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Valorising Agricultural Residues through Pelletisation

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Abstract: The agricultural sector and its related production chains are good sources of residual biomass. Olive and vineyard pruning residues are present in high quantities in Italy. The limited bulk and energy densities of these biomass materials affect the harvesting and logistic costs, limiting energy and environmental sustainability. Pelletisation is the most efficient process for increasing bulk and energy densities. This study evaluates the pelletisation process of olive and vineyard prunings, pure, or blended with variable quantities of spruce sawdust. A 15 kW pelletisation system was chosen, in line with production at the farm level. The most important quality parameters of the produced agripellets were analyzed. The results of this investigation suggest that blending could valorize other biomass materials less suitable for pelletisation and reach the pellet quality required by Italian technical standards. The addition of pruning residues to spruce sawdust leads to an improvement in durability. Spruce sawdust pellets have a durability value of 78.4%. Adding 20% of olive prunings (S80O20) increases this value to 92.2, while adding 20% vineyard prunings (S80V20) increases this value up to 90.3. The addition of 20% of pruning residues significantly increased the length and decreased fines.

Keywords: pelletisation; solid biofuel; agripellet; agricultural residues; durability; ash

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1. Introduction

The agricultural sector and its related production chains are sources of a high amount of residual biomass, representing a significant feedstock for the bioenergy sector and potentially for the bio-based industry. The Italian agency ENEA estimated a yearly availability (excluding the zootechnical sector) of around 25 Mt dry matter (d.m.) of residual biomass from agriculture and forestry, corresponding to about 10 million tons of equivalent (Mtoe) thermal energy [1]. More than 5 Mt are constituted of tree prunings. These estimates were confirmed in 2013 by the results of the Extravalore Project [2], funded by the MiPAAF Italian ministry, where an amount of 5.1 Mt d.m./year was reported. The same authors quantified 30% of the available solid biomass as corresponding to 1.53 Mt d.m./year and 660 ktoe of thermal energy. Statistics show that over 60% of the available tree pruning comes from vine and olive cultivations, justifying several authors' interest in the energetic valorisation of this biomass material [3–8].

Vineyard pruning residues are spread over 3.2 million hectares in Europe and 725,000 hectares in Italy [9], producing about 2.67 Mt/year, while olive prunings are about 2.3 Mt/year [2]. Vineyard pruning residues could partly replace traditional wood assortments for energy and industrial use [10]. They may also play an important subsidiary role in supplying bioenergy plants with renewable fuel [11], especially in rural areas where forest resources are scarce.

These values are the reason for the current effort to valorise this resource for energy application in combustion plants. In recent years, European and national policies promoted the use of residual biomass materials and quantification at the European level [12]. However, this kind of biomass material's limited bulk and energy densities affect the harvesting and logistic costs [13] and can partly limit the energy and environmental sustainability [14].

Pelletisation is the most efficient process for increasing bulk and energy densities of residual biomass. To produce pellets, the biomass is pressed mechanically to compress the wood's cell structure and make it denser. Thus, the energy density increases considerably, the moisture content decreases, and transport and storage costs are reduced [15–17]. Pellets are more homogeneous in size and structure than the raw biomass, an advantage that facilitates automated feeding in continuous boiler systems [18]. The low moisture content of about 8 to 11%, and the energy content of approximately up to 20 MJ/kg, allows them to burn with very high efficiency and makes this fuel close to traditional fuels such as coal [19]. Biomass Lab of Università Politecnica delle Marche provided a study of the pellet quality of the Italian market, analysing 88 different woody pellets. The results of this study shows a mean Net Calorific Value of 17.1 MJ/kg with a standard deviation of 0.5 MJ/kg that corresponds to about 18 MJ/kg of energy content [20].

Like other biomass feedstocks, pellets are carbon neutral. The carbon emitted during their combustion is taken up in the re-growth of the biomass used to produce them [21].

Wood pellets are made by pressing wood materials at high pressure and temperature. The steps to produce wood pellets are: separation, crushing, drying, pelleting, cooling, and storage [22]. Recently, attention has been paid to the densification of this material with mobile systems, thereby avoiding the transportation of low bulk density materials. Other authors studied pelletisation at the farm scale with systems characterised by low-medium production capacity [9].

The sustainability of heat production from vineyard pruning pellets has been evaluated by some authors [23] by a life cycle assessment. They considered two scenarios: a fixed pelletising plant and a mobile pelletiser. Pelletisation can solve a problem for vineyard operators, who need to discard their residual material and often decide to burn it on fields, causing environmental pollution. Finding some use for vineyard pruning residues would allow them to convert a disposal problem into a collateral production, with a potential for revenues or reduced management costs. Pruning residue harvesters have been developed to effectively recover vineyard pruning residues and make them available to the markets [13].

The heterogeneity and average quality of these residues, highlighted by different authors, make direct combustion difficult in small and medium combustion systems. This problem can be overcome by producing agripellets to standardize biofuel, which is more suitable for stoves and boilers [24].

Pelletisation also improves other characteristics apart from bulk density. Pellets have high homogeneity, low moisture content, high energy density, and easy to handle, qualities essential for logistics and efficient use [25,26]. However, there are limited studies on the physical properties of pellet production from different orchard residues [27]. A. García-Maraver et al. tried to improve the quality of pellets from woody agricultural residues and their application in the domestic and industrial sectors, especially one of the most common woody residues in southern Spain (i.e., olive tree residues) [28]. Michela Zanetti et al. investigated the possibility of using vineyard pruning residues to produce type B pellets for non-industrial use as defined by the in-force international ISO standard. Some comparisons have been made with the requirements of the standard EN ISO 17225- 6:2014 for non-woody pellets (ISO, 2014c) [29]. The current Italian standards UNI/TS 11772 [30] and UNI/TS 11773 [31] on woody agricultural pellets present new quality classes on pellet and briquette produced from tree pruning and obtained by efficient harvesting and storage systems.

Based on the abovementioned considerations and the interesting results obtained in pelletisation at the farm scale [9], the present study aims to evaluate the pelletisation process of olive and vineyard prunings, pure or blended with variable quantities of spruce wood, and the suitability of these biomass materials in agglomeration by extrusion. The pelletisation system chosen is in line with production at the farm scale. This activity is a further step to the practical application of this production chain, giving valuable indications to the involved stakeholders.

2. Materials and Methods

The study was based on several pelletisation tests of olive and vineyard pruning. The residual material was open-air dried for 24 h, milled, and pelletised pure or blended with spruce sawdust from a sawmill. The vineyard prunings were obtained from vineyards located in Verona province (North Italy 45°26′17.37″ N, 10°59′37.47″ E), while olive prunings were obtained from farms in Ascoli Piceno province (Center Italy 42°51′12″ N, 13°34′26″ E). The sawdust was also obtained from a pelletisation plant, Enerlegno, located in Cesena province.

2.1. Sample Acquisition and Preparation

To produce representative samples and to have enough materials for carrying out the work plan, 1.2 t vineyard pruning, 1.1 t olive pruning, and 2.0 t spruce sawdust were collected. Biomass materials were stored in sealed 208 L drums in the fridge to avoid moisture loss and wood degradation. Milling was performed with a specific mill (ORMA model MG1802) of 4 kW power with a grid of 5 mm mesh size. There was no need to reduce the particle size of the sawdust as its diameter was already less than 6 mm. For each biomass material, three samples of 3 kg each were obtained. These samples were used to perform analytical analyses for evaluating moisture content, ash, lower calorific value (LCV), chlorine (Cl), sulfur (S), and nitrogen (N) content. These quality parameters can help determine the productivity of the process and understand the pellet machine's response. They are also fundamental to verify compliance with the standards that represent a point of reference for the market, plant manufacturers, and institutional bodies. Before pelletisation tests, biomass blends preparation was performed by mechanically mixing spruce sawdust and prunings until chromatic homogeneity was achieved.

2.2. Reference Standards

Moisture content was determined following the ISO 18134-3 (E) standard [32]: a sample of 300 g was dried in a forced ventilation oven at 105 ± 2 °C until the constant mass was achieved. The accuracy of weighing was 10 mg. Each test was performed in triplicate.

The ash content was determined in accordance with ISO 18122 (E) standards [33]. The porcelain crucible containing a minimum of 1.0 g of sample was burnt in a muffle furnace at 550 ± 10 °C for at least 2 h. The accuracy of weighing was 0.1 mg.

Higher calorific value (HCV) was determined in accordance with EN ISO 18125 [34]. Under specified conditions, a pellet sample (1.0 ± 0.2 g) was burned in high-pressure oxygen in a bomb calorimeter (Isoperibolic calorimeter mod.C2000 basic, IKA). Lower calorific value was calculated considering moisture and hydrogen contents.

Chlorine (Cl) and sulfur (S) content was determined following the ISO 16994 (E) [35] with a liquid ion chromatographer (mod. 761 COMPACT IC, Metrohm).

The nitrogen content was determined following the ISO 16948 (E) standard [36] using an elemental analyzer (Perkin Elmer mod. 2400 Series II CHNS/O System). About 100 mg of wood powder was burned at 950 °C (for about 2 min) under an oxygen atmosphere. At this temperature, all forms of N were oxidized to NOx. After humidity and ash elimination, the concentrations of NO2 and NOx were determined by thermal conductivity.

2.3. Pelletisation Tests

The milled biomass materials, pure or in a blend, were pelletised by a 15 kW pellet machine (La Meccanica—model CLM 200). The machine was equipped with a hopper and a variable speed metering screw to feed the biomass. The press block included the ring die installed on a cast-iron base. According to the data sheet of the machine, the die inner diameter was 200 mm, and the working surface was 220 cm^2. The total die width was 62 mm with a working width of 35 mm. The die holes diameter was 6 mm. Two rolls (96 mm diameter) were mounted inside the die to push the biomass material inside the die holes. The distance between rollers and die was 0.6 mm.

As shown in Figure 1, agripellet color is affected by the blend composition used for pelletisation. The darker pellets are richer in olive prunings, while the lighter ones are richer in spruce sawdust.

Figure 1. Agripellets produced.

Before each pelletisation test, the pelletizer was warmed up until a temperature of 80°C was reached, monitored by a dedicated analogue thermometer (range 50–110 °C; 1°C—accuracy 1°C). The thermometer probe was located in the upper part of the pelletisation chamber, close to rolls. The heating was obtained by pelletising a certain amount of spruce sawdust. Subsequently, 120 kg of selected biomass materials was tested. Each test was performed in triplicate, where pelletisation time (tp), expressed in unit of measurement of hour, pellets process average temperature (Tm), expressed in unit of measurement of °C, and pellet yield (Qp) expressed as kg, were recorded. The production capacity (Pr) was calculated by dividing Qp with tp.

The average power (P) absorbed by the electrical motor was measured through a power meter during each test. The idle power was less than 1.5 kW. At the end of each test, the die was cleaned with sunflower seed and wheat bran mixture. Three pellet samples (5 kg each) were taken from the test's initial, mid, and final parts for each test. Samples were cooled at ambient air for 24 h before performing laboratory analysis.

The work plan included pelletisation tests with pure biomass materials (spruce, olive pruning, vineyard pruning) and three blends with spruce sawdust for each pruning residue. Tests and specific compositions are reported in Table 1.

Table 1. Work plan of pelletisation tests.

N°Test	Blend	Blend Composition		N°Test	Blend	Blend Composition	
		Spruce Sawdust	Olive Pruning			Spruce Sawdust	Vineyard Pruning
		(%)	(%)			(%)	(%)
1–3	S100-O0	100	0	16–18	S100-V0	100	0
4–6	S80-O20	80	20	19–21	S80-V20	80	20
7–9	S50-O50	50	50	22–24	S50-V50	50	50
10–12	S20-O80	20	80	25–27	S20-V80	20	80
13–15	S0-O100	0	100	28–30	S0-V100	0	100

As shown in Table 1, the distribution of blends is regular and sufficient to highlight its effects on the qualitative parameters of the pellet. It also reflects the dosage sensitivity of small-medium plants.

2.4. Analyses of Biomass Materials and Pellet Samples

The analytical work performed in this study is fundamental to evaluate pellet quality in relationship to current technical standards, verify the correct blending and assess the effect of blends in the pelletisation process.

Methods and equipment used for the analytical work aligned with the current technical ISO standards about the quality assessment of solid biofuels. In Table 2, standards employed for each parameter analyzed for the raw biomass materials and pellet are reported. The motivation for performing the analyses and significant thresholds are also defined.

Table 2. Parameters analysed on biomass materials and pellet and standards used.

Parameter	Standard	UM *	Biomass	Pellet	Instruments
Moisture content (M)	ISO 18134	% a.r.	To check that the biomass has a low moisture value: generally, less than 13% on standard woody materials and 18% on pruning.	To evaluate the quality and completeness of the pelletising process. Usually, less than 10% for the pellet produced.	Forced ventilation oven (mod. M120-VF, MPM Instruments–Bernareggio, Italy)
Ash content (A)	ISO 18122	% d.m.	The measurement of these parameters allows verifying the quality of the raw materials used in the tests and the final products.		Muffle furnace (mod. ZA, Prederi Vittorio & figli–Milano, Italy)
Higher Calorific Value (HCV)	ISO 18125	MJ/kg			Isoperibolic calorimeter (mod.C2000 basic, IKA-Staufen im Breisgau, Germany)
Nitrogen content (N)	ISO 16948	% d.m.			Elemental analyzer (mod. 2400 Series II CHNS/O System, Perkin Elmer-Milano, Italy)
Chlorine content (Cl)	ISO 16994	% d.m.			Liquid ion chromatographer (mod. 761 COMPACT IC, Metrohm-Formello, Roma, Italy)).
Sulfur content (S)	ISO 16994	% d.m.			Liquid ion chromatographer (mod. 761 COMPACT IC, Metrohm–Formello, Roma, Italy)).
Durability (D)	ISO 17831-1	%	Not applicable	To evaluate the compaction efficiency of the pelletising process.	Mechanical durability tester (Andritz Sprout rotation pellet testing apparatus-Esbjerg, Denmark)
Length (L)	ISO 17829	mm	Not applicable	They are considered indicators of biomass cohesion during the extrusion process.	Standard laboratory equipment
Fines (F)	ISO 18846	%	Not applicable		Standard laboratory equipment

* UM: measurement unit.

Biomass materials and pellet samples were prepared according to UNI EN ISO 14780—Solid biomass, sample preparation [37]—mill cleaning between different samples was done carefully to avoid possible contaminations.

The analyses were performed at the Biomass Lab of Università Politecnica delle Marche (www.biomasslab.it–last accessed on 15 January 2022) using equipment and instruments in line with the standard requirements. Table 2 also presents the instruments employed for each parameter analysed.

2.5. Data Elaboration

For each blend, three tests were performed to permit a statistical evaluation without high analytical costs. The results were analysed to evaluate several aspects of the performance of the pelletisation process concerning the residual materials used. An analysis of variance (ANOVA) was performed. Tests were carried out to check the ANOVA assumptions before conducting the analysis. Levene's test was used to check the homogeneity of variance and a Shapiro–Wilk test was used to check normality of distribution. ANOVA Results were evaluated with Tukey's test at the 0.05 level of significance as a post hoc analysis using the software Minitab ver. 20.1.2 (Minitab Ltd., Coventry, UK). Tukey's test is a single-step procedure that can be used to find means that are significantly different from each other. Tukey's test compares the means of every treatment to the means of every other treatment; that is, it applies simultaneously to the set of all pairwise comparisons.

In addition, the following relationships were considered:

- Effects of the blend on process parameters (Pr and Tm) and the mechanical quality of the pellet produced (D);
- Specific relation between process factors (Tm vs. Pr);
- Specific relation between quality factors (F vs. D).

The results of the characterization of pellets and initial biomass materials were finally compared with the requirements of the international standard ISO 17225-2 [38] and the recently published Italian standard UNI/TS 11773. This last standard provides specifications and classifications of woody and non-woody pellet classes supplementary to UNI EN ISO 17225-2 and UNI EN ISO 17225-6 and is specific for the Italian market of agripellets.

3. Results

The results of this study provide valuable indications both on qualitative and technical aspects. Data on the quality of the residual biomass materials and agripellets produced are reported in the following paragraphs. In addition, indications of these materials' pelletisation process and cohesion ability during the extrusion process are highlighted.

3.1. Results of Analyses Performed on Biomass Materials and Pellets

Results of the investigation, described in Section 2.5, are shown in Table 3.

Table 3. Results of analyses carried out on milled biomass materials: olive and vineyard pruning, spruce sawdust (average values with standard deviation in parenthesis).

Parameter	Unit	Olive Pruning	Vineyard Pruning	Spruce Sawdust	ISO 17225-1 Table B.4 [(a)]	ISO 17225-1 Table B.1 [(b)]
M	(%)	17.5 a (0.4)	18.2 a (0.7)	12.8 b (0.4)	—	—
A	(% d.m.)	2.9 b (0.3)	4.4 a (0.4)	0.5 c (0.1)	0.5–4.0	0.2–1.0
LCV	(MJ/kg d.m.)	17.7 a (0.3)	17.9 a (0.3)	18.2 a (0.2)	17.6–19.0	18.4–19.8
N	(% d.m.)	0.43 b (0.03)	0.64 a (0.04)	0.23 c (0.02)	0.1–0.8	0.1–0.5
Cl	(% d.m.)	0.04 a (0.01)	0.05 a (0.01)	0.02 b (0.01)	0.03–0.10	0.01–0.03
S	(% d.m.)	0.03 a (<0.01)	0.03 a (0.01)	0.01 b (<0.01)	0.01–0.11	0.01–0.05

[(a)]: ISO 17225-1–Table B.4–Typical values for virgin wood materials, short rotation coppice. [(b)]: ISO 17225-1–Table B.1–Typical values for virgin wood materials without bark, leaves and needles. Note: values in the same row that do not share a letter are significantly different at *p*-value 0.05.

The results obtained are in line with international databases [39] for the same materials. They are comparable with typical values reported in ISO 17225-1 [40] for virgin wood, short rotation coppice, and virgin wood without bark. The tree prunings were obtained from annual operations. Therefore a comparison was made with data on the short rotation coppice. The ash content of the studied prunings was relatively low for this kind of biomass. According to other studies, pellets from the leaves of olive trees generated a higher percentage of ash content than pellets from olive tree branches. In any case, it was observed that values exceeded the usual ash content of wood, whose values are between

0.4 and 0.8% for softwood and between 1 and 1.3% for hardwood [28]. This suggests the use of efficient harvesting methods which avoid contamination with soil impurities [9]. The spruce sawdust is in line with the typical values reported in ISO 17225-1 for that kind of biomass without bark. The quality of this biomass was significantly better compared to pruning residues. For this reason, it is used not only for comparison but also in blends for evaluating the opportunity to improve agripellet quality. It is worthy of note that the moisture content of the pruning residues was below 20%. This value highlights how the harvesting and managing of the biomass favors the loss of water. According to other authors dealing with straw pellets, for moisture contents between 9 and 17%, very low compaction was achieved during the process, the result being an undesirable mass of powder comprising scarce pellets. These are fragile short pellets (15–20 mm long) with very low durability (65–90%) that increases with the straw moisture [41]. A positive correlation between the moisture content of raw materials and pellet durability has been found by Lehtikangas (2001) [42]. As underlined in other studies [24], this aspect is important from many points of view, in particular in reducing economic and environmental costs of production and in making production operation simpler.

Moisture content is essential for successful pellet production, and the biomass preparation process plays a crucial role in pelletisation, especially in small and simplified production systems. In fact, water favors particle bonding, and the best durability is achieved for straw moisture contents between 19 and 23%, for which most of the ground straw properly pelletizes and the product presents low fines content [41].

The results of analyses carried out on pellets produced (Tables 4 and 5) are in line with the expected values considering blend compositions and the properties of milled biomass materials (Table 3). These results, shown in Table 4, were compared with the limits expressed with the standards and confirm that the blending process was correctly conducted.

Table 4. Results of analyses carried out on pellets produced with the different blends of spruce sawdust and olive pruning residues (average values with standard deviation in parenthesis).

Parameter	Unit	S100O0	S80O20	S50O50	S20O80	S0O100	ISO 17225-2 [(a)]	UNI/TS 11773 [(b)]
M	(%)	6.2 a (0.2)	6.8 a (0.2)	6.6 a (0.2)	6.7 a (0.4)	6.5 a (0.2)	≤10	≤10
A	(% d.m.)	0.5 a (0.1)	1.04 b (0.1)	1.6 c (0.2)	2.6 d (0.2)	3.1 e (0.2)	≤3.0	≤5.0
LCV	(MJ/kg d.m.)	18.0 a (0.2)	17.8 a (0.2)	18.0 a (0.1)	18.1 a (0.2)	17.9 a (0.1)	—	—
LCV	(MJ/kg a.r.)	16.9	16.6	16.8	16.9	16.7	≥16.5	≥15.0
N	(% d.m.)	0.25 a (0.03)	0.27 a (0.02)	0.35 b (0.03)	0.44 c (0.02)	0.47 c (0.03)	≤0.6	≤1.5
Cl	(% d.m.)	0.02 a (0.01)	0.02 a (0.01)	0.03 ab (0.01)	0.04 b (0.01)	0.04 b (0.01)	≤0.1	≤0.1
S	(% d.m.)	0.01 a (<0.01)	0.02 ab (<0.01)	0.02 ab (<0.01)	0.02 ab (<0.01)	0.03 b (<0.01)	≤0.05	≤0.05

[(a)]: Limits of I3 quality class, Table 2; [(b)]: Limits of I4 quality class. Note: values in the same row that do not share a letter are significantly different at *p*-value 0.05.

Table 5. Results of analyses on pellets produced with the different blends of spruce sawdust and vineyard pruning residues (average values with standard deviation in parenthesis).

Parameter	Unit	S100V0	S80V20	S50V50	S20V80	S0V100	ISO 17225-2 [(a)]	UNI/TS 11773 [(b)]
M	(%)	6.2 a (0.2)	6.6 a (0.2)	6.8 a (0.4)	6.7 a (0.4)	6.7 a (0.2)	≤10	≤10
A	(% d.m.)	0.5 a (0.1)	1.3 b (0.1)	2.1 c (0.2)	3.6 d (0.3)	4.3 e (0.2)	≤3.0	≤5.0
LCV	(MJ/kg d.m.)	18.1 a (0.1)	18.0 a (0.1)	18.3 a (0.2)	18.0 a (0.2)	18.2 a (0.1)	—	—
LCV	(MJ/kg a.r.)	17.0	16.8	17.1	16.8	17.0	≥16.5	≥15.0
N	(% d.m.)	0.21 a (0.01)	0.27 b (0.02)	0.31 b (0.02)	0.39 c (0.02)	0.44 c (0.03)	≤0.6	≤1.5
Cl	(% d.m.)	0.02 a (0.01)	0.03 ab (0.01)	0.04 b (0.01)	0.04 b (<0.01)	0.05 b (0.01)	≤0.1	≤0.1
S	(% d.m.)	0.01 a (<0.01)	0.02 ab (<0.01)	0.02 ab (<0.01)	0.03 b (<0.01)	0.03 b (0.01)	≤0.05	≤0.05

[(a)]: Limits of I3 quality class; [(b)]: Limits of I4 quality class. Note: values in the same row that do not share a letter are significantly different at *p*-value 0.05.

The pellet quality in many cases results within the limits of ISO 17225-2 class I3, the lowest class for industrial pellet. The quality of pellets produced with olive pruning residues is better than those obtained from vineyard pruning residues, especially considering ash content. According to other studies the average low calorific value of vineyard pellets is 16.7 MJ/kg [27], which is close to the value obtained by our study. In general terms, all the agripellets fall within the quality thresholds of the current Italian standard UNI/TS 11773:2020. Compliance with these standards indicates a good potential of this solid biofuel to address the specification for thermal appliances. It should be noted that the values of parameters such as A, N, Cl, and S are comparable with those of a wood chip (ISO 17225-1–Table 2), making agripellets a competitive solid biofuel.

3.2. Results of Pelletisation Tests

For a possible production at farm scale using pruning residues, together with standard analyses of pellet quality, it is important to highlight specific factors affecting the pelletisation process. Tables 6 and 7 present some factors measured during the pelletisation tests with different blends. From the results, the addition of pruning residues significantly improves the durability (D) of all the pellet blends. These biomass materials are suitable for pelletisation and the produced agripellets have good mechanical properties. As shown in Tables 6 and 7, there is a significant difference in D, between spruce pellets containing 100% or 80% spruce and the blends containing higher pruning residues. However, only the blends with 80% or 100% of pruning residues met the requirements of ISO 17225-2 class I3 (>96.5%) or UNI/TS 11773 class I4 (>96%). Agripellets containing olive pruning residues showed higher durability than those containing vineyard pruning residues at the same percentage.

Table 6. Results of pelletisation tests with different blends of olive pruning residues and spruce sawdust (average values with standard deviation in parenthesis).

Test	Mi	Mf	D	L	F	Pr (kg/h)	P (kW)	Tm
S100O0	11.9 a (0.4)	6.2 a (0.2)	78.4 a (2.7)	12.9 a (0.3)	5.6 a (0.4)	56.2 a (1.7)	10.7 a (0.1)	84.6 a (0.8)
S80O20	12.6 a (0.6)	6.8 a (0.2)	92.2 b (1.3)	32.3 b (1.1)	1.7 b (0.1)	59.1 ab (1.0)	11.8 b (0.1)	96.4 b (0.6)
S50O50	15.5 b (1.0)	6.6 a (0.2)	95.8 bc (0.3)	42.9 c (1.1)	0.6 c (0.1)	60.5 b (0.8)	12.7 c (0.1)	102.0 c (0.9)
S20O80	16.5 bc (0.5)	6.7 a (0.4)	97.8 c (0.3)	44.5 c (0.3)	0.2 c (<0.1)	59.0 ab (1.2)	13.1 c (0.1)	104.0 c (1.6)
S0O100	17.5 c (0.4)	6.5 a (0.2)	99.3 c (0.3)	44.1 c (0.2)	0.2 c (<0.1)	58.3 ab (0.9)	14.0 d (0.1)	107.3 d (1.2)

Note: values in the same column that do not share a letter are significantly different at *p*-value 0.05. Abbreviations: Moisture of biomass milled material (Mi); Moisture of pellets (Mf); Durability (D); Length (L); Fines (F); Production capacity (Pr); Average power (P); Average Temperature (Tm).

Table 7. Results of pelletisation tests with different blends of vineyard pruning residues and spruce sawdust (average values with standard deviation in parenthesis).

Test	Mi	Mf	D	L	F	Pr (kg/h)	P (kW)	Tm
S100V0	11.8 a (0.4)	6.2 a (0.2)	78.4 a (2.7)	12.9 a (0.3)	5.6 a (0.4)	56.2 a (1.8)	10.7 a (0.1)	85.3 a (1.3)
S80V20	12.9 a (0.8)	6.6 a (0.2)	90.3 b (1.6)	25.1 b (1.2)	2.1 b (0.1)	57.5 a (1.4)	11.7 b (0.1)	94.6 b (0.4)
S50V50	14.9 b (0.3)	6.8 a (0.4)	94.8 c (0.3)	33.1 c (1.0)	1.7 b (0.2)	59.3 a (1.6)	12.2 c (0.1)	98.4 c (1.5)
S20V80	17.4 c (0.4)	6.7 a (0.4)	96.9 c (0.5)	40.1 d (0.4)	1.1 c (0.2)	63.5 b (1.2)	12.4 c (0.1)	100.6 c (2.0)
S0V100	18.4 c (0.7)	6.7 a (0.2)	98.3 c (0.3)	40.4 d (0.7)	0.9 c (0.2)	68.8 c (1.6)	12.9 d (0.1)	100.0 c (1.0)

Note: values in the same column that do not share a letter are significantly different at *p*-value 0.05. Abbreviations: Moisture of biomass milled material (Mi); Moisture of pellets (Mf); Durability (D); Length (L); Fines (F); Production capacity (Pr); Average power (P); Average Temperature (Tm).

All the pellets had similar Mf in the range 6.2–6.8%, well within the limits of the abovementioned technical standards. At the studied Mi levels, similar Mf levels were obtained, so this parameter did not affect the outcome of the pelletisation tests. With higher levels of Mf over 10% (the technical standard limit), some issues about pellet quality were observed.

As observed for D, L was also higher and significantly different for the blends with 80% or 100% of pruning residues and the other agripellets produced. This was also demonstrated by the high correlation found between the two factors (Figure 2) checked statistically with the analysis of residuals.

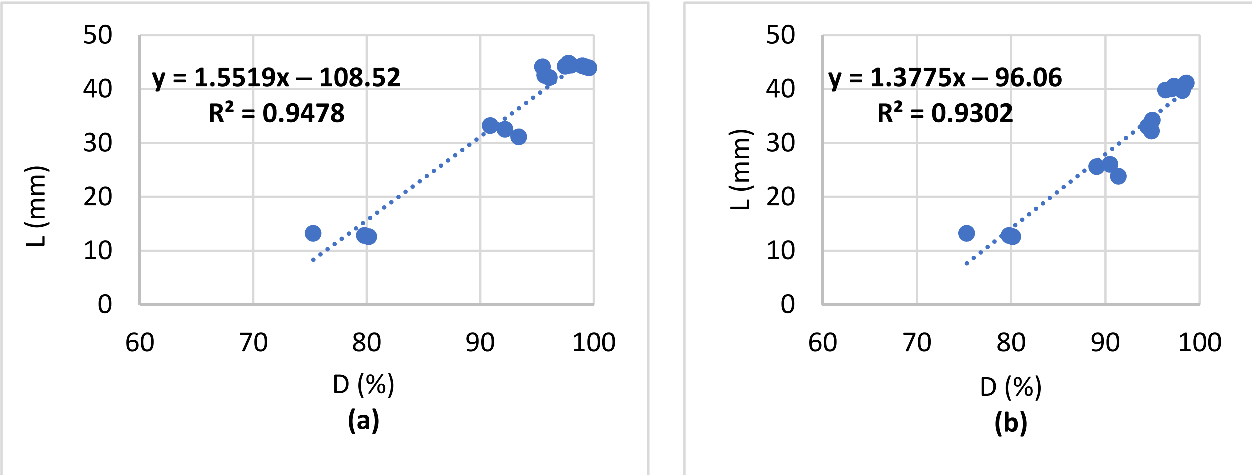

Figure 2. Correlations between durability and length of agripellets: (**a**) blends of olive pruning residues; (**b**) blends of vineyard pruning residues.

Similarly, F values are significantly lower for 100% spruce sawdust than for agripellet. It is worthy of note that a relatively small amount (20%) of pruning residue can decrease F significantly, improving quality. Figure 3 shows the correlation between F and D for both olive and vineyard pruning residues.

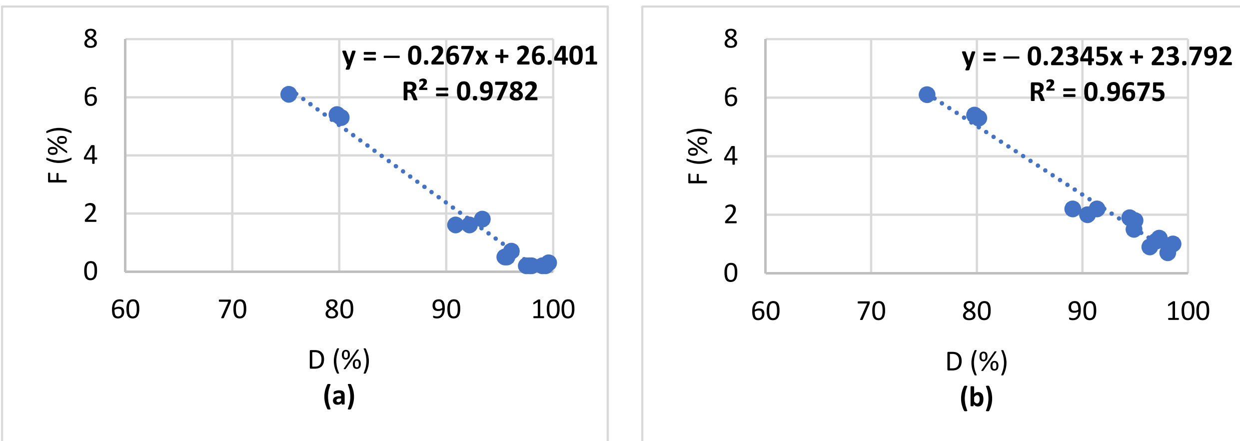

Figure 3. Correlations between durability and fines of agripellets: (**a**) blends of olive pruning residues; (**b**) blends of vineyard pruning residues.

These correlations suggest that pruning residues can improve the particles aggregation in the pelletisation process by increasing D and decreasing F.

In relation to process indicators Pr and Tm, differences between the two typologies of pruning residues were observed. The blends with olive prunings showed an increase of Pr up to 50% of pruning content, then Pr decreased with higher percentages of pruning. In contrast, Tm increased with the higher pruning content.

The Pr effect was not visible with vineyard pruning, where the Tm was also slightly lower. In this case, the P absorbed by the electrical engine was lower than the tests with olive pruning residues. Considering Pr, the power consumption was in the range of 0.19–0.21 kWh/kg. With olive pruning residues, specific energy consumption increased with the pruning percentage up to 0.24 kWh/kg. This can be caused by the lower extractive content. As highlighted by other authors, extractives can cause a lubricating effect, decreasing the friction in the press channels and therefore producing lower pressure and temperature [13,43,44].

4. Discussion

Considering the results of this study, the choice to use olive and vineyard pruning residues to produce agripellets in small production systems represents a possible solution both for qualitative and technical aspects.

Agripellets produced from correctly harvested, and managed pruning residues can fulfill the limits of the UNI/TS 11773. The agripellets from olive pruning, in particular, are comparable to the standard quality reference in ISO 17225-2. Only the sample S0O100 slightly exceeded in the ash content (A), at 3.1% against 3.0% of the standard. This is probably linked to the low share of bark in olive pruning residues due to larger diameters if compared with vineyard prunings.

Although the pelletisation tests can return specific (e.g., pellet machine, die, roll speed) and not absolute results, they can also give a general indication of the suitability of pruning residues to be successfully pelletised. The blends richer in pruning residues showed higher D, up to 96.9 in the case of S20V80, probably due to a favorable physical–chemical composition. This value increases up to 98.3 for 100% vineyard pellets. According to the scientific literature, bulk density, holocellulose, lignin contents, and extractives are only some factors that can play a role in pellet formation and affect D [45]. The higher cohesion of agripellets produced with pruning residues was also demonstrated by the higher L of pellets exiting the die. In brief, some factors related to pruning residues facilitate the particles' cohesion (positive correlation D vs. L), limiting the physical disaggregation (negative correlation D vs. F). A highly cohesive pellet is more resistant to mechanical stress and generates less fines [46]. The possibility of producing more integrated and homogeneous (same L) pellets during pelletisation can improve logistical aspects. In addition, more regular and length-controlled pellets improve the combustion behavior in thermal devices due to a more regularised feeding process [47,48].

If available at a low cost, the addition of spruce sawdust or another suitable forestry wood species can represent a solution to enhance pellet quality, improving some parameters. As an example, considering the present study results, it is possible to suggest using 30% spruce sawdust with 70% pruning residues to reach the quality requested by ISO 17225-2 class B, including the A parameter. This could create the possibility of using agripellets in non-industrial applications and at the rural level for greenhouse heating or even in domestic applications.

The production of agripellets with added quantities of wood sawdust can potentially enhance this raw material when it comes from small companies that process wood and who do not have sufficient quantities to justify the autonomous production of pellets.

The results from this study reveal that a higher percentage of spruce sawdust could require a greater compression at die level to reach high D. This would be linked to higher energy consumption with related economic and environmental costs. However, this is only an indication because the behavior of the tested typologies of pruning residue results are slightly different in terms of specific energy consumption.

5. Conclusions

When correctly harvested and managed, olive and vineyard pruning residues are suitable for pelletisation in small systems in line with production at the farm level. The results show that it is possible to reach the quality required by UNI/TS 11773 class I4 or ISO 17225-2 class I3. The physical–chemical differences among agricultural residue biomasses can be managed by appropriate blending to produce standard agripellets. Tests show the possibility of compromising mechanical and geometric parameters and chemical quality by choosing an appropriate biomass mixing level.

This study highlights the perspective of valorising agricultural residues at the farm level through pelletisation. Producing good quality agripellets using simplified farm-level pellet plants addresses the sustainability and circular economy goals that the agricultural sector must achieve, preventing the unwanted field combustion of agricultural residues well-known for emitting pollutants into the atmosphere.

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Abbreviations

Moisture content (M); Ash content (A); Lower Calorific Value (LCV); Nitrogen content (N); Chlorine content (Cl); Sulfur content (S); Durability (D); Length (L); Fines (F).

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