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Pellet Production from Residual Biomass of Greenery Maintenance in a Small-Scale Company to Improve Sustainability

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Abstract: Replacing fossil energy sources with renewable energy sources is a key strategic action to limit environmental issues. To achieve this goal, substitution with biomass is beneficial due to its versatility in various fields. In terms of circular economy and sustainability, the possibility of energy exploitation of residual biomass is particularly desirable in small-medium enterprises. The use of supply chain by-products can improve sustainability and create opportunities for companies. The purpose of this study is to evaluate the suitability of residual biomass of conifers and broad-leaved trees to produce quality pellets using an agri-pellet machine activated by the power take-off of a tractor. This system can be employed at the farm level. Wood biomass of four species was tested; poplar, stone pine, black locust, and oak. Wood chips samples were analyzed to determine their qualitative characteristics following the technical standard ISO 17225-4. Based on the results, different wood blends were created to produce pellets, subsequently characterized according to ISO 17225-2. The analyses carried out on wood chips and pellets were bulk density, moisture, ash content, calorific value, elemental composition, chlorine, sulfur, and heavy metals. In addition, particles size was measured only for wood chips, while the length, diameter, mechanical durability, and ash melting behaviors were determined only for pellets. Some of the analyzed mixtures show acceptable values according to the current ISO technical standards. The values related to the apparent pellet bulk density and the durability test highlight that not all the mixtures are suitable to produce quality pellets. Results also represent a good starting point for future studies.

Keywords: biomass; biofuels; ashes; poplar; stone pine; black locust; oak; pellet

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1. Introduction

Between 2007 and 2017, investments for projects upon renewable energy (RE) production and use have increased worldwide [1]. In a global contest, investments in renewable energy for power generation and biofuels were 310 USD billion (304 for power and 6 for biofuels), representing 19.5% of total supply investment [2]. The increasing use of energy from renewable sources and energy efficiency are the fundamental and essential themes of any future energy strategy aiming at sustainable and inclusive economic growth [3]. As declared by International Energy Agency (IEA) in the World Energy Outlook (WEO) 2018, the share of renewable energy in the Sustainable Development Scenario will be about 66% for power mix, 25% for heat, and 22% for transport [3]. In 2008 the largest global RE contributor was biomass accounting for about 10% of total RE (1.3% of total primary energy supply) [4]. Given the relevance of the use of biomass, the discussion about their actual sustainability is still controversial and distinguishes two different groups: traditional and modern biomass [5]. The difference between them lies in the production and management, which is considered sustainable in the case of modern biomass. This implies that, to be included into this category, biogenic materials must respect some generic characteristics, such as coming from tree cultivation or residual forest or urban material.

Biomass can be produced from several sectors, mainly forestry or greenery maintenance, agriculture, and livestock [6–12]. Due to the wide variety of residual materials, biomass materials are uniformly diffused and not always concentrated in small areas. On the other hand, biomass materials are highly variable in terms of technological and energy characteristics [13], and they present a reduced energy content compared to fossil fuels. This variability can negatively affect combustion efficiency and cause pollution, decreasing sustainability. There are several strategies for the standardization of biomass for energy use depending on the final objective: for example, the removal of the bark or the green structures of the woody plants contributes to the reduction of the ash content [14]; the thermal treatment increases the energy density [15,16]; the densification increases bulk density and facilitates logistics, transportation, and use of the biofuel [17].

One of the most representative upgraded biomass materials in Europe is the pellet. Europe is both the leading consumer and producer of pellets [18]. Despite this, European production does not meet domestic demand; therefore, a substantial share is imported as a supplement. In 2008, most of the pellets consumed by Europe came from Canada (about 60% of total production) and the US (20%) [19]. For the reasons explained, the research for new processes and raw materials to produce densified biofuels such as pellets is undoubtedly interesting, especially among by-products or waste from local supply chains in a circular economy perspective. Several authors have dealt with this issue over the years, focusing on woody and herbaceous species [8,20–26].

Pellet production from wood residues and, in particular, from greenery maintenance is a typical example of a RE technology that can be deployed close to the point of use, such as in urban environments [4]. Furthermore, the use of biogenic materials such as biomass can promote the development of small urban centers and rural areas through job creation [27].

The woody biomass market intended for energy use has been regulated by specific standards for many years. In particular, the ISO 17225 [28] standard and related subgroups establish, for each biomass category, the analytical parameters to be analyzed, the procedures, and the limits of the same parameters for inclusion in qualitative classes. In detail, for wood chips [29], the most limiting parameter for inclusion in classes A1, A2, B1, and B2 (decreasing in quality) is ash content which must be less than 3.0% and 1.5% for B (1 and 2) and A (1 and 2), respectively. Also, for wood pellets [30], one of the key parameters is the ash content, which must be less than or equal to 0.7%, 1.2%, and 2.0% for classes A1, A2, and B, respectively (the pellet has only one quality class B). For pellets, the mechanical durability and the bulk density are also considered, which are partly linked to the production process, specifically: the mechanical durability must be greater than 96.5%, 97.5%, and 98.0% for B, A2, and A1, respectively; the bulk density must range between 600 and 750 kg/m^3 for all the quality classes.

Thus, this study aims to assess the compliance to the ISO standard on solid biofuels (17225:2021) of products derived from woody biomass from greenery maintenance available in a small Italian company. The solid biofuel productions were carried out using a self-propelled woodchipper/grinder and a tractor propelled wood pelletizer suitable for small-scale company use. Wood chips and wood pellets produced from different biomass blends were assessed following ISO 17225-4 and ISO 17225-2, respectively.

2. Materials and Methods

The company under analysis is located in the Macerata district, in the middle-south part of the Marche region. Its main activities are tree felling and greenery maintenance. The company also manages the residual material as a service to the customer. The residues are currently divided into two groups: the first includes wood material deriving from felling and pruning, with a diameter greater than 15 cm; the second consists of other residues like green pruning material, leaves, or grass. The wood is processed and sold as firewood. All the other residues are chipped and stored for more than two years to produce compost for garden top dressing or transplanting. The material obtained from the greenery management belongs to many different plant species. The most frequent woody material, representing 90% of the total annual volume processed, belongs to four species: poplar, black locust, stone pine, and oak. Only two typologies are currently of interest for combustion in fireplaces: black locust and oak are preferred by the market probably due to their combustion dynamics. The other two species are considered uninteresting or even harmful by the consumer for several reasons: poplar is too fast burning and has a low calorific value; stone pine produces char and tar, which accumulate in the flues, thus increasing frequency and costs for maintenance.

About 30 to 40 kg of each species with bark and debarked were taken from the stacks of air-dried logs. Subsequently, the material was cut into smaller pieces, split, and chipped using a self-propelled woodchipper (Green Technik by Green Produzione Srl, Vezza d'Alba, Cuneo, Italy, mod. CIP 1500). Wood chip samples were kept in sealed plastic bags and sent for analysis. The analyses on wood chips were used to set up seven blends of biomass materials for pelletization, using an excel model to predict ash content. Pellet samples were analyzed as well.

The detailed description of the analytical work and the blend determination are reported in the following subsections.

2.1. Wood Chip and Pellet Characterization

For each wood chip and pellet sample, the parameters reported in Table 1 were measured. Analyses for parameters relating to the fresh substance (moisture and bulk density) were conducted within 24 h of being transferred to the laboratory. Moisture content was determined following ISO 18134-2:2015 by drying in duplicate a sample of about 500 g at 105 ± 2 °C. Bulk density was determined following ISO 17828:2015 using a volume of 50 L. The replicates used for moisture analysis after drying were exploited for particles size determination. The analysis followed ISO 17827-1:2016 using eight sieves from 100.00 to 3.15 mm. The following parameters were determined using a sample previously stabilized in the oven at 40 °C for 24 h and then milled at 1 mm using a mill (RETSCH GmbH, Haan, Germany, model SM2000). Ashes were determined using a thermogravimetric analyzer (LECO Italy Srl, Milano, Italy, model TGA701) by incinerating about 1 g of the sample at 550 °C. For wood chip samples, a one-way ANOVA analysis with Tukey test was carried out considering the results of ash content and moisture using Minitab 16. The same statistical analysis was carried out for the pellet mix considering ash content. The analyzer also measured the moisture content of the sample due to a drying step at 105 ± 2 °C. Gross Calorific Value (GCV) was measured in accordance with ISO 18125:2017 using an isoperibolic calorimeter (IKA Werke GmbH & CO, Staufen, Germany, model C2000 Basic). Total carbon (C), hydrogen (H), and nitrogen (N) contents were analyzed following ISO 16948:2015 using an elemental analyzer (Perkin Elmer Italia SpA, Milano, Italy, model Series II 2400). As indicated by the reference standard for CHN measurement, oxygen was calculated as the difference to 100% of the sum of carbon, hydrogen, nitrogen, chlorine, sulfur, and ash (all expressed on a dry basis). Chlorine and sulfur were determined by ISO 16994:2015 using combustion and washing water coming from GCV analysis; the employed instrument is an ion chromatograph (Metrohm Italiana Srl, Origgio, Varese, Italy, model 761 compact IC). Net Calorific Value (NCV) was calculated starting from GCV and CHNO analysis. Metal analyses were carried out on two woodchips samples (BLbC and PPbC) using an ICP-MS (Agilent Technologies Inc., Santa Clara, CA, USA, model 7500ce.) except for mercury, which was determined using an atomic absorption spectrometer with gold amalgam (LECO Italy Srl, Milano, Italy, model AMA 254).

Table 1. Quality parameters determined following ISO 17225-4 for wood chips and ISO 17225-2 for wood pellet.

Parameter	Unit	Analysis Type	Standard
Moisture [1,2]	$\%_{ar}$	Drying 105 °C	ISO 18134-2:2015
Bulk density [1,2]	$kg/m^3{}_{ar}$	Mass 50 L volume	ISO 17828:2015
Ashes [1,2]	$\%_{db}$	Incineration 550 °C	ISO 18122:2015
NCV [1,2]	kWh/kg_{ar}	Calorimeter	ISO 18125:2017
GCV [1,2]	kWh/kg_{db}	Calorimeter	
CHN [1,2]	$\%_{db}$	Elemental analyzer	ISO 16948:2015
Chlorine [1,2]	$\%_{db}$	Chromatography	ISO 16994:2015
Sulfur [1,2]	$\%_{db}$	Chromatography	
Dimension of particles [1]	%	Sieves	ISO 17827-1:2016
Length [2]	Mm	Caliper	ISO 17829:2015
Diameter [2]	Mm	Caliper	
Ash melting [2]	°C	Ash fusion analyzer	UNI CEN/TS 15370-1:2006
Mechanical durability [2]	%	Durability tester	ISO 17831-1:2015
Arsenic [1,2]	mg/kg_{db}	ICP	UNI EN ISO 16968:2015 UNI EN ISO 11885:2009
Cadmium [1,2]	mg/kg_{db}	ICP	
Chromium [1,2]	mg/kg_{db}	ICP	
Copper [1,2]	mg/kg_{db}	ICP	
Lead [1,2]	mg/kg_{db}	ICP	
Nickel [1,2]	mg/kg_{db}	ICP	
Zinc [1,2]	mg/kg_{db}	ICP	
Mercury [1,2]	mg/kg_{db}	DMA	EPA 7473 2007

[1] Analysis performed on woodchips. [2] Analysis performed on wood pellet. ar (as received), db (dry basis).

Four characteristic parameters for the densified materials were included following the analyses carried out for the wood chips and the parameters already described. Length and diameter were determined according to ISO 17829:2015 using a digital caliper; ash melting was analyzed following standard UNI CEN/TS 15370-1:2006 using an F2000 ash fusion controller and an IRF 1600F furnace of SYLAB; mechanical durability was assessed in accordance with ISO 17831-1:2015 using a pellet tester, ANDRITZ. Metal characterization was performed only for the three most promising samples, considering mechanical durability results (Mix1, Mix3, and Mix4), including pellets.

2.2. Wood Chip Sample Processing and Blend Determination

Woodchip samples were milled to 2 mm particle size. The experimental plan was designed to ensure the pellets produced fell into ISO classes A1 and A2 considering ashes, starting from eight different biomass materials (four with bark and four debarked). The model calculates the ash content taking a progressive amount of biomass (in percentage) of one sample and varying the amount of the other seven samples to reach 100% blend. An example is reported in Table 2, where the percentage increase was set at 5%. The first column of Table 2 shows the amount (percentage) of BLbC added to the other samples listed in the first row. The values reported from the second column to the last are the expected ash contents from the mix between BLbC and the biomass labeled in the first row.

Table 2. Calculation model for ash forecasting in progressive percentage blends of black locust chips with bark (BL_bC) with the other samples.

%	BL_bC	BL_nC	OK_bC	OK_nC	PP_bC	PP_nC	SP_bC	SP_nC
0	1.6	1.1	3.7	1.1	2.3	1.3	0.9	0.5
5	1.6	1.13	3.6	1.13	2.27	1.32	0.94	0.56
10	1.6	1.16	3.5	1.16	2.24	1.34	0.98	0.62
15	1.6	1.19	3.4	1.19	2.21	1.36	1.02	0.68
20	1.6	1.22	3.3	1.22	2.18	1.38	1.06	0.74
25	1.6	1.25	3.2	1.25	2.15	1.4	1.1	0.8
30	1.6	1.28	3.1	1.28	2.12	1.42	1.14	0.86
35	1.6	1.31	3	1.31	2.09	1.44	1.18	0.92
40	1.6	1.34	2.9	1.34	2.06	1.46	1.22	0.98
45	1.6	1.37	2.8	1.37	2.03	1.48	1.26	1.04
50	1.6	1.4	2.7	1.4	2	1.5	1.3	1.1
55	1.6	1.43	2.6	1.43	1.97	1.52	1.34	1.16
60	1.6	1.46	2.5	1.46	1.94	1.54	1.38	1.22
65	1.6	1.49	2.4	1.49	1.91	1.56	1.42	1.28
70	1.6	1.52	2.3	1.52	1.88	1.58	1.46	1.34
75	1.6	1.55	2.2	1.55	1.85	1.6	1.5	1.4
80	1.6	1.58	2.1	1.58	1.82	1.62	1.54	1.46
85	1.6	1.61	2	1.61	1.79	1.64	1.58	1.52
90	1.6	1.64	1.9	1.64	1.76	1.66	1.62	1.58
95	1.6	1.67	1.8	1.67	1.73	1.68	1.66	1.64

Notes: Ash content is expressed as a dry basis. Green, yellow, and brown indicate, respectively, the fulfillment of A1, A2, and B ISO 17225-2 classes for pellet, no color indicates the ash contents exceeding ISO standard thresholds or pure BL_bC.

Seven different blends (Table 3) were selected to produce pellets using only stone pine and poplar based on the simulations carried out. The other biomass materials already have a suitable economic valorization for energy application. Two of these blends (2bis and 5bis), following the ISO 17225-2, were added with 2% of corn flour (a common additive in pelletization) to increase pellet durability because this latter parameter is expected to be lower for the mix with a high amount of poplar.

Table 3. Biomass blends for pellet production considering stone pine and poplar chips and expected ash content.

Blend	SP_nC	SP_bC	PP_nC	PP_bC	Ash Content Expected $\%_{db}$	Expected ISO 17225-2 Class
Pellet 1	90%		10%		0.58	A1
Pellet 2	40%		60%		0.98	A2
Pellet 2bis	40%		60%		1.00	A2
Pellet 3	95%			5%	0.59	A1
Pellet 4		90%		10%	1.04	A2
Pellet 5		40%	60%		1.14	A2
Pellet 5bis		40%	60%		1.74	B

Pellet 2bis and pellet 5bis are the same as pellet 2 and 5 with corn flour (2%) to increase pellet durability. db (dry basis).

The pelletizing of the biomass blends was carried out using an agri-pellet machine (Green Technik by Green Produzione Srl, Vezza d'Alba, Cuneo, Italy, mod. PTM50) activated by the power take-off of a tractor, Figure 1.

The pelletizer has a horizontal die with 6 mm holes (d). There are two compression rollers with oblique grooves (40 mm radius). The geometry of the die holes is cylindrical without a pre-compression chamber, with a total length of 22 mm (L). Therefore, the compression ratio of the pellet (i), deriving from the length of the hole and its diameter (L/d), is 3.7.

Figure 1. Green Technik mod. PTM50, pelletizer used for the production of pellet samples in the small-scale company.

The parameters analyzed on pellet samples are reported in Table 1. Before pellet production, six different pelletization tests were conducted to set the machine properly. The setup process consists of adjusting the distance of the rollers from the die. In this typology of horizontal pelletizer, the adjustment is made by screwing or unscrewing two screws that support the die. In contrast, the rollers are fixed on the vertical axis and cannot be regulated. In Figure 2, six tests are reported. The order from Figure 2a–f reflects the variability of compression intensity of pellet formation. In the Figure 2f test, the rollers were at zero distance from the die causing the highest compression, while the distance was maximum in the a) test causing minimum compression. The intermediate adjustments were made by dividing the stroke of the adjusting screws into equal parts.

Figure 2. (**a**–**f**) Pelletizer regulation tests: pellet results produced with a decreasing distance between rollers and die from test (**a**) to test (**f**).

When adjusting the machine, the best results considering the mechanical durability of the pellets, were recorded for test Figure 2e. This regulation was therefore chosen to produce pellets deriving from the mixtures of the various biomass materials.

The pellets were produced in a single session by the same operator. The moisture content of the milled wood was lowered to values between 10% and 15%, considered optimal for pelletization, using a forced ventilation oven set to 40 °C.

3. Results

Wood Chip Characterization

Woodchip characterization results are reported in Table 4. Detected moisture is relatively low for all the samples due to the natural drying that occurred during storage. The registered bulk density (BD) stands at high levels thanks to the reduced size of the particles. Considering this parameter PPbC, PPnC, and SPnC samples fall within BD250 (A1 and A2), while all the others are in BD300 (only A2). Concerning the particle size, only two samples can be assigned to a dimensional reference class. According to Table 1 of standard ISO 17225-4:2021, BLbC, and SPbC can be classified as P16S, while all the other samples show a too high distribution of mass to a fine fraction (<3.15 mm) widely greater than 15%. Considering moisture content, PPbC, and PPnC fall within class A2, while the others fall under class A1 based on the moisture threshold for naturally dried wood (≤25%). SPbC and SPnC fall into the A1 class for ash content, while BLnC, PPnC, and OKnC are in the A2 class. The rest fell under the B class. Nitrogen, sulfur, chlorine, and metals values were below the maximum values for all the samples. The statistical analysis for ash content and moisture shows a significant difference between samples (confidence level 99%, *p*-value < 0.001), Table 4 reports the grouping information based on the Tukey test.

Table 4. Wood chips characterization results.

Parameter		BLbC	BLnC	PPbC	PPnC	OKbC	OKnC	SPbC	SPnC
Moisture (%)		15.1 ± 0.01 ^{c}	14.8 ± 0.1 ^{cd}	28.4 ± 0.3 ^{a}	27.0 ± 1.3 ^{a}	12.9 ± 0.3 ^{de}	12.3 ± 0.1 ^{e}	17.5 ± 0.01 ^{b}	17.4 ± 0.1 ^{b}
Bulk density ($kg/m^3{}_{ar}$)		303.7	317.0	293.2	282.0	347.3	321.0	301.8	287.7
Ash ($\%_{db}$)		1.7 ± 0.07 ^{c}	1.1 ± 0.05 ^{de}	2.3 ± 0.18 ^{b}	1.3 ± 0.06 ^{cd}	3.7 ± 0.32 ^{a}	1.1 ± 0.09 ^{de}	0.9 ± 0.13 ^{e}	0.5 ± 0.1 ^{f}
NCV (kJ/kg_{ar})		14941	14779	12346	11913	14420	16139	15919	15738
NCV (kJ/kg_{db})		18038	17778	18197	17235	16914	18746	19803	19564
GCV (kJ/kg_{db})		19232	19009	19481	18482	18113	19910	21097	20837
C ($\%_{db}$)		48.8	48.9	49.7	48.3	49.5	49.0	51.5	50.1
H ($\%_{db}$)		5.5	5.6	5.9	5.7	5.5	5.3	5.9	5.8
N ($\%_{db}$)		0.4	0.3	0.3	0.1	0.3	0.2	0.1	0.1
O ($\%_{db}$)		44.7	44.0	41.8	44.6	41.0	44.4	41.5	43.4
Chlorine ($\%_{db}$)		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sulfur ($\%_{db}$)		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Dimension of particles (%)	>100	1.17	4.42	0.00	0.00	1.76	2.30	0.00	0.97
	63–100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	45–63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	31.5–45	1.38	1.18	1.19	0.00	1.07	0.00	0.41	0.20
	16–31.5	8.78	8.80	7.27	8.25	6.72	9.28	16.39	9.90
	8–16	30.66	16.11	29.08	13.61	22.09	18.57	38.21	20.22
	3.15–8	45.77	33.10	41.01	36.02	44.09	30.27	34.90	38.31
	<3.15	12.24	36.40	21.44	42.11	24.28	39.58	10.09	30.39
Arsenic (mg/kg_{db})	-	<1	-	<1	-	-	-	-	-
Cadmium (mg/kg_{db})	-	<0.005	-	0.1	-	-	-	-	-
Chromium (mg/kg_{db})	-	<1	-	<1	-	-	-	-	-
Copper (mg/kg_{db})	-	1	-	1	-	-	-	-	-
Lead (mg/kg_{db})	-	<1	-	<1	-	-	-	-	-
Nickel (mg/kg_{db})	-	<1	-	<1	-	-	-	-	-

Table 4. *Cont.*

Parameter		BLbC	BLnC	PPbC	PPnC	OKbC	OKnC	SPbC	SPnC
Zinc (mg/kg$_{db}$)	-	<5	-	26	-	-	-	-	-
Mercury (mg/kg$_{db}$)	-	<0.05	-	<0.05					

Notes: The range reported for dimension of particles for each sieve is expressed in mm; ar (as received) and db (dry basis); values in the same row that do not share a letter are significantly different at p-value < 0.001.

The results of pellet characterization are reported in Table 5. It can be observed that moisture content is consistently below 10% except for Mix2bis that cannot be considered a pellet according to the ISO standard. Bulk density is equal for all the classes and must be over 600 kg/m^3; the samples that match this requirement are Mix1, Mix3, and Mix4 (i.e., all mix containing 90% or more of stone pine). All the other samples cannot be considered pellets. Considering ashes, as expected, Mix1 and Mix3 fell within A1 class. Mix2, Mix2bis, and Mix4 were in class A2, while Mix5bis was in B class. Only Mix5 is in an unexpected class (B instead of A2). Nitrogen, sulfur, and chlorine values were below the threshold for the A1 class for all the samples. Length and diameter results were compliant with all the classes. Mechanical durability is too low even to fall within B class, so none of the samples can be considered pellet. Regarding NCV, all the samples meet the ISO values. Lastly, all metals values were below the threshold. The ANOVA test for ash content shows a strong significance between samples (confidence level 99%, p-value < 0.001), the grouping of the Tukey tests shows a clear separation between groups with similar blend characteristics.

Table 5. Pellet characterization results.

Parameter		Mix1	Mix2	Mix2bis	Mix3	Mix4	Mix5	Mix5bis
Moisture (%)		8.6 ± 0.05	9.2 ± 0.01	10.1 ± 0.02	7.7 ± 0.03	8.7 ± 0.00	9.7 ± 0.01	9.9 ± 0.02
Bulk density (kg/m^3$_{ar}$)		654.4	583.2	526.0	647.2	666.8	525.6	537.6
Ash (%$_{db}$)		0.7 ± 0.01 ^{c}	1.2 ± 0.01 ^{b}	1.2 ± 0.04 ^{b}	0.6 ± 0.00 ^{c}	1.1 ± 0.00 ^{b}	1.3 ± 0.02 ^{a}	1.3 ± 0.02 ^{a}
NCV (kJ/kg$_{ar}$)		17089	16596	16954	17389	17309	16788	16548
NCV (kJ/kg$_{db}$)		18924	18520	19129	19033	19182	18865	18634
GCV (kJ/kg$_{db}$)		20190	19942	19939	20269	20447	20122	19849
C (%$_{db}$)		51.1	50.4	50.3	51.0	51.3	50.6	49.9
H (%$_{db}$)		5.8	6.5	5.7	5.7	5.8	5.8	5.6
N (%$_{db}$)		0.1	0.2	0.2	0.1	0.2	0.2	0.2
O (%$_{db}$)		42.3	41.8	42.7	42.6	41.6	42.1	43.1
Chlorine (%$_{db}$)		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sulfur (%$_{db}$)		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Length (mm)		19.5	19.6	25.2	27.6	26.4	18.0	21.9
Diameter (mm)		6.2	6.3	6.1	6.1	6.2	6.1	6.2
Ash melting (°C)	Shrink	730	730	740	740	750	750	730
	Deformation	>1480	>1480	>1480	>1480	>1480	>1480	>1480
	Hemisphere	>1480	>1480	>1480	>1480	>1480	>1480	>1480
	Flow	>1480	>1480	>1480	>1480	>1480	>1480	>1480
Mechanical durability (%)		95.4	88.6	88.4	95.1	95.9	92.2	92.9
Arsenic (mg/kg$_{db}$)		<1	-	-	<1	<1	-	-
Cadmium (mg/kg$_{db}$)		<0.005	-	-	<0.005	0.0180	-	-
Chromium (mg/kg$_{db}$)		<1	-	-	<1	<1	-	-
Copper (mg/kg$_{db}$)		1.00	-	-	<1	1.00	-	-

Table 5. *Cont.*

Parameter	Mix1	Mix2	Mix2bis	Mix3	Mix4	Mix5	Mix5bis
Lead (mg/kg_{db})	<1	-	-	<1	<1	-	-
Nickel (mg/kg_{db})	<1	-	-	<1	<1	-	-
Zinc (mg/kg_{db})	6.00	-	-	<5	10.0	-	-
Mercury (mg/kg_{db})	<0.05	-	-	<0.05	<0.05		

Note 1: ar (as received), db (dry basis). Note 2: Values in the same row that do not share a letter are significantly different at *p*-value <0.001.

4. Discussion

Considering the results obtained in this study and those found in scientific literature, for some parameters, similar values are reported. In detail, the results related to parameters such as net calorific value and moisture content are absolutely comparable to pellets made up of different species, virgin or residual wood, or agricultural residues [31–35]. Other parameters such as ash content can vary enormously considering the origin of the material, collection methods, logistics, and part of the plant considered [36,37]. The main novelty of this study is the choice to vary the type and quantity of different woody materials to meet the limits indicated in the 17225-2:2021 standard to produce a solid biofuel with good quality for real energy application. Similar to other studies [20], it has been confirmed that the removal of the bark contributes to reducing the ash content. The critical parameters for the pellet highlighted in the tests performed (mechanical durability and bulk density) are the same as those identified from the results of other similar studies [25,32].

Based on the analyses conducted on wood chips from residual wood from greenery management, it is clear that the assessed material is suitable to be used in boilers as the results obtained are comparable to the requirements of the reference standard. The only exception found was OKbC, which does not fall into any of the quality classes of the ISO 17225-4 standard because of its high ash content. According to Table 2 of the ISO 17225-4:2021, BLnC, OKnC, SPbC, and SPnC can be classified in A1. PPnC must be included in the A2 class because of the high moisture content. BLbC and PPbC are classified as B due to the high ash content. The debarking process brings changes to all biomass. It reduces ash content [14] and calorific value, with the only exception of oak, due to the different energy contributions that different anatomical parts of the wood provide (bark, sapwood, and heartwood) [38].

The parameters related to the production of wood chips, such as bulk density and particle size, indicate that the chipper reduces the material into tiny particles, thus generating a relatively high bulk density. It is worthy to note that none of the blends tested fully met the standard requirements (ISO 17225-2) for consideration as pellets. The parameter that most compromises compliance with the ISO standard on wood pellets is the mechanical durability, which is influenced by the selected wood species [17,39]. In this case study, pellet durability is also affected by the type of pelletizer. Green Technik mod. PTM50 is designed for non-industrial use, and the reduced dimension (especially of the die) does not allow the fulfillment of minimum technical standards requirements for durability. Nevertheless, the main factors influencing durability were carefully kept within the optimal ranges found in the literature. Before pelletizing, the samples were stabilized to a moisture content lower than 15% [40]. The reduced particle size (2 mm diameter) could have negatively influenced the compaction process [41], even if this is probably more influenced by the presence of the binding agents for wood [40]. No improvement was observed following the addition of corn flour in mixes 2 and 5. Excluding the mechanical durability, which did not exceed the minimum threshold in any case, the mixes could however be classified as follows: Mix 1 and Mix 3 fall within A1 class, Mix 4 falls within A2, and the other mixes are not classifiable due to their low bulk density.

5. Conclusions

This study was mainly developed to analytically define the quality of residual woody biomass produced in marginal areas and the solid biofuels obtainable from this material. Considering the real use of the analyzed biomasses, it is clear there is not always consistency between what the market considers to be the best and what is analytically better. The debarking process improved all the analyzed biomass materials by reducing the ash content by between 35 and 70%. This process can allow poor-quality biomass to be included within supply chains to produce higher-quality, densified biofuels. For this case study, the chipping process reduced the wood into very fine elements: this could be a disadvantage for storage because it does not allow an optimal exchange of air in a heap, with a consequent risk of biological deterioration or autoignition. Concerning pellet, the low durability makes it unsuitable for transport even over short distances as it generates fines formation. A low durability pellet is incompatible with standard screw feeding systems. If burned directly at the production point, the issue related to low durability is minimized and this solid biofuel could contribute to improving the sustainability of the company by partly substituting fossil fuels.

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Abbreviations

Biomass black locust with bark (chips)	BL_bC
Biomass black locust without bark (chips)	BL_nC
Biomass poplar with bark (chips)	PP_bC
Biomass poplar without bark (chips)	PP_nC
Biomass oak with bark (chips)	OK_bC
Biomass oak without bark (chips)	OK_nC
Biomass stone pine with bark (chips)	SP_bC
Biomass stone pine without bark (chips)	SP_nC

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