Study on the Effect of a New Rotor Designed for Chipping Short Rotation Woody Crops

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Abstract

The particle size distribution of wood chips, along with the moisture content, are some of the main parameters for defining the quality of most wood fuels. A new experimental rotor, powered by the self-propelled forage harvester Claas Jaguar was developed by the Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria (CRA), Agricultural Engineering Research Unit (CRA-ING). The rotor allowed for improved dimensional features of wood chips. The comminution achieved with the CRA–ING drum increased the percentage of 16–45 mm wood chips fraction from 63.69% to 73.29%, and progressively reduced the fraction of chips less than 16 mm from 35.20 to 25.35%. Consequently, the bulk density of the chips decreased by 8.57% in comparison with products obtained by standard devices. The dimensional increments achieved by the rotor and the percentage reduction of the smallest fractions represent two valuable elements affecting the behaviour of the wood chips during storage and handling.

Keywords: rotor, poplar, short rotation coppice, harvesting, comminution, wood chips

1. Introduction

As a source of lignocellulosic biomass, energy crops are used as fuel in power stations, combined heat and power (CHP) plants, biogas stations, large heating plants and small combustion units (Abdallah et al. 2011). Among lignocellulosic perennial crops, poplar is considered as the best suited for the Italian environmental conditions, and plantation programmes in Italy are largely based on this species (Spinelli et al. 2009). Several studies have reported high productivity levels of the energy crop grown in Italy (Paris et al. 2011, Bergante et al. 2010, Makeschin 1999).

In general, techniques for harvesting poplar can be broadly grouped into the single pass cut and chip, and the whole stem systems (Mattison and Mitchell 1995). Since the latter method is not commonly used at present, biomass is usually stored in comminuted form. Although harvesting coincides with period of high demand for wood fuel, short time storage is unavoidable. The storage phase plays a pivotal role on the energy balance, and the economic efficiency is linked to several factors, especially the handling cost and the susceptibility to decay. It is therefore necessary to identify methods and conditions for the storage of comminuted wood, which could minimise loss of biomass or decline in quality.

Particles size distribution of wood chips is one of the most important parameters characterizing the biomass quality (Hartmann et al. 2006, Paulrud and Nilson 2004, Suadicani and Gamborg 1999), since it influences the storage behaviour (Jirjis 1995, Jirjis 2005, Barontini et al. 2013), the handling properties (Nati et al. 2010, Spinelli et al. 2012) and the combustion efficiency (Wu et al.2011).

High proportion of small particles or fines may be detrimental during storage of chips since it results in compaction of chip piles and subsequent reduction in air movement. It may contribute to the maintenance of a high moisture content and, consequently, a delay in the dissipation of heat, which is a key factor in cooling chip piles (Kubler 1982, Afzal et al. 2010). Under such conditions, the risk of spontaneous fuel ignition increases (Kubler 1987) and the loss of dry matter may rise up to a rate of 3% per month (Mattison and Mitchel 1995). Another important aspect to consider is the heterogeneous particle size distribution that might create problems during combustion of the fuel (Jirjis 1995).

Shifting particle size distribution towards higher dimensional classes and/or improving the homogeneity of the wood chips would yield a high grade fuel. Comminution relies on some mechanical properties of the wood such as the cleavage strength, the shear strength parallel to the grain, and the compressive strength parallel to the grain (Abdallah et al. 2011, Mc Lauchlan and Lapointe 1979, Twaddle 1997). Such properties vary according to the anatomical plane because the cell elements are inter-connected by forces of various type and intensity, mainly covalent bonds along the longitudinal axis and secondary bonds on the transverse plane (Goli et al. 2004). The components of the compressive forces react with the splitting force of the wood and with the shear stress parallel to the arrangement of fibres leading to chip formation. The thickness of the chips can be increased by reducing the cutting angle (Buchanan and Duchinicki 1963, Monico and Soule 1979), while the increasing of the cutting speed results in high percentage of small chips and fine sized particles (Edelma and Stuart 1992, Hartler 1986, Hernandez and Jacques 1997).

Currently, harvesting of short rotation coppice (SRC) in Italy is performed using large size foragers equipped with dedicated SRC headers such as the Claas (Spinelli et al. 2009), Krone or John Deere (Spinelli et al. 2011), although the Claas Jaguar is by far the most popular (Spinelli et al. 2008). Rotors mounted on such machines were designed for harvesting grass crops. Jirjis et al. (2008) and Pari et al. (2008) noted that the reduced size of product obtained from such rotors could negatively affect the storability.

With this background, CRA–ING started a program aimed at developing a new drum chipper for application in self propelled forage harvesters in order to shift the particles size distribution towards the 16–45 mm dimensional class. A new rotor was designed after a preliminary experience, that showed the feasibility of increasing the longitudinal section of the chips (Pari et al. 2009, Pari et al. 2010). The objective of this study was to evaluate the quality of products obtained from the CRA–ING rotor compared with that of a standard design in terms of bulk density, particle size distribution and size of individual chips.

2. Materials and methods

2.1 The rotors

The standard rotor of Claas Jaguar 800 series mounts 24 bladeholders each 340 mm long, 12 per side, equally distributed on a drum weighting 195 kg and having diameter and length of 630 mm and 750 mm, respectively. The inclination of the bladeholders is 136° while the cutting angle of the knives reaches 32.5°. When operating on wood species, the device usually uses 12 out of the 24 knives (6 per side) but the other bladeholders interact passively during the chipping.

The CRA–ING rotor differs from the standard in terms of weight, number of bladeholders and knives, bladeholders inclination and cutting angle of the knives. The new device weighs 256 kg and is equipped with 10 bladeholders and 10 knives. The bladeholders are inclined at 129° resulting in a cutting angle of the knives of 22°, as shown in Table 1.

Table 1 Technical characteristics of the tested rotors

Characteristics	Units	Rotor	
		Standard	CRA–ING
Weight	kg	195	256
Diameter	mm	630	
Length	mm	750	
Bladeholder	n	24	10
Length	mm	340	
Inclination	degrees	136°	129°
Knives	n	12–24	10
Angle of cut	degrees	34°	22°

The study was carried in the year 2011 in the Treviso province (Italy). A Claas Jaguar 890 was used to harvest a poplar plantation in an area measuring 4000 m^2. The spacing between plants were 3 x 0.5 m, and the roots and stems were aged four and two years (R4S2), respectively. Two treatments were compared, the standard and the CRA–ING rotor both over an area of 2000 m^2 at the same forward speed of 1.25 m s^{-1}. During the study, the forage harvester worked first with the standard rotor and, after a week, with the rotor designed by CRA–ING (Fig. 1).

2.2 Qualitative assessment of wood chip

In accordance with Mitchel et al. (1997), the following traits were recorded over the entire area: plant density, percentage of lacking plants, diameter and height of the main and secondary stems, number and size of the branches (Table 2).

Fig. 1 Experimental drum mounted on self propelled chipper Claas Jaguar 890

Table 2 Site description and morphological characterization (means ±standard deviation) of the poplar stand at the second cycle (R4S2: root 4 years; stem 2 years)

Site	Cà Tron Treviso
Cutting cycle	R4S2
Surface, ha	0.41
Elevation (m a.s.l.)	0
Plant density, p ha^{-1}	–
Theoretical	6666
Effective	5866
Shoots/coppice, n.	5.1±2.18
Main stem	–
Height, m	8.58±0.49
Diameter, mm	68.18±9.60
Secondary stems	–
Height, m	5.35±1.97
Diameter, mm	35.84±15.16
Branches, n.	52.80±21.09
Diameter, mm	6.60±2.64
Length, m	0.83±0.33

At the collection point, wood chips produced by the two rotors were stored in two separate piles. Moisture content was determined by collecting six samples of approximately 500 g from each heap. The samples were immediately sealed in suitable non breathable bags and transported to the laboratory, where they were left to dry in an oven with forced ventilation at a temperature of 103 ± 2°C according to EN 14774-2.

The bulk density was measured using a steel cylinder of known internal volume following EN 15103. A cylinder of 0.026 m^3 was filled with wood chips and then weighed using a dynamometer. For each treatment, the weights of 8 samples were measured and recorded. The ratio between the net weight of samples in the cylinder and its internal volume represented the bulk density, expressed in kg m^{-3}.

For the particle size characterization, an amount of 10 kg (corresponding approximately to 24 l) of wood chips for each rotor was collected. After dying in air, ten sub-samples of 1 kg were used for the sieving in order to avoid the overloading of the mechanical sieve shaker (Analysette 18, Fritsch) and favouring the optimal separation of the wood chips. As required by the European Standard, this is to ensure that the filling height on the upper sieve shall never exceed 5 cm (CEN/TS 15149-1). Four sieves (normalized in accordance with ISO 3310-1) were used in order to separate the five following chip length classes: 100–63 mm, 63–45 mm, 45–16 mm, 16–3.15 mm and < 3.15 mm (CEN/TS 15149-1).

Table 3 Means (± standard deviation) of the main dimensional parameters measured for the chips falling in the 16–45 mm class obtained from the two rotors (for each rotor n. = 50)

Parameters	Rotor		Increment, %
	Claas	CRA–ING	
Length, mm	38.57±5.85	43.39±8.07	12.5
Width, mm	22.67±6.25	28.62±6.94	26.2
Thickness, mm	13.05±3.41	16.76±5.81	28.4
Weight, g	3.28±1.69	5.47±2.56	66.8
Volume, ml	8.18±4.49	11.07±7.06	35.3

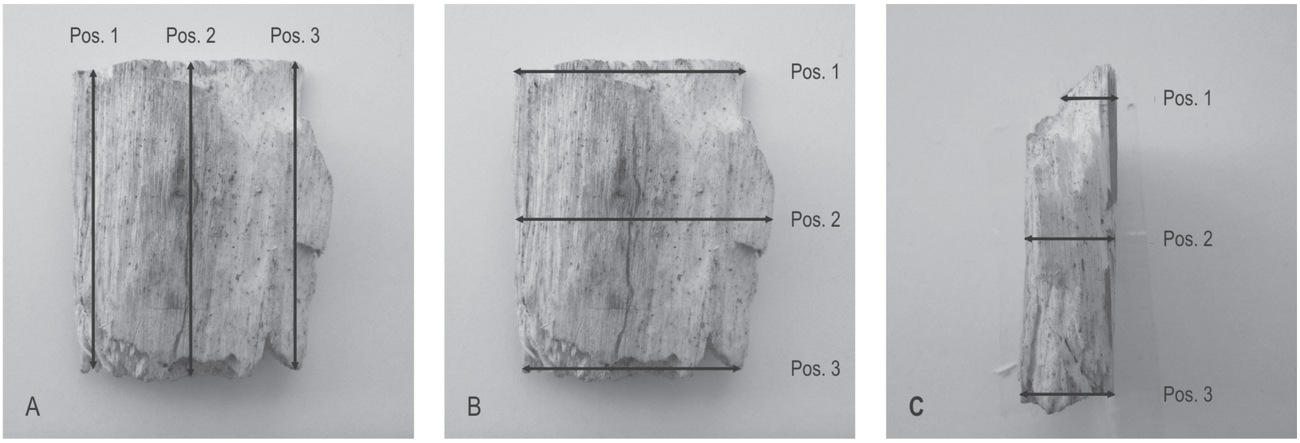

Fig. 2 Position of measurements carried out on each anatomical direction of chips: A – length, B – width, C – thickness

The study was completed through a careful analysis of the sizes of chips belonging to the most representative size fractions (16–45 mm). A sample of 50 chips was drawn from the 16–45 mm size fraction of each rotor and their weight, volume, dimensions (length, width and thickness) of each chip were measured using a precision balance (d:0.01), a xilometer and an electronic caliper, respectively. Owing to the uneven shapes of the chip profiles, their dimensions were measured and reported as means of three measurements made at three different positions on each anatomical direction (Fig. 2).

2.3 Statistical analysis

All data were analyzed with the PAST, Statistica and MSTATC software, in order to check the statistical significance of the differences between treatments. Homoscedasticity and normality were checked before testing.

The data collected were statistically analyzed using the Student's *t*-test for the bulk density and moisture content evaluation. The particle size distribution was analyzed using two way ANOVA, where the rotor and the size class were the factors analyzed. For the analy-

Table 4 Results from the 50–50 Manova (for each rotor n. = 50)

Source	*DF*[a]	*ex*VarSS	*n*PC	*n*Bu	*ex*VarPC	*ex*VarBU	*p*-Value
Rotor	1	0.134360	2	3	0.835	1.000	0.000000
Error	98	0.865640					

DF[a] – Degrees of Freedom; *ex*VarSS – explained variances based on sums of squares; *n*PC – number of principal components used for testing; *n*Bu – number of principal components used as buffer components; *ex*VarPC – variance explained by *n*PC components; *ex*VarBU – variance explained by (*n*PC+*n*BU) components; *p*-Value – the result from 50–50 MANOVA testing

Table 5 Rank of variables analyzed by rotation simulation test (for each rotor n. = 50)

Rank*Nr*[a]	*var*Name	*p*Raw	*p*AdjFDR	*p*99999
1	Weight	0.000020	0.000020	0.000020
2	Width	0.000018	0.000065	0.000100
3	Thickness	0.000183	0.000293	0.000520
4	Length	0.000906	0.001242	0.002070
5	Volume	0.021323	0.021294	0.020620

Rank *Nr*[a] – rank of the variables analyzed; *p*Raw – ordinary univariate *p*-values; *p*AdjFDR – adjusted *p*-values according to false discovery rates; *p*99999 – adjusted *p*-values according to the familywise error rate

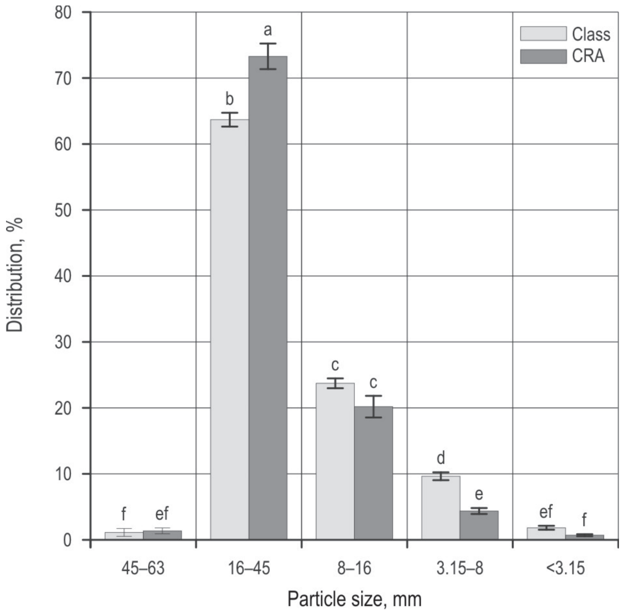

Fig. 3 Chip size distribution (% ±S.E) for the wood chips collected using Claas and CRA rotors. Before the ANOVA analysis (Two Way Anova: interaction factors A – B <0.001), the data were transformed as square root of the arcsine. Different letters indicate a significant difference at the level of $p \leq 0.05$ after HSD Tukey's test

sis, the data of the frequency (%) of chip classes were transformed as square root of the arcsine.

After ANOVA, the Tukey's post-hoc test (significance level $\alpha = 0.05$) was applied.

The 50–50 MANOVA was used for the dimensional analysis of the chips. The method is a modified variant of classical MANOVA that integrates the Principal Component Analysis (PCA) in its algorithm. In this way, the dimensionality of the data is reduced by using principal component decompositions and the final tests are performed by ordinary MANOVA. The data were standardized before MANOVA. Ranks of the variables observed (volume, length, width, weight and thickness) were analyzed by using the rotation test, an application of the 50–50 MANOVA. The rotation test adjusts the single response *p*-values keeping the type I error controlled according to the familywise error rate criterion. In this way the adjusted *p*-values can now be compared to the same threshold level of significance (α).

3. Results

A first clue of the rotor effect on the modification of chip size was appreciable by observing the values of bulk density. These varied from 288.12 ± 4.08 kg m^{-3} obtained from the standard device to 263.42 ± 13.91 kg m^{-3} by the CRA–ING rotor. Moisture contents were 55.27% ± 0.63 and 54.60% ± 0.60 for the standard and CRA rotor, respectively. The results of *t*-tests showed a statistically significant difference between the bulk densities (*p*-value 0.0012) but not for the moisture contents (*p*-value 0.055). From a practical standpoint, the lower bulk density could lead to a 8.57% reduction of material delivered per trip, that is 1.97 t less for a truck of 80 m^3 capacity. Moreover, concerning the storage, a heap of 50 t would require a volume around 190 m^3, 16 m^3 more than the corresponding pile built with wood chips comminuted by the standard rotor and mainly attributable to a higher proportion of macroporosity.

Concerning the particle size distribution (Fig. 3), it is apparent that the presence of oversized (45–63 mm) and undersized (< 3.15 mm) materials were extremely limited in both cases. Fractions ranging from 45 to 8 mm were the most represented for both rotors, accounting for about 97%, which assured compliance with the quality specifications described in the CEN/TS 14961 standard for wood chip commercialization. Accordingly, for the P45 class, the gross fraction identified as the particles quantity with dimensions exceeding 63 mm, has a limit of 1%, while the finer parts (< 1 mm) have a limit of 5%. Interestingly, the comminution achieved with the CRA–ING drum increased the percentage of 16–45 mm fraction from 63.69 to 73.29% and progressively reduced the proportion of classes lower than 16 mm (from 35.20 to 25.35%). Such differences assumed a statistical significance for the fractions 16–45 mm and 3.15–8 mm. These results suggest that the increased percentage of chips produced by CRA–ING rotor in the 16–45 mm class was due to a general increase in the size of the individual chips at the expense of the lower size fractions.

The additional dimensional analysis carried out on individual wood chips revealed more details on the positive effects deriving from the use of the new rotor (Table 3), emphasizing the positive percentage increment for all the dimensional factors, especially for weight and volume.

The results of 50–50 MANOVA test showed a statistically significant difference among the size of the chips produced by the two rotors (Table 4). The rotation test included in the 50–50 MANOVA test (Table 5) helped to identify the rank of the variables analyzed (rank Nr column), according to adjusted *p*-values controlled by familywise error rate (*p*99999). Among these, weight and width were found to be the most important variables. Such analysis is extremely helpful to identify the main factors that cause an increase in the dimensions of chips.

4. Discussion

The main devices producing wood chips are drum and disc chipper. The size of wood chips is one of the parameters used to measure the quality of the chips produced, bought or sold and that must comply with quality standards. Therefore, comminution required for massive mobilization of feedstock is a crucial step along the supply chain. Experimental works on parameters affecting the wood chips shape are rather scarce and, as stated by Abdallah et al. (2011, 2014) and Krajnc and Dolsac (2014), there is inadequate information on mechanism of chip formation. Spinelli and coworkers (Nati et al. 2014, Spinelli et al. 2013, Nati et al. 2010, Spinelli et al. 2005) have conducted a series of studies focused on the comparison among two main chipping devices (drum and disk). Also, Abdallah et al. (2011, 2014) performed a deep analysis about the effect of various factors affecting disc chipper, whilst Krajnc and Dolsac (2013, 2014) studied the parameters influencing the wood chip production using a drum chipper. Therefore, to our knowledge, the present work gives a significant contribution to this issue. As reported, CRA–ING brought some changes to the standard rotor in order to produce larger wood chips aimed at improving some physical properties such as air permeability during the storage. The reader must keep in mind that the study, starting from a basic research on constructional parameters, was aimed at answering an applicative issue such as improving storage conditions; hence, wood chip quality. The new rotor was heavier than the standard, but with less bladeholders (10 vs 24) and knives (10 vs 12), a reduced inclination of both the bladeholders (129° vs 136°) and cutting angle of the knives (22° vs 32.5°).

A first concrete result, suggesting the effectiveness of the modifications, was the reduction of the bulk density of the chips, due to the increase of their size. From a practical standpoint, such a reduction would lead to an increase in transport costs; on the other side, it determines an improvement of wood grade during the storage phase due to the improved air the circulation through the chip pile.

Our results also suggest that modifications of the drum elements that are involved in the cutting action (number and inclination of the bladeholders, number and cutting angle of the knives) may lead to the achievement of the desired objective. The basic reasoning that guided such choices was that increasing the dimension of the raw material inlet to the cutting knives would lead to an increase in the percentage of larger chips.

These results suggest that the positive effect of the CRA–ING rotor affected two aspects: i) a shift in particle size distribution towards the 16–45 mm fraction; ii) just for this class, a repositioning of the wood chip size toward the higher class limit, whereas the result may differ for the remaining fractions.

When a feeding system is used, reducing the number of knives increases the feed per tooth and consequently the chip length, but also results in proportionate increase in the other dimensions (Abdallah et al. 2014). Such observation was confirmed by the results given in Table 3, which suggests that removal of two knives contributed (beside the other factors) to the increase in the dimension of wood chips.

The positive effect of a smaller knife angle observed in this study is consistent with the observations by Krajnc and Dolsac (2014) that obtained a better form and size structure of the single particles using an inclination of 29° rather than 34°. However, the results could not be adequately comparable since the authors reported the average grain size and a subjective estimation of form constancy, without a complete particle size distribution. Our results and the findings of Krajnc and Dolsac (2014) are in contrast with the conclusion drawn by Abdallah et al. (2014) for the chipping process on a disc chipper. Among the factors analyzed, Abdallah et al. (2014) observed that an increase in the cutting angle would lead to a higher proportion of large size classes. However, the dimensional classes ranged from 1 to > 10 mm, generally less than the size distribution examined in the present work, without any reference to recognized standards. More importantly, the data are referred to a disc chipper, which is conceptually different from the drum chipper studied. Nevertheless, such work provides new insights for future studies on how additional factors such as cutting speed, feed per tooth, and the sharpness angle could influence the size of wood chip.

5. Conclusions

The production of wood chip matching the quality requirements of heating plants is a tricky process influenced by several variables related to mechanical aspects (chipper type, rotor configuration, blade wear, screen type) as well as feedstock type (species, age, comminuted branches or stems). The outcome of the study appears worthy and susceptible to prompt further in depth studies. By varying the number of bladeholders and knives, bladeholders inclination and cutting angle of the knives, it is possible to substantially modify the particle size distribution and improve the fuel grade. When compared to the standard ones, comminution accomplished by the CRA–ING rotor led to a feedstock with a higher percentage of wood chips in the 16–45 mm fraction (+ 15%) at the expense of the classes finer than 16 mm (– 28%), thus lowering the bulk density (– 8.57%). In addition, the accurate dimensional analysis of the single chips disclosed a secondary effect of the CRA–ING rotor concerning a distribution closer to the higher class limit of the wood chips within the most representative fraction.

The dimensional increments obtained and the percentage reduction of the smallest fractions represent two valuable elements having a positive influence on both the behaviour of the wood chips during storage and the fuel handling in processing plants. Starting from the present and previous studies on the factors affecting the wood chip quality, future activities could also addresse storage, in order to check the storage quality benefit offered by different particle size distributions.

6. References

Abdallah, R., Auchet, S., Méausoone, P.J., 2011: Experimental study about the effects of disc chipper settings on the distribution of wood chip size. Biomass and Bioenergy 35(2): 843–852.

Abdallah, R., Auchet, S., Méausoone, P.J., 2014: A dynamic measurement of a disc chipper cutting forces. Biomass and Bioenergy 64: 269–275.

Afzal, M.T., Bedane, A.H., Sokhansanj, S., Mahmood, W., 2010: Storage of comminuted and uncomminuted forest biomass and its effect on fuel quality. Bioresources 5(1): 55–69.

Barontini, M., Scarfone, A., Santangelo, E., Gallucci, F., Spinelli, R., Pari, L., 2013: The CRA ING experience on storage of poplar wood chips. In: Proceedings of the 21st European Biomass Conference and Exhibition, Copenhagen, Denmark 2013, 170–172 p.

Bergante, S., Facciotto, G., Minotta, G., 2010: Identification of the main site factors and management intensity affecting the establishment of Short-Rotation-Coppices (SRC) in Northern Italy through Stepwise regression analysis. Central European Journal of Biology 5(4): 522–530.

Buchanan, J.G., Duchinicki, T.S., 1963: Some experiments in low-speed chipping. Pulp & Paper Magazine of Canada 5: 235–245.

CEN/TS 14961:2005 Standards: Solid biofuels – fuel specifications and classes.

CEN/TS 15149-1:2010 Standards: Solid biofuels-determination of particle size distribution part 1: oscillating screen method.

Edelma, J.S., Stuart, W.B., 1992: Effect of disk speed on sawmill residue wood chip quality. In: Proceeding of TAPPI pulping conference, Boston, USA, 375–380 p.

EN 14774-2, 2009: Solid biofuels–determination of moisture content-oven dry method – part 2 simplified method.

EN 15103, 2010: Solid biofuels – determination of bulk density.

Goli, G., Marchal, R., Uzielli, L., 2004: Superfici e loro formazioneXylon 3: 68–73.

Hartler, N., 1986: Achievement and significance of optimal chip quality. Tappi Journal 79(2): 259–264.

Hartmann, H., Böhm, T., Jensen, P.D., Temmerman, M., Rabier, F., Golser, M., 2006: Methods for size classification of wood chips. Biomass and Bioenergy 30(11): 944–53.

Hernandez, R., Jacques, B., 1997: Effect of the rotation speed on the size distribution of black spruce pulp chips produced by chipper-canter. Forest Products Journal 47(4): 43–49.

Jirjis, R., 1995: Storage and drying of wood fuel. Biomass and Bioenergy 9(1–5): 181–190.

Jirjis, R., 2005: Effects of particle size and pile height on storage and fuel quality of comminuted Salix viminalis. Biomass and Bioenergy 28(2): 193–201.

Jirjis, R., Pari, L., Sissot, F., 2008: Storage of poplar wood chips in northern Italy. In: Proceedings of the World Bioenergy 2008 Congress. Jonkoping, Svezia 2008, 85–89 p.

Krajnc, M., Dolsak, B., 2013: Computer and experimental simulation of biomass production using drum chipper. International Journal of Simulation Modelling 12(1): 39–49.

Krajnc, M., Dolšak, B., 2014: The influence of drum chipper configuration on the quality of wood chips. Biomass and Bioenergy 64: 133–139.

Kubler, H., 1982: Air convection in self-heating piles of wood chips. Tappi Journal 65(8):63–79.

Kubler, H., 1987: Heat generation processes as cause of spontaneous ignition in forest products. Forest Products Abstracts 10(11): 299–322.

Makeschin, F., 1999: Short Rotation Forestry in Central and northern Europe – Introduction and Conclusions. Forest Ecology and Management 121(1–2): 1–7.

Mattison, J.E., Mitchell C.P., 1995: IEA bioenergy agreement task IX harvesting and supply of woody biomass for energy 1992 – 1994. Biomass and Bioenergy 9(1–5): 117–125.

McLauchlan, T.A., Lapointe J.A., 1979: Production of chips by disc chippers. In: Chips quality monograph. Pulp and paper technology series, No 5, Joint Textbook Committee of the Paper Industry, CPPA/TAPPI, (Hatton J.V. ed.), Vancouver, 15–32 p.

Mitchell, C.P., Kofman, P.D., Angus–Hankin, C.M., 1997: Guidelines for conducting harvesting trials in short rotation forestry. Aberdeen University, Department of Forestry (eds), Aberdeen 1–50 p.

Monico, J.A., Soule, H.M., 1979: A machine to harvest and chip brush stands. Winter Meeting. American Society of Agricultural Engineers, New Orleans, USA 1979, 16 p.

Nati, C., Eliasson, L., Spinelli, R., 2014: Effect of chipper type, biomass type and blade wear on productivity, fuel consumption and product quality. Croatian Journal of Forest Engineering 35(1): 1–7.

Nati, C., Spinelli, R., Fabbri, P., 2010: Wood chips size distribution in relation to blade wear and screen use. Biomass and Bioenergy 34(5): 583–587.

Pari, L., Civitarese, V., Del Giudice, A., 2010: Quality of wooden chips produced by CLAAS Jaguar equipped with experimental CRA–ING rotor. In: Proceedings of the 18th European Biomass Conference and Exhibition. From research to industry and markets, Lyon, France, 1717–1720 p.

Pari, L., Civitarese, V., Gallucci, F., 2009: Development of a chipping apparatus prototype mounted on a Claas Jaguar 890. In: Proceedings of the 17th European Biomass Conference & Exibition. From research to industry and markets, Hamburg, Germany, 247–251 p.

Pari, L., Fedrizzi, M., Ciriello, A., 2008: SRF poplar chips stocking methods comparison to lessen fuel depletion from production to utilization. In: Proceedings of the 16th European Biomass Conference & Exbition, Valencia, Spain, 74–78 p.

Paris, P., Mareschi, L., Sabatti, M., Pisanelli, A., Ecosse, A., Nardin, F., Scarascia–Mugnozza, G., 2011: Comparing hybrid Populus clones for SRF across northern Italy after two biennial rotations: survival, growth and yield. Biomass and Bioenergy 35(4): 1524–1532.

Paulrud, S., Nilsson, C., 2004: The effects of particle characteristics on emissions from burning wood fuel powder. Fuel 83(7): 813–821.

Suadicane, K., Gamborg, C., 1999: Fuel quality of whole-tree chips from freshly felled and summer dried Norway spruce on a poor sandy soil and a rich loamy soil. Biomass and Bioenergy 17(3):199–208.

Spinelli, R., Cavallo, E., Eliasson, L., Facello, A., 2013: Comparing the efficiency of drum and disc chippers. Silva Fennica 47(2): article id 930.

Spinelli, R., Hartsough, B.R., Magagnotti, N., 2005: Testing mobile chippers for chip size distribution. International Journal of Forest Engineering 16(2): 29–35.

Spinelli, R., Nati, C., Magagnotti, N., 2008: Harvesting short rotation poplar plantations for biomass production. Croatian Journal of Forest Engineering 29(2): 129–139.

Spinelli, R., Nati, C., Magagnotti, N., 2009: Using modified foragers to harvest short-rotation poplar plantations. Biomass and Bioenergy 33(5): 817–821.

Spinelli, R., Magagnotti, N., Picchi, G., Lombardini, C., Nati, C., 2011: Upsized harvesting technology for coping with the new trends in short-rotation coppice. Applied Engineering in Agriculture 27(4): 551–557.

Spinelli, R., Nati, C., Pari, L., Mescalchin, E., Magagnotti, N., 2012: Production and quality of biomass fuels from mechanized collection and processing of Vineyard pruning residues. Applied Energy 89(1): 374–379.

Tharakan, P., Volk, T., Abrahamson, L., White, E., 2003: Energy feedstock characteristics of willow and hybrid poplar clones at harvest age. Biomass and Bioenergy 25(6): 571–580.

Twaddle, A., 1997: The influence of species, chip length, and ring orientation on chip thickness. Tappi Journal 80(6): 123–131.

Wu, M.R., Schott, D.L., Lodewijks, G., 2011: Physical properties of solid biomass. Biomass and Bioenergy 35(5): 2093–2195.

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