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Co-Pelletization of Lavender Waste and Pine-Wood for Sustainable Fuel Pellet Production

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Abstract

In the current study, lavender plant (*Lavandula angustifolia* Mill.) waste, as obtained after the essential oils steam distillation process as well as lignocellulose biomass of two of the most common pine species (*Pinus nigra* L., *Pinus brutia* L.), was characterized in terms of chemical composition, moisture, ash content, and calorific value, in order of its potential to be used as feedstock material in pellets production to be assessed, studying different materials ratios. The lavender material was introduced at low percentages (0, 5, 10 and 15% *w*/*w*) in the feedstock of pellets, in order to maintain the total ash content of the mixed feedstock as adequately low-lying, ensuring the classification of pellets in qualitative categories of A1, A2 and B (residential uses, ENplus). The resultant lavender–pine mixed syntheses were densified in a multi-mold pelletizing machine and the pellets were characterized with regard to physical, morphological, mechanical, hygroscopic, and thermal characteristics, based on the limits set by the respective ENplus standards as benchmarks. The results demonstrated that although lavender waste has a high content of ash and extractives compared to wood, it can be used in a mixture (<15% lavender percentage) with pure wood material to produce pellets of adequate quality for residential use. The lavender waste presence favored pellets' mechanical strength, dimensions, hydrophobicity, dimensional stability, bulk density (marginally) and resultant quality of the pellets. Lavender slightly decreased the calorific value of pellets, though without recording a significant adverse impact. The lavender material mixed with black pinewood (at 15%) revealed the best pellets' feedstock performance. The findings exhibited that lavender lignocellulosic residues are suitable for producing high-performance residential pellets, provided that the lavender content does not exceed 15% of the feedstock.

Keywords: biofuel; biomass; fuel; lavender; pellet; pine wood; residue; wood

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1. Introduction

The constantly increasing demand for sustainable energy sources arises from the pressing need to address global challenges, such as climate change, environmental degradation, and the finite nature of traditional fossil fuels. As societies worldwide experience rapid population growth and industrialization, the consumption of energy keeps rising, intensifying concerns about greenhouse gas emissions and the depletion of non-renewable resources [1,2]. In response to conventional energy sources of fossil fuels, there is a growing recognition of the urgency of the transition towards cleaner, renewable energy sources alternatives [3,4]. Wind, solar, hydroelectric and other renewable energy sources such as biomass (including wood and other forest lignocellulosic material waste, agricultural

residues, bioenergy crops, plantations, marine plants, etc.), offer a sustainable and environmentally friendly alternative to conventional energy options [3–7].

As researchers and policymakers seek innovative solutions to meet the increasing energy demands while mitigating environmental concerns, studies investigating the integration of such unconventional biomass into energy production play a pivotal role in shaping the future of sustainable energy. In this context, the exploration of unconventional biomass sources, such as those of aromatic plants and especially lavender biomass waste, obtained as residue from industrial processes, towards their utilization in biofuels and energy production becomes crucial [8].

Lavender constitutes a widely cultivated evergreen aromatic shrub plant of the *Lamiaceae* family, which is typical of southern Europe, particularly the Mediterranean area. Since the flowers of the species *Lavandula angustifolia, Lavandula latifolia* L. [9] and the hybrid *L. angustufolia* X *L. latifolia* can provide desirable essential oils, these species are primarily harvested to be used in essential oil extraction and use in industry applications. As lavender essential oil is used in so many different types of products, it constitutes the most sought-after product to come from the lavender crop [10]. The essential oil derived from lavender accounts globally for around 1500 tons/year [11], used mainly in perfumery, cosmetics, paint and varnish production, etc. [12–14]. Bulgaria and France are the major lavender producers, followed by Russia and several other countries of middle Europe and America, Asia and Australia [15]. Consumer behavior has triggered the increase in demand over the last few years; therefore, farms growing lavender in Europe and other countries outside of Europe have been highly expanded [16,17].

The production of essential oils in distilleries generates a large amount of residual plant solid biomass (distilled straws) that needs to be discarded or managed, increasing the costs for farmers and industries, etc. [18]. It is remarkable that only 2–10% of the total dry biomass of the plant corresponds to oil, indicating that the highest amount of annual residual biomass is discarded after lavender essential oil extraction. These vast quantities of residual mass remain unexploited, usually being abandoned to decompose in the fields adjacent to distillation plants or burnt. This creates an environmental problem, which requires answers that adhere to the idea of sustainable development. In view of the circular economy, it is crucial to recycle and use these lignocellulosic residues optimally into high value-added products, thus generating additional income for essential oil producers and the local community [19].

Fundamental obstacles towards the wide utilization of lignocellulose biomass in energy applications are its density, variability, size, shape, and volume, among others, which further cause feed-handling, storage, and transportation challenges [3,20]. The process of mechanical densification of biomass material via the die channel holes generates pellets, a standardized product of acceptable quality in terms of exceptional consistency, low moisture and ash contents, absence of harmful substances, acceptable calorific value, dimensions, and bulk density, among other properties of interest [21]. Pellets and briquettes are widely used in energy applications, with the overall consumption of wood pellets in 2021 being 23.1 million metric tons [22,23], because of the enhanced physical (size, shape, density), mechanical properties, energetic efficiency, easier feeding, stable flow, consistent quality, and predictable performance, etc., compared to the traditional fuelwood [24]. Lavender waste, in contrast to other lignocellulosic residues (straw, husks, bagasse, grape pomace), contributes a unique biochemical profile to the pellet matrix, containing traces of oils and tannins, as well as a high concentration of volatile chemicals, secondary metabolites, and other components that even after distillation can influence combustion, binding, and even the pellet properties [12,18].

Blending biomass of the lavender plant, among other herbaceous species with pure wood biomass, could overcome the limitations of higher ash content and lower density, carbon, lignin, and heating value of this biomass waste material (compared to wood). Pure lavender material has been previously proposed as a feedstock of fuel pellets, though it presents a high ash content, and an improvement of elemental/proximate composition [25]. Mašán et al. [26] characterized and pelletized six different lignocellulosic materials, among which pure (100%) lavender, which resulted in a marginally acceptable mechanical strength of pellets (96.4–98.8%) and percent of moisture (7.5–11.5%). They concluded that such a material type could be combined with the ordinary materials of solid biofuels, like wood. However, there are no relevant data or information provided in the literature concerning the mixture of lavender waste material and pure wood, their particles potential adhesion and their potential to be used in mixture as solid biofuels feedstock.

Studies on pelleting process characteristics indicated that higher percentages of woody biomass in feedstock blends result in pellets of higher durability and bulk density [25]. Moisture content is a crucial variable affecting density, durability, and overall energy consumption in the densification process [25,27]. Depending on the raw material, optimal moisture content at the time of densification is 10–17%, in order to facilitate the activation of lignin (the glass transition temperature of lignin decreases in such moisture contents), which acts as a binding agent of biomass particles [28,29]. On the contrary, the moisture content of the final product of fuel pellets should be lower than 10%, in order to ensure optimum combustion characteristics and energy efficiency [30]. The biomass chemical composition (e.g., lignin content) and granulometry also influence the quality of densified products. In the course of densification, lignin (23–34% of wood) undergoes a glass transition, while hemicelluloses and extractives (2–25%), like starch and sugars, may act as natural binding agents through polymerization [29]. Additionally, cellulose chain crystallinity may increase, since the pure crystalline regions remain intact, while the cellulose amorphous regions degrade, resulting in an increased affinity between particles [24,31]. The wood extractives, as mentioned by Stelte et al. [32], could weaken the pellets' resistance to compression forces. However, the extractives significantly contribute to the calorific value increase [33]. Żabiński et al. [34] compared the heat of combustion of waste biomass from several herb species, reporting that the heat of combustion varied among the herb species, with lavender to show the highest one (20.47 MJ/kg) [35]. Chakyrova and Doseva [36] reported that the heat generated from lavender waste pyrolysis products covered the process costs (11.3616 MJ/kg) and provided surplus energy (24.624 MJ/kg) for other applications, while direct burning of lavender stalks produced a lower energy output (19.5696 MJ/kg). Therefore, the energetic utilization of lavender lignocellulosic waste not only proven to be environmentally beneficial, but also economically viable. Utilizing a byproduct from the high-value essential oil industrial sector, which chemically differs fundamentally from residues, obtained from food or feed production, due to its unique aromatic profile and chemical composition, renders a novel character to the current work. Furthermore, in contrast to the abrasive quality of other silica-rich residues (rice husk, etc.), the addition of lavender waste may serve as a natural binding enhancer and lubricant during the pelletization process, potentially lowering energy consumption during milling and densification, emitting a pleasant aroma during combustion, and contributing to pellets of superior functional features (easier manufacture, better burning, and pleasant perfume).

In the present study, lavender distillation solid waste (also referred to in the literature as lavender stalks or straws) was characterized and valorized as feedstock material for fuel pellets, in a mixture with wood particles of two softwood species that are commonly used in fuel pellets, namely, Turkish pine and black pine. Pinewood is typically incorporated in pellets because of the satisfying heating value attributed to the presence of resin acids

and higher lignin content [37]. Different material ratios of low lavender waste contents (5–15%) in wood were applied and studied, in order to ensure that the pellets' total amount of ash will be reasonably low to comply with ENplus system [38] requirements. The different feedstock materials were assessed with regard to chemical composition analysis, heating value, ash content, etc. Afterwards, the resultant lavender–pine syntheses were pelletized in a lab horizontal multi-mold pelletizing machine, and the resultant pellets were assessed concerning the physical, morphological, hygroscopic, mechanical, and thermal characteristics, based on the limits set by the respective ENplus standards as benchmarks to evaluate the compliance degree of these different pellets with industrial standards.

2. Materials and Methods

2.1. Feedstock Material Processing and Characterization

In the frame of this research goals fulfillment, two logs of *Pinus brutia* L. (PB) (of around the age of 35 years) and *Pinus nigra* L. (PN) (37 years old) were obtained from AUTh University Campus in the Finikas region (Thessaloniki, North Greece). Due to the young age of the trees, the wood harvested may have been composed highly of juvenile wood, which demonstrates distinct properties. The smaller cut pieces of the logs were organized in the lab environment, where the bark was removed using hand tools, and only defect-free wood material was selected to be used in the current work. A total of 20 disks were obtained from each trunk at different trunk heights (1–2.5 m). Lavender solid residues, obtained after lavender essential oil extraction through a steam distillation process, were provided from the VESSEL MON IKE Biorefinary Company (Neo Rysio, Thessaloniki, Greece) (Figure 1A,B).



(**A**) (**B**) (**C**)

Figure 1. View of the distilled lavender stalks as obtained (**A**), samples of crushed materials (Lavender on the right and black pine on the left) (**B**), and lab pelletizing press (**C**). (Figures were elaborated by the authors of the current work).

All materials were reduced in size using a hammer mill (Laizhou Chengda Machines Co., Ltd., Yantai, China) and sieved using an Endecotts sieve shaker (Endecotts, London, UK) to acquire particles' granulometry of 3 classes (from 0 to 0.5 mm, 0.5 to 1 mm and 1 to 2 mm). Mixtures of 10% of the finest material (0–0.5 mm), 85% of the medium size particles of 0.5–1 mm and 5% of the 1–2 mm particles were prepared, in order to achieve higher cohesion of the pellet material and an acceptable mechanical durability of pellets [29]. In order to guarantee an even and constant raw material flow within the pelletizing multi-mold die, the mixes were appropriately blended by hand for roughly ten minutes each. Both pine wood and lavender particles were allowed to attain a constant weight, placed in a lab air-conditioning chamber at 63 ± 2% relative humidity (rh) and 20 ± 3 °C. The ground-based materials were utilized to ascertain equilibrium moisture content (EMC) using a digital thermo-balance (KERN DAB 100-3, KERN & SOHN GmbH, Balingen, Germany),

applying 4 replications in measurement of each material category. The mean equilibrium moisture content (EMC) values (%) for *P. brutia* wood (PB), *P. nigra* wood (PN) and lavender residual biomass (L) were 9.14 (±0.50), 9.05 (±0.59) and 6.14 (±0.8), respectively.

Concerning the chemical characterization of the raw materials, ASTM D1107-21 [39] was used to investigate the extractives' content, which are soluble in ethanol-toluene mixtures, employing Soxhlet extraction set-ups of 250 mL. An analytical balance, a glass desiccator filled with silica gel, and a lab air drying chamber were also used in the process. Six samples of 2 g served for the assessment of each category of material.

ASTM D1106-96 [40] standard was used to determine the klason lignin content, while three replicates were examined for each material category. Holocellulose content was determined by the following procedure based on previous studies [24,41]. Dry, extractives-free wood material with dimensions of 180–250 μm was used. A total of 1 g of biomass material was exposed to 10 mL of $NaClO_2$ (25%) and placed in a water bath under stable conditions for 5 h (70 °C, pH around 4). Then, the material was filtered and washed with water to eliminate Cl_2, and weighted after drying. This procedure was carried out until a consistent mass was attained. The residual material in the glass flask constitutes the polysaccharides (cellulose and hemicelluloses) of the initial biomass material studied. At least three replications of each material category were carried out, and the related standard deviation and mean value were derived.

The materials' ash content was measured by means of ASTM D1102 [42]. Samples of biomass material of 1 g ± 0.1 mg are placed in dry, pre-weighed porcelain crucibles, transferred to a muffle furnace at room temperature (Heraeus MR 170). They were heated to 250 °C for a duration of 50 min, holding this temperature level for 1 h. The temperature was increased gradually from 250 °C to 550 °C for 1 h, and was kept stable for 3 more hours. The crucibles were placed on a vacant desiccator, lacking a covering for 5 min, then left for 15 min with a fixed covering, prior to being weighed. The standard deviation and mean values were obtained by employing four replicates, respectively.

The lower heating value (LHV) of the studied materials constituted the fuel's useful energy content and was assessed in the current work using a Sundy SDC311 CALORIMETER Bomb (Changsha, China). It was calibrated using a certified reference standard of benzoic acid, in accordance with the manufacturer's instructions. The measurement was based on the sample being completely burned in a bomb calorimeter at high pressure and with oxygen inside [43]. The heat of combustion was measured in the calorimeter by monitoring the temperature rise. A previously densified pellet (pressure of 3000 kg applied) in the form of pill (0.6–1 g) was inserted into the bomb calorimeter, and the electrodes were wrapped with the ends of the ignition wire. An analytical balance with a high precision (±0.0001 g) was used. After being sealed and inflated, the calorimeter was loaded with oxygen (>99.5% pure, 30 bar). The device was loaded with water that was 1 °C colder than the water in the calorimeter jacket. The sample was electrically ignited. Until equilibrium was achieved, the temperature increase in the calorimeter jacket was continuously observed. The temperature at the end was noted. This process was carried out at least three times for every sample in order to guarantee repeatability and statistical significance.

2.2. Feedstock Mixture Preparation—Pellet Production

Wood biomass material was blended with lavender material at variant proportions (lavender percentage of 0%, 5%, 10% and 15% *w*/*w*), in order to keep the amount of ash at low-lying levels fulfilling the demands of standard dealing with solid biofuels (pellets) production that defines an ash content lower than 2% for residential applications, and lower than 3% for industrial applications [30] (Table 1). The syntheses were blended manually for approximately 10 min for each category to make it uniform throughout the mass. In the

current work, an appropriate amount of water was sprayed in the mixtures of shredded wood/lavender materials during the blending process, until the achievement of 15–19% MC, which constitutes an optimum moisture content for biomass densification according to the literature [25,27–29]. The different pellet feedstock materials were then stored in sealed plastic bags to retain this MC level.

Table 1. Mean ash content values (%) of the studied feedstock mixtures of lavender waste biomass (0%, 5%, 10%, 15% participation) with wood of *Pinus nigra* L. (PN) or *Pinus brutia* L (PB).

Lavender Content	*Pinus nigra* L.—PN	*Pinus brutia* L.—PB
0%	0.5	0.7
5%	0.82	1.01
10%	1.15	1.33
15%	1.47	1.64

Pellets were produced, employing a lab-scale horizontal multi-mold/die pelletizing machine of 100 kg h^{-1} output efficiency (Figure 1C). During densification, the biomass particles were pressed (100–200 bar obtained through the friction of the biomass materials with the walls and grinder rollers) through the horizontal die (45 mm thickness) with the grinder rollers of 110 × 45 × 110 mm, working with a gap of 1 mm between the rollers and die. The horizontal die has a working width of 1600 mm and bears 400 channeling holes of 6 mm diameter. Initially, the press was working for 15 min, only pelletizing grains of corn material, until the die becomes adequately greased for the die temperature to approach 100–110 °C, and only then were the studied materials gradually inserted to be pelletized. In total, approximately 6.5 kg for each studied pellet feedstock category was produced. The hot pellets were conditioned at a constant weight (63 ± 2% rh and 20 °C), while the EMC values (%) were investigated based on ISO 18134-1 [44], applying the described methodology: Weighting of pellets, drying them in a heating oven for 24 h at 103 ± 2 °C, placing in a desiccator to allow them to cool at room temperature to avoid any moisture gain, and weighting them again.

2.3. Characterization of Pellets

A representative sample of 50 pellets per category was chosen at random from the developed product. The dimensions of the pellets—that is, their length and diameter—were measured using a Mitutoyo digital caliper (Mitutoyo 500-196-30) with a resolution of 0.01 mm in accordance with ISO 17829 [45].

Since mechanical durability is a reliable indicator of the potential danger of pellet deterioration and fines production during storage and transportation, it is regarded as one of the most essential metrics for evaluating pellet level of quality. Pellets' mechanical durability was assessed using ISO 17831-1 [46] methodology. Two 500 ± 10 g typical pellet samples (Figure 2A) were loaded into the durability testing device's containers (Figure 2B), which rotated for 10 min (which corresponds to 500 circles), resulting in friction and pellet destruction. After the test procedure, the removed, small-grain material was removed from the particles using a sieve with a 3.15 mm hole diameter. The removed fraction of the pellets was then weighed. For each pellet category, two measurements were applied.



(A) (B)

Figure 2. View of mechanical durability samples (**A**) and the respective testing device (**B**) (elaborated by the authors of current work).

The pellets' bulk density was determined by applying ISO 17828 [47]. Two standardized containers (1. diameter of 360 mm and height of 491 mm, 2. diameter of 167 mm and height of 228 mm) were loaded excessively with pellets of each pellet category, and collapsed with a consistent, light vibration exposure, carried out in an identical manner each time. Using a spatula, the pellets that became apparent on the container's top were leveled. As required by the standard, the material's specified moisture content was used to indicate the bulk density, which was derived using the net weight per standard volume. Each pellet category underwent at least two measurements of bulk density.

2.4. Statistical Analysis

Bonferoni and Tamhane's approach in one-way ANOVA analysis (statistical software SPSS Statistics Version 28) was utilized to ascertain the statistically significant differences between the mean values of the characteristics of the various pellet categories. Levene's test, which was used to evaluate the homogeneity of variances, revealed unequal variances, supporting the use of the Tamhane post hoc test. The impact of ash, lignin, polysaccharides (cellulose, hemicelluloses combined), extractives, wood species (black pine/Turkish pine), and percentage of lavender particles (0%, 5%, 10%, 15%) in feedstock material were all examined using a multiple linear regression analysis (f-test) to determine how these factors affected the mechanical strength of the pellets (one of the key properties of pellets). Variance Inflation Factor (VIF) values below 5 indicated acceptable levels of multicollinearity in the model's predictors. The lignin and ash content were found to be the main parameters impacting mechanical strength in the final model, both of which were significant ($p < 0.05$). The significance ($p < 0.05$) and the amount (%) that the aforementioned independent factors had an impact upon the dependent variable (mechanical strength) were investigated using multilinear regression analysis, aiming to identify potential connections between the different attributes and the possibility of optimizing the quality of lavender–wood pellets.

3. Results

3.1. Raw Material Characterization

The chemical analysis results (Figure 3) revealed similar chemical composition of the two different pine species, with the black pine wood demonstrating a significantly higher content of extractives, a lower ash content, a slightly higher lignin content, and slightly lower contents of holocellulose (cellulose and hemicelluloses), compared to Turkish pine wood. The lavender material presented statistically significant higher contents of ash and

extractives and slightly higher holocellulose than the two wood species studied, while the lignin content was measured to be slightly lower (no statistical significance was observed). Respectively, concerning the lavender material, Chakyrova and Doseva [36] reported a lignin content of 25.4 ± 3.2%, a cellulose content of 13.9 ± 3.9%, and a hemicelluloses content of 33.6 ± 5.2%. Pulidori et al. [48] recorded the contents of lignin, cellulose and hemicelluloses of lavender waste material to be 16%, 41% and 23%, respectively. Additionally, Angelova et al. [49] demonstrated the contents of 24.48%, 38.16%, and 14.57% for lignin, cellulose, and hemicelluloses, respectively. Furthermore, regarding the chemical composition of black pine wood, several researchers [50–52] have provided data that comply with the findings of the current study, as well as for the chemical composition of Turkish pine wood [53].

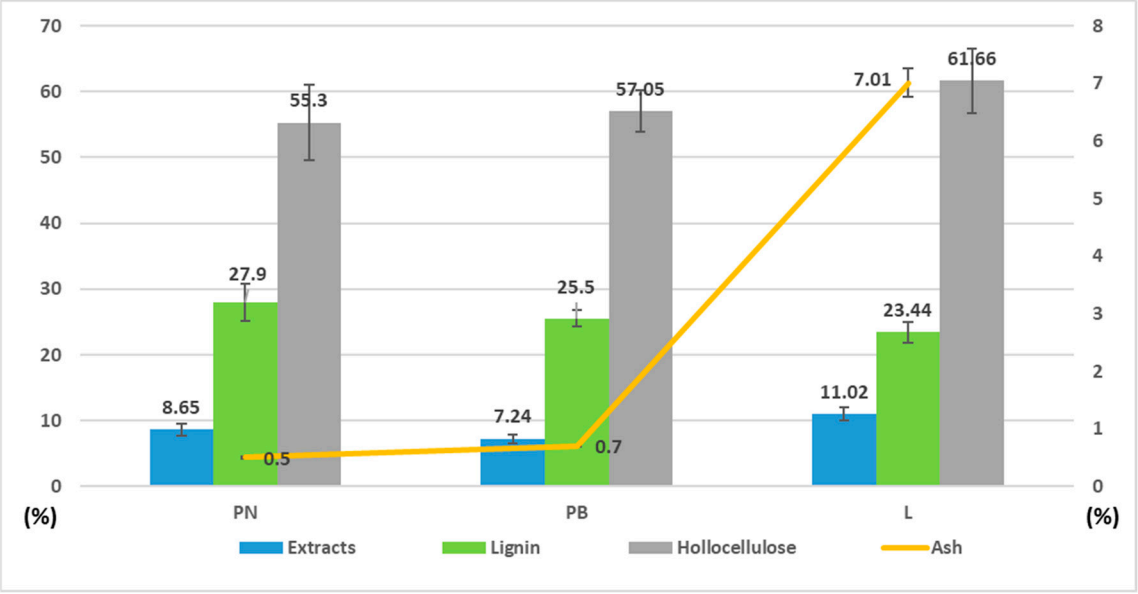


Figure 3. Chemical components (%) (extracts, lignin, holocellulose and ash contents) of PN (*Pinus nigra* L.), PB (*Pinus brutia* L.), and L (lavender waste). The left axis corresponds to all the chemical components, while the right axis corresponds only to ash content values.

Therefore, because of the high ash content, the waste lavender material appeared to be inappropriate to be used as a pure feedstock of fuel pellets production for either industrial or domestic use [30]. Angelova et al. [49] reported a similar (slightly lower) ash content value of lavender straw biomass material (6.59%) compared to the value recorded in the current research (7.01%). Nevertheless, in mixtures of appropriate ratios with types of biomass of lower ash contents, lavender could also be used for the production of higher quality classes: those of A1 and A2 for residential applications. Specifically, the threshold of the A1 class concerning the ash content is 0.7% and the respective value for the A2 class is 1.2% [30]. That is the reason why it was determined in the current research to study the incorporation of lavender material at 0%, 5%, 10% and 15% in the wood mixture with the two pine wood species. Pure wood pellets usually are classified in the best quality category of A1 (a fact that applies to both wood species under consideration). By incorporating lavender material at 5%, 10% and 15%, the produced pellets could be categorized, in terms of ash content, into qualitative categories of domestic uses: those of A1/A2/B, respectively.

The lower heating value (LHV) (known also as the net calorific value) serves as a crucial parameter in evaluating the thermochemical characteristics of various fuels, including biomass. Lavender distillation waste material presented a much lower calorific value (LHV) compared to the material of wood species, which complies with its lower lignin content.

As is apparent in Figure 4, the lavender incorporation in the pellets feedstock material slightly decreased the heating value. Nevertheless, all the studied material mixtures in the current research fulfilled by far the requirements of ISO 18125 [54], regarding the minimum threshold of feedstock LHV (≥16.5 MJ/kg as received) for the best quality of residential applications. The black pine wood presented a slightly higher LHV compared to Turkish pine wood (without marking a statistically significant difference), which is probably attributed to the higher extractives and lignin contents of black pine wood. Concerning the LHV of lavender material after the distillation process, three studies have been detected so far in the literature, reporting 19.6 MJ/kg [51], 20.47 MJ/kg [34] and 15.5 MJ/kg [49], respectively. Respectively, other waste lignocellulosic materials, such as nut shells, also exhibited a high calorific value (20–22 MJ/kg) due to high carbon content and low ash (1–3%), surpassing olive pomace (19–21 MJ/kg) [55]. Rice husk had the lowest value (13–15 MJ/kg) due to excessive silica ash (15–20%) [56], while straws and stovers (leaves and stalks of field crops, such as corn (maize), sorghum, or soybean that are commonly left in a field after harvesting the grain) are limited by alkali ash (K^+, Na^+) causing slagging.

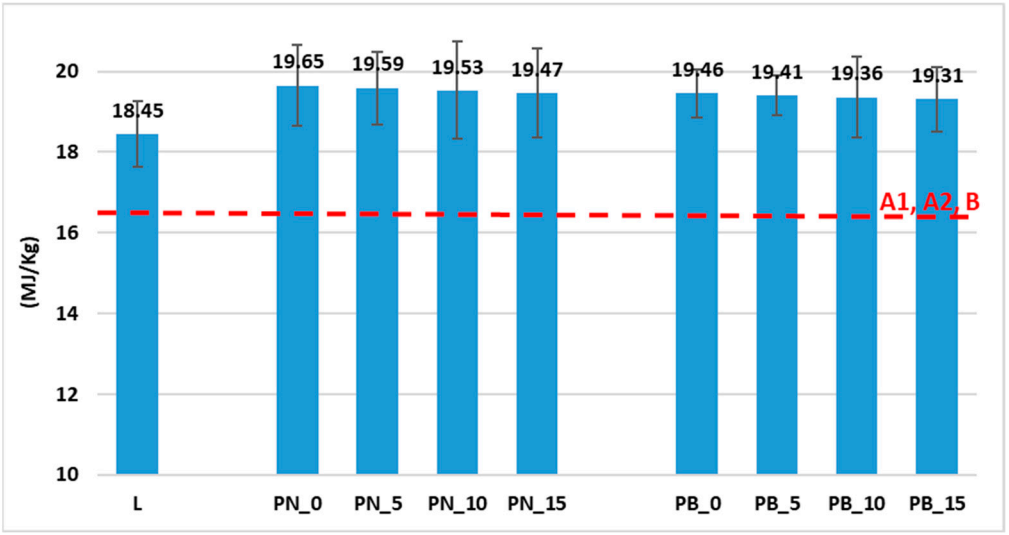
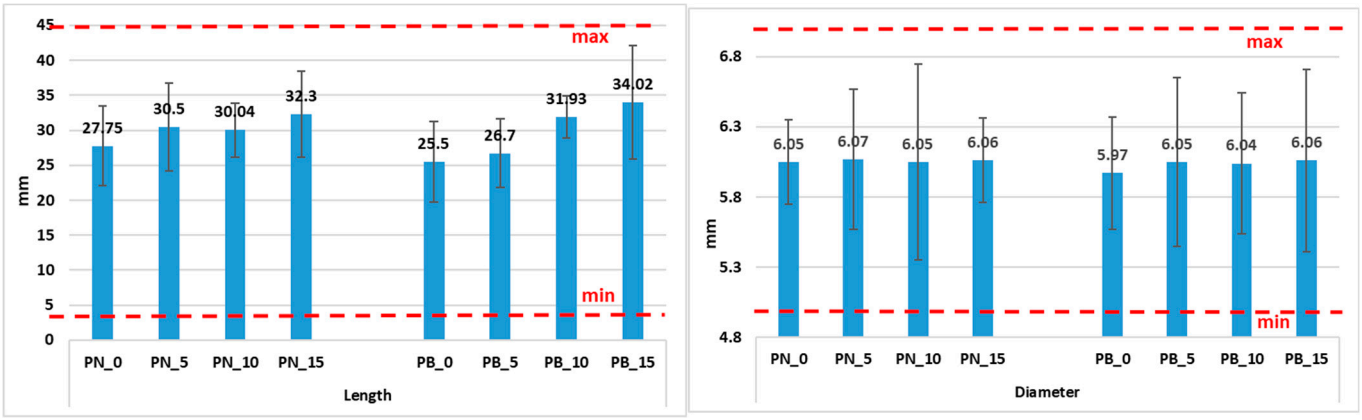


Figure 4. Lower heating value (MJ/Kg) of the raw materials (L: lavender, PN_0: black pine, PB_0: Turkish pine) and their mixtures (PN_5, PN_10, PN_15, PB_5, PB_10, PB_15, which correspond to lavender contents of 5%, 10% and 15%). The red short-dashed line corresponds to the limit of residential applications' qualitative classes of pellets (16.5 MJ/kg) (for pellet categories of A1, A2, B based on the respective standard used, [54]).

3.2. Pellet Characterization

When it comes to combustion, pellet dimensions, both length and diameter, are fundamental. Particularly in tiny furnaces, lower-diameter pellets provide a more consistent combustion rate than higher-diameter ones [57]. The fuel-feeding properties of pellets are influenced by their length; more specifically, the shorter the pellets, the simpler it is to set up a continuous flow. The ISO 17829 [45] standard specifies that for pellets to be classed within the quality classes for domestic use (A1, A2, and B), their diameter and length should fall within the range of 6 ± 1 mm and 3.15–40 mm, correspondingly. The mean length values of the various pellet categories ranged from 25.5 mm to 34.02 mm, as shown in Figure 5A, and were all found to be within the dimensional length restrictions given by the appropriate international standard. More specifically, as the content of lavender waste material in pellets feedstock increased from 0% to 15%, the pellets marked higher length values, though without marking any statistically significant differences, while the PN_15 and PB_15 pellets provided the highest length values in the cases of both wood species,

respectively. The diameter values of the pellets produced from different feedstock materials did not present any significant differences from one another (Figure 5B).



(**A**) (**B**)

Figure 5. Mean length (mm) (**A**) and mean diameter values (mm) (**B**) of the produced pellets (the red dashed lines depict the limit values of residential applications qualitative classes of A1, A2, B, [45]). (L: lavender, PN_0: black pine, PB_0: Turkish pine) and their mixtures (PN_5, PN_10, PN_15, PB_5, PB_10, PB_15, for which the numbers correspond to lavender contents 5%, 10% and 15%, respectively).

The ISO 17831-1 [46] standard specifies that the lowest limit value for pellets' mechanical durability is ≥98% for the highest quality class A1, and 97.5% for the A2 and B quality classes, respectively. All pellet categories prepared in the current work presented mechanical durability values higher than 98.1%, which means that the mechanical durability is high enough for the produced pellets to be classified in the A1 quality class (Figure 6). Nevertheless, the PN_0 pellet samples that correspond to pure black pine wood feedstock marked markedly and statistically significantly lower mechanical durability compared to the other pellet categories that contain lavender waste material at different rates, especially that of the highest lavender content (15%), which marked the highest mean value of mechanical durability. A similar tendency was recorded in the case of the Turkish pine pellet categories. Even though lavender waste contains a higher ash content, which is usually negative for mechanical durability, it greatly improved the wood pellets' mechanical durability and hydrophobicity. In Figure 6, it is obvious that the rise in lavender content favors the mechanical durability of pellets made of the studied feedstock materials ratios and species. This beneficial effect could be attributed to the higher extractives content of lavender material, compared to pure wood, which, when combined with a lignin chemical compound, may act as a binder of the particles of a different nature, exhibiting an improved adherence. When the temperature of the material rises at the time of the pelletization process (>100 °C), some extractives act as a binder of the biomass particles and tend to migrate to the surface of the densified pellet [29] and polymerize there, contributing to the surface modification and the cohesion of pellets [27,58]. Although the high ash content has been associated in several studies with lower particles interbonding and affinity concerning several different biomass-densified material applications, such as wood-based composites [21,59,60], in the current research work, the ash content (higher in lavender waste material) was not found to influence the particles' adhesion or cohesion and therefore, the mechanical durability of the pellets. Although pellets of PB_15 presented the highest value of mechanical durability, significant differences between the mechanical durability values of the two species of black pine and Turkish pine were not recorded. Nevertheless, it is apparent that the lavender waste material incorporation highly favored the mechanical durability of Turkish pinewood pellets, which corresponds to the statistically significant differences

between the strength of PB_0 and the lavender–wood mixture pellets. Under the heat and pressure of pelletization, sticky extractives (resins and waxes) and lignin, that are naturally present in lavender function, can act as excellent binding agents, plasticizing, flowing, and successfully adhering the particles together to form a denser and more resilient matrix that substantially makes up for the inert ash's weakening effect. Some waxy compounds migrate to the pellet surface, forming a smooth, sealed, and water-repellent layer that drastically reduces moisture uptake. As a result, the overall benefits of these waterproofing and binding qualities greatly exceed the drawbacks of the higher ash concentration.

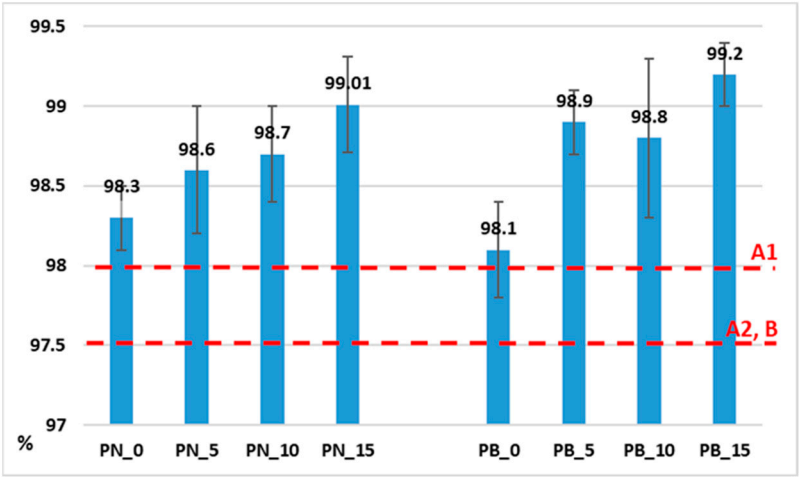


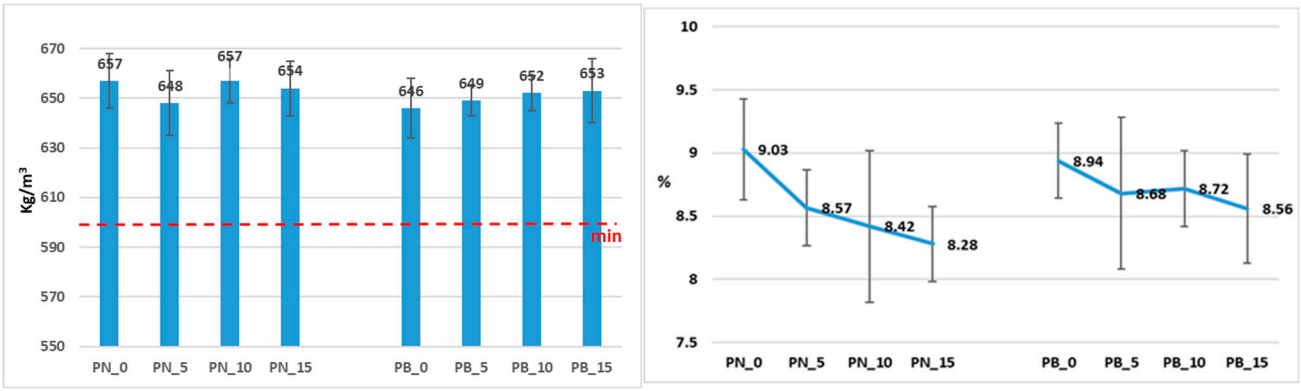
Figure 6. Mean values of mechanical durability (%) of the studied pellets (the red dashed lines depict the qualitative classes' minimum limit values as concerns A1, A2 and B quality classes). (L: lavender, PN_0: black pine, PB_0: Turkish pine) and their mixtures (PN_5, PN_10, PN_15, PB_5, PB_10, PB_15, for which the numbers correspond to lavender contents, 5%, 10% and 15%, respectively).

According to the literature related to other non-wood biomass in pellet production, nut shells (almond, walnut) surpass stovers and straws in terms of durability (96–99%) because of their solid structure and high lignin content (20–30%) [61], and in parallel, nut shells present low ash content (1–3%) and Ca/Mg dominance, decreasing the slagging risks. López et al. [62] attributed the remarkable durability of olive pomace to residual oils, although this could lead to storage problems. Torrefaction is necessary to reduce silica abrasion due to the modest durability (92–96%) of rice husk [63].

Bulk density constitutes an important characteristic of pellets, since it represents the amounts of fuel that may be stored in particular spaces, carried in particular bags, and so on, all of which have an impact on the price of fuel [21,64]. High energy density and large mass to be carried or stored in a container or fixed volume silo are correlated with high bulk density of pellets, which lowers the cost of transportation, processing, and storage in this way [65].

Residential-use pellets should have a bulk density of 600–750 kg/m^3, according to ISO 17828 [47]. As a consequence, all the produced pellet samples have met the requirements of the standard best quality pellets intended for residential applications (Figure 7). The PN_0 pellet category had the highest mean bulk density value of all the feedstock categories, while the PB_0 pellet category had the lowest mean value of bulk density among the samples, despite the fact that significant differences between the mean values of bulk density of different pellet categories have not been recorded. In general, the lavender material addition in pellets' feedstock appeared to slightly influence their bulk density in a positive way, especially in the case of Turkish pine wood feedstock. The slight decrease in the bulk density of pellets between PN_0 and PN_5 has not been explained, since it does not correspond to statistically significant differences. In general, black pine wood demonstrated

slightly higher bulk density values compared to Turkish pine wood feedstock, though without marking statistically significant differences. Respectively, in accordance with López et al. [62] for olive pomace, nut shells have the maximum bulk density (650–750 kg/m^3) because of their homogeneous particle size and low porosity [59]. Due to structural hollows, straw and husk pellets have a low density (<600 kg/m^3) and need densification additives (such as lignosulfonates) [63].



(**A**) (**B**)

Figure 7. Mean bulk density values (kg/m^3) of the studied pellet categories (the red dashed line highlights the quality class's minimum limit value of 600 kg/m^3 for residential-use A1, A2 and B classes). (PN_0: black pine, PB_0: Turkish pine) and their mixtures (PN_5, PN_10, PN_15, PB_5, PB_10, PB_15, for which the numbers correspond to lavender contents 5%, 10% and 15%) (**A**), Mean equilibrium moisture content EMC values (%) of the studied pellets (the red dashed line corresponds to the quality class's maximum threshold value of 10% for residential-use A1, A2 and B classes). (PN_0: black pine, PB_0: Turkish pine) and their mixtures (**B**).

The measurement of mean EMC values of the different pellets' feedstock materials revealed that the presence of lavender slightly decreased the hygroscopic nature of the materials (Figure 7B). This tendency could be attributed to the higher extractives content of lavender, which polymerize in the mass and surface of pellets and the chemical changes induced on the surface layer of the pelletized material. The higher consistency of pellets containing lavender material, due to the potential closer affinity of the particles after densification, a fact proven also by the higher mechanical durability values marked by these categories that contain lavender waste, could also provide an explanation for the lower hygroscopicity of these lavender–wood mixture pellets. However, a statistically significant difference among the EMC values of the produced pellets was presented only in the case of black pine species (PN), between the PN_0 and PN_15. The EMC values of the different raw materials that had been measured before the pelletization process reinforce the perspective that the presence of lavender material may result in less hygroscopic nature and lower the EMC values of the feedstock.

The results of the multiple linear regression analysis of the properties of the raw materials and the produced pellets showed that the chemical composition of the mixture materials with regard to extractives, lignin, polysaccharides (cellulose and hemicelluloses), and ash content values (regarded as independent variables) and the mechanical durability of the pellets (regarded as one of the significant dependent variables) showed a statistically significant (sig. = 0.000) correlation. As the material's temperature rises towards its plasticization level, it is commonly acknowledged that lignin has a tendency to function as an adhesive, binding the various particles together [66,67]. Feedstock materials of higher lignin contents have been reported in the literature to produce pellets that are more abrasion-resistant and mechanically robust [67], which is also supported by the findings of

the current study. Higher mechanical durability of pellets has been associated with higher extractives and lignin content and lower holocellulose content.

As demonstrated in Table 2, a high correlation between the variables is evident when Pearson's r is near to one. It is evident that there was a significant relationship between mechanical durability and the constituents of extracts and lignin (r = 0.907 and r = 0.829, respectively). Consequently, the mechanical durability of pellets was identified to be positively associated with the pellets' extractives content and lignin content, influencing its variability by 90.7% and 82.9%, respectively. Additionally, the mechanical durability of pellets is measured to be associated inversely to the amount of ash and polysaccharides of pellets, influencing their variability by 66.5% and 64.5%. In addition, the lavender waste in the pellets' feedstock appears to affect the mechanical durability by 79.4%, suggesting that as the feedstock content of lavender rises, the mechanical durability of the pellets rises as well. The pellets' durability was also shown to be significantly and inversely associated with their EMC values; however, no correlation has been detected between mechanical durability and other parameters that were studied, such as bulk density.

Table 2. The degree and importance of correlations between the pellet sample characteristics are represented by Pearson correlation coefficients. The significantly correlated values (<0.05) are shown in bold in the second part of the table.

Correl. Coeffic.		Mechan. Durability	Ash	Lignin	Polysaccharides	Extracts	Lavender Percentage
Pearson Correl.	Mechan. Durability	1.000	−0.664	0.829	−0.645	0.907	0.792
	Ash	−0.664	1.000	−0.387	0.316	0.575	0.629
	Lignin	0.829	−0.387	1.000	0.127	0.296	−0.177
	Polysaccharides	−0.645	0.316	0.127	1.000	0.978	0.986
	Extracts	0.907	0.575	0.296	0.978	1.000	0.974
	Lavender Percentage	0.792	0.629	−0.177	0.986	0.974	1.000
Sig.	Mech. Durability	-	**0.009**	**0.002**	**0.001**	**0.000**	**0.001**
	Ash	**0.009**	-	**0.007**	0.159	0.115	0.237
	Lignin	**0.002**	**0.007**	-	0.345	0.175	0.407
	Polysaccharides	**0.001**	0.015	0.045	-	**0.000**	**0.000**
	Extractives	**0.000**	0.115	0.075	**0.000**	-	**0.000**
	Lavender Percentage	**0.001**	0.237	0.017	**0.000**	**0.000**	-

By going beyond the initial extraction of essential oils to attain near-total biomass utilization of the lavender plant, the present utilization approach represents a cascading valorization of lavender and develops a novel circular economy model for the aromatic plant business. Although lavender distillation takes place over a concentrated period of time, the waste is produced as a single, stable batch, which increases the predictability of the supply for pellet production.

The extensive availability of pine residues and the value-adding of lavender cultivation/distillation byproducts make lavender–pine pellets have high scalability potential, especially in Mediterranean areas where both feedstocks are abundantly available. A favorable balance between mechanical durability (>98%) and calorific value (≥18.5 MJ/kg) further enhances their industrial use. According to the current study, the low-lavender (5–15%) pellets fulfill ISO 17225 criteria for residential heating and emit aromatic chemicals that alleviate the need for synthetic additives in pellet production. The combustion performance, in terms of ash, melting behavior, and emissions (e.g., NO_x, SO_x, Cl) constitute critical properties [68] that could be examined in future studies in the frame of the evaluation of the practical suitability of lavender-blended pellets in residential applications.

The process of recycling lavender distillation waste into pellets provides a major positive impact on the environment by keeping agricultural waste out of open burning or

landfills, which lowers air pollution and methane emissions, while promoting a circular bioeconomy. Economically speaking, this technique offsets disposal costs and improves energy independence by turning low-value leftovers into high-demand biomass fuels, which generates an extra revenue stream for lavender growers and distilleries [69]. Additionally, the manufacturing of pellets derived from lavender could promote sustainable farming methods and decrease dependence on fossil fuels, which is consistent with environmental objectives and rural communities' economic resilience [70].

4. Conclusions

The solid residue of the lavender distillation process contains a substantially higher percentage of ash and extracts compared to wood and cannot be used as such (pure 100% lavender) in the production of high-quality pellets, though it could be utilized when blended (at 5–15%) with pine wood material for the production of pellets of residential use. Pellets with 5% lavender were classified into A1 quality class, pellets with 10% lavender into A2 and pellets with 15% lavender into B quality class, respectively, with the ash content to be highlighted as the most critical factor in classification.

The two pines exhibited similar behavior as pellets' feedstock, though black pine wood in most cases ensured a superior pellet performance compared to Turkish pine, which can be attributed to higher extractives and lignin contents, lower ash, and holocellulose contents. However, the lavender waste incorporation mainly benefited the properties and performance of Turkish pinewood pellets. Lavender material substantially favored the quality of pellets, in terms of their mechanical durability, dimensions, EMC, and hydrophobocity, while the bulk density of pellets was marginally improved. The lavender percentage of 15% in pellets induced the highest improvement of the mentioned pellets' properties. The slight increase in pellets' ash content and decrease in calorific value of lavender–wood mixture pellets, induced by the lavender waste incorporation, do not correspond to a statistically significant adverse impact on pellets' quality, given the low lavender portions applied (5–15%).

All things considered, lavender–pine pellets are a scalable and promising bio-based fuel with a lot of prospects for industrial energy applications. They provide a sustainable approach to value forestry and agricultural waste, while advancing the goals of the circular economy in the bioenergy industry.

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