Energies **2012**, *5*, 3803-3816; doi:10.3390/en5103803

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Characterization of Woodchips for Energy from Forestry and Agroforestry Production

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Received: 21 August 2012; in revised form: 18 September 2012 / Accepted: 18 September 2012 / Published: 27 September 2012

Abstract: We set out to determine the particle-size distribution, the fiber, the bark and the leaves content, the heating value, the CNH and the ash content of a wide sample of wood chips, collected from 10 forestry and 10 agroforestry production sources. This sampling focused on two main production types: forestry (Full Tree System—FTS—and logging residues—LR) and agroforestry (Short Rotation Coppice—SRC). For the forestry production wood chips from coniferous and broadleaf species were considered. For the agroforestry production wood chips from poplar plantations were examined (different clones with two different harvesting intervals). Overall, we collected 400 samples. Particle size distribution was determined with an automatic screening device on 200 samples. The higher heating value was determined on 200 subsamples using an adiabatic bomb calorimeter. The CNH and the ash content was ascertained on another 200 subsamples. FTS and SRC (with three year old sprouts) offered the best quality, with high fiber content (71%–80%), favorable particle-size distribution and good energetic parameters. On the contrary, both logging residues and SRC (with two year old sprouts) presented a high bark content (18%–27%) and occasionally a mediocre particle-size distribution, being often too rich in fines (6%–12%), but the energetic parameters are in the normal range.

Keywords: woody biomass; high heating value; ash content; fiber; bark

1. Introduction

A recent study on timber trade in the World, based on FAO statistics [1], revealed a rising trend in the use of the wood for various markets, especially in response to energy demand [2]. Because of increasing crude oil prices, the limited availability of fossil fuels and the deterioration of environmental quality due to greenhouse gases, mainly CO_2, various biomass solid materials have recently been proposed for use as fuels [3].

According to the analysis carried out by the European Renewable Energy Council, the EU aims for a 100% renewable energy future by 2050, where biomass will potentially supply about 36% of the total European primary energy consumption, while the potential for many developing countries is higher since their resources in such areas are larger [4,5].

The versatile nature of wood biomass fuels is both a main asset and a significant obstacle at the same time. On one hand, wood biomass is available in many forms and in all parts of the World, allowing the deployment of bioenergy almost everywhere, once the useful sources have been identified and assessed [6]. On the other hand, this same diversity makes biomass a complex and difficult fuel.

Wood is still the dominant source of fuel in many developing countries. Until now, about 15% of world energy requirements are provided by biomass. About 13% of wood fuels is used in developing countries, while 2% is used in developed countries [7]. Among the many methods of potentially sustainable energy generation in the latter countries, biomass has been receiving increasing attention. Among the biomass sources that may be used for energy production, wood shows the greatest potential from both the productive and environmental point of view [7].

The quality of the wood fuel varies according to site characteristics, harvesting season and silvicultural treatment. Moreover, because of high moisture content, irregular shape and size, and low bulk density, woody biomass is very difficult to handle, transport, store, and utilize in its original form. These are the main reasons of interest in determining the relationship between the origin of the wood fuel and such main quality characteristics as: particle-size distribution, bark content and calorific value. Particle-size distribution is crucial to fuel handling efficiency, to its drying and reaction rate, to the energy required for conversion into ethanol, and to the yield of bio-oil obtained from pyrolysis. Bark has a high ash and alkali metal content, which causes corrosion and sintering of the boilers, although the ash content in tree bark is 4–5 times lower than in than seen in straw and other herbaceous crops [6]. A high bark to fiber ratio has a crucial and negative effect on pulping, as well as on heating value the latter related to the higher moisture content of bark compared to fiber. A high bark content also has a significant impact on pelletizing potential and pellet durability. Calorific value is an essential quality for any fuels, and is relatively constant for wood fuels in their dry status [6].

Transformation of woody biomass materials into pellets, briquettes, or chips reduces costs and problems with handling, transportation, storage, and utilization of low bulk density biomass materials. Among the various transformation methods tried one in particular—chipping—seems to have achieved a good compromise. Comminution (or chipping) is an essential element of all modern energy wood

chains, because automated boilers only accept homogeneous fuel particles within specified size limits. Furthermore, comminution may offer additional benefits in terms of increased load density and improved handling quality [8].

Wood chips can be obtained from various agricultural, forestry or industrial practices. In this paper we focused on two main production types: forestry and agroforestry. In the forestry practices we analyzed the chips produced by the full tree harvesting system (FTS) from coniferous woods and by the logging residues (LR) from the coppice. These are the more interesting forest production sources from the economic and technical point of view for Italian wood chip production. Addressing logging residues is a good practice for fire prevention and in many cases creates a favorable environment for agroforestry and forest plantations by reducing the difficulty of the regeneration work and improving the quality and productivity of the site preparation and planting work [9,10].

In the agroforestry practices we analyzed only the short rotation coppice (SRC) for wood chip production. The specialized plantations for woody biomass production can be defined as short rotation coppice when they have high density (8,000–15,000 stumps/ha) and short harvesting intervals (2–5 years). SRC for energy purposes is rapidly expanding in Europe because of the reduced dependence on foreign sources of energy and the availability of large areas of set-aside agricultural land [11]. Energy crops appear as a promising option for ensuring feedstock. The profitability of energy crops is highly dependent on an appropriate logistics, logging scheme, and specially, crop yields [12,13].

In this research we set out to determine the particle-size distribution, the fiber, the bark and the leaves content, the heating value, the CNH and the ash content of a wide sample of woodchips, collected from 10 forestry and 10 agroforestry production types in Italy. This sample was chosen to represent a cross-section of the Italian fuel chip production, and focused on two main production types: forestry (full tree harvesting, logging residues) and agroforestry (short rotation coppice). For the forestry production chips from coniferous (*Pinus* spp. and *Picea abies* L.) and broadleaves (*Quercus* spp. and *Fagus sylvatica* L.) were examined. For the agroforestry production wood chips from poplar plantations (five different clones with two different harvesting intervals) were analyzed. The main aim was to evaluate the wood chip energetic characteristics for their rational use for energy purposes.

2. Materials and Methods

Twenty yards for wood chips production in Italy, 10 in forest sites and 10 in agroforestry, were sampled. All these yards were for fuel wood production. This sample was selected to represent a cross-section of the Italian fuel chip production, and focused on two main production types: forestry (FTS, LR) in Table 1 and agroforestry (SRC) in Table 2. For the forestry production there were wood chips from coniferous (*Pinus* spp. and *Picea abies* L.) and broadleaves (*Quercus* spp. and *Fagus sylvatica* L.). These two productions sources, though obviously stemming from traditional forestry activities, in reality they also differ in three main aspects that affect differently the chip quality. The first difference concerns the tree types considered from the two production types, in "LR" broadleaves (hardwood) and in "FTS" coniferous species (softwood). This difference has a strong impact on heating value and other chip characteristics. The second difference concerns the content of

leaves, "LR" contains no leaves, because it consists of coppice branches harvested in winter, when no leaves are present, whereas "FTS" contains significant amounts of leaf material because it consists of conifer trees. The third difference concerns the bark content, "LR" consists of small tree parts (branches), whereas "FTS" includes the entire tree, with an obvious effect on the bark to fiber ratio.

Table 1. The experimental matrix of 10 different forestry yards.

Types	Main trees	Code	Samples	Average DBH cm ± SD
FTS	*Picea abies* L.	a	20	15.6 ± 1.1
FTS	*Picea abies* L.	b	20	16.5 ± 1.9
FTS	*Pinus nigra* Arn.	c	20	22.1 ± 1.5
FTS	*Pinus pinaster* Ait.	d	20	23.3 ± 2.1
FTS	*Pinus halepensis* Mill.	e	20	16.6 ± 0.9
Types	**Main trees**	**Code**	**Samples**	**Average topping diameter cm ± SD**
LR	*Quercus cerris* L.	a	20	8.2 ± 1.3
LR	*Quercus pubescens* Willd.	b	20	8.1 ± 1.0
LR	*Quercus cerris* L.	c	20	9.6 ± 1.6
LR	*Fagus sylvatica* L.	d	20	8.2 ± 1.1
LR	*Fagus sylvatica* L.	e	20	7.6 ± 0.8

Table 2. The experimental matrix of 10 different agroforestry yards in SRC plantation.

Harvesting interval	Poplar clones	Code	Samples
2 years	AF2	a	20
3 years	AF2	a	20
2 years	AF6	b	20
3 years	AF6	b	20
2 years	Monviso	c	20
3 years	Monviso	c	20
2 years	Monviso	d	20
3 years	Monviso	d	20
2 years	Muur	e	20
3 years	Muur	e	20

For the agroforestry production there were wood chips from poplar plantations (different clones with two different harvesting intervals). For each site 20 chip samples were randomly collected and each sample consisted of approximately 1 kg of chips, which were put in individual bags, and duly tagged in order to identify the type and provenance. Sampling aimed at providing a representative cross-section of current operations and did not follow in detail any specific design to balance treatments for comparative purposes. For the forestry yards, the FTS sample types were obtained from first thinning of coniferous woods (range of age 27–35 years), while the LR sample types were obtained from broadleaved logging residues of final coppice cuts (range of age 19–30 years). Logging residues consisted of tops and branches, left after the harvesting of adult trees from final cuts. For the 10 agroforestry yards for the four clones, two harvesting intervals were selected, the 2 years interval and the 3 years one. In all the yards the samples had been processed with the same chipper, an

industrial chipper assembled on a truck with a drum unit. This machine was equipped with an independent engine (power 100 kW) and hydraulic crane. This was important because chipper characteristics have been shown to significantly affect particle-size distribution and chips quality [14].

The samples were analyzed for: (1) component breakdown, (2) particle-size distribution and (3) higher heating value (HHV), (4) content of Carbon (C), Nitrogen (N) and Hydrogen (H) and (5) ash content. Each of the 400 samples was divided into five sub-samples with different masses. For the analysis (1) each sub-sample was 0.2 kg, while for the analysis (2) each sub-sample was 0.5 kg and for the analyses (3–5) each sub-sample was 0.1 kg. The sub-samples were randomly extracted from the larger pool of original samples.

Component breakdown was determined on 200 g sub-samples, by manually separating their content into the following main components: fiber, bark, twigs, leaves, dust and other [14]. Each component was weighed with an Orma (model BC16D) precision scale. Particle-size distribution was determined on 500 g subsamples, according to CEN/TS 15149-1:2011 "Solid biofuels—Determination of particle size distribution—Part 1: Oscillating screen method using sieve apertures of 1 mm and above", using a certified model FTL0200 automatic screening device. Five sieves were used in order to separate the six following chip length classes: >100 mm, 100–63 mm, 63–45 mm, 45–16 mm, 16–3.15 mm, <3.15 mm. Each fraction was then weighed with the Orma (model BC16D) precision scale.

According to the European Standard UNI EN 14918:2010 "Solid biofuels—Method for the determination of calorific value", for the measurement of the higher heating value a sub-sample of 100 g was ground with an Ika Werke MF10B rotating-blade mill equipped with a 0.7 mm sieve, then 1 g of wood dust was selected and compressed into pellets with a Parr manual press. The pellet was burned in a Parr 6200 adiabatic bomb calorimeter.

According to the European Standard UNI EN 15104:2011 "Solid biofuels—Determination of total content of carbon, hydrogen and nitrogen—Instrumental methods", the content of C, H, and N was determined in a sub-sample of 100 g. Biomass content of C, H and N was analyzed in a Leco CHN 1000 elemental analyzer by the LECO-1 method using a combustion analyzer.

Standard ash was prepared according to UNI EN 14775:2010 "Solid biofuels—Determination of ash content". The fuel sub-sample of 100 g was ground with an Ika Werke MF10B rotating-blade mill equipped with a 1 mm sieve. Then, only 50 g was placed in a laboratory furnace in such a way that the sample loading did not exceed 1.0 kg/m^2. The furnace was heated to 250 °C at a rate of 0.083 °C/s. The sample was left at this temperature for 1 h to allow devolatilization before ignition. Afterwards, the furnace was heated at 0.083 °C/s to 550 °C. The sample was maintained at this temperature for 2 h, removed from the furnace, cooled in ambient air for approximately 5 min, then transferred to a dessicator and after cooling to ambient temperature, weighed.

Data were analyzed with the Statistica 2010 advanced statistics software, in order to check the statistical significance of the eventual differences between treatments with ANOVA and MANOVA techniques. *Post-hoc* tests were conducted with Tukey HSD test method.

3. Results

3.1. Component Breakdown

Table 3 shows the results obtained for fiber, bark, twig and foliage content of the chip samples from the 10 different forestry yards. The applied MANOVA only shows a significant difference between the two types (FTS *vs.* LR; $p < 0.01$ for all the variables). As an average, the chips produced in the 100 FTS samples contain 79.2% of wood fiber, 13.3% of bark, 3.2% of twigs and 4.3% of "other" (mainly foliage). In the worst case, fiber content can drop to 76.7% and bark and twigs increase to 19.2% of the total weight. As an average, the chips produced in the 100 LR samples contain 74.1% of wood fiber, 18.4% of bark, 5.9% of twigs and 1.6% of "other" (mainly dust). In the worst case, fiber content can drop to 72.3% and bark and twigs increase to 26.0% of the total weight.

Table 3. Fiber, Bark, and Twig content of the chip samples from the 10 different forestry yards.

Types	Code	Samples	Fiber %	Bark %	Twigs %	Other %	
FTS	a	20	76.7	15.9	3.3	4.2	
FTS	b	20	81.1	11.4	3.9	3.6	
FTS	c	20	77.4	15.1	2.9	4.6	$p > 0.05$
FTS	d	20	79.9	12.6	2.7	4.8	
FTS	e	20	81.1	11.4	3.2	4.3	
FTS	**All**	**100**	**79.2 ± 7.96**	**13.3 ± 5.18**	**3.2 ± 1.44**	**4.3 ± 1.21**	
LR	a	20	78.0	14.5	5.9	1.6	
LR	b	20	73.4	19.1	5.9	1.6	
LR	c	20	74.1	18.4	5.9	1.6	$p > 0.05$
LR	d	20	72.3	20.2	5.8	1.7	
LR	e	20	72.8	19.7	5.9	1.6	
LR	**All**	**100**	**74.1 ± 7.51**	**18.4 ± 1.10**	**5.9 ± 0.71**	**1.6 ± 0.33**	

Note: ''other'' includes dust, foliage and other materials in minimum amounts.

Table 4 shows the results obtained for fiber, bark, twig and foliage content of the chip samples from the 10 different agroforestry yards in SRC plantation. The applied MANOVA shows significant differences between the two harvesting intervals (2 years *vs.* 3 years; $p < 0.05$ for all the variables) and among the clones for some variables ($p < 0.05$). As an average, the chips produced in the 100 "2 years" samples contain 66.3% of wood fiber, 26.2% of bark, 3.6% of twigs and 3.9% of "other" (mainly dust). In the worst case, fiber content can drop to 62.0% and bark and twigs increase to 34.4% of the total weight. As an average, the chips produced in the 100 "3 years" samples contain 71.5% of wood fiber, 21.0% of bark, 4.3% of twigs and 3.2% of "other" (mainly dust). In the worst case, fiber content can drop to 69.6% and bark and twigs increase to 26.4% of the total weight.

Table 5 shows the results of the MANOVA and Tukey tests for component breakdown, determined on 400 samples from the 20 different yards (200 samples for the forest sites and 200 for the agroforestry sites). The tests show some significant differences among the four types (FTS *vs.* LR *vs.* 2 years *vs.* 3 years; $p < 0.05$ for the fiber variable; $p < 0.05$ for the bark variable). In particular for the twigs variable the types "FTS" and "2 years" not have differences ($p > 0.05$) and the same result was obtained also for the "other" variable. The average proportion of fiber is 72.8%, but it drops to 66.3%

in the worst case. The SRC "2 years" has the largest proportion of bark 26.2%, while broadleaves logging residues types have the largest proportion of twigs 5.9%. In the FTS types it is important to note that the variable "other" is the highest, with a value of 4.3 (mainly foliage).

Table 4. Fiber, bark, and twig content of the chip samples from the 10 different agroforestry yards in SRC plantation.

Harvesting interval	Poplar clones	Code	Samples	Fiber %	Bark %	Twigs %	Other %	
2 years	AF2	a	20	66.5	26.0	3.9a	3.6 a,b	
2 years	AF6	b	20	66.7	25.8	3.4 a,b	4.1b	
2 years	Monviso1	c	20	62.0	30.5	3.9 b	3.6a	$p < 0.05$
2 years	Monviso2	d	20	70.8	21.7	3.8 b	3.7 a	
2 years	Muur	e	20	65.3	27.2	3.0 a,b	4.5 a,b	
2 years	**All**		**100**	**66.3 ± 9.26**	**26.2 ± 4.14**	**3.6 ± 1.06**	**3.9 ± 1.10**	
3 years	AF2	a	20	69.6	22.9	3.5 a	4.0 a,b	
3 years	AF6	b	20	73.7	18.8	3.9 a	3.6 b	
3 years	Monviso1	c	20	70.5	22.0	4.7 b	2.8 a	$p < 0.05$
3 years	Monviso2	d	20	70.6	21.9	4.5 b	3.0 a	
3 years	Muur	e	20	73.4	19.1	5.0 a,b	2.5 b	
3 years	**All**		**100**	**71.5 ± 7.79**	**21.0 ± 2.12**	**4.3 ± 0.97**	**3.2 ± 1.01**	

Note: ''other'' includes dust, foliage and other materials in minimum amounts. Different letters for statistical differences among the clones (or codes), with the Tukey test.

Table 5. Fiber, Bark, and Twig content of the chip samples.

Types	Samples	Fiber %	Bark %	Twigs %	Other %
FTS	100	79.2 a	13.3 a	3.2 a	4.3 a
LR	100	74.1 b	18.4 b	5.9 b	1.6 b
2 years	100	66.3 c	26.2 c	3.6 a	3.9 a
3 years	100	71.5 d	21.0 d	4.3 d	3.2 d
All	**400**	**72.8 ± 9.38**	**19.7 ± 2.31**	**4.3 ± 1.55**	**3.2 ± 1.01**

Note: ''other'' includes dust, foliage and other materials in minimum amounts; different letters show significant differences among values in a column (Tukey test).

3.2. Particle-Size Distribution

Table 6 shows the results obtained for particle-size distribution, determined on 200 samples from the 10 different forestry yards. The applied MANOVA only shows a significant difference between the two types (FTS *vs.* LR; $p < 0.01$ for all the three variables). As an average, the chips produced in the 100 FTS samples contain 0.6% of oversize particles (>63 mm), and 8.0% of fines (<3 mm) and the 91.4% is represented from particles from 63 to 3 mm, while, the chips produced in the 100 LR samples contain 6.4% of oversize particles (>63 mm), and 6.4% of fines (<3 mm) and the 87.2% is represented from particles from 63 to 3 mm. Table 7 shows the results obtained for particle-size distribution, determined on 200 samples from the 10 different agroforestry yards in SRC plantations. The applied MANOVA shows only a significant difference between the two harvesting intervals (2 years *vs.*

3 years; $p < 0.05$ for all the three variables). On average, the chips produced in the 100 "2 years" samples contain 1.0% of oversize particles (>63 mm), and 11.8% of fines (<3 mm) and the 87.3% is represented from particles from 63 to 3 mm, while, the chips produced in the 100 "3 years" samples contain 2.3% of oversize particles (>63 mm), and 8.0% of fines (<3 mm) and the 89.7% is represented from particles from 63 to 3 mm.

Table 6. Particle size distribution of the chip samples from the 10 different forestry yards.

Types	Code	Samples	Oversize %	Acceptable %	Fines %	
FTS	a	20	0.6	91.5	7.8	
FTS	b	20	0.5	91.3	8.2	
FTS	c	20	0.5	91.7	7.8	$p > 0.05$
FTS	d	20	0.6	91.5	7.9	
FTS	e	20	0.6	91.2	8.2	
FTS	**All**	**100**	**0.6 ± 0.14**	**91.4 ± 1.18**	**8.0 ± 1.16**	
LR	a	20	6.8	85.0	8.1	
LR	b	20	6.6	87.6	5.9	
LR	c	20	6.1	88.0	5.8	$p > 0.05$
LR	d	20	6.1	87.0	6.9	
LR	e	20	6.5	88.4	5.1	
LR	**All**	**100**	**6.4 ± 0.98**	**87.2 ± 2.10**	**6.4 ± 1.73**	

Note: Oversize = particles > 63 mm; Acceptable = particles from 63 to 3 mm; Fines = particles < 3 mm; eventual values in bold represent a difference between the code.

Table 7. Particle size distribution of the chip samples from the 10 different agroforestry yards in SRC plantation.

Harvesting interval	Poplar clones	Code	Samples	Oversize %	Acceptable %	Fines %	
2 years	AF2	a	20	0.9	86.8	12.3	
2 years	AF6	b	20	0.9	90.4	8.7	
2 years	Monviso1	c	20	1.0	88.9	10.1	$p > 0.05$
2 years	Monviso2	d	20	1.0	87.2	11.9	
2 years	Muur	e	20	1.0	83.2	15.9	
2 years	**All**		**100**	**1.0 ± 0.31**	**87.3 ± 4.65**	**11.8 ± 4.66**	
3 years	AF2	a	20	2.4	85.9	11.8	
3 years	AF6	b	20	2.4	91.4	6.1	
3 years	Monviso1	c	20	2.2	90.7	7.1	
3 years	Monviso2	d	20	2.3	89.5	8.2	$p > 0.05$
3 years	Muur	e	20	2.0	91.1	6.9	
3 years	**All**		**100**	**2.3 ± 0.45**	**89.7 ± 3.03**	**8.0 ± 2.93**	

Note: Oversize = particles > 63 mm; Acceptable = particles from 63 to 3 mm; Fines = particles < 3 mm; eventual values in bold represent a difference between the code.

Table 8 shows the MANOVA results obtained for particle-size distribution, determined on 400 samples from the 20 different yards. The test shows some significant differences between the four types (FTS *vs.* LR *vs.* 2 years *vs.* 3 years; $p < 0.01$ for the oversize variable; $p < 0.05$ for the acceptable variable; $p < 0.05$ for the fines variable). In particular for the acceptable variable the types "LR" and "2 years" have no differences, while for the fines variable the types "FTS" and "3 years" have no differences.

The average proportion of the acceptable fraction (63 to 3 mm) is 88.9%, but it drops to 73.1% in the worst case. Broadleaved logging residues have the largest proportion of oversize particles 6.4%, while SRC "2years" types has the largest proportion of fines particles 11.8%.

Table 8. Particle size distribution of the chip samples.

Types	Samples	Oversize %	Acceptable %	Fines %
FTS	100	0.6 a	91.4 a	8.0 a
LR	100	6.4 b	87.2 b	6.4 b
2 years	100	1.0 c	87.3 b	11.8 c
3 years	100	2.3 d	89.7 c	8.0 a
All	**400**	**2.56 ± 2.38**	**88.91 ± 3.50**	**8.54 ± 3.54**

Note: Oversize = particles > 63 mm; Acceptable = particles from 63 to 3 mm; Fines = particles < 3 mm; different letters show significant differences among values in a column (Tukey test).

3.3. Energetic Characterization

Table 9 shows the results obtained for energetic parameters, determined on 200 samples from the 10 different forestry yards. The applied MANOVA shows a significant difference between the two types (FTS *vs.* LR; $p < 0.01$ for all the variables) and among the five "codes" (a–e; $p < 0.05$ for some variables). As an average, the HHV of the chips produced in the 100 FTS samples is 20.6 MJ/kg$_{d.m.}$ and the ash content is 0.9% (but with significant statistical differences among the codes), while for chips produced in the 100 LR samples the HHV is 19.5 MJ/kg$_{d.m.}$ and the ash content is 1.5% (but for the two variables with significant statistical differences among the code). As an average, the C content of the chips produced in the 100 FTS samples is 50.2%, the N is 0.2% (for both with significant statistical differences among the codes) and the H content is 6.3% (but with low statistical differences among the codes), while for chips produced in the 100 LR samples the C content is 47.9%, the N is 0.2% (for both without any differences among the codes) and the H content is 6.1% (but with low statistical differences among the codes).

Table 10 shows the results obtained for energetic parameters, determined on 200 samples from the 10 different agroforestry yards in the SRC plantations.

Table 9. Higher heating value, ash and CNH content of the chip samples from the 10 different forestry yards.

Types	Code	Samples	HHV MJ/kg$_{d.m.}$	Ash %$_{d.m.}$	C %$_{daf}$	N %$_{daf}$	H %$_{daf}$	
FTS	a	20	20.7 a	1.2 a	49.5 a	0.2 a,b	6.4 b	
FTS	b	20	20.6 a	1.1 a,b	49.8 a	0.1 a	6.3 a,b	
FTS	c	20	20.4 a	0.6 d	50.0 a,b	0.2 c	6.3 a,b	$p < 0.05$
FTS	d	20	20.6 a	0.8 c	50.6 b,c	0.2 c	6.1 a	
FTS	e	20	20.9 a	0.9 b,c	50.9 c	0.2 b,c	6.1 a,b	
FTS	**All**	**100**	**20.6 ± 0.51**	**0.9 ± 0.30**	**50.2 ± 0.91**	**0.2 ± 0.05**	**6.3 ± 0.35**	
LR	a	20	19.5 a,b	1.5 a,b	47.9 a	0.2 a	6.2 b	
LR	b	20	19.3 a	1.5 a,b	48.0 a	0.2 a	6.3 b	
LR	c	20	19.6 a,b	1.2 a	47.8 a	0.2 a	6.1 a,b	$p < 0.05$
LR	d	20	19.6 a,b	1.7 b	47.9 a	0.2 a	5.9 a	
LR	e	20	19.7 b	1.5 a,b	47.9 a	0.2 a	6.1 a,b	
LR	**All**	**100**	**19.5 ± 0.41**	**1.5 ± 0.53**	**47.9 ± 0.51**	**0.2 ± 0.03**	**6.1 ± 0.33**	

Note: different letters show significant differences among values in a column (Tukey test).

Table 10. Higher heating value, ash and CNH content of the chip samples from the 10 different agroforestry yards in SRC poplar plantation.

Harvesting interval	Clone	Samples	HHV MJ/kg$_{d.m.}$	Ash %$_{d.m.}$	C %$_{daf}$	N %$_{daf}$	H %$_{daf}$	
2 years	AF2	20	19.1 a	4.0 b	49.5 a	0.2 a,b	6.4 b	
2 years	AF6	20	20.1 a,b	2.8 a	49.7 a,b	0.2 a	6.1 a,b	
2 years	Monviso1	20	19.9 b	4.0 b	49.9 b	0.2 c	6.1 a	$p < 0.05$
2 years	Monviso2	20	20.5 b	3.9 b	50.0 b	0.2 c	6.2 a	
2 years	Muur	20	19.4 a,b	3.7 b	51.2 c	0.2 b	6.0 a	
2 years	**All**	**100**	**19.7 ± 0.93**	**3.8 ± 1.02**	**50.0 ±0.86**	**0.2 ± 0.04**	**6.2 ± 0.35**	
3 years	AF2	20	20.1 a,b	3.2 b	49.5 a	0.2 a	6.4 b	
3 years	AF6	20	20.4 a,b	2.1 a	49.7 a,b	0.1 a	6.2 a,b	
3 years	Monviso1	20	20.6 b	2.9 b	50.2 b	0.2 c	6.2 a,b	$p < 0.05$
3 years	Monviso2	20	20.6 b	3.1 b	50.1 b	0.2 c	6.2 a,b	
3 years	Muur	20	19.7 a	2.9 b	51.0 c	0.2 b	6.1 a	
3 years	**All**	**100**	**20.2 ± 0.70**	**2.8 ± 0.93**	**50.1 ± 0.85**	**0.2 ± 0.05**	**6.2 ± 0.34**	

Note: different letters show significant differences among values in a column (Tukey test).

The applied MANOVA shows a significant difference between the two harvesting interval (2 years *vs.* 3 years; $p < 0.01$ for all the variables) and among the poplar clones (a–e; $p < 0.05$ for all the variables). On average, the HHV of the chips produced in the 100 "2 years" samples is 19.7 MJ/kg$_{d.m.}$ and the ash content is 3.8% (for the two variables with significant statistical differences among the codes), while for chips produced in the 100 "3 years" samples the HHV is 20.2 MJ/kg$_{d.m.}$ and the ash content is 2.8% (for the two variables with significant statistical differences among the codes). On average, the C content of the chips produced in the 100 "2 years" samples is 50.0%, the N is 0.2% and the H content is 6.2% (for all with significant statistical differences among the codes), while for chips produced in the 100 "3 years" samples the C content is 50.1%, the N is 0.2% (for both without any

differences among the codes) and the H content is 6.2% (for all with significant statistical differences among the codes).

4. Discussion and Conclusions

4.1. Component Breakdown and Particle Size Distribution

Bark and twigs content (Tables 3–5) are also higher in LR (respectively 18.4% and 5.9%, both oaks and beech) and SRC (both 2 years and 3 years harvesting interval) (bark 26.2%, twigs 3.0% and bark 21.0%, twigs 4.3%, respectively). The presence of bark and twigs in general decreases the quality of the chips, as well as a non-uniform particle size distribution. The particle size distribution (Tables 6–8), is worst in the samples from the LR (both oaks and beech) and the SRC "2 years". Particle-size distribution is a function of different variables, and is significantly affected by chipper type, blade wear and screen size [14,15]. That may explain the limited difference obtained for feedstock type, since in our study only a specific chipper model was used. Nevertheless, it is interesting to notice that for the FTS samples the high proportion of fines is likely to depend on the abundant presence of needle material, which tends to pulverize on impact, as previously attested by others authors [6,15]. This is another not appreciated feature. Compared to these two physical characteristics, the best chips are the types obtained from FTS and SRC "3 years". These chips are the most manageable for the automated handling systems and feeding of the burners.

4.2. Energetic Characterization

The energetic parameters, Tables 9 and 10, show the best score for the "FTS" types (HHV 20.6 MJ/kg$_{d.m.}$ and ash content 0.9%$_{d.m.}$), while the chips obtained from the "3 years" SRC have a good heating value (HHV 20.2 MJ/kg$_{d.m.}$) but a high ash content (2.8%$_{d.m.}$). These results, in particular one related to the chips obtained from coniferous woods and their higher heating value are well documented in the literature, and naturally related to the high resin content [16]. In this regard, the original contribution of our work is not as much in proving something that is already well known, but rather in associating specific energetic characteristics to specific physic features (fiber and bark content), so as to allow an accurate determination of fuel energy content through proximate analysis, as also suggested by others authors [6,17].

A high C content within a biomass suggests their excellent behavior for energetic purposes. The determination of N is another useful element to determine the energetic attitude of a biomass, although it is not yet possible to provide the optimal range of its content in the tree species to be used for energy purposes [18]. The percentage content of C, N and H may also be useful for the indirect estimation of heating value, even though the biological and structural variability of the considered species, the different harvesting period, the growth environments examined, etc. it makes extremely complicated to identify exhaustive formulas for estimating the heating value [19].

The ash content of the fuel (see Tables 9 and 10) is essential for the choice of the appropriate combustion and gas-cleaning technologies. Furthermore, fly ash formation, ash deposit formation as well as logistics concerning ash storage and ash utilization/disposal depend on the ash content of the fuel [20]. Fuels with low ash content are therefore preferable. The wood (only fiber) usually contains

relatively low amounts of ash, while significantly higher values are typically found in bark, needles and pine cones. Grate or fluidized bed combustion are suitable technologies for ash-rich fuels. Underfeed stokers are not suitable for ash-rich fuels due to the formation of ash layers on the surface of the fuel bed which can cause irregular breakthroughs of the gas and combustion air resulting in increased emissions. The composition, density, size and amount of the fly ash emissions formed are influenced by the amount of ash-forming elements in the fuel as well as by the combustion technology and process control applied [20].

4.3. Suggestions to Practice and Future Research

This research focused on some characteristics of fuel chips obtained from four main sources, namely full tree system, logging residues, and two short rotation coppice typologies. Chips obtained from thinning of coniferous woods (FTS) offer the best combination of good product quality characteristics. In Italy currently the wood produced from first thinning in coniferous forests has no market, for this reason it is very important to ascertain its good energetic characteristics to create an adequate interest for the logging companies. Chips obtained from SRC with "3 years" harvesting interval represent a good fuel, in line with what has also been found by other authors [21] concerning the improvement of the wood chip properties obtained from SRC with extended harvesting intervals. The others two chip sources (LR and SRC with "2 years" harvesting interval) are less valuable fuels considering their various physical and energetic parameters. Particularly with regard to LR, it is important to underline that this woody biomass is a residue of another productive activity. It is thus an excellent source of biomass supply at low cost, even if it lacks optimal energetic characteristics. Further research will be extended to other species, different cropping systems and dedicated plantations for woody biomass production. These analyzes will be conducted, however, taking into account the specific scenarios in terms of mass production, costs and environmental impacts. Regarding the scenarios of this research a specific Life Cycle Assessment (LCA) study is already in progress that will allow us to evaluate the woody chips with the best intrinsic and extrinsic characteristics.

Acknowledgments

The work is carried out within the Scientific Studies for the Conversion of Agricultural Crops into Energy (SUSCACE) project, funded by the Italian Ministry for Agriculture, Food and Forestry.

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