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Production of Wood Pellets from Poplar Trees Managed as Coppices with Different Harvesting Cycles

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Abstract: High-density biomass plantations have played a key role in the national energy landscape in Italy since the 1990s but, to date, an inversion of tendency and a significant reduction of cultivated areas has been noted. Despite this, the existing plantations have seen their coppicing rotation become significantly lengthened, resulting in large quantities of biomass per hectare. This study aimed to identify the best raw material suitable for pellet production using whole trees or stems without branches from poplar plantations at the end of the third, sixth and ninth year of age. All types of pellets made reach the requirements of class A1 for diameter, length, moisture content, ash melting point, lower heating value, as well as nitrogen (N), sulfur (S), and heavy metals. None of the theses satisfied the bulk density parameters while for ashes and mechanical durability, a great variability was observed according to the different raw materials used. An improvement in terms of heating value was observed by transforming the poplar wood chips refined into pellets. The pelletizing process using high density poplar plantation as a raw material highlights the possibility of obtaining a product that meets many of the quality standards required on the market. These aspects are closely related to the innovation carried out in the agro-forestry sector for effective energetic sustainability.

Keywords: chipping; pellet; poplar; SRWC; pelletization; biomass quality; energy quality

1. Introduction

The critical issues related to the decreasing availability of energy sources of fossil origin, as well as their geographical distribution in politically unstable areas, together with huge environmental problems at a global scale, have led to an increased focus on the search for alternative energy sources. The use of renewable energy has increased steadily over time due to the need to mitigate climate change by reducing the use of fossil fuels [1,2], which are responsible for the constant increase in the concentration of greenhouse gases (GHG) in the atmosphere [3].

The European Commission, through the 2020 climate and energy package, has drafted a set of binding rules to ensure that the EU achieves its climate and energy targets by 2020, providing for the cutting of 20% of greenhouse gas emissions (compared to the levels of 1990), 20% of energy requirements needing to be derived from renewable sources, and a 20% improvement in energy efficiency [4].

Although biomass has been a subject of great interest in terms of power generation, its use at the industrial level has attracted less attention; the various factors to explain this lack of attention are mainly the low mass and energy density, the dispersion of the raw material and its availability in less convenient forms, and the high transport costs [5].

One way to overcome the limitations resulting from the low bulk density and high transport costs is to use densification processes (pelletization and/or briquetting) before using this material for energy purposes, in order to exploit a homogeneous and easy-to-use solid biofuel, which is also characterized by a higher energy density [6,7].

For these reasons the pellet sector, unlike biomasses from Short Rotation Woody Crops (SRWC), has seen important developments both in terms of production and in terms of the number of installed transformation plants, with a market price exceeding €300/tons in 2018 [8].

The pellet production process is an extrusion process that consists of subjecting the very fine dry biomass to a high pressure and high temperatures, compressing it through a hole of a few millimeters and producing small cylinders that are cut to the desired length and cooled [9,10].

The bioenergy policies implemented by the individual Member States of the European Union are characterized by tax exemptions, mandatory targets to be achieved, subsidies, and biomass sustainability policies that stimulate the growth of the imported wood pellets [11]. The global annual production of wood pellets was recently estimated by the International Energy Agency (IEA) to be about 6 to 8 million tons, with a net potential of about 13 million tons [12]. Pellet production grew from 1.7 million tons in the year 2000 to 28 million tons in 2015 [13], showing an annual increase of 14% compared to 2011 [14]. It is estimated that the demand for pellets from 2020 will be about 50 million tons per year [15] and the consumption of industrial pellets will grow steadily at a rate of 21% year^{-1}, whereas the increment in the consumption of domestic pellets will reach 8.5% year^{-1} [7].

Europe is the major pellet producer and consumer, followed by the USA and then the rest of the world. Europe is also a global net importer of wood pellets [13,16]: the highest consumption of pellets is recorded in the United Kingdom, Finland and Sweden, where they are mainly used to produce electricity and heating; other important pellet consumers in the EU are Belgium, the Netherlands, Denmark and Italy [17]. On the production side, Portugal and Latvia are Europe's biggest exporters of pellets, followed by Germany, Lithuania, Estonia, Finland and Sweden [18,19]. In 2016 the thermal energy obtained from biomasses in Italy amounted to about 7.06 Mtep [20].

In this context the Council for Agricultural Research and Economics (CREA) (AGROENER project Energy from agriculture: sustainable innovations for the bio-economy, financing MiPAAF D.D. n. 26329 of 4 April 2016 [21]) and the Department of Agriculture and Forest Sciences (DAFNE-University of Tuscia, Italy) started an experimental activity aimed to enhance the value of different lignocellulosic materials through the promotion of a demonstration model of pellet production on a company scale.

In Italy high-density biomass plantations have played a key role in the national energy landscape since the 1990s [22,23] but, to date, the interest in this type of crop seems to be disappeared, indicating an inversion of tendency and a significant reduction of cultivated areas [24]. Despite this, the existing plantations have seen their coppicing rotation significantly lengthened, reaching even 5 to 6 years to over 9 to 10 years and this results in larger quantities of biomass per hectare, with much better qualitative characteristics than those found in the classic two- or three-year cycles.

The market price is a key factor for the development of pellet manufacturing [13] and the shredded material from SRWC (Short Rotation Wood Coppice) can then be valorized through a pelletization process, thereby allocating the transformed material to much more profitable markets.

The purpose of the work was to evaluate the possibility of enhancing the SRWC of poplar, verifying the ability for this type of biomass to be transformed into pellet, starting from different coppicing intervals (third, sixth and ninth year of vegetation) and different fractions (whole trees and stems without branches). The dendrometric characteristics of the raw wood material and the qualitative characteristics of the pellets produced were assessed. Some parameters, such as the calorific and moisture content, ashes and heavy metals were determined before and after pelleting in order to identify any differences directly related to the transformation process.

2. Materials and Methods

The activity, developed within the CREA farm (Lat. 42° 06′ 07″ N, Long. 12° 37′ 39″ E), involved the plantation of Short Rotation Coppice of poplar (clone AF6-Populus x Euroamericana), with a density of 7142 stumps per hectare, divided into sectors characterized by different coppicing intervals, with shoots aged between 3 and 11 years [25]. The experimentation was carried out using different treatments with harvesting cycle of: 3 years (roots of 11 years and stems of 3 years), 6 years (roots of 11 years and stems of 6 years), and 9 years (roots and stems of 9 years). The experimental design involved a total of 30 sample trees, 10 for each crop cycle, taken by following the indications suggested by Mitchell et al. [26]. The dimensional analyses concerned the basal diameter of the stem, the total height, the percentage by weight of the branches and the relative dimensions (diameter, length and number).

The sample trees cut down on the 20 February 2018 (time T0), were left in a storage yard for two months (time T1), subdivided by crop cycle and type of product:

- five three-year-old whole trees,
- five six-year-old whole trees,
- five nine-year-old whole trees,
- five three-year-old stems without branches,
- five six-year-old stems without branches,
- five nine-year-old stems without branches.

The biomass was subsequently chipped, refined and positioned within six different bins. The dehydration process of the material was enhanced by periodically exposing it to sunlight for further 40 days (time T2). The pelletization was finally carried out the following day (time T3). The chipping, refining and pelletizing were carried out, respectively, with a Farmi Forest CH260 forestry chipper, a BL-100 shredder, and a 4 kW Bianco line pelletizer. For the reining process, a 6 mm grid was used according to the method provided by Bergstrom et al. [27].

The moisture content [28] of the biomass was monitored from the date of the felling of trees to the time of final pelleting, by detecting the parameters in the 4 intervals of time mentioned above (T0, T1, T2, T3). During the storage in the field, the main meteorological data (monthly precipitation, rainy days, average monthly temperatures) were also recorded by the local weather station, in order to provide information about the climatic trend of the area.

The initial moisture content (T0) was detected on samples taken from other trees of the same crop cycle cut down on the same day. Specifically, basal, median and apical stem wheels were used (thickness of 1.5 cm), as well as portions of different diameters and lengths of branches and treetops, in order not to compromise the integrity of the stored material.

The moisture content of the biomass in the three intervals of time T1, T2, and T3 was determined by taking a total of 90 samples of 500 g of chips, refined and pelletized material (5 for each crop cycle, fraction, type of transformation and reference period considered). After the storage, a further reduction of moisture content may occur during the production process because the biomass is subjected to high pressures with a significant increase in temperature. For this reason, particular attention was paid to verify the possible differences of moisture content before (T2) and after the passage in the pellet machine (T3).

The characterization of the biomass was carried out at the CREA and DAFNE laboratories and concerned the ash content and ash melting point, the heating value, the metals, nitrogen and sulfur, the bulk density, the pellet dimensions, the mechanical durability, and the moisture content. Five samples were used for each parameter, except for pellet sizes (50 samples).

The ash content was calculated according to EN ISO 18122 [29]. Samples of about 1 g were placed in the Lenton EF11/8B muffle furnace and heated to 250 °C for one hour. Subsequently, the temperature was raised to 550 °C for two hours. The determination of ash content was calculated considering the weight loss of the sample before and after the heating process.

The ash samples subsequently underwent a granulometry reduction process in order to obtain a fine and homogeneous powder that was able to guarantee the preparation of the samples for the fusion analysis with a more regular form. Subsequently, the procedure provided for the preparation of a cylindrical ash sample to be introduced into the Sylab SHV-IF 1500 analyzer, according to the CEN/TS 15370-1 [30]. The fusibility analysis is based on the identification of the temperature which corresponds to the start of sample deformation, monitored by a camera connected to a computer (image analysis).

The most important parameter to characterize a substance as fuel is the heating value, determined according to EN ISO 18125 [31]. A sample of dried wood chips was first ground by a knife mill Retsch SM 100, and secondly by a centrifuge mill Retsch ZM 200. The Higher Heating Value (HHV) was determined using the calorimeter Anton Paar 6400 while the Lower Heating Value (LHV) was determined using a logarithmic formula. Four samples of shredded wood were prepared by means of the pellet mill Pellet Press 2810 to produce tablets, weighing 1 g each. Before every single analysis, the instrument was calibrated with benzoic acid.

The determination of heavy metals, which directly influence the formation of aerosols and fly ash during the combustion of wood material [32], was performed using Agilent 7700 ICP-MS according to the provisions of EN ISO 16968 [33]. An aliquot of each sample (about 500 mg), was transferred into special Teflon containers and subjected to acid attack (HNO_3 and H_2O_2) using a microwave digester (Start D, Milestone S.r.l., Sorisole, Italy), and the solutions obtained were diluted and subjected to analysis.

The content of nitrogen (N) and sulfur (S) were measured according to EN ISO 16948 [34] and EN ISO 16994 [35] using an elemental analyzer CHNS-O Costech ECS 4010. The tin capsules with approx. 1 mg of sample were inserted through the autosampler into the analyzer's combustion oven.

The bulk density was evaluated in accordance with EN ISO 17828 [36]. A standard container was filled with a certain amount of shredded material of a given size and shape and subsequently weighed. The bulk density was calculated from the net weight per standard volume and reported with the determined moisture content. The bulk density of the pellet was calculated using a metal cylinder of known volume (0.005 m^3), filled to the rim and weighed using a field dynamometer. The measurement was replicated 8 times.

The pellet dimensions were determined according to EN ISO 17829 [37] by measuring the length and diameter of 50 individual pellets randomly selected per sample. Average values for diameter and length were calculated.

The mechanical durability was analyzed by means of a mechanical durability tester (Andritz Sprout rotation pellet testing apparatus) according to EN ISO 17831-1 [38].

The moisture content was determined according to EN ISO 18134-1 [39], using a Memmert UFP800 drying oven. The samples were taken to the laboratory where they were oven-dried at 103 ± 2 °C, until a constant weight was achieved (weight variation not exceeding 0.2% during a further drying period of 60 minutes). The determination of moisture content was calculated as a percentage of weight loss before and after the drying process.

Data were statistically analyzed using PAST and Statistics software. Morphometric parameters were examined by using One-Way Anova, Welch F test and Kruskal-Wallis. A T-test and Welch F test for moisture content, bulk density and for the comparison of physical-chemical parameters between refined and pelletized wood, were performed.

3. Results

3.1. Size Characteristics of the Crops

Figure 1 shows the main morphometric parameters of the poplar detected in the three cultivation cycles considered. Trees of 3 years were characterized by a diameter, a height, and a weight equal to 8.32 cm, 6.97 m, and 19.62 kg. The length and diameter of branches insertion were slightly less than 1 m and 1 cm while the average length of the treetops was 1.79 m, with a diameter of about 2 cm.

Significantly larger sizes were recorded for the poplars of 6 and 9 years of age: 16.09 and 21.39 cm in diameter, 13.07 and 17.70 m in height, as well as 79.63 and 183.92 kg in weight. The 9-year-old branches were almost double the size of the 6-year-old material, both in terms of length and diameter of insertion on the stem. The treetops, on the other hand, showed very similar dimensions with an average length of more than 3 m and a diameter of about 5 cm.

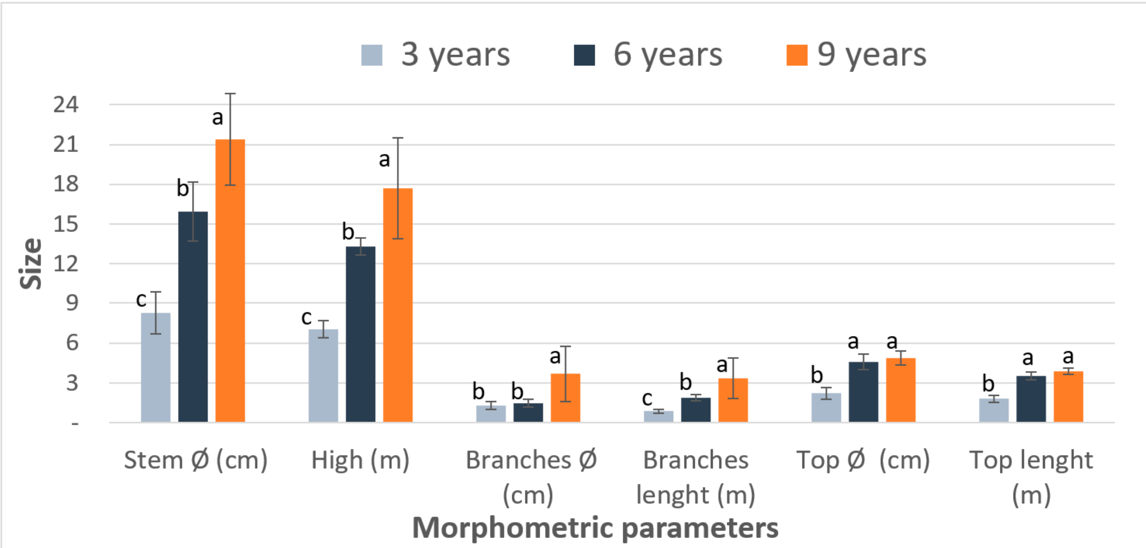

Figure 1. Main morphometric parameters (mean ± St. dev.) of SRWC of poplar at the third, sixth and ninth year of vegetation. Stem diameter (One-Way Anova and Tuckey post hoc test): F = 66.97, df = 27, $p < 0.001$; height (Welch F test and Tuckey post hoc test): F = 253.1, df = 16.15, $p < 0.001$; branches diameter (Welch F test and Tuckey post hoc test): F = 8.997, df = 16.1, $p < 0.01$; branches length (Welch F test and Tuckey post hoc test): F = 71.99, df = 15.39, $p < 0.001$; treetops diameter (One-Way Anova and Tuckey post hoc test): F = 82.41, df = 27, $p < 0.001$; treetops length (Kruskal-Wallis and Mann-Whitney pairwise comparisons Bonferroni corrected): H = 21.83, Hc = 21.87, $p < 0.001$. Different letters indicate statistically significant differences between the groups obtained by post hoc tests applied ($p < 0.05$).

Statistical analysis showed no significant differences with respect to the diameter of the 3- and 6-year-old branches and to the diameter and length of the 6- and 9-year-old treetops. In all other cases, the differences were significant.

The percentage by weight of branches and treetops increased progressively with the increase of the age of the shoots, with the poplar of 3 years that was characterized by the lower average value (Table 1). The one-way Anova highlighted the existence of significant differences between material of 3 years of age and that of 6 and 9 years of age ($p < 0.05$). However, there were no statistically significant differences between the poplars of 6 and 9 years. In the latter case, the values measured were very similar to each other, with about 80% of the weight represented by the stem.

Table 1. Percentage weight distribution of stems, branches and tops (mean ± St. dev.). One-Way Anova: F = 3.603, df = 27, $p < 0.05$. Tuckey post hoc test: different letters indicate statistically significant differences ($p < 0.05$). Percentage values were previously transformed into a square root of the arcosine.

Harvesting Cycle	3 Years	6 Years	9 Years
Branches and tops	17.65% (bc)	19.41% (ac)	20.36% (a)
Stems	82.35%	80.59%	79.64%

3.2. Dehydration Process and Moisture Content of Different Types of Biomass

During the outdoor storage of the wood material, 365 mm of rain were recorded in 33 days, mainly concentrated in the month of March. Average temperatures were 5.72, 11.48 and 15.1 °C, respectively, in the last week of February, in March and in the first two weeks of April. At the time the trees were cut down, they had an average moisture content of 54.74% (T0) reaching, after 2 months of storage, an average value of 46% (T1). Subsequently, the refined biomass was conserved under the roof and periodically exposed to sunlight, attested on average values of just under 10% (T2).

The reduction of the moisture content after pelleting, which was assessed comparing the values for T2 and T3 periods, ranged between 7.61 and 18.53 percentage points. The t-test performed showed, in all the examined cases, statistically significant differences (Table 2).

Table 2. Biomass moisture content in the 4 reference periods and loss of moisture during palletization (mean ± St. dev.). T test columns Δ T3/T2. The asterisks indicated different levels of statistical significance: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***). Percentage values were previously transformed into a square root of the arcosine.

Type of Biomass Source	Trees T_0 20 February	Chips T_1 20 April	Refined T_2 31 May	Pellet T_3 1 June	Δ T_3/T_2
3 years old whole tree	52.28% (±0.96)	46.05% (±4.07)	9.53% (±0.38)	8.32% (±0.37)	−12.72% (±2.42) ***
3 years old stem	52.72% (±0.73)	46.69% (±3.07)	10.21% (±0.43)	8.46% (±0.35)	−17.04% (±4.77) ***
6 years old whole tree	53.98% (±0.87)	45.77% (±4.39)	10.05% (±0.55)	8.30% (±0.23)	−17.25% (±4.72) ***
6 years old stem	53.88% (±1.36)	48.03% (±3.43)	9.43% (±0.33)	8.71% (±0.31)	−7.61% (±4.96) **
9 years old whole tree	56.27% (±1.81)	47.95% (±3.93)	9.32% (±0.63)	8.35% (±0.31)	−10.24% (±4.54) *
9 years old stem	56.85% (±2.09)	50.78% (±4.53)	10.40% (±0.39)	8.47% (±0.37)	−18.53% (±4.94) ***
Average	**54.74%**	**46.05%**	**9.76%**	**8.50%**	**−12.62%**

3.3. Length, Diameter and Bulk Density of the Pellets

The average diameter of the cylinders was just over 6 mm, with a length between 15.13 and 17.93 mm for the whole material and 17.35 and 20.08 mm for the material without branches. At the same crop cycle, the pellets obtained from whole trees were characterized by a lower average length: −7.48%, −5.84% and −32.65% for the cycle of 3, 6 and 9 years, even if this lower average length was statistically significant exclusively for the poplar of a 9-year-old (One-way Anova and Tuckey post hoc test. Df: 144, MS: 32.7052, F: 2.51, $p < 0.05$).

Bulk density, on the other hand, varied between 576 and 584 kg·m^{-3} for trees without branches and 553 and 556 kg·m^{-3} for whole trees. The use of the branches and tree-tops leaded to a reduction in the average bulk density values, confirming the trend observed for the length of the material produced. The reductions recorded stood at −4.32%, −5.53% and −3.67% for the poplar of 3, 6 and 9 years. The statistical analysis, in this case, showed significant differences between the whole material and that without branches in all the cycles considered (Figure 2).

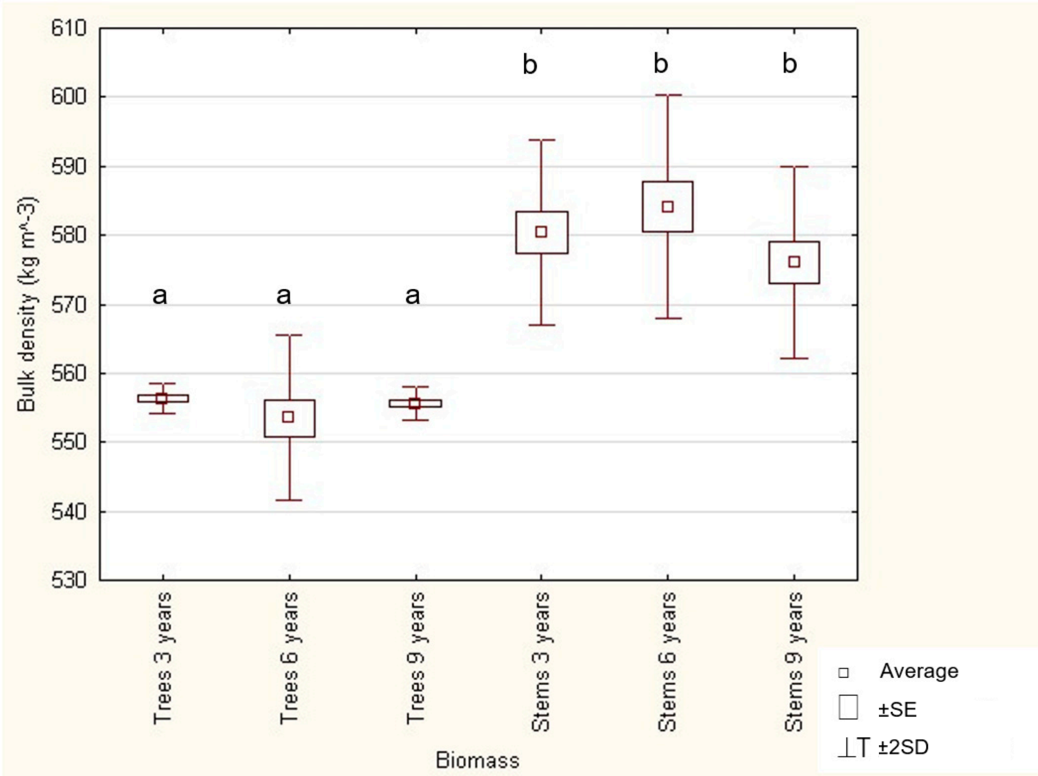

Figure 2. Bulk density of the pellets (average, standard error, standard deviation). Welch F test and Tuckey post hoc test): F = 26.12, df = 10.47, $p < 0.001$). Different letters indicate statistically significant differences between the groups obtained by Tukey post hoc test ($p < 0.001$).

3.4. Heating Value, Ash Content, Ash Melting Point and Heavy Metals of the Pellets

Tables 3 and 4 show the average values of lower heating value, ash content, ash melting point and heavy metals detected in the various types of pellet produced.

Table 3. Heating value, ash content and ash melting point of the different types of pelletized biomass (mean ± St. dev.). LHV: Kruskal Wallis, H = 3.134, Hc = 3.136, $p > 0.05$; Ash content: Welch F test and Tuckey post hoc test, F = 94.56, df = 10.77, $p < 0.001$; Ash melting point: Welch F test and Tuckey post hoc test, F = 189.8, df = 9.981, $p < 0.001$. Different letters indicate statistically significant differences between the groups obtained by Tukey post hoc test ($p < 0.01$).

Biomass Source after Pelletization	LHV (MJ·kg^{-1})	Ash (%)	Ash Melting Point (°C)
3 years old whole tree	17.67 ^{a} ±0.27	2.78 ^{a} ±0.09	1433.4 ^{c} ±4.4
3 years old stem	17.85 ^{a} ±0.38	2.71 ^{a} ±0.31	1455.8 ^{d} ±5.8
6 years old whole tree	17.85 ^{a} ±0.11	1.82 ^{c} ±0.23	1404.6 ^{c} ±17.2
6 years old stem	17.68 ^{a} ±0.26	1.89 ^{c} ±0.08	1433.2 ^{c} ±4.3
9 years old whole tree	17.72 ^{a} ±0.28	2.27 ^{b} ±0.06	1479.8 ^{a} ±1.1
9 years old stem	17.55 ^{a} ±0.62	1.87 ^{c} ±0.04	1457.6 ^{b} ±4.6

Table 4. Heavy metals of the different types of pelletized biomass (mean ± St. dev.). As: One-Way Anova, F = 11.07, df = 24, $p < 0.001$. Cd, Cr, Cu, Pb, Ni, Zn: Kruskal-Wallis and Mann-Whitney pairwise comparisons Bonferroni corrected, H = 26.03, 27.05, 27.85, 28.23, 28.23, 25.39 respectively, Hc = 26.18, 27.58, 27.92, 28.39, 28.33, 25.94, $p < 0.001$ Different letters indicate statistically significant differences between the groups obtained by Tukey post hoc test ($p < 0.05$).

Biomass Source after Pelletization	As (mg·kg^{-1})	Cd (mg·kg^{-1})	Cr (mg·kg^{-1})	Cu (mg·kg^{-1})	Pb (mg·kg^{-1})	Ni (mg·kg^{-1})	Zn (mg·kg^{-1})
3 years old whole tree	0.0050 ^{b,c} ±0.0007	0.2282 ^{a} ±0.0011	0.1562 ^{b} ±0.0015	0.9330 ^{c} ±0.0071	0.0352 ^{e} ±0.0004	0.2406 ^{c} ±0.0009	12.1950 ^{c} ±0.1897
3 years old stem	0.0056 ^{a,c} ±0.0009	0.2318 ^{a} ±0.0056	0.1440 ^{c} ±0.0007	0.8874 ^{e} ±0.0017	0.0464 ^{c} ±0.0009	0.2222 ^{d} ±0.0019	11.4421 ^{d} ±0.2845
6 years old whole tree	0.0046 ^{b,c} ±0.0009	0.1946 ^{c,d} ±0.0082	0.1558 ^{b} ±0.0024	0.8306 ^{f} ±0.0138	0.0320 ^{f} ±0.0012	0.2022 ^{e} ±0.0013	12.5868 ^{c} ±0.2566
6 years old stem	0.0028 ^{d} ±0.0011	0.1966 ^{c} ±0.0018	0.1058 ^{e} ±0.0043	0.9950 ^{a} ±0.0007	0.0418 ^{d} ±0.0013	0.1742 ^{f} ±0.0011	12.3915 ^{c} ±0.2021
9 years old whole tree	0.0068 ^{a} ±0.0011	0.2028 ^{b} ±0.0011	0.2462 ^{a} ±0.0055	0.9470 ^{b} ±0.0102	0.0756 ^{a} ±0.0005	1.6852 ^{a} ±0.0018	14.4502 ^{a} ±0.1057
9 years old stem	0.0044 ^{b,c,d} ±0.0005	0.1878 ^{d} ±0.0018	0.1308 ^{d} ±0.0029	0.9078 ^{d} ±0.0100	0.0678 ^{b} ±0.0011	0.3354 ^{b} ±0.0009	14.3222 ^{b} ±0.1020

The heating value detected for the poplar ranged between 17.55 and 17.85 MJ·kg^{-1} with non-significant statistical differences (Kruskal Wallis test, $p > 0.05$).

In our study, an ash content of less than 1.9% for material of 6 years of age (with and without branches) and 9-year-old stems was detected; values between 2.27% and 2.78% were detected for the whole trees of 9 and 3 years of age, respectively. With reference to the latter parameter, the Welch F test and the Tuckey post hoc test revealed significant differences between the various cultivation cycles with the same fraction used, excepted for the material of 6 and 9 years of age without branches. At the same coppicing intervals, however, it was possible to see a statistically significant difference only in the 9-year-old trees, obtaining a reduction of 17.62% in ash content by using stems without branches instead of the whole trees.

By analyzing the data related to the heavy metals content we identified the types of pellets characterized by their lower concentration: As, Ni and Cr in the pellet obtained from the poplar of 6 years without branches, Pb and Cu in the pellet of 6 years with branches, Zn in the pellet of 3 years without branches, Cd in the poplar of 9 years without branches. The wood material with the highest concentration of heavy metals in absolute was the whole 9-year-old poplar, relative to the values of As, Cr, Pb, Ni, and Zn ($p < 0.05$). Ash melting point was always higher than 1400 °C. About this parameter, there were no significant differences between the whole 3-year-old poplar and the 6-year-old poplar without branches, and between 3 and 9-year-old poplar without branches. In all other cases, however, the differences were statistically significant at a level $p < 0.01$.

Other parameters examined, and not showed in Table 3, concern the concentration of sulfur (S), equal to 0.0%, nitrogen (N), with values between 0.04% and 0.26% and the mechanical durability, with values between 97.1% for the 9-year-old poplar without branches and 98.6% for the whole 6-year-old poplar. Regarding this last parameter, the Kruskal Wallis test did not reveal a significant difference ($p > 0.05$). Tables 5 and 6, unlike the previous ones, highlight the qualitative parameters of the refined material immediately before of the passage into the pellet machine. The heating value ranged between 16.35 and 17.74 MJ·kg^{-1}, while the ash content was always higher than 2% (1.95%), with peak of 2.97%. As showed in Table 7, with high statistical significance, the refined material would tend to be characterized by a lower heating and ash fusibility values compared to the pelletized material. The other percentage differences showed in Table 7, which refer to ash content and heavy metals content, were not statistically confirmed.

Table 5. Heating value, ash content and ash melting point of the different types of refined biomass (mean ± St. dev.).

Biomass Source before Pelletization	LHV ($MJ \cdot kg^{-1}$)	Ash (%)	Ash Melting Point (°C)
3 years old whole tree	16.93 ±0.07	2.14 ±0.21	1438.2 ±3.11
3 years old stem	17.07 ±0.15	2.97 ±0.22	1378.6 ±23.6
6 years old whole tree	17.47 ±0.09	1.95 ±0.34	1377.0 ±6.8
6 years old stem	16.72 ±0.34	2.39 ±0.21	1433.0 ±4.39
9 years old whole tree	17.74 ±0.31	2.57 ±0.20	1406.0 ±4.42
9 years old stem	16.35 ±0.32	2.42 ±0.13	1431.8 ±1.1

Table 6. Heavy metals of the different types of refined biomass (mean ± St. dev.).

Biomass Source before Pelletization	As ($mg \cdot kg^{-1}$)	Cd ($mg \cdot kg^{-1}$)	Cr ($mg \cdot kg^{-1}$)	Cu ($mg \cdot kg^{-1}$)	Pb ($mg \cdot kg^{-1}$)	Ni ($mg \cdot kg^{-1}$)	Zn ($mg \cdot kg^{-1}$)
3 years old whole tree	0.0018 ±0.0004	0.2222 ±0.0013	0.1522 ±0.0051	0.9126 ±0.0017	0.0256 ±0.0005	0.2226 ±0.0005	10.7319 ±0.1648
3 years old stem	0.0056 ±0.0009	0.2328 ±0.0062	0.2292 ±0.0059	0.9193 ±0.0091	0.1008 ±0.0008	0.3434 ±0.0013	11.9100 ±0.0624
6 years old whole tree	0.0058 ±0.0008	0.1912 ±0.0006	0.2072 ±0.0062	0.8707 ±0.0018	0.1338 ±0.1935	0.4136 ±0.0009	13.4410 ±0.1845
6 years old stem	0.0120 ±0.0010	0.2050 ±0.0009	0.1448 ±0.0033	1.0230 ±0.0024	0.0654 ±0.0005	0.3366 ±0.0011	12.6780 ±0.1146
9 years old whole tree	0.0070 ±0.0012	0.2064 ±0.0038	0.1242 ±0.0016	0.9782 ±0.0045	0.0750 ±0.0029	1.3270 ±0.0060	15.3179 ±0.3089
9 years old stem	0.0046 ±0.0009	0.1866 ±0.0009	0.2026 ±0.0032	0.9099 ±0.0056	0.0688 ±0.0004	1.4142 ±0.0008	14.8296 ±0.2872

Table 7. Average values of heating value, ash content, ash melting point and heavy metals relative to biomass (mean ± St. dev.) before and after pelleting, in addition the t-test result referred to independent samples (* statistically significant).

Parameter	Refined	Pellet	Δ (%)	*t*-Value	DF	*p*-Value
LHV ($MJ \cdot kg^{-1}$)	17.05 ± 0.52	17.72 ± 0.38	+3.95 *	−5.959	58	0.001
Ash content (%)	2.41 ± 0.38	2.22 ± 0.43	−7.88	1.819	58	>0.05
As ($mg \cdot kg^{-1}$)	0.006 ± 0.003	0.005 ± 0.002	−20.62	1.950	58	>0.05
Cd ($mg \cdot kg^{-1}$)	0.207 ± 0.020	0.207 ± 0.018	0	0.088	58	>0.05
Cr ($mg \cdot kg^{-1}$)	0.177 ± 0.039	0.156 ± 0.044	−11.45	1.872	58	>0.05
Cu ($mg \cdot kg^{-1}$)	0.936 ± 0.085	0.917 ± 0.053	−2.03	1.404	58	>0.05
Pb ($mg \cdot kg^{-1}$)	0.078 ± 0.079	0.049 ± 0.017	−36.34	1.919	58	>0.05
Ni ($mg \cdot kg^{-1}$)	0.676 ± 0.503	0.476 ± 0.552	−29.52	1.463	58	>0.05
Zn ($mg \cdot kg^{-1}$)	13.15 ± 2.023	12.90 ± 1.145	−1.90	0.656	58	>0.05
Ash melting point (°C)	1404.2 ± 38.2	1444.1 ± 25.2	+2.84 *	−4.773	58	0.001

Another aspect to consider was the improvement of the quality parameters that could be obtained by transforming the poplar wood chips into pellets (Table 7).

Comparing the surveyed data, before and after pelletization, there was an average increase in the heating value of 3.95% and an increase in the ash melting point of 2.84%, with statistical significance, while the possible reduction in heavy metals content was not statistically confirmed. Another important aspect was the noticeable increase in bulk density, which was not less than 80%.

4. Discussion

Populus spp. is considered an excellent source to produce wood, for technological [40] and energy purposes [2]. It is also one of the best choices for the SRWC establishment in Italy [41] resulting in the crop with the highest productive response, as showed in some recent studies [2,42]. In general, the Short Rotation Coppice guarantees a good biomass production, varying between 3 and 20 Mg·ha^{-1}·year^{-1} of dry matter [23,43,44], an acceptable combustion quality [45–47] and a functional and well-structured logistics.

The raw materials utilized in this study had different starting characteristics. Taking as reference the diameters of insertion of the branches, the basal diameters of the stem and the heights, it is possible to highlight, respectively, average sizes higher than 12%, 47% and 48% in the comparison between shoots of 6 and 3 years and of 150%, 32% and 34% in the comparison between shoots of 9 and 6-years-old. The qualitative characteristics of the pellets produced, therefore, may differ as a function of coppicing cycle and wood fraction considered. As a result, this can make a general improvement of the fuel possible, as it offers longer coppicing and/or fractions without branches.

In fact, the pellet obtained from the stems without branches ensures a greater aggregation of the particles and it is characterized by a greater bulk density (between +3.6% and +5.5%) and by a greater average length (between +5% and +32%). The lengthening of the cycle would seem, instead, not to make direct improvements in these terms. Undoubtedly, the fraction of the branches mainly influences the densification phase of the material, creating discontinuity between the particles and favoring a more evident fragmentation of the cylinders which, consequently, turns out to be shorter.

The heating value is between 17.55 and 17.85 MJ·kg^{-1} confirming what reported in literature by other authors [48]. Concerning the ash content, the worst result was found for the 3-year-old material. In this case, the lengthening of the rotation leads to a significant reduction in average values. The presence of the branches, however, would seem to influence this parameter only for the long cycle.

The values of heavy metal content and the temperature of ash fusibility fully comply with the values indicated by the current regulations.

Every biomass contains a certain amount of metal compounds, but in the last decade, the metal-contaminated biomass achieved increasing attention [49]. There are various toxicological effects of heavy metals emission during combustions for human health or for the environment, and the pollutants generated depends on their amount in the biomass [50]. The heavy metals content in biomass fuels should be limited, especially considering their utilisation in small-scale systems, which are usually not equipped with dust precipitation devices [51].

Although none of the materials analyzed exceeded the limits set by the regulation, it is clear that the quality characteristics of the 6-year old poplar guarantee the attainment of a preferable product. The management of the SRWC could be oriented in this sense to avoid an excessive lengthening of the crop interval, benefiting from a general reduction of the metals content.An average value of 10% in moisture content of the raw material is considered to be optimal for the subsequent process of pelletization, as well as in terms of durability of the final product, as reported by Samuelsson et al. [52], Whittaker and Shield [9], Lehtikangas [53], and Filbakk et al. [54]. However, it is necessary to consider the loss of moisture content that is only directly attributable to the pelletization process, which has been quantified to range between 8.50% and 9.76%, as verified in all the tested theses, with statistically significant differences. This factor must be considered during the transformation phase, as it will affect the stability and final energy yield of the product.

Referring to EN ISO 17225-2 [55], we can identify the quality parameters that are respected by our poplar pellets (Table 8).

Table 8. Quality parameters of poplar pellets compared to [55]: ✓✓✓(A1); ✓✓(A2); ✓(B); □ (not classified).

Years	**3**		**6**		**9**	
Type	**Tree**	**Stem**	**Tree**	**Stem**	**Tree**	**Stem**
Diameter	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Length	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Moisture content	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Ash content	□	□	✓	✓	□	✓
LHV	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Bulk density	□	□	□	□	□	□
N	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
S	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
As	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Cd	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Cr	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Cu	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Pb	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Ni	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Zn	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Ash melting point	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Durability	✓✓✓	✓✓	✓✓✓	✓✓	□	□

As shown in Table 8, all the products meet the requirements of class A1 for diameter, length, moisture content, ash melting point, lower heating value, as well as N, S, and heavy metals.

In order to define the pellet's quality, it is also important to know the ash content. A high ash content can cause problems in the combustion of biomass, as it produces slag, incrustations and corrosion in the combustion device, with an inevitable reduction in performance of the plant itself [56]. The pellet of poplar can respect only the parameters of class B and not for all the types of material used, excluding the material of 3 years of age and the entire trees of 9 years of age.

As regards the mechanical durability, it is possible to respect the parameters of class A1 for whole poplar of 3 and 6 years and A2 for poplar of 3 and 6 years without branches.

Lastly, none of the theses analyzed can satisfy the bulk density in the three reference classes, according to Monedero et al. [57].

Other studies report the difficulty in producing good quality pellets from poplar or willow short rotation coppices [58], especially using solely this type of material [59].

There are different actions, however, that can be put in place to improve the quality of the material, such as preheating the feed material [60], binding additives [61], and increasing the pelleting pressure [62–64].

Monedero et al. [57] refers, for example, to the possibility of achieving quality classes A1 and A2 using poplar and pine mixtures, in variable percentages depending on the result to be obtained.

The increasing demand for wood pellets and the limited availability of the biomass traditionally used for its processing, requires the use of other sources of raw materials [65]. In this perspective, many resources and research activities are now focused on the exploitation of agricultural by-products or energy grasses. However, several studies carried out show problems of low durability of pellets produced from cereal residues [66], high ash content over 3.5%, 5.5% and 6.5% for miscanthus, rape straw and wheat straw respectively [58], 2.27% and 4.2% for apple pruning [67] and vineyard pruning [68].

The qualitative characteristics of these materials are therefore lower than those found in dedicated wood crops.

5. Conclusions

The performed research and the analysis of the results reveals that it is possible to produce a good quality pellet starting from wood chips obtained from Short Rotation Coppice of poplar and thereby converting a material with a low commercial value into superior merchandise material, in terms of quality, cost and energy. This represents an interesting development opportunity for potential small and medium scale agro-energy chains.

Among the various types of pelletized material, of the types palletized for six years produced the best results, especially in terms of ash content which, at the moment, is the most limiting factor. The qualitative improvement that can be achieved by cutting the branches before chipping appears to be convenient only in terms of bulk density. To enhance the value of the SRWCs through a densification process, it would therefore be advisable to direct the management of the crop cycles towards a 5–6 year interval, avoiding a too short rotation of 2 or 3 years, due to the excessive ash content, and cultivation cycles that are too long, which would lead to a greater accumulation in heavy metals and require, in any case, even more specialized harvest mechanization.

Despite the general qualitative improvement that can be achieved through the pelletizing process, some of the parameters required by the legislation are not respected using only this type of material, especially the ash content and the bulk density. The legislation that manages the market is very restrictive, compared to the traditional one of the wood chips, so the introduction of specific quality standards, otherwise, could facilitate and encourage the exploitation of wood biomass produced by dedicated plantations in a market of great interest, such as that of pellets.

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References

1. Huang, Y.; Finell, M.; Larsson, S.; Wang, X.; Zhang, J.; Wei, R.; Liu, L. Biofuel pellets made at low moisture content e Influence of water in the binding mechanism of densified biomass. *Biomass Bioenergy* **2017**, *98*, 8–14. [CrossRef]
2. Picchio, R.; Spina, R.; Sirna, A.; Monaco, A.L.; Civitarese, V.; Del Giudice, A.; Suardi, A.; Pari, L. Characterization of Woodchips for Energy from Forestry and Agroforestry Production. *Energies* **2012**, *5*, 3803–3816. [CrossRef]

3. IPCC Climate Change. *Synthesis Report Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK. Available online: https://www.researchgate.net/publication/262260453_IPCC_2007_Climate_Change_2007_Synthesis_Report_Contribution_of_Working_Groups_I_II_III_to_the_Fourth_Assessment_Report_of_the_Intergovernmental_Panel_on_Climate_Change_Geneva (accessed on 6 February 2019).
4. European Commission. 2020 Climate & Energy Package. Combating Climate Change the EU Leads the Way, European Move Service 24. Available online: https://ec.europa.eu/clima/policies/strategies/2020_en (accessed on 8 January 2019).
5. Tumuluru, J.S. Effect of process variables on the density and durability of the pellets made from high moisture corn stover. *Biosyst. Eng.* **2014**, *119*, 44–57. [CrossRef]
6. Tumuluru, J.S.; Wright, C.T.; Hess, J.R.; Kenney, K.L. A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. *Biofuels Bioprod. Biorefining* **2011**, *5*, 683–707. [CrossRef]
7. Sánchez, J.; Curt, M.D.; Sanz, M.; Fernández, J. A proposal for pellet production from residual woody biomass in the island of Majorca (Spain). *AIMS Energy* **2015**, *3*, 480–504. [CrossRef]
8. Associazione Italiana Energie Agroforestali (AIEL). Available online: http://www.aielenergia.it/public/rassegna_stampa/378_1%20febbraio%202019%20biomassapp.it.pdf (accessed on 10 July 2019).
9. Whittaker, C.; Shield, I. Factors affecting wood, energy grass and straw pellet durability—A review. *Renew. Sustain. Energy Rev.* **2017**, *71*, 1–11. [CrossRef]
10. Karkania, V.; Fanara, E.; Zabaniotou, A. Review of sustainable biomass pellets production—A study for agricultural residues pellets' market in Greece. *Renew. Sustain. Energy Rev.* **2012**, *16*, 1426–1436. [CrossRef]
11. Alberici, S.; Boeve, S.; van Breevoort, P. Subsidies and Costs of EU Energy. European Commission. Available online: https://ec.europa.eu/energy/en/content/inal-report-ecofys (accessed on 12 January 2019).
12. Peksa-Blanchard, M.; Dolzan, P.; Grassi, A.; Heinimoe, J.; Junginger, M.; Ranta, T.; Walter, A. *Global Wood Pellets Market and Industry: Policy, Drivers, Market Status and Raw Material Potential*; IEA bioenergy Task 40; International Energy Agency: Paris, France, 2007; Available online: https://www.researchgate.net/publication/27709106_Global_Wood_Pellets_Markets_and_Industry_Policy_Drivers_Market_Status_and_Raw_Material_Potential (accessed on 15 February 2019).
13. Gravelsins, A.; Muižniece, I.; Blumberga, A.; Blumberga, D. Economic sustainability of pellet production in Latvia. *Energy Procedia* **2017**, *142*, 531–537. [CrossRef]
14. GSE (Energy Services Manager). Rapporto Delle Attività. Energia in Movimento. Available online: https://www.gse.it/documenti_site/Documenti%20GSE/Rapporti%20delle%20attivit%C3%A0/GSE_RA2017.pdf (accessed on 5 March 2019).
15. Haruna, N.Y.; Afzalb, M.T. Effect of Particle Size on Mechanical Properties of Pellets Made from Biomass Blends. *Procedia Eng.* **2016**, *148*, 93–99. [CrossRef]
16. Supin, M. Wood Processing and Furniture Manufacturing Challenges on the World Market: Wood Pellet Global Market Development 2015. pp. 255–260. Available online: https://www.researchgate.net/publication/286443751_Wood_Pellet_Global_Market_Development (accessed on 7 February 2019).
17. Acda, M.N.; Jara, A.A.; Daracan, V.C.; Devera, E.E. Opportunities and Barriers to Wood Pellet Trade in the Philippines. *Ecosyst. Dev. J.* **2016**, *6*, 27–31. Available online: https://www.researchgate.net/publication/303680604_Opportunities_and_barriers_to_wood_pellet_trade_in_the_Philippines (accessed on 7 February 2019).
18. European Biomass Association (AEBIOM) Bioenergy. A Local and Renewable Solution for Energy Security. Available online: https://www.slideshare.net/AEBIOM2/biomass (accessed on 8 January 2019).
19. Verhoest, C.; Ryckmans, Y. Industrial Wood Pellets Report. Available online: http://www.bpa-intl.com/images/stories/present-1/PELLCERT%20-%20Industrial%20Wood%20Pellets%20Report%20(2012).pdf (accessed on 5 March 2019).
20. GSE (Energy Services Manager). Rapporto Statistico. Energia Da Fonti Rinnovabili. Available online: https://www.gse.it/documenti_site/Documenti%20GSE/Rapporti%20statistici/Rapporto%20statistico%20GSE%20-%202016.pdf (accessed on 5 March 2019).
21. Energia Dall'agricoltura: Innovazioni Sostenibili Per la Bioeconomia. Available online: http://agroener.crea.gov.it (accessed on 1 June 2019).

22. Di Candilo, M.; Facciotto, G. Colture da biomassa ad uso energetico Potenzialità e prospettive. In *Progetti Di Ricerca Suscace e Faesi. Recenti Acquisizioni Scientifiche per Le Colture Energetiche*; Supplemento n. 2 a Sherwood-Foreste ed Alberi Oggi n. 183; Compagnia delle Foreste Srl: Roma, Italy, 2012; pp. 10–19.
23. Paris, P.; Mareschi, L.; Sabatti, M.; Pisanelli, A.; Ecosse, A.; Nardin, F.; Scarascia-Mugnozza, G. Comparing hybrid Populus clones for SRF across northern Italy after two biennial rotations: Survival, growth and yield. *Biomass Bioenergy* **2011**, *35*, 1524–1532. [CrossRef]
24. Facciotto, G. Storia della SRF e suo sviluppo in Italia. In *Progetti Di Ricerca Suscace e Faesi. Recenti Acquisizioni Scientifiche per Le Colture Energetiche*; Supplemento n. 2 a Sherwood-Foreste ed Alberi Oggi n. 183; Compagnia delle Foreste Srl: Roma, Italy, 2012; pp. 26–30.
25. Verani, S.; Sperandio, G.; Picchio, R.; Marchi, E.; Costa, C. Sustainability Assessment of a Self-Consumption Wood-Energy Chain on Small Scale for Heat Generation in Central Italy. *Energies* **2015**, *8*, 5182–5197. [CrossRef]
26. Mitchell, C.P.; Kofman, P.D.; Angus-Hankin, C.M. *Guidelines for Conducting Harvesting Trials in Short Rotation Forestry*; Forestry Research Paper; Aberdeen University: Aberdeen, UK, 1997; pp. 1–50.
27. Bergström, D.; Israelsson, S.; Öhman, M.; Dahlqvist, S.-A.; Gref, R.; Boman, C.; Wästerlund, I. Effects of raw material particle size distribution on the characteristics of Scots pine sawdust fuel pellets. *Fuel Process. Technol.* **2008**, *89*, 1324–1329. [CrossRef]
28. Monaco, A.L.; Todaro, L.; Sarlatto, M.; Spina, R.; Calienno, L.; Picchio, R. Effect of moisture on physical parameters of timber from Turkey oak (Quercus cerris L.) coppice in Central Italy. *For. Stud. China* **2011**, *13*, 276–284. [CrossRef]
29. EN ISO 18122. *Solid Biofuels—Determination of Ash Content*; ISO: Geneva, Switzerland, 2015.
30. CEN/TS 15370-1. *Solid Biofuels—Method for the Determination of Ash Melting Behaviour. Part 1: Characteristic Temperatures Method*; CEN/TS: Geneva, Switzerland, 2006.
31. EN ISO 18125. *Solid Biofuels—Determination of Heating Value*; ISO: Geneva, Switzerland, 2015.
32. Ghafghazi, S.; Sowlati, T.; Sokhansanj, S.; Bi, X.; Melin, S. Particulate matter emissions from combustion of wood in district heating applications. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3019–3028. [CrossRef]
33. EN ISO 16968. *Solid Biofuels—Determination of Minor Elements*; ISO: Geneva, Switzerland, 2015.
34. EN ISO 16948. *Solid Biofuels—Determination of Total Content of Carbon, Hydrogen and Nitrogen*; ISO: Geneva, Switzerland, 2015.
35. EN ISO 16994. *Solid Biofuels—Determination of Total Content of Sulfur and Chlorine*; ISO: Geneva, Switzerland, 2016.
36. EN ISO 17828. *Solid Biofuels—Determination of Bulk Density*; ISO: Geneva, Switzerland, 2015.
37. EN ISO 17829. *Solid Biofuels—Determination of Length and Diameter of Pellets*; ISO: Geneva, Switzerland, 2015.
38. EN ISO 17831–1. *Solid Biofuels—Determination of Mechanical Durability of Pellets and Briquettes. Part 1: Pellets*; ISO: Geneva, Switzerland, 2015.
39. EN ISO 18134-1. *Solid Biofuels—Determination of Moisture Content—Oven Dry Method*; ISO: Geneva, Switzerland, 2015.
40. Pelosi, C.; Agresti, G.; Calienno, L.; Lo Monaco, A.; Picchio, R.; Santamaria, U.; Vinciguerra, V. Application of spectroscopic techniques for the study of the surface changes in poplar wood and possible implications in conservation of wooden artefacts. In Proceedings of the SPIE—The International Society for Optical Engineering, Munich, Germany, 30 May 2013; Volume 8790, p. 879014.
41. Picchio, R.; Verani, S.; Sperandio, G.; Spina, R.; Marchi, E. Stump grinding on a poplar plantation: Working time, productivity, and economic and energetic inputs. *Ecol. Eng.* **2012**, *40*, 117–120. [CrossRef]
42. Civitarese, V.; Faugno, S.; Picchio, R.; Assirelli, A.; Sperandio, G.; Saulino, L.; Crimaldi, M.; Sannino, M. Production of selected short-rotation wood crop species and quality of obtained biomass. *Eur. J. For. Res.* **2018**, *137*, 541–552. [CrossRef]
43. Bergante, S.; Facciotto, G.; Minotta, G. Identification of the main site factors and management intensity affecting the establishment of Short-Rotation-Coppices (SRC) in Northern Italy through stepwise regression analysis. *Open Life Sci.* **2010**, *5*, 522–530. [CrossRef]
44. Di Matteo, G.; Sperandio, G.; Verani, S. Field performance of poplar for bioenergy in southern Europe after two coppicing rotations: Effects of clone and planting density. *iForest—Biogeosci. For.* **2012**, *5*, 224–229. [CrossRef]

45. Bungart, R.; Hüttl, R.F. Growth dynamics and biomass accumulation of 8-year-old hybrid poplar clones in a short-rotation plantation on a clayey-sandy mining substrate with respect to plant nutrition and water budget. *Eur. J. For. Res.* **2004**, *123*, 105–115. [CrossRef]
46. Hauk, S.; Knoke, T.; Wittkopf, S. Economic evaluation of short rotation coppice systems for energy from biomass—A review. *Renew. Sustain. Energy Rev.* **2014**, *29*, 435–448. [CrossRef]
47. Huber, J.A.; May, K.; Hülsbergen, K.J. Allometric tree biomass models of various species grown in short-rotation agroforestry systems. *Eur. J. For. Res.* **2017**, *136*, 75–89. [CrossRef]
48. Telmo, C.; Lousada, J. Heating values of wood pellets from different species. *Biomass Bioenergy* **2011**, *35*, 2634–2639. [CrossRef]
49. Kovacs, H.; Szemmelveisz, K. Heavy metal contaminated biomass combustion as treatment after phytoremediation—A review. *Mater. Sci. Eng.* **2016**, *41*, 69–78.
50. Ružinská, E.; Štollmann, V.; Hagara, V.; Jabłoński, M. Analysis of selected heavy metals in biomass for preparation of biofuels—Part I. Toxicological effects of heavy metals. *Ann. Wars. Univ. Life Sci. SGGW For. Wood Technol.* **2015**, *92*, 383–389.
51. Obernbergera, I.; Theka, G. Physical characterisation and chemical composition of densified biomass fuels with regard to their Combustion behavior. *Biomass Bioenergy* **2004**, *27*, 653–669. [CrossRef]
52. Samuelsson, R.; Thyrel, M.; Sjöström, M.; Lestander, T.A. Effect of biomaterial characteristics on pelletizing properties and biofuel pellet quality. *Fuel Process. Technol.* **2009**, *90*, 1129–1134. [CrossRef]
53. Lehtikangas, P. Quality properties of pelletised sawdust, logging residues and bark. *Biomass Bioenergy* **2001**, *20*, 351–360. [CrossRef]
54. Filbakk, T.; Skjevrak, G.; Høibø, O.; Dibdiakova, J.; Jirjis, R. The influence of storage and drying methods for Scots pine raw material on mechanical pellet properties and production parameters. *Fuel Process. Technol.* **2011**, *92*, 871–878. [CrossRef]
55. EN ISO 17225. *Solid Biofuels—Fuel specifications and classes—Part 2: Graded wood pellets*; ISO: Geneva, Switzerland, 2014.
56. Toscano, G.; Riva, G.; Pedretti, E.F.; Corinaldesi, F.; Mengarelli, C.; Duca, D. Investigation on wood pellet quality and relationship between ash content and the most important chemical elements. *Biomass Bioenergy* **2013**, *56*, 317–322. [CrossRef]
57. Monedero, E.; Portero, H.; Lapuerta, M. Pellet blends of poplar and pine sawdust: Effects of material composition, additive, moisture content and compression die on pellet quality. *Fuel Process. Technol.* **2015**, *132*, 15–23. [CrossRef]
58. Carroll, J.P.; Finnan, J. Physical and chemical properties of pellets from energy crops and cereal straws. *Biosyst. Eng.* **2012**, *112*, 151–159. [CrossRef]
59. Porsö, C.; Hansson, P.-A. Time-dependent climate impact of heat production from Swedish willow and poplar pellets—In a life cycle perspective. *Biomass Bioenergy* **2014**, *70*, 287–301. [CrossRef]
60. Kaliyan, N.; Morey, R.V. Factors affecting strength and durability of densified biomass products. *Biomass Bioenergy* **2009**, *33*, 337–359. [CrossRef]
61. Ahn, B.J.; Chang, H.-S.; Lee, S.M.; Choi, D.H.; Cho, S.T.; Han, G.-S.; Yang, I. Effect of binders on the durability of wood pellets fabricated from *Larix kaemferi* C. and *Liriodendron tulipifera* L. sawdust Renew. *Energy* **2014**, *62*, 18–23.
62. Nielsen, N.P.K.; Gardner, D.J.; Poulsen, T.; Felby, C. Importance of temperature, moisture content, and species for the conversion process of wood residues into fuelpellets. *Wood Fibre Sci.* **2009**, *41*, 414–425.
63. Stelte, W.; Holm, J.K.; Sanadi, A.R.; Barsberg, S.; Ahrenfeldt, J.; Henriksen, U.B. A study of bonding and failure mechanisms in fuel pellets from different biomass resources. *Biomass Bioenergy* **2011**, *35*, 910–918. [CrossRef]
64. Lee, S.M.; Ahn, B.J.; Choi, D.H.; Han, G.-S.; Jeong, H.-S.; Ahn, S.H.; Yang, I. Effects of densification variables on the durability of wood pellets fabricated with *Larix kaempferi* C. and *Liriodendron tulipifera* L. sawdust. *Biomass Bioenergy* **2013**, *48*, 1–9. [CrossRef]
65. Stelte, W.; Sanadi, A.R.; Shang, L.; Holm, J.K.; Ahrenfeldt, J.; Henriksen, U.B. Recent developments in biomass Pelletisation: A review. *Bioresources* **2012**, *7*, 4451–4490.
66. Adapa, P.; Tabil, L.; Shoenau, G.; Opoku, A. Pelleting characteristics of selected biomass with and without steam explosion pretreatment. *Int. J. Agric. Biol. Eng.* **2010**, *3*, 62–79.

67. Brand, M.A.; Barnasky, R.R.D.S.; Carvalho, C.A.; Buss, R.; Waltrick, D.B.; Jacinto, R.C. Thermogravimetric analysis for characterization of the pellets produced with different forest and agricultural residues. *Ciênc. Rural* **2018**, *48*, 1–10. [CrossRef]
68. Toscano, G.; Alfano, V.; Scarfone, A.; Pari, L. Pelleting Vineyard Pruning at Low Cost with a Mobile Technology. *Energies* **2018**, *11*, 2477. [CrossRef]