure of distribution curve steepness; x_{50} – hypothetical dimension of sieve mesh diagonal to sift out 50% chopped plant material mixture, in mm; F – Fisher-Snedecor test; R^2 – determination coefficient, in %.

Source: Own results of the authors.

ing rolls $0.82 \text{ m}\cdot\text{s}^{-1}$ enables to obtain the mixture of average dimensions 4.71–8.18 mm (with theoretically possible dimension 4.9 mm).

CONCLUSIONS AND STATEMENTS

1. No unequivocal connection between energy plants moisture content and the chopped material dimensions was found, although plant material harvested in late June was characterized by higher moisture content (76.3%) than that harvested in late July (big bluestem, switchgrass) or in early October (the remaining plants, 62.7%). The values for Jerusalem artichokes, giant knotweed, Virginia mallow, big bluestem and switchgrass decreased from 10.40, 8.18, 7.83, 5.91 and 5.39 to 6.86, 7.69, 6.88, 5.10 and 4.71 mm, respectively. The values for miscanthus and spartina increase from 6.24 and 5.08 mm to 6.36 and 5.54 mm, respectively.
2. Basing on geometric mean of particle dimensions (x_g) and hypothetical dimension of sieve mesh (x_{50}) that will sift out 50% of mixture there was obtained a similar ranking of ascending values for plants harvested in June and at technical maturity phase (July or October): switchgrass, spartina, big bluestem, miscanthus, Virginia mallow, giant knotweed, Jerusalem artichokes.
3. Application of forage harvester with chopping unit at disk angular speed 104.7 s^{-1} and 10 knives and feeding speed of the withdrawing-compacting rolls $0.82 \text{ m}\cdot\text{s}^{-1}$ enabled to obtain the mixture of average particle dimensions 4.71–8.18 mm (except

for Jerusalem artichokes harvested in late June – 10.40 mm); they fulfill the requirements connected with particle dimensions of the material designed for biogas production (4–8 mm). However, part of long particles can create problems in operation of agitators; their separation from the mixture might be advisable.

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- (palczatka Gerarda, proso różgowate) lub na początku października (pozostałe rośliny, 62,7%), ale nie stwierdzono jednoznacznego związku z wymiarami rozdrobnionego materiału, gdyż dla topinambura *Helianthus tuberosus*, rdestowca sachalińskiego *Polygonum sachalinense*, ślazuwca pensylwańskiego *Sida hermaphrodita*, palczatki Gerarda *Andropogon gerardii* i prosa różgowatego *Panicum virgatum* wartości zmniejszyły się z zakresu 10,40–5,39 mm do 6,86–4,71 mm, a dla miskanta olbrzymiego *Miscanthus × giganteus* i spartiny periwowej *Spartina pectinata* zwiększyły odpowiednio z 6,24 i 5,08 mm do 6,36 i 5,54 mm. Rozkłady skumulowane aproksymowano modelem RRSB, które zweryfikowano testami statystycznymi.

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Streszczenie: Wymiary cząstek materiału roślinnego przeznaczonego do produkcji biogazu. Celem pracy było opracowanie charakterystyk rozdrobnionej biomasy z roślin energetycznych zbieranych w dwóch fazach rozwojowych z przeznaczeniem do produkcji biogazu. Materiał roślin energetycznych zebranych pod koniec czerwca (I termin) charakteryzował się większą wilgotnością (76,3%) niż zebranych pod koniec lipca