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Article

Characterization of Several Pellets from Agroforestry Residues: A Comparative Analysis of Physical and Energy Efficiency

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Abstract: The use of agroforestry biomass provides several advantages, both from an environmental point of view, in terms of the mitigation of global warming, and in terms of a circular economy for agricultural or agroforestry companies that reuse pruning residues as a source of energy. However, even if the use of energy pellets resulting from the pruning residues of various agroforestry species has excellent potential for the valorization of agricultural by-products, the physicochemical characteristics of these pellets have been scarcely studied by the scientific community. In this context, this study aims to assess the valorization potential of various lignocellulosic material residues produced during agroforestry activities. The objectives of the study include evaluating the chemical and physical characteristics of pellets produced with different mixtures of agroforestry biomass (olive, citrus, black locust, poplar, paulownia, etc.) in order to determine the optimal pellet blend from an energy and physicochemical perspective. The results of this study demonstrate that this comprehensive analysis provides valuable information on the optimization of biomass mixtures for better energy valorization, addressing both compositional and combustion-related challenges. In fact, it is observed that the addition of citrus and olive biomass to the various mixtures increases their energy potential. Furthermore, all of the pellets analyzed are found to possess an adequate and useful durability index (PDI) for their handling during storage and transport operations. This study demonstrates that olive and citrus pruning residues can be used to improve biomasses that have poor suitability in energetic, physical, and chemical terms. Further studies could be useful to understand which specific interaction mechanisms have an influence on emissions in order to optimize mixtures using different biomass sources for sustainable energy production.

Keywords: wood; biomass quality; fuel; pruning; forest; mechanical durability

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1. Introduction

The need to use renewable sources and matrices that possess energy potential is widely recognized. Energy, as a resource, is one of the main indicators of the human development index level, and the availability of reliable and accessible energy is essential to ensure economic and social stability. Countries with good energy security can satisfy their domestic demand without being excessively dependent on imports [1–3], while a dependence on fossil resources produces significant environmental impacts and affects the economy [4]. In recent decades, this excessive use of fossil fuels has motivated research on alternative energy sources, the use of which could both meet the growing demand for energy and reduce environmental impacts [5]. In particular, the development of innovative technologies aimed at the improvement of energy conversion processes and the reduction of environmental impacts has received increasing attention from both the scientific community and policymakers. Several studies have demonstrated that the quantity of residual biomass represents a very important energy alternative, considering both the intrinsic quality of the biomass itself and its globally available quantity [6,7].

Biomass is clearly a broad category, including materials with various properties, forms, and values from forestry and related industries, as well as from agricultural residues, as defined by the European Commission. Although most of the biomass used is derived from forestry-related activities, the agricultural and agroforestry sectors have been providing ever-increasing quantities of biomass resulting from the pruning residues of agricultural orchards. In fact, the European Community has determined that traditional sources of bioenergy production (the forestry sector) are insufficient to meet future energy needs or respond to new energy policies [8,9]. As such, there has been a surge in researchers attempting to creatively exploit various plant-derived biomasses and quantify their potential [10]. For these reasons, scientific interest in the exploitation of agricultural residues as biofuels for energy purposes has increased, with more researchers implementing pilot projects and experimental investigations [5,10,11].

The agroforestry system (or farm forestry) represents an important resource that offers alternative and more sustainable modes of land use, but is typically poorly developed. The residues produced from annual pruning operations represent a valid alternative for energy purposes; for example, in Poland, the woody biomass generated from pruning operations has compensated for the deficit in forestry wood for the production of solid biofuels [12]. In Europe, however, the potential energy resources deriving from agroforestry pruning residues remain underexploited for multiple reasons.

Biomass still has several weak points related to its logistics and handling which increase its associated costs, in addition to its low energy density [13–15]. In Italy, there is an estimated availability of 3,585,106 tonnes of pruning residues, of which 1,500,106 t are usually burned in the field [16,17]. Such open burning leads to the uncontrolled combustion of biomass and the release of large quantities of pollutants into the atmosphere. In contrast, controlled combustion using biomass boilers allows one to obtain energy and control the environmental impact of the process.

Agricultural pruning residues can guarantee advantages not only from an environmental point of view through mitigating global warming, as has been reported by Jones et al. [18], but also in terms of creating a circular economy for agricultural or agroforestry companies that re-use pruning residues as an energy source [19,20]. Many authors have demonstrated that the limitations that weaken the agroforestry biomass energy sector can be overcome or limited through densification processes that increase energy density, decrease volume, and favor a significant reduction in transportation and storage costs [13,21–23]. During the pelleting process, particles are pressed together by applying a mechanical force to create interparticle bonding [24,25], causing the product to become denser, more manageable, and (usually) more durable [26].

Europe is the world's largest consumer of pellets, with 24.8 million tonnes consumed in 2022 [27], of which 6 million tonnes were imported from America, Russia, and Eastern Europe [4]. In particular, Italy was the top consumer of wood pellets in the E.U. last year, at 3.4 million metric tons, followed by Germany at 3.2 million metric tons, and the Netherlands at 2.95 million metric tons [27]. Recent studies have shown that pelletization improves the thermochemical conversion efficiency in both industrial and domestic heating systems in terms of producing a better response [28,29]. García-Maraver et al. [30] determined that only forest residues have feasible technologies and associated markets for their exploitation in Europe, as pellets produced using agricultural residues are not always in accordance with the parameters defined by ISO 17225-2. A recent review [31] has confirmed that pellet production from pruning residues can facilitate the economical sustainability of the supply chain, considering that pruning collection has a certain cost by itself.

Furthermore, Holt et al. [32] reported a lower ash content produced by pelletized agricultural residues compared to the residues in their original form. It has also been recognized by many authors that pruning residues potentially have a higher ash content than purely forest biomass [33–35]. This aspect, linked to the ash content, limits the use of pellets produced from agroforestry residues in simpler heating systems with lower maintenance requirements when compared to domestic heating systems, which are much more sensitive and delicate concerning the management of ash produced by combustion. However, a lower ash content can be obtained by mixing the biomass to be pelletized. In fact, some wood species have a lower ash content than others [36–38]. Therefore, the pelletizing of blends provides not only a lower ash content in the pellet obtained, but also a different composition of the ash itself, as shown by different authors such as Fusi et al. [39] and Thy et al. [40]. However, research on the use of agroforestry biomass blends to improve the obtained pellets remains limited, and systematic investigations evaluating new opportunities for their production are scarce. In fact, even if the use of energy pellets derived from the pruning residues of various agroforestry species has excellent potential for the valorization of agricultural by-products, the physicochemical characteristics of the created pellets have been barely studied by the scientific community. Garcia et al. [41] tested pine sawdust with many agricultural alternative raw materials, evaluating the quality of the obtained pellet. Olive pruning residues have been mixed with olive pomace, producing a good-quality pellet which had better durability and a lower ash content [42]. Lajili et al. [43] studied the physicochemical characterization and thermal degradation of blended samples prepared from different mass fractions of pine sawdust and olive solid waste. Acampora et al. [44] tested pellets of hazelnut and olive tree pruning biomass. Notably, their results did not meet the current standards, suggesting that further studies on blending with different types of wood are necessary. Recent scientific articles have studied the characteristics of biomass obtained from the pruning residues of olive and citrus trees, demonstrating that these two species are valid alternatives as energy sources, both in terms of their performance and environmental impacts (e.g., emissions) [34,45,46]. Palma et al. [47] used olive and citrus residues as a primary source to produce energy pellets of raw biomass material, starting with a characterization of the biomass, and showed that the investigated pellets generally have a lower average humidity value compared to other biomasses, leading to good combustibility and a potentially lower production of pollutants. Additionally, Proto et al. [17] have reported the interesting characteristics of olive and citrus woodchips; in particular, their high energy potential and low emissions (within legal limits). In this context, this study aims to enhance the valorization of various residual lignocellulosic materials derived from agricultural activities through promoting agro-pellet production. In particular, our objectives were (i) to test whether the considered types of raw materials are suitable for the production of pure and mixed pellets; (ii) to evaluate the chemical, physical, and energy characteristics of the pellet obtained; and (iii) to classify the best pellet that corresponds to the qualitative standards required.

2. Material and Methods

2.1. Biomass Harvesting, Pelletization, and Blend Percentages

The pruning residues were collected from various agroforestry companies in the province of Reggio Calabria (Italy) during a specific pruning period. Only the plant material that was considered not to be marketable by the company was collected and, therefore, everything was defined as “vegetable waste” (Table 1).

Table 1. Type of biomass used as vegetable waste.

Sample Acronym	Biomass Species
G	Grapevine
Ci	Citrus
Ol	Olive

Kw	Kiwi
Pp	Poplar
Ro	Robinia
Pw	Paulownia
Eu	Eucalyptus

The choice of wood pruning residues is representative of the most important and widespread agricultural crops in marginal agroforestry areas in Italy. In the preparation of the mixtures, the woody residues of the olive and citrus trees were considered as basic matrices, into which the residues of other agricultural crops (i.e., vegetable waste) were integrated at different percentages. Olive and citrus fruit residues were chosen as the basic matrix as they are characteristic of the Mediterranean area and have been reported to possess good physical and energetic characteristics when pelletized [4,5,30,47]. To observe the pelletizing behavior of the residues, as well as their associated characteristics, a classification of the basic matrix samples (olive and citrus) was established based on the weight percentage of the components of each of the mixtures created with the vegetable wastes. In fact, different matrices were generated, taking into account a final weight of biomass to be pelletized of 4 kg for each mixture generated. Mixtures with various weight percentages were then obtained according to the following scheme:

- Pellets with 100% basic matrix only (Ol, Ci);
- Pellets with base matrix mixtures of 75, 50, or 25% and vegetable waste mixtures of 25, 50, or 75%, respectively;
- Pellets with only 100% vegetable waste (G, Kw, Pp, Ro, Pw, Eu).

The collected pruning residues were transported to the laboratory of the Department of Agraria (University of Reggio Calabria), where they were chipped using a Chipper/Shredder (Peruzzo model T3), equipped with its own combustion engine, with a power of 9 kW. The size of the wood chips created was regulated using diverse perforated sieves with different diameters of holes for the wood chips exiting. The chipped biomass was sieved and placed in a hopper. Subsequently, biomass mixtures containing different percentages for each plant species were generated (Table 2), and humidity measurements were carried out to standardize all mixtures to a water content of 12–14%, which is the optimal range for the wood chip pelletizing process.

Table 2. Types of biomass used as vegetable waste. The biomass belonging to the species G, Kw, Pp, Ro, Pw, and Eu were mixed with the "Ol" biomass in percentages of 75%, 50%, or 25% and with the "Ci" biomass in percentages of 75%, 50%, or 25%. For example, the mixed sample "Kw-75_Ci-25" corresponds to 75% kiwi biomass and 25% citrus biomass. Furthermore, for each species, samples of pure biomass (100%) were also pelleted.

		Grapevine			**Kiwi**	
Olive	G-75_Ol-25	G-50_Ol-50	G-25_Ol-75	Kw-75_Ol-25	Kw-50_Ol-50	Kw-25_Ol-75
Citrus	G-75_Ci-25	G-50_Ci-50	G-25_Ci-75	Kw-75_Ci-25	Kw-50_Ci-50	Kw-25_Ci-75
		Poplar			**Robinia**	
Olive	Pp-75_Ol-25	Pp-50_Ol-50	Pp-25_Ol-75	Ro-75_Ol-25	Ro-50_Ol-50	Ro-25_Ol-75
Citrus	Pp-75_Ci-25	Pp-50_Ci-50	Pp-25_Ci-75	Ro-75_Ci-25	Ro-50_Ci-50	Ro-25_Ci-75
		Paulownia			**Eucalyptus**	
Olive	Pw-75_Ol-25	Pw-50_Ol-50	Pw-25_Ol-75	Eu-75_Ol-25	Eu-50_Ol-50	Eu-25_Ol-75
Citrus	Pw-75_Ci-25	Pw-50_Ci-50	Pw-25_Ci-75	Eu-75_Ci-25	Eu-50_Ci-50	Eu-25_Ci-75

The pellets of the different wood chip mixtures obtained were produced using a rotating roller pelletizer (Peruzzo model Minipel E80, 11 kW electric motor—Figure 1) installed on a die with 6 mm diameter holes. The pelletizer also included an H-24 rotating flat die with 24 mm long channels; these channels had a pre-compression chamber thanks to a 60-degree angle flare present at the mouth of the channel. Upon exiting the pelletizer, the pellets were allowed to cool and measurements were taken of the average length and diameter of the pellets, as well as the durability index (PDI) value of each blend (Figure 1), using an automated pellet durability Holmen tester (NHP200, TEKPRO). The durability or abrasion resistance test simulated mechanical or pneumatic handling, therefore simulating the transport environment of the pellets from the production factory to the point of sale. These tests can help assess the densification process and, therefore, the quality of the pellet. Durability is the prevalent form of measurement and the expression of pellet quality in the leather goods sector. The Holmen tester was used to measure the durability of the densified products, during which the mechanical movement of the pellets is simulated, allowing for the determination of any dust produced due to mechanical movement. Once a pellet sample is loaded into the machine, any fine particles are removed, the sample is weighed, and the pellets are tested by agitating them with air at a fixed pressure of 70 mbar. Then, the remaining sample is weighed and its PDI is calculated. The average test lasts only 4 min, where the test time is automatically set based on the diameter of the pellet inserted. Furthermore, compared to traditional methods, this type of test eliminates the possibility of human error, providing an accurate and reliable test method.

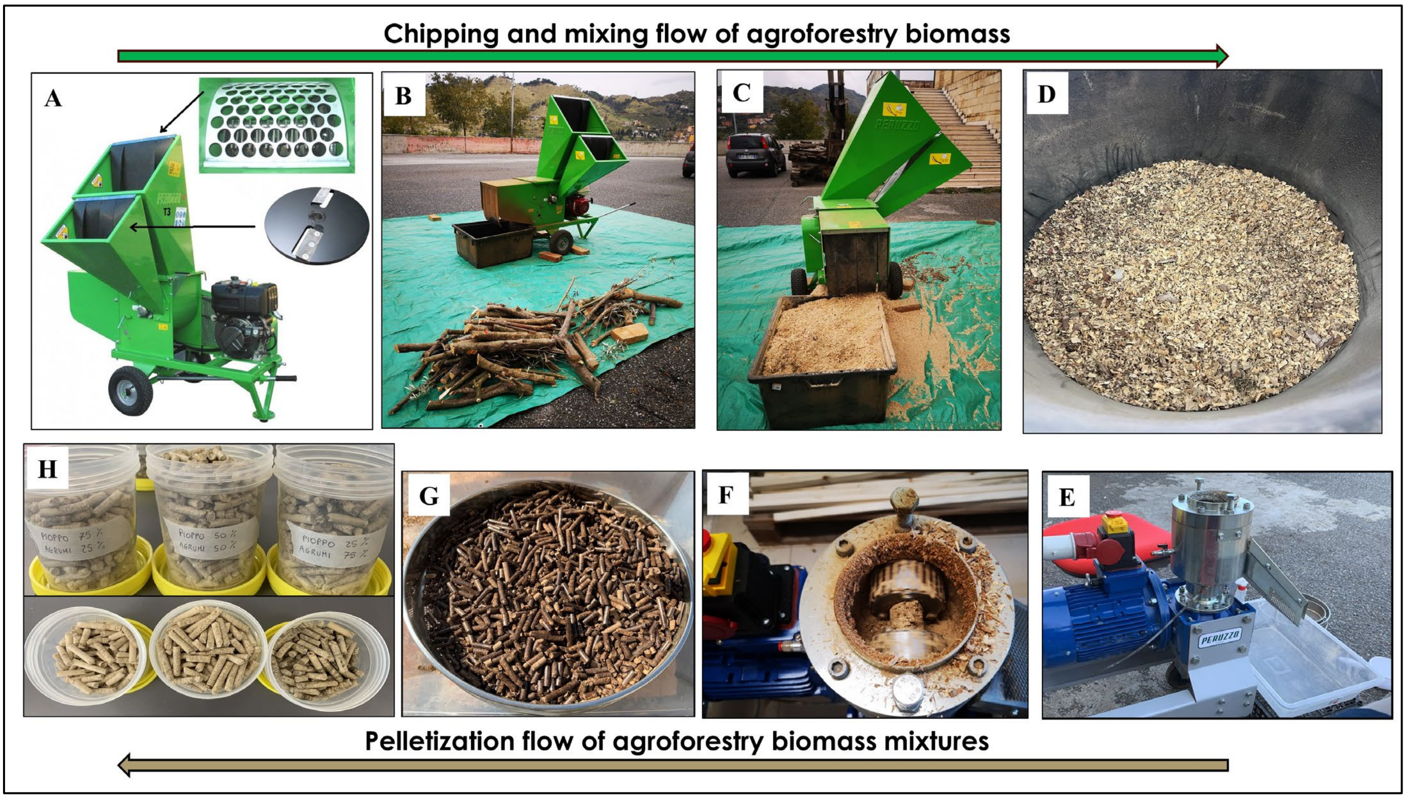

Figure 1. Flow of the chipping and pelletizing processes of agroforestry pruning residues: (**A**) Chipper/Shredder "Peruzzo model T3; (**B**) start of the chipping phase of olive tree pruning residues; (**C**) completion of the chipping phase of olive tree pruning residues; (**D**) mixing process of different agroforestry wood residues; (**E**) rotating roller pelletizer (Peruzzo model Minipel E80); (**F**) detail of the rollers of the pelleting machine during the pelletizing phase; (**G**) freshly produced olive wood pellets (100%) in the cooling phase; and (**H**) samples of pellets made with different percentage blends of poplar and citrus.

2.2. Pellet Characterization

The elemental composition, carbon content (C), hydrogen content (H), and nitrogen content (N) were measured using a Costech ECS 4010 CHNS-O elemental analyzer abd according to ISO 16948 [48]. Before this analysis, the dried sample was ground with a Retsch SM 100 cutting mill for preliminary size reduction and, thereafter, through a Retsch

ZM 200 rotor mill, reaching a granulometry of 1 mm. Ash content was measured for entire pellets using a Lenton EF11/8B muffle furnace and according to ISO 18122 [49]. The higher heating value (HHV) was determined for entire pellets by means of a Parr 6400 isoperibol calorimeter and according to ISO 18125 [50]. The lower heating value (LHV) was calculated from the higher heating value, depending on the hydrogen content.

2.3. Statistical Analysis

The statistical analysis was entirely conducted in R ver. 3.6.1. The multivariate data analysis was conducted using principal component analysis (PCA) to evaluate the relationships between pellet properties. A cluster analysis was performed using the Ward technique, the aim of which is to achieve hierarchical classification through minimizing the variance of the variables within each group. At each stage, the groups that produce the smallest increase in the total variance within the groups are merged. As the evaluation of the energetic potential of the biomass was a main goal of this study, differences between the LHV of pellets were tested through a One-Way ANOVA at the 0.05 significance level, allowing for an evaluation of the effects of biomass mixing on energetic parameters. The individuation of such differences was subsequently obtained with a post hoc Tukey HSD test, allowing us to compare group means and to define whether the LHV presented significant differences according to the pellet blends.

3. Results and Discussion

Co-pelletization has been considered a reliable way to increase the quality of feedstocks and a detailed characterization of such blends has been conducted to understand whether new emergent properties can improve the pellets' qualities in terms of transport, storage, and energy valorization. The physical and mechanical behaviors resulting from agricultural and woody biomass blending have already been studied [31], indicating that the density of the biomass precursor and blended biomass both increase with a decrease in the feed particle size; for example, a stronger pellet could be produced from a precursor with a smaller particle size range. However, the energetic yield improvement and combustion-related emissions of woody agricultural and forestry blended feedstocks have been less frequently explored in the existing scientific literature.

The results of the conducted compositional and energetic analyses are reported in Table S1. The pellets composed of only citrus and olive prunings are immediately recognizable for their high nitrogen content with respect to the other blends. A high N content variability can be observed when all the blends are considered (N = 0.64 ± 0.58). As evidenced by previous studies, citrus stands out as the primary biomass contributing to this variability, exhibiting values of significantly differing magnitudes. For the pellets' energetic valorization, this N abundance in citrus has been seen as an issue regarding NOx production during combustion [17]. Indeed, the production of nitrogen oxides can stem from various factors. For instance, fuel nitrogen oxidation occurs during combustion when high temperatures lead to the release of nitrogen-containing compounds from biomass. This phenomenon becomes particularly noteworthy at elevated combustion temperatures, facilitating the generation of thermal NOx. Prompt NO formation takes place through a swift and direct pathway in the combustion process, with its primary influences being the availability of oxygen and nitrogen in the combustion environment. Therefore, it is primarily influenced by the combustion conditions. Finally, thermal NO formation results from the reaction between nitrogen and oxygen at high temperatures. This mechanism becomes significant in combustion processes where temperatures exceed 1300 °C [51,52]. The blending of pruning biomasses allows for a decrease in nitrogen content in the final pellet, reducing the possibility of NOx emissions, particularly due to fuel nitrogen oxidation. In fact, even when the Ci percentage was 75%, the N content never exceeded 1%. Through cluster analysis utilizing the Ward method (Figure 2), the pure pellets (Ci-100 and Ol-100, categorized within Group A) were distinctly separated from the remaining blends. Two other primary clusters were identified: Group B and Group C. Group

B primarily comprises mixtures of pellets wherein Ol and Ci were combined with kiwi (Kw) and grapevine (G), while Group C encompasses pellets of Ol and Ci blended with Paulownia (Pw), Poplar (Pp), Eucalyptus (Eu), and Robinia (Ro). Through employing variables such as C, H, N, Ash, and LHV, it becomes feasible to differentiate between pellets sourced solely from the horticultural sector, where fruit crops predominate (agroforestry pellets; Group B), and those derived from forest, urban, or short-rotation tree sources (forestry pellets; Group C).

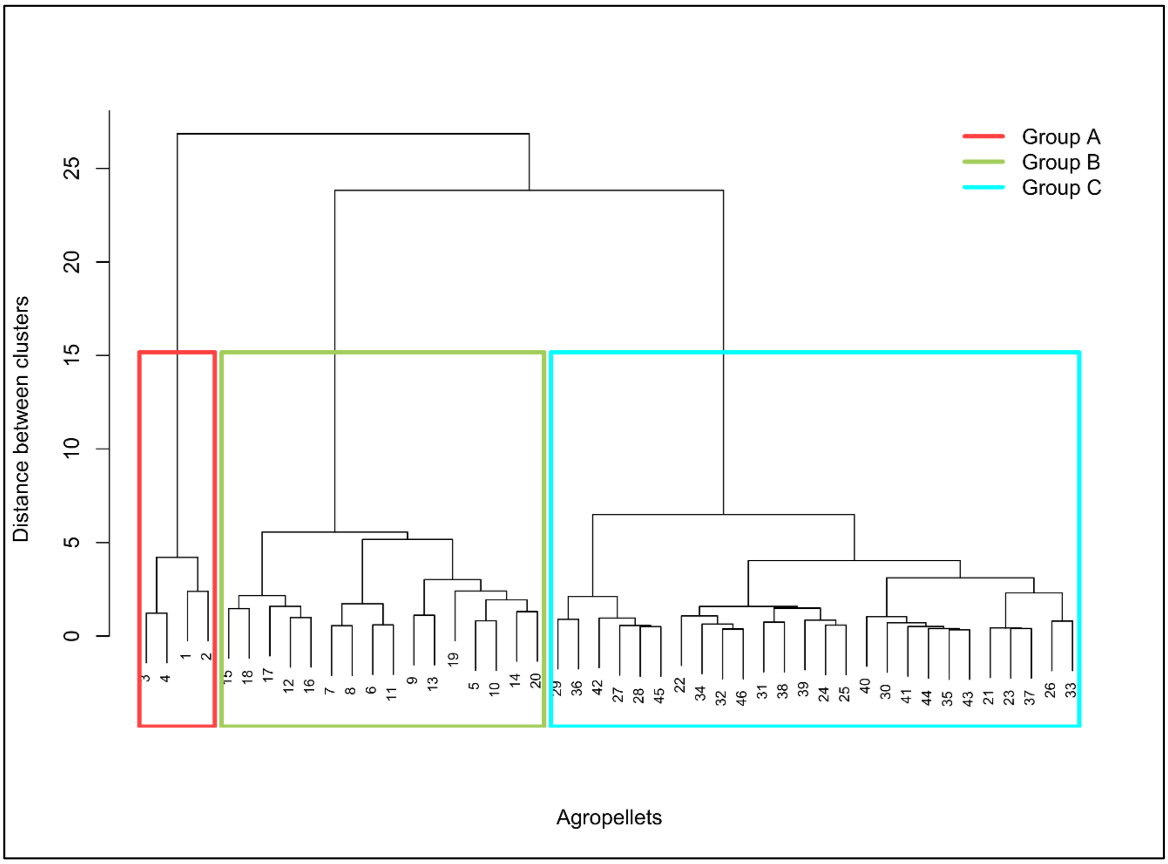

Figure 2. Cluster analysis of the agropellets according to the Ward hierarchical clustering method. The numbers indicated are the ID numbers presented in Table S1 (Supplementary Materials).

When exploring how compositional and energetic variables might impact this hierarchical grouping, the PCA (Figure 3) provided insights into how the pellets are distributed based on these variables. PC1 and PC2 collectively accounted for 82.4% of the variance. Given the primary hypothesis of utilizing Ci and Ol to enhance the energetic yield of lower-grade lignocellulosic biomass, pure pellets of these biomasses naturally positioned themselves in the region of the plot associated with higher LHVs. Additionally, as previously noted, the presence of N significantly influenced the separation of Group A, characterized by a higher N percentage. Group B and C were also differentiated notably in terms of LHVs. Group C (depicted by the blue cloud), comprising forestry pellets, exhibited higher LHVs when blended with Ci and Ol compared to pellets sourced from agroforestry biomasses (depicted by the green cloud). Furthermore, the ash content played a crucial role in distinguishing between Group B and Group C. Specifically, Group C, composed of forestry pellets, was situated in a region opposite to the direction of the ash arrow, indicating lower ash production during combustion compared to the agroforestry pellets.

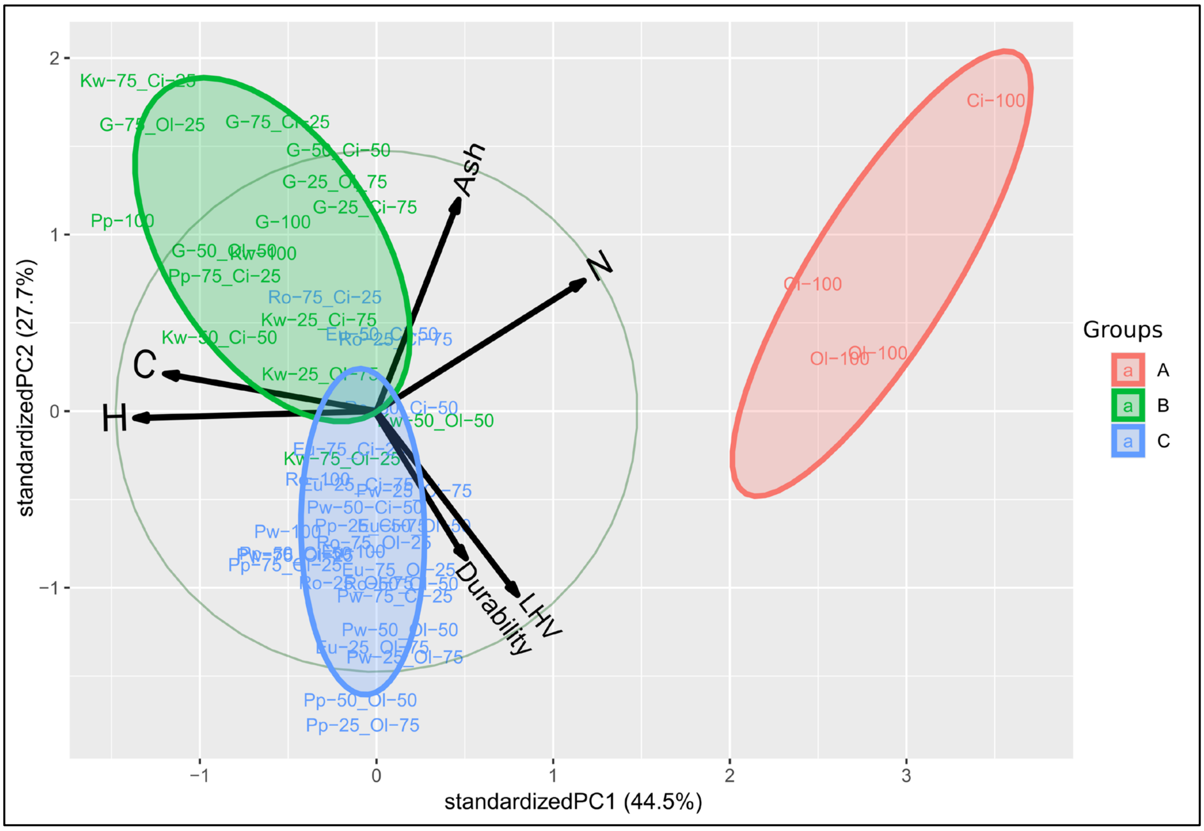

Figure 3. Principal component analysis (PCA) biplot using the C, H, N, ash, durability, and LHV variables. The biplot graph was constructed using the first two principal components, which capture the most significant variance in the data (72%). Groups A, B, and C from the hierarchical analysis are represented in orange, green, and blue, respectively.

To see how the addition of Ol and Ci biomass can improve pellets when lower energetic potential biomasses are also used, an ANOVA was performed on the LHVs and the other variables of the pellet groups with different percentages of Ci and Ol (Figure 4). The pellets composed without Ol or Ci showed the lowest LHVs, while the 100% Ol and Ci pellets presented significantly higher values. When the Ci and Ol percentages increased, the LHVs also increased. Despite a visible positive trend, no statistical significance was detected for the pellet groups containing 25 or 50% Ci and Ol. When a percentage of 75% was reached, the LHVs were significatively higher than in the 0% group, equal to those of the pure Ci and Ol blends. The higher calorific value presented by Ol and Ci can be attributed to various factors. As observed in several studies [53,54], olive and citrus are generally denser than many other woods. The density of wood is directly related to its calorific value: denser woods have more mass per unit volume and, thus, contain more energy. Olive wood, for instance, is known for its high density and hardness, which contribute to its higher energy content during combustion. The chemical composition of olive and citrus wood includes higher concentrations of lignin and extractives compared to other types of wood. Lignin has a higher calorific value than cellulose and hemicellulose, which are the other primary components of wood.

Clear differences between the 0% and 100% groups are noticeable for all other variables, as confirmed statistically. However, the increase in olive and citrus percentages did not result in significant changes, even when reaching 75%. Despite the PCA suggesting a strong correlation between LHV and durability, and despite the similar trend observed for the percentage groups (Figure 4a–f), durability did not exhibit the same level of statistical significance as observed for LHV. As other studies [55,56] have confirmed, there is a strong connection between LHV and compositional analysis, particularly in terms of C, H, and N. The lower ash production of forestry pellets compared to agro-industrial pellets during combustion can be attributed to the fact that forestry residues typically contain lower amounts of minerals compared to agricultural residues. Vamvuka and Zografos [57] have reported that agricultural residues often have higher concentrations of elements such as potassium, chlorine, and silica, which contribute to higher ash formation. Forestry residues, on the other hand, have lower levels of these elements, resulting in less ash during combustion.

The durability of a pellet, unlike its elemental composition, may have a lesser impact on its lower heating value (LHV) due to the nature of the combustion process. While durability affects the physical integrity of the pellet and its ability to withstand handling and transportation, it does not directly influence the chemical composition responsible for energy release during combustion [58]. The primary factors determining LHV are the carbon, hydrogen, and nitrogen contents of the pellet, as previously discussed. These elements undergo chemical reactions with oxygen to release heat energy. In contrast, physical properties such as pellet durability primarily affect the handling and storage characteristics of the pellet, but do not alter its chemical composition and only slightly influence its energy content [59].

Several studies [60–64] have demonstrated that the durability of pellets is closely linked to their lignin content. Lignin is a complex phenolic polymer that provides mechanical resistance to cell walls. Both quantity and composition are important to determine the durability of the pellet. The lignin composition varies between woody species and, therefore, between softwood and hardwood biomasses; in turn, this affects the temperature which, when reached, plasticizes the lignin. This parameter is classified as the glass transition (Tg) that must be reached for plasticization, which affects the temperature at which the biomass plasticizes, also known as the glass transition temperature (Tg). Wolfgang Stelte et al. [65] showed that hardwood lignin tends to contain fewer phenolic hydroxyl groups and more methoxy groups than softwood, which has the effect of decreasing the Tg. Therefore, carrying out the pelletizing process at a temperature of 100 °C for hardwoods results in greater durability due to their stronger bonds compared to softwoods.

Therefore, while durability is important for practical considerations such as storage, transportation, and handling, its impact on the actual energy content of the pellet—as measured according to the LHV—is secondary to its elemental composition. This distinction underscores the importance of considering both chemical and physical properties when evaluating pellet quality and performance.

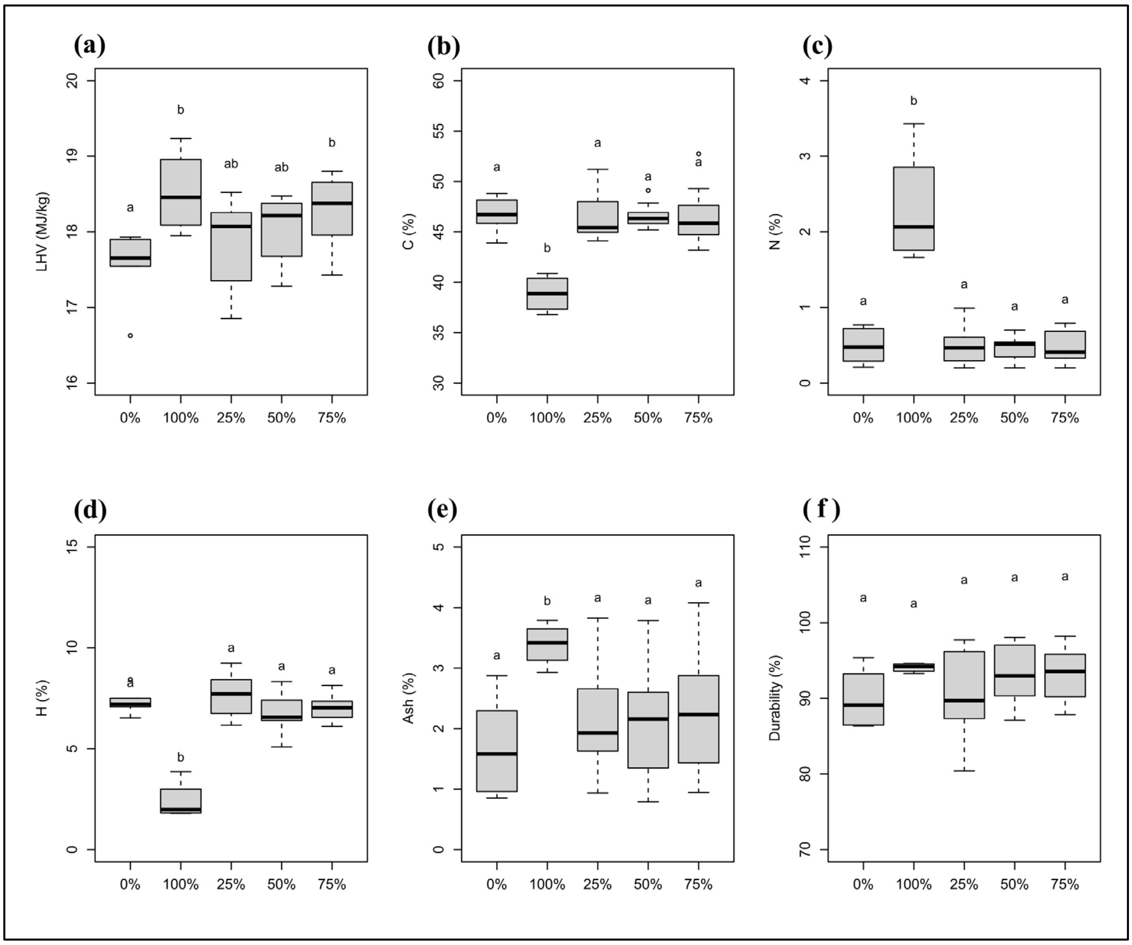

Figure 4. LHV (**a**), C (**b**), N (**c**), H (**d**), ash (**e**), and durability (**f**) boxplots of pellets with different Ol and Ci percentages. Boxes not accompanied by the same letter are significantly different at $p < 0.05$ according to Tukey's HSD test.

4. Conclusions

The comprehensive analysis detailed in this study provided valuable insights into the optimization of biomass blends for enhanced energetic valorization, addressing both compositional and combustion-related challenges. The selection of appropriate agricultural residual resources for energy production is paramount, as this can lead to the development of new biomass materials with emergent properties that are significantly different from those of the original feedstock. This line of research is crucial for advancing economically and environmentally sustainable applications in the field of bioenergy. The composition and energetic yield of woody biomass have also been observed to change during storage, mostly due to cell respiration, biological degradation, and thermo-chemical oxidative reactions [66]. Hence, storage also represents a crucial step in understanding the real potential of woody residual biomasses. Understanding these changes is essential, as storage conditions can significantly impact the real potential of woody residual biomasses for energy production.

In fact, some characteristics of the pellets obtained, such as durability, can change during storage; therefore, it is important that the durability index is high. Most of the pellets obtained in the present study were found to have a suitable and useful durability index (PDI), enabling the handling of pellets during storage and transport operations. The tests carried out in this work indicated that the use of two strong matrices (Ci and Ol) made it possible to develop pellets which improve the quality of agroforestry residues that would otherwise not reach the minimum quality standards for use in industrial pellet-fueled boilers, especially in terms of their durability and LHV. The use of these different combinations of woody matrices did not serve to determine the absolute best pellet in terms of product quality but, rather, to develop a classification for their industrial-scale use, given the high availability of agroforestry wood residues from pruning. Further explorations could involve investigating the specific mechanisms through which Ci and Ol affect combustion emissions and the potential for optimizing blends with different biomass sources for sustainable energy production. This could lead to optimized biomass blends that not only enhance energy output but also minimize environmental impacts. Additionally, considering the environmental implications and economic feasibility of such optimized biomass blends could contribute to the broader discussion on bioenergy utilization. The ongoing research into biomass blends and their properties during storage highlights the importance of selecting appropriate agricultural residues. This approach can foster the creation of innovative biomass materials with improved sustainability profiles, addressing both economic and environmental goals in the realm of bioenergy.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/fire7070239/s1, Table S1: Compositional and energetic characteristics of pellets made with different mixtures of biomass.

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