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Combustion of Pelletized Coffee Residues for Bioenergy Valorization Within a Circular Economy Vision

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Abstract: Coffee is one of the most widely consumed beverages in the world; the European Union alone consumes about 2.5 million tons of coffee per year. Yearly, millions of tons of coffee residues are generated, becoming an attractive material for circular economy flows. This study explores the potential of utilizing pelletized coffee residues as sustainable bioenergy sources within the framework of a circular economy. The coffee residues, obtained from damaged capsules and pods from factories, were utilized in pure form or blended with sawdust at different percentages, then analyzed with respect to their physical and thermochemical parameters. The results indicate that unblended coffee residues exhibit favorable combustion properties with respect to heating value (18.84 MJ kg^{-1}), but also high concentrations of N (4.14%) compared to the conventional pellets obtained from other agricultural residues. The blending with woody material negatively affects both durability and bulk density, but simultaneously promotes a reduction in ash content (3.09%) and N content (1.94%). In general, this study confirmed the findings of previous scientific reports, highlighting that at least 50% blending with low-nitrogen biomasses is necessary to reach the marketability of the product. In addition, this study highlighted the criticality in terms of durability that these mixtures confer to the final product, emphasizing that future research should focus on optimizing the combination of these factors to improve the properties of the pellet.

Keywords: blending; pellet; N content; industrial residues; durability

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1. Introduction

One of the major global environmental concerns is the increasing concentration of CO_2 in the atmosphere due to the high use of fossil fuels, driven by the ever-growing global demand for energy [1,2]. It is projected that global energy demand will grow by approximately 1.3% per year between 2020 and 2030 [3]. In recent years, the European Union has increasingly focused on supporting and promoting effective actions to combat climate change. Together with policies aimed at achieving greater energy efficiency, these efforts can foster the development of a more sustainable economic, energy, and environmental system [4]. With the adoption of the new Renewable Energy Directive, RED III [5], mandatory renewable energy targets for member states have been redefined, urging the transition to cleaner energy sources. The main goal of this new European measure, which amends the previous RED II Directive [6], is to achieve a share of energy from renewable sources of 42.5% (up from the previous 32%) of the overall EU energy mix by 2030. Additionally, a climate neutrality target for the EU by 2050 and an intermediate target of a net reduction in greenhouse gas emissions of at least 55% by 2030 have been set [7]. Numerous studies have confirmed the role and usefulness of woody biomass in mitigating pollutant

emissions, reinforcing its status as a reliable and renewable energy source [8–13]. However, woody biomass, whether derived from dedicated energy crops or not, is characterized by low energy density, high moisture content, and heterogeneous geographical distribution, which makes transport costs high and limits its energy use [14,15]. These limitations can be addressed through the pelletization process of the source woody material, optimizing its energy valorization, improving storage, and facilitating the logistics and supply of this solid biofuel as an energy feedstock [16–19]. Consequently, wood pellets have become the most widely used form of biomass for efficient heating. This has led to a growth in pellet production and consumption in Europe by around 20% in recent years [2], with the total demand estimated to reach around 50 million tons per year by 2020 [20]. In 2022, the production of pellets in the 27 EU countries was about 21 million tons [21]. To overcome the rising production costs of wood pellets and the difficulty of sourcing raw materials, extensive research is being conducted on the use of by-products and agricultural waste for the production of agro-pellets, aiming to completely replace wood biomass [22–24]. The agro-industry has seen an increase in the production of residues due to the rapid industrialization of the global economy. Currently, the production of agricultural waste is growing at a rate of 7.5% per year, leading to a global sustainability challenge [25]. If agricultural waste is not treated and managed properly, it emits various greenhouse gasses that further pollute the environment. The agri-food sector, with all its stages—production, processing, consumption, and waste—is responsible for emitting more than 20% of total greenhouse gasses [26,27]. Among the most commonly produced residues by the agri-food sector are wastes from olive (olive pomace), vine, sugar cane, tomato, and coffee processing [24,28–35]. The energy valorization of these residues is crucial for their environmental management. This valorization can be achieved by reintroducing agro-food waste into production cycles, which are the foundation of the circular economy that is becoming increasingly important in the daily lives of societies [36,37].

An interesting opportunity for the energetic valorization of agro-industrial residues derives from coffee [38–40]. Coffee is one of the most widely consumed beverages in the world, representing a commodity of great impact on the environment, health, and the economy [27,38,41]. The production and processing of coffee generates high quantities of both liquid and solid residues, second only to those of the oil industry and similar to those of the olive oil industry [42]. The active ingredient (caffeine) is commonly considered an anthropogenic marker, as it is considerably detected in wastewater treatment plants effluents, surface water, and groundwater [43]. Regarding its availability, recent statistics of the International Coffee Organization suggest that Europe is the largest global consumer of coffee, importing about 32% of the global production and utilizing about 2.5 million tons of coffee beans per year [44]. Considering that methods of coffee extraction use non-destructive approaches [45], as million tons of coffee are used, millions of tons of waste is generated: in Italy, the per capita annual consumption is about 6 kg and over 360,000 tons of coffee grounds are generated, a potentially recoverable raw material that ends up in the waste [46]. However, coffee residues are not just coffee grounds; for instance, big factories of pods and capsules make a discharge of great quantities of freshly ground coffee due to manufacturing defects. This requires an economic effort for disposal and determines environmental pollution if not properly managed [11,23,47].

It has been verified that coffee residues can be utilized for many purposes, especially in the agricultural and energy sector, to produce compost, biochar, and pellet [48–50]. Recent combustion experiences on coffee pellets in Italy displayed a very interesting energy yield and low residual by-product (ash), demonstrating a good potential of coffee grounds to be exploited as biofuel for energy purposes, but at the same time showing some risks due to NOx production [51]. The NOx interacts with water, oxygen, and other chemicals in the atmosphere to form acid rain. Acid rain harms sensitive ecosystems such as lakes and forests [52]. It is displayed in the literature that coffee residues have high N content, and that N content correlates well with NOx emissions during combustion [51,53]. Other studies indicate that the use of blends with coffee grounds is suitable for energy valorization due to

the high calorific value [54,55], optimizing both boiler efficiency and the overall reduction in CO emissions [50]. In addition, Solowiej and Neugebauer (2016) [56] used blends with coffee grounds, rice straw, pine wood, and tea grounds. Therefore, the use of coffee grounds mixed with pruning residues or other residues from forestry/agricultural or industrial practices can provide a quality product to be used for energy purposes. The goal of this paper is to evaluate the most relevant combustion parameters of coffee residues as fresh powder obtained from defected capsules and pods, in pure form or blended in different percentages with a low-nitrogen-content sawdust. With respect to the available literature, deeper attention has been paid to the balancing between physical and chemical parameters, which is key to identifying the ideal compromise to reach marketability standards. In addition, fresh wasted coffee powder was used for the first time in its pure form and in a blended solution with *Ecalyptus* spp. The products obtained have been classified according to European standards and have been compared with similar studies in order to enrich the scientific knowledge on coffee waste valorization perspectives.

2. Materials and Methods

The pellet was produced using a 4 kW Bianco Line pellet machine, utilizing waste coffee powders obtained from damaged and unused capsules or pods (Figure 1). The initial moisture content of the material was 7% (P7), and the first test was conducted on this pure feedstock. Subsequently, the moisture content was increased to 11% by uniformly adding water, with the samples left to stabilize for 24 h. This percentage was chosen based on a literature review, which indicated that a moisture content of 10–11% in biomass facilitates densification during pelletizing, efficiency combustion, and a reduction in emissions, and enhances the durability during storage. Additionally, this moisture level minimizes energy consumption during production by balancing the need for lubrication and the binding properties of the material [57]. In total, five types of pellets were prepared:

- Coffee with a 7% moisture content (P7);
- Coffee with a 9% moisture content (P9);
- Coffee with a 11% moisture content (P11);
- A mix of 75% coffee and 25% *Eucalyptus* spp. (*Eucalyptus* (L'Hér., 1789)) with a 11% moisture content (P11M25);
- A mix of 50% coffee and 50% *Eucalyptus* spp. (*Eucalyptus* (L'Hér., 1789)) with a 11% of moisture content (P11M50).

Figure 1. Example of pellet produced with pure coffee ground with 7% (**a**), 9% (**b**), 11% (**c**) of moisture content and mixed pellet with 25% (**d**) and 50% (**e**) of *Eucalyptus* spp. sawdust.

The pelletizing tests were carried out in September 2024, at the CREA IT headquarters in Monterotondo (Rome) (42°06′05″ N, 12°37′37″ E). The coffee waste and eucalyptus sawdust were collected in January 2024 and March 2023, respectively, and the raw material was stored in our laboratories in jute bags until pelletizing (Figure 2).

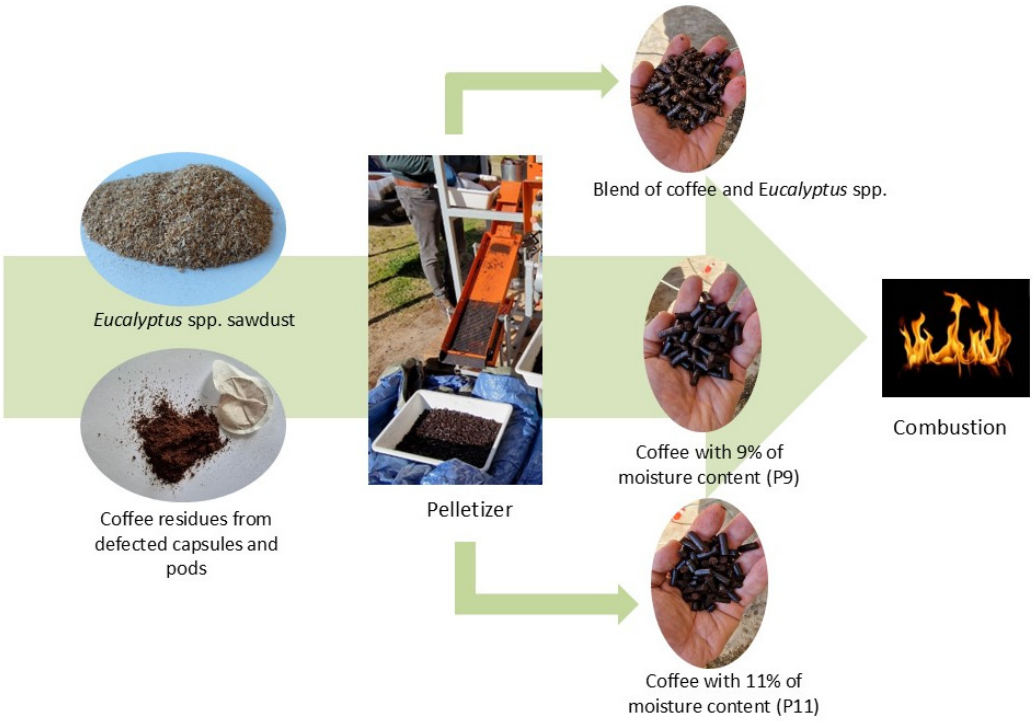

Figure 2. Flowchart from raw material to energy generation.

The characteristics of the biomass were carried out by evaluating the moisture content (3 samples per pellet); the bulk density and durability (10 repetitions per pellet); the length, weight, and diameter (40–50 repetitions per pellet); the ash content; the heating value; the nitrogen; and the chlorine and the sulfur (3 repetitions per pellet). The analytical methodologies used in accordance with industry standards were described below:

Moisture content: This procedure determined the moisture content in the solid biofuels by weighing and heating the samples in an oven at 105 °C until a constant mass was achieved. A reference tray was used to correct for the buoyancy effect due to the weight difference between the hot and cold trays. After heating, the trays were weighed quickly to avoid moisture absorption. The moisture content, calculated on a wet basis, was expressed as the average of the two measurements and rounded to the nearest tenth of a percentage point. For the pre-dried samples, the formula accounted for both the moisture loss during pre-drying and the residual moisture measured. This was in accordance with EN ISO 18134-1:2015 [58];

Bulk density: The bulk density of the sample was calculated by filling the container with the material, pouring it from a height of 200–300 mm, and applying three controlled drops by allowing it to fall from 150 mm. After leveling the material with a straightedge, the filled container was weighed. At least two measurements were made to obtain an average. The bulk density on a wet and dry basis was calculated, and for the dry basis, the moisture content was considered. This was in accordance with EN ISO 17828:2016 [59];

Durability: The procedure for testing the mechanical durability of the pellets involved tumbling a 500 g test portion in a designated device for 500 rotations, followed by sieving to remove the fine particles. The durability was calculated by comparing the pellet mass before and after treatment, expressed as the average of two duplicate tests. To ensure accuracy, repeatability, and reproducibility, limits were respected in the results. This was in accordance with EN ISO 17831-1:2016 [60];

Length, weight and diameter: To determine the diameter class, the diameter of 10 pellets was measured with a caliper, and the average was calculated, assigning it to the closest class according to ISO 17225-2 [61]. For length, each pellet in a 40–50 pellet sample was measured in millimeters and recorded. For weight, each pellet in a 40 pellet sample was measured with a lab scale. Finally, the mean value and standard deviation for the diameter,

weight, and length were calculated and reported to the nearest 0.1 mm. The standards used for length and diameter followed the ISO 17829:2016 [62], while the standards for the weight measurement standards were not identified;

Ash content: the analysis sample, at least 1 g, was weighed in the dish and spread evenly. For combustion, the dish was heated in a furnace, first reaching 250 °C in 30–50 min and maintaining this temperature for 60 min to release volatiles. Then, the temperature was increased to 550 ± 10 °C over 30 min and maintained for at least 120 min. Subsequently, the dish was cooled and weighed again to determine the ash content. In case of incomplete incineration (e.g., presence of soot), combustion was repeated at 550 °C for additional 30 min periods, optionally adding distilled water or an ammonium nitrate solution to facilitate incineration. The ash content on a dry basis was calculated with a specific formula, considering the weight of the empty dish, the weight of the dish with the sample, and the weight of the dish with the ashes, and including the moisture content of the sample. This was in accordance with EN ISO 18122:2016 [63];

Heating value: The biofuel sample had to be prepared and ground (with particle sizes up to a maximum of 1 mm) and ideally tested in pellets weighing 1.0 ± 0.2 g. To determine the calorific value, the procedure required two calorimetric experiments—one with benzoic acid (as a calibration standard) and one with the biofuel, both conducted under identical conditions to minimize systematic errors. Combustion took place in high-pressure oxygen (30.0 ± 2.0 bar) inside the bomb, which was then placed in the calorimeter. The temperature was measured in three phases (before, during, and after combustion) to account for any heat losses. At the end, the residues were analyzed to verify complete combustion, and corrections were applied to precisely determine the calorific value of the sample. This was in accordance with EN ISO 18125:2018 [64];

Content of N: The procedure for biofuel analysis consisted of three steps. First, the test portion of the sample, containing carbon, hydrogen, and nitrogen, was weighed to a precision of 0.1% and placed in a suitable container. Second, instrument calibration was performed according to the manufacturer's instructions, using certified reference materials and control samples to create control charts and ensure the required measurement uncertainty. Third, the samples were analyzed, and regular calibration checks were necessary during the analysis using reference substances to maintain instrument accuracy. Calibration samples, control samples, and recalibration were repeated for each sample batch. Any deviations greater than 10% indicated a possible instrument malfunction. This was in accordance with EN ISO 16948:2015 [65];

Determination of total Cl and S: The procedure for the analysis of biofuels began with the preparation of the sample, which must have had a nominal granulometry of a maximum of 1 mm and been decomposed through combustion in a closed bomb or digestion in a closed vessel. As already described in the method for determining the higher heating value at the end of the combustion, the residues and gasses were collected in a flask for analysis. The preferred detection method was ion chromatography, possibly filtering the solution. For calibration, it was necessary to establish a calibration function following the manufacturer's instructions, verify precision with the reference materials, and maintain quality control schemes. This was in accordance with EN ISO 16994:2017 [66].

The different types of pellets have been certified in accordance with the EN 17225-6:2021 regulation about non-woody pellets [67], as suggested by Bottani et al. 2019 [68]. The laboratory equipment used for chemical and energy analyses has been the following: a LECO AC600 calorimeter (LECO Corporation, St. Joseph, MI, USA) for the heating value, a LECO Thermogravimetric Analyzer 801 (LECO Corporation, St. Joseph, MI, USA) for the ash content, a 761 Compact Ion Chromatograph (Metrohm, Herisau, Switzerland) for the sulfur and chlorine, and a TruSpec Micro CHN analyzer (LECO Corporation, St. Joseph, MI, USA) for the nitrogen.

Statistical Analysis

The collected data were statistically analyzed using Jamovi version 2.2.5-1.6 (New Zealand). A one-way ANOVA followed by Fisher's post hoc test was conducted to evaluate the statistically significant differences in the pellet characteristics across the different types. For the data that violated the assumption of homoscedasticity, the Welch F-test was applied, followed by Games–Howell post hoc comparisons. In cases where the normality assumption was not satisfied, a non-parametric Kruskal–Wallis test was used, with Dwass–Steel–Critchlow–Fligner pairwise comparisons and comparisons corrections. Down below, a summarizing table of the statistical tests utilized can be found (Table 1).

Table 1. List of the statistical tests utilized to study the pellet parameters. Data with non-normal distributions (length, Cl, S) were analyzed using the non-parametric Kruskal–Wallis test, while a one-way ANOVA was applied to the normally distributed data with homogeneous variances (ash, weight, N). For the variables with normally distributed data but non-homogeneous variances (diameter, bulk density, durability, and LHV), the Welch F-test was used.

Parameter	Statistical Test Utilized
Weight	One-Way Anova—Fisher's and Tukey post hoc
Lengths	Kruskal–Wallis and Dwass–Steel–Critchlow–Fligner pairwise comparisons corrected
Diameter	Welch's F test and Games–Howell post hoc test
Bulk density	Welch's F test and Games–Howell post hoc test
Durability	Welch's F test and Games–Howell post hoc test
LHV	Welch's F test and Games–Howell post hoc test
Ash	One-Way Anova—Fisher's and Tukey post hoc
Cl	Kruskal–Wallis and Dwass–Steel–Critchlow–Fligner pairwise comparisons corrected
S	Kruskal–Wallis and Dwass–Steel–Critchlow–Fligner pairwise comparisons corrected
N	One-Way Anova—Fisher's and Tukey post hoc

Welch-F Test is a variant of the ANOVA test used to compare the means of multiple groups without the assumption of equal variances, providing greater robustness under conditions of heterogeneity [69]. Kruskal–Wallis Test is an alternative to ANOVA, useful for comparing the means of groups with non-normal distributions [70]. The post hoc tests used for each analysis allowed for identifying specific differences between the groups: Fisher's test is useful when sample sizes are small [71]; the Games–Howell test is particularly suited when variances are unequal [72]; the Dwass–Steel–Critchlow–Fligner test is ideal for comparing groups without the assumption of normal distributions [73].

3. Results

Physical, Mechanical, Chemical, and Energy Characteristics of the Pellets

Table 2 shows the results of the parameters analyzed with respect to the pellet length, the diameter, the bulk density, the durability, the low heating value, ash, Cl, S, and N.

The data exhibited variability depending on the type of pellet under investigation and the moisture content of the biomass prior to pelletizing. The mean weight of the cylinder ranged from 0.51 g of P11M50 to 0.63 g of P9 and the lengths ranged from 17.51 mm for coffee P11M50 to 24.66 mm for P11, while the diameters varied between 6.10 mm (P11M50) and 6.4 mm (P9). The bulk density of P11M25 and P11M50 was below 600 kg m^{-3}, whereas the pure coffee pellets consistently exceeded this threshold, with the highest value slightly surpassing 700 kg m^{-3} for P7.

Table 2. Length, diameter, bulk density, mechanical durability, low heating value, ash content, chlorine, sulfur and nitrogen of different types of pellets produced.

Pellet	Mean Weight of One Pellet (g)	Length (mm)	Diameter (mm)	Bulk Density (kg m^{-3})	Durability (%)	LHV (MJ kg^{-1})	Ash (%)	Cl (%)	S (%)	N (%)
P7	0.54 [a1] ± 0.14	20.24 [a1] ± 1.85	6.23 [b] ± 0.11	706 [d] ± 24	81.15 [a] ± 8.80	18.84 [b] ± 0.03	4.66 [c] ± 0.09	0.015 [a] ± 0.00	0.080 [a] ± 0.03	4.14 [c] ± 0.02
P9	0.63 [a] ± 0.14	23.47 [b] ± 2.74	6.40 [c] ± 0.11	639 [c] ± 9	95.68 [b] ± 1.15	18.84 [b] ± 0.03	4.66 [c] ± 0.09	0.015 [a] ± 0.00	0.080 [a] ± 0.03	4.14 [c] ± 0.02
P11	0.56 [a] ± 0.9	24.66 [b] ± 2.80	6.29 [b] ± 0.13	602 [b] ± 9	97.09 [c] ± 0.42	18.84 [b] ± 0.03	4.66 [c] ± 0.09	0.015 [a] ± 0.00	0.080 [a] ± 0.03	4.14 [c] ± 0.02
P11M25	0.53 [a] ± 0.15	23.10 [b] ± 2.69	6.22 [ab] ± 0.20	567 [a] ± 10	94.90 [b] ± 0.93	18.32 [b] ± 0.38	3.94 [b] ± 0.06	0.008 [a] ± 0.00	0.016 [a] ± 0.00	2.96 [b] ± 0.06
P11M50	0.51 [a] ± 0.9	17.51 [a] ± 6.18	6.12 [a] ± 0.12	566 [a] ± 12	94.41 [b] ± 1.17	17.44 [a] ± 0.08	3.09 [a] ± 0.10	0.005 [a] ± 0.00	0.011 [a] ± 0.00	1.96 [a] ± 0.09

[1] Different letters indicate statistical significant differences among the pellets analyzed for each parameter considered.

Regarding durability, all the produced pellets exhibited values below 97.10%. For the chemical and energy parameters, only three types of products were compared, as the original material of P11 was the same as P7 and P9. The ash content ranged from 3.09% for P11M50 to 4.66% in P11, while the calorific value was above 17.44 MJ kg^{-1}.

Laboratory analyses of the chemical elements indicated chlorine contents of 0.015%, 0.008%, and 0.005% for P11, P11M25, and P11M50, respectively; sulfur contents of 0.08%, 0.016%, and 0.011%; and nitrogen contents of 4.14%, 2.96%, and 1.96%. Statistically, excluding sulfur and chlorine content, all the other parameters showed significant differences between two or more pellet types.

Specifically, for the physical parameters, the lengths of P7 and P11M50 differed significantly from P9, P11, and P11M25. For the diameter, no significant differences were observed between P7, P11, P11M25, and between P11M25 and P11M50. The bulk density of coffee mixed with eucalyptus differed from those made of pure coffee. The durability did not significantly differ between P9, P11M25, and P11M50. Finally, the ash and nitrogen contents differed significantly across all the treatments, while the calorific value between P11 and P11M25 had no significant differences.

The correlation between the physical parameters was examined using Pearson's test (Figure 3 and Table 3). Specifically, positive correlations were identified between the diameter and the length and between the diameter and the bulk density, while the bulk density and the durability were negatively correlated.

Table 3. Pearson's correlation displayed with confidence interval.

	Diameter	Length	Bulk d.	Durability
Diameter				
Length	0.181 *			
Bulk d.	0.312 *	0.044		
Durability	0.065	0.230	−0.645 **	

* $p < 0.05$, ** $p < 0.01$.

As can be seen, pellets P7, P9, and P11M25 faced simultaneous issues with durability and nitrogen, while P11 and P11M50 were penalized for only one of the parameters: nitrogen for P11 and durability for P11M50. The latter could therefore be considered qualitatively superior to the other types, as environmental aspects should prevail over purely mechanical considerations.

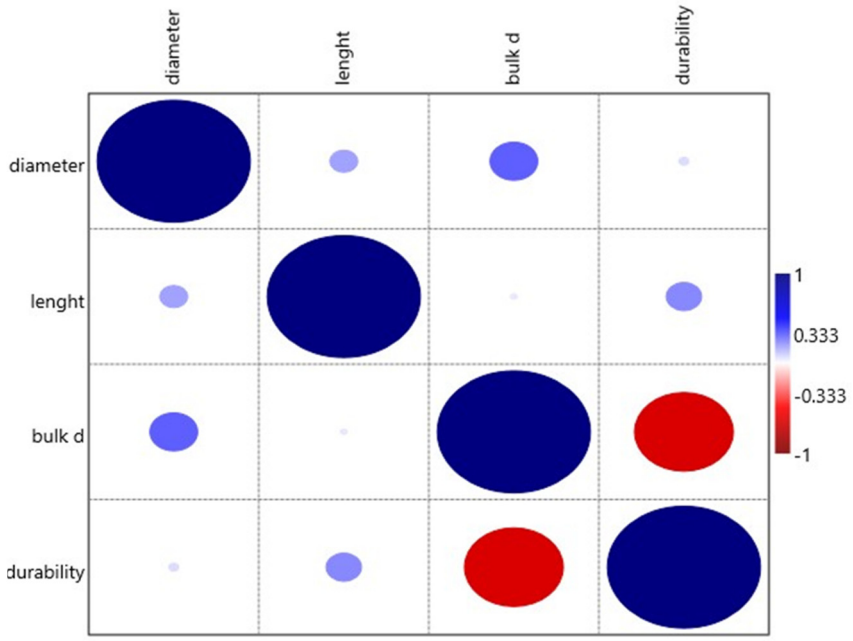

Figure 3. Pearson's correlation test related to the physical parameters.

Table 4 highlights the compliance of the measured parameters with the reference values established by the 17225-6 standard.

Table 4. Classification of parameters according to the regulation 17225-6.

	P7	P9	P11	P11M25	P11M50
Moisture	A	A	A	A	A
Diameter	A	A	A	A	A
Length	A	A	A	A	A
Bulk d.	A	A	A	B	B
Durability	X	X	B	X	X
Ash	A	A	A	A	A
LHV	A	A	A	A	A
N	X	X	X	X	B
S	A	A	A	A	A
Cl	A	A	A	A	A

A, B: pellet quality classes corresponding to the reference quality standards; X: pellet not corresponding to the reference quality standards.

4. Discussion

The physical and chemical parameters of the pellets analyzed were indeed influenced by factors such as machinery type, biomass type, and initial moisture content. For in-stance, a study on the mechanical properties of Khaya senegalensis biomass energy pellets highlighted how the pelletizing temperature and pressure significantly affect pellet durability and compressive strength [74]. Another research article discusses the impact of the physical and mechanical properties of biomass wood pellets on energy release and carbon emissions, emphasizing the role of moisture content and pellet dimensions [75].

In terms of pellet durability, the best results were achieved at the highest moisture content, with the P11 reaching a value just below the 97.5% threshold required for Class A. Conversely, regarding bulk density, the trend was the opposite, with the highest value (700 kg m^{-3}) obtained at the lowest moisture percentage (P7). The bulk density obtained with 11% moisture (P11) was still above the regulatory limit of 600 kg m^{-3}. In this regard, [76] highlighted that increasing the coffee content resulted in a corresponding increase in the HHV and apparent density, suggesting the improved compactness and density

of the pellets. Similarly, mechanical durability exhibited an upward trend with higher coffee content.

The relationship between bulk density and durability is complex and varies depending on the materials and processing conditions used: excessive densification can alter the internal structure of a material, reducing its cohesion [77]; a high bulk density may result from excessively low moisture content, which weakens the binding between pellets; furthermore, suboptimal densification may lead to alterations in lignin distribution [78]. Theoretically, a higher apparent density should correspond to a more durable pellet; however, these two parameters are negatively correlated, as evidenced by the Pearson's correlation test. Other research has shown that higher bulk density does not always result in improved durability [79–84].

In this study, chemical characterization included the analysis of elements such as Cl, S, and N. The investigation of these elements in biomass is required from the standards for commercialization because the combustion of material containing Cl, S, and N is risky for human health and environment. For instance, chlorine can form hydrochloric acid (HCl) and dioxins, and sulfur can form sulfur oxides (SO_x), such as sulfur dioxide (SO_2), while nitrogen can for nitrogen oxides (NO_x) and carbon monoxide (CO). These compounds are harmful to human health, causing respiratory issues and other illnesses, but is also risky for the environment [85]. In addition, in the case of coffee residues (with an of origin of a berry seed) it is important to evaluate such parameters because it is a non-conventional biomass source and because the process of manufacturing can vary from country to country, with possible risks of contamination. The high nitrogen content found in the analyzed samples poses a significant limitation for the use of pure coffee pellets due to its associated NO_x and CO emissions [86,87]. Consequently, pure coffee grounds and biofuel blends with significant coffee content cannot be considered a safe green fuel [88]. In this study, the nitrogen content was over 4%, prompting the creation of two blends with eucalyptus at 25% and 50%. The eucalyptus, sourced from a medium-term cultivation of six years, exhibited a relatively low nitrogen content of approximately 0.20%. Nevertheless, only the 50% blend reduced the nitrogen content to levels below 2%, the threshold required to classify the material in Class B. To achieve the requirements for Class A, approximately 70% *Eucalyptus* would have been necessary. Additionally, the study analyzed the presence of Cl and S, but their presence was very low, indicating that coffee beans do not naturally contain these elements or were not contaminated.

Other authors studying the use of coffee grounds as fuel have utilized blends with coffee content varying from 30% upwards [86,89]. In this context, the contribution of Kougioumtzis et al. (2024) [38] enabled the evaluation of various mixtures of coffee residues with other residual biomasses such as forest residues, wood processing industry residues, urban pruning, corn residues, peach pruning, etc. The authors highlighted that the nitrogen content for 50% blending was between 1.83 and 2.3%. Our study is in line with these results, showed a value of nitrogen of 1.96% for 50% blending. In another study, Park et al. (2020) [89] produced pellets with 50% coffee grounds and 50% agricultural residues, examining various properties of the pellets and noting a nitrogen content ranging from 1.1% to 1.4%.

Nosek et al. (2020) [39] examined the influence of coffee ground content on the elemental composition of pellets produced from pine sawdust. The results reported significant changes in their carbon, hydrogen, and nitrogen content, obtained by varying the proportions of coffee grounds in the pellets. Specifically, as the coffee grounds content increased from 30% to 70%, there was an increase in both the carbon and hydrogen content of the pellets, while the nitrogen content showed a decreasing trend with higher coffee grounds content. In a study conducted by Allesina et al. (2017) [49], the use of coffee grounds in pellet production was examined, focusing on mixtures with spruce and pine sawdust. Pellets composed of 50% coffee grounds and 50% spruce mixture showed a nitrogen content of 2.22% and an ash content of 2.2%.

Limits of the Study

The primary limitation of this study lies in the restricted number of blends and feedstock types utilized for blending. This constraint was primarily due to the extensive number of analyses required and the associated costs. While the selected blends provided valuable insights, a broader range of feedstock could potentially yield more comprehensive results. Future research should aim to include a wider variety of blends to enhance the generalizability of the findings and provide a more robust understanding of the effects of different feedstock combinations.

5. Conclusions

The present study investigated the potential of utilizing pelletized unspent coffee powder, and wood–coffee mixtures as sustainable bioenergy sources within the framework of a circular economy. This study shows that blending woody material with coffee residues negatively affects both durability and bulk density, but simultaneously promotes a reduction in the ash content until 30% and the N content for more than 50%. An acceptable level of N (1.96%) can be reached by blending 50% the coffee with sawdust, but durability in such a condition is compromised, determining its unmarketability. On the other hand, durability is a parameter that, in a practical way, can be easily adjusted by using some natural binding additives such as starch. In addition, as cited in the Section 4, other biomasses such as forest residues, industrial residues, urban pruning, maize residues, peach pruning, etc. can be used successfully in similar blending percentages to reach acceptable quantity of N.

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References

1. Kizuka, R.; Ishii, K.; Sato, M.; Fujiyama, A. Characteristics of wood pellets mixed with torrefied rice straw as a biomass fuel. *Int. J. Energy Environ. Eng.* **2019**, *10*, 357–365. [CrossRef]
2. Padilla-Rivera, A.; Barrette, J.; Blanchet, P.; Thiffault, E. Environmental Performance of Eastern Canadian Wood Pellets as Measured Through Life Cycle Assessment. *Forests* **2017**, *8*, 352. [CrossRef]
3. Jezerska, L.; Sassmanova, V.; Prokes, R.; Gelnar, D. The pelletization and torrefaction of coffee grounds, garden chaff and rapeseed straw. *Renew. Energy* **2023**, *210*, 346–354. [CrossRef]
4. Sperandio, G.; Suardi, A.; Acampora, A.; Civitarese, V. Environmental Sustainability of Heat Produced by Poplar Short-Rotation Coppice (SRC) Woody Biomass. *Forests* **2021**, *12*, 878. [CrossRef]
5. Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as Regards the Promotion of Energy from Renewable Sources and Repealing Council 2023. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023L2413 (accessed on 22 May 2024).
6. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources. 2030 Climate and Energy Frameworks. *Off. J. Eur. Union* **2018**, *5*, 82–209.
7. Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 Establishing the Framework for Achieving Climate Neutrality and Amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (European Climate Law) 2021. Available online: https://eur-lex.europa.eu/eli/reg/2021/1119/oj (accessed on 22 May 2024).
8. Atabani, E.; Mahmoud, E.; Aslam, M.; Naqvi, S.R.; Juchelková, D.; Bhatia, S.K.; Badruddin, I.A.; Yunus Khan, T.M.; Hoang, A.T.; Palacky, P. Emerging potential of spent coffee ground valorization for fuel pellet production in a biorefinery. *Environ. Dev. Sustain.* **2023**, *25*, 7585–7623. [CrossRef]
9. Wu, P.; Wang, Z.; Bolan, N.S.; Wang, H.; Wang, Y.; Chen, W. Visualizing the development trend and research frontiers of biochar in 2020: A scientometric perspective. *Biochar* **2021**, *3*, 419–436. [CrossRef]

10. Woo, D.-G.; Kim, S.H.; Kim, T.H. Solid Fuel Characteristics of Pellets Comprising Spent Coffee Grounds and Wood Powder. *Energies* **2021**, *14*, 371. [CrossRef]
11. Setter, C.; Borges, F.A.; Cardoso, C.R.; Mendes, R.F.; Oliveira, T.J.P. Energy quality of pellets produced from coffee residue: Characterization of the products obtained via slow pyrolysis. *Ind. Crops Prod.* **2020**, *154*, 1127312020. [CrossRef]
12. Garcia, R.; Gil, M.V.; Rubiera, F.; Pevida, C. Pelletization of wood and alternative residual biomass blends for producing industrial quality pellets. *Fuel* **2019**, *251*, 739–753. [CrossRef]
13. Owusu, P.A.; Asumadu-Sarkodie, S. A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Eng.* **2016**, *3*, 1167990. [CrossRef]
14. Nunes, L.J.R.; Godina, R.; Matias, J.C.O.; Catalão, J.P.S. Evaluation of the utilization of woodchips as fuel for industrial boilers. *J. Clean Prod.* **2019**, *223*, 270–277. [CrossRef]
15. Tumuluru, J.S. Effect of pellet die diameter on density and durability of pellets made from high moisture woody and herbaceous biomass. *Carbon Resour. Convers.* **2018**, *1*, 44–54. [CrossRef]
16. Stachowicz, P.; Stolarski, M.J. Short rotation woody crops and forest biomass sawdust mixture pellet quality. *Ind. Crops Prod.* **2023**, *197*, 116604. [CrossRef]
17. Cardozo, E.; Malmquist, A. Performance comparison between the use of wood and sugarcane bagasse pellets in a Stirling engine micro-CHP system. *Appl. Therm. Eng.* **2019**, *159*, 113945. [CrossRef]
18. Purohit, P.; Chaturvedi, V. Biomass pellets for power generation in India: A techno-economic evaluation. *Environ. Sci. Pollut. Res.* **2018**, *25*, 29614–29632. [CrossRef]
19. Ruiz, D.; San Miguel, G.; Corona, B.; López, F.R. LCA of a multifunctional bioenergy chain based on pellet production. *Fuel* **2018**, *215*, 601–611. [CrossRef]
20. Harun, N.Y.; Afzal, M.T. Effect of Particle Size on Mechanical Properties of Pellets Made from Biomass Blends. *Procedia Eng.* **2016**, *148*, 93–99. [CrossRef]
21. Bioenergy Europe Policy Brief: Pellets—A Growing Market. Available online: https://bioenergyeurope.org/wp-content/uploads/2023/12/Pellets_Policy-Brief23.pdf (accessed on 18 September 2024).
22. Svensson, A.; Almarstrand, M.; Axelsson, J.; Nilsson, M.; Timmerman, E.; Venkatesh, G. Valorising Agricultural Residues into Pellets in a Sustainable Circular Bioeconomy. *Probl. Sustain. Dev.* **2024**, *19*, 272–278. [CrossRef]
23. Rajabi Hamedani, S.; Colantoni, A.; Bianchini, L.; Carnevale, M.; Paris, E.; Villarini, M.; Gallucci, F. Environmental life cycle assessment of spent coffee ground pellet. *Energy Rep.* **2022**, *8*, 6976–6986. [CrossRef]
24. Lee, K.-T.; Yi-Tse Shih, Y.-T.; Rajendran, S.; Park, Y.-K.; Chen, W.-H. Spent coffee ground torrefaction for waste remediation and valorization. *Environ. Pollut.* **2023**, *324*, 121330. [CrossRef] [PubMed]
25. Lee, K.-T.; Chen, W.-H.; Sarles, P.; Park, Y.-K.; Ok, Y.S. Recover energy and materials from agricultural waste via thermalchemical conversion. *One Earth* **2022**, *5*, 1200–1204. [CrossRef]
26. Paini, J.; Benedetti, V.; Ail, S.S.; Castaldi, M.J.; Baratieri, M.; Patuzzi, F. Valorization of Wastes from the Food Production Industry: A Review Towards an Integrated Agri-Food Processing Biorefinery. *Waste Biomass Valorization* **2022**, *13*, 31–50. [CrossRef]
27. Sugebo, B. A review on enhanced biofuel production from coffee by-products using different enhancement techniques. *Mater. Renew. Sustain. Energy* **2022**, *11*, 91–103. [CrossRef]
28. Contreras, M.M.; Romero, I.; Moya, M.; Castro, E. Olive-derived biomass as a renewable source of value-added products. *Process Biochem.* **2020**, *97*, 43–56. [CrossRef]
29. Lisowski, A.; Olendzki, D.; Swietochowski, A.; Dabrowska, M.; Mieszkalski, L.; Ostrowska-Ligeza, E.; Stasiak, M.; Klonowski, J.; Piatek, M. Spent coffee grounds compaction process: Its effects on the strength properties of biofuel pellets. *Renew. Energy* **2019**, *142*, 173–183. [CrossRef]
30. Kraiem, N.; Lajili, M.; Limousy, L.; Said, R.; Jeguirim, M. Energy recovery from Tunisian agri-food wastes: Evaluation of combustion performance and emissions characteristics of green pellets prepared from tomato residues and grape marc. *Energy* **2016**, *107*, 409–418. [CrossRef]
31. Cruz-Lopes, L.; Prozil, S.; Evtuguin, D.V.; Arshanitsa, A.; Solodovnik, V.; Telysheva, G.M. Evaluation of grape stalks as a feedstock for pellets production. In Proceedings of the 13th European Workshop on Lignocellulosics and Pulp, Seville, Spain, 24–27 June 2014; p. 4.
32. Vera, D.; Jurado, F.; Margaritis, N.K.; Grammelis, P. Experimental and economic study of a gasification plant fuelled with olive industry wastes. *Energy Sustain. Dev.* **2014**, *23*, 247–257. [CrossRef]
33. Jenjariyakosoln, S.; Gheewala, S.H.; Sajjakulnukit, B.; Garivait, S. Energy and GHG emission reduction potential of power generation from sugarcane residues in Thailand. *Energy Sustain. Dev.* **2014**, *23*, 32–45. [CrossRef]
34. Idowu, I.A.; Hashim, K.; Shaw, A.; Nunes, L.J.R. Energy recovery from brewery spent grains and spent coffee grounds: A circular economy approach to waste valorization. *Biofuels* **2023**, *14*, 333–342. [CrossRef]
35. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.; Hultink, E.J. The circular economy–a new sustainability paradigm ? *J. Clean. Prod.* **2017**, *143*, 757–768. [CrossRef]
36. Camana, D.; Manzardo, A.; Toniolo, S.; Scipioni, A. Assessing environmental sustainability of local waste management policies in Italy from a circular economy perspective. An overview of existing tools. *Sustain. Prod. Consum.* **2021**, *27*, 613–629. [CrossRef]
37. Adami, L.; Schiavon, M. From circular economy to circular ecology: A review on the solution of environmental problems through circular waste management approaches. *Sustainability* **2021**, *13*, 925. [CrossRef]

38. Kougioumtzis, M.A.; Filippou, V.; Rontogianni, A.; Karampinis, E.; Grammelis, P.; Kakaras, E. Valorization of spent coffee ground by mixing with various types of residual biomass for pellet production: Evaluation of solid biofuel properties at different mixtures. *Biofuels Bioprod. Bioref.* **2024**, *18*, 968–989. [CrossRef]
39. Nosek, R.; Maw Maw Tun, M.M.; Juchelkova, D. Energy Utilization of Spent Coffee Grounds in the Form of Pellets. *Energies* **2020**, *13*, 1235. [CrossRef]
40. Mendoza Martinez, C.L.; Sermyagina, E.; de Cassia Oliveira Carneiro, A.; Vakkilainen, E.; Cardoso, M. Production and characterization of coffee-pine wood residue briquettes as an alternative fuel for local firing systems in Brazil. *Biomass Bioenergy* **2019**, *123*, 70–77. [CrossRef]
41. Iryani, D.A.; Halimatuzzahra, H.; Taharuddin, T.; Haryanto, A.; Hidayat, W.; Hasanudin, U. Physicochemical Characterization of Wood Mixed with Coffee Waste Pellet. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1187*, 012007. [CrossRef]
42. Serna-Jiménez, J.A.; Siles, J.A.; Martín, M.A.; Chica, A.F. A review on the applications of coffee waste derived from primary processing: Strategies for revalorization. *Processes* **2022**, *10*, 2436. [CrossRef]
43. Buerge, I.I.; Poiger, T.; Müller, M.D.; Buser, H.R. Caffeine, an anthropogenic marker for wastewater contamination of surface waters. *Environ. Sci. Technol.* **2003**, *37*, 691–700. [CrossRef]
44. International Coffee Organization. *The Future of Coffee: Investing in Youth for a Resilient and Sustainable Coffee Sector*; International Coffee Organization: London, UK, 2021; Available online: https://www.ico.org/documents/cy2022-23/coffee-development-report-2021.pdf (accessed on 22 May 2024).
45. Cordoba, N.; Fernandez-Alduenda, M.; Moreno, L.F.; Ruiz, Y. Coffee extraction: A review of parameters and their influence on the physicochemical characteristics and flavour of coffee brews. *Trends Food Sci. Technol.* **2020**, *96*, 45–60. [CrossRef]
46. Stragiotti, M. The Italian Coffee Market. Competitive Strategies in a Saturated Market. Master's Thesis, Polytechnic of Turin, Turin, Italy, 2021.
47. do Espírito Santo Nóbrega, C.R.; da Silva, J.B.S.; Monteiro, T.O.; Paula Manoel Crnkovic, P.M.; Cruz, G. An investigation on the kinetic behavior and thermodynamic parameters of the oxy-fuel combustion of Brazilian agroindustrial residues. *J Braz. Soc. Mech. Sci. Eng.* **2023**, *45*, 65. [CrossRef]
48. Johnson, K.; Liu, Y.; Lu, M. A Review of Recent Advances in Spent Coffee Grounds Upcycle Technologies and Practices. *Front. Chem. Eng.* **2022**, *4*, 838605. [CrossRef]
49. Allesina, G.; Pedrazzi, S.; Allegretti, F.; Tartarini, P. Spent Coffee Grounds as Heat Source for Coffee Roasting Plants: Experimental Validation and Case Study. *Appl. Therm. Eng.* **2017**, *126*, 730–736. [CrossRef]
50. Atabani, A.E.; Mercimek, S.M.; Arvindnarayan, S.; Shobana, S.; Kumar, G.; Cadir, M.; Al-Muhatseb, A.H. Valorization of Spent Coffee Grounds Recycling as a Potential Alternative Fuel Resource in Turkey: An Experimental Study. *J. Air Waste Manag. Assoc.* **2018**, *68*, 196–214. [CrossRef]
51. Colantoni, A.; Paris, E.; Bianchini, L.; Ferri, S.; Marcantonio, V.; Carnevale, M.; Palma, A.; Civitarese, V.; Gallucci, F. Spent coffee ground characterization, pelletization test and emissions assessment in the combustion process. *Sci. Rep.* **2021**, *11*, 5119. [CrossRef] [PubMed]
52. Jaffe, D. Nitrogen Cycle, Atmospheric. In *Encyclopedia of Physical Science and Technology*; Academic Press: Cambridge, MA, USA, 2003; pp. 431–440. [CrossRef]
53. Senneca, O. Kinetics of pyrolysis, combustion and gasification of three biomass fuels. *Fuel Process. Technol.* **2007**, *88*, 87–97. [CrossRef]
54. Brunerova, A.; Roubik, H.; Brozek, M.; Haryanto, A.; Hasanuddin, U.; Iryani, D.A.; Herak, D. Valorization of Bio-Briquette Fuel by Using Spent Coffee Ground as an External Additive. *Energies* **2019**, *13*, 54. [CrossRef]
55. Farobie, O.; Hartulistiyoso, E. Palm Oil Biodiesel as a Renewable Energy Resource in Indonesia: Current Status and Challenges. *Bioenergy Res.* **2022**, *15*, 93–111. [CrossRef]
56. Sołowiej, P.; Neugebauer, M. Impact of coffee grounds addition on the calorific value of the selected biological materials. *Agric. Eng.* **2016**, *20*, 177–183. [CrossRef]
57. Ungureanu, N.; Vlăduț, V.N.; Voicu, G.; Dinca, M.N.; Zabava, B.-S. Influence of biomass moisture content on pellet properies—Review. *Eng. Rural Dev.* **2018**, 1879–1883. [CrossRef]
58. *EN ISO 18134-1*; Solid Biofuels—Determination of Moisture Content—Oven Dry Method. ISO: Geneva, Switzerland, 2015.
59. *EN ISO 17828*; Solid Biofuels—Determination of Bulk Density. ISO: Geneva, Switzerland, 2016.
60. *EN ISO 17831-1*; Solid Biofuels—Determination of Mechanical Durability of Pellets and Briquettes. Part 1: Pellets. ISO: Geneva, Switzerland, 2016.
61. *EN ISO 17225-2*; Solid Biofuels—Fuel Specifications and Classes. Part 2: Graded Wood Pellets. ISO: Geneva, Switzerland, 2021.
62. *EN ISO 17829*; Solid Biofuels—Determination of Length and Diameter of Pellets. ISO: Geneva, Switzerland, 2016.
63. *EN ISO 18122*; Solid Biofuels—Determination of Ash Content. ISO: Geneva, Switzerland, 2016.
64. *EN ISO 18125*; Solid Biofuels—Determination of Heating Value. ISO: Geneva, Switzerland, 2018.
65. *EN ISO 16948*; Solid Biofuels—Determination of Total Content of Carbon. Hydrogen and Nitrogen. ISO: Geneva, Switzerland, 2015.
66. *EN ISO 16994*; Solid Biofuels—Determination of total content of sulfur and chlorine. ISO: Geneva, Switzerland, 2017.
67. *EN ISO 17225-6*; Solid biofuels—Fuel specifications and classes—Part 6: Graded non-woody pellets. ISO: Geneva, Switzerland, 2021.

68. Bottani, E.; Tebaldi, L.; Volpi, A. The Role of ICT in Supporting Spent Coffee Grounds Collection and Valorization: A Quantitative Assessment. *Sustainability* **2019**, *11*, 6572. [CrossRef]
69. Delacre, M.; Leys, C.; Mora, Y.L.; Lakens, D. Taking Parametric Assumptions Seriously: Arguments for the Use of Welch's ′F′-test instead of the Classical ′F′-test in One-Way ANOVA. *Int. Rev. Soc. Psychol.* **2021**, *32*, 13. [CrossRef]
70. Gagnon, L. A review of nonparametric methods for comparing multiple groups with non-normal distributions. *J. Stat. Res.* **2020**, *45*, 113–127.
71. Faruk, S.; Azad, M. Application of Fisher's exact test in modern statistical inference. *Int. J. Stat. Sci.* **2022**, *38*, 211–221.
72. Lee, J.T.; Walker, A. Games-Howell test: An alternative for unequal variances in ANOVA. *Stat. Anal. J.* **2022**, *41*, 83–99.
73. Zhang, J.; Li, Y. Post hoc analysis following Kruskal-Wallis: The role of the Dwass-Steel-Critchlow-Fligner test. *J. Stat. Methods* **2021**, *48*, 305–318.
74. Ismail, R.I.; Khor, C.Y.; Mohamed, A.R. Pelletization Temperature and Pressure Effects on the Mechanical Properties of Khaya senegalensis Biomass Energy Pellets. *Sustainability* **2023**, *15*, 7501. [CrossRef]
75. Scott, C.; Desamsetty, T.M.; Rahmanian, N. Unlocking Power: Impact of Physical and Mechanical Properties of Biomass Wood Pellets on Energy Release and Carbon Emissions in Power Sector. *Waste Biomass Valorization* **2024**. [CrossRef]
76. Rupasinghe, R.L.; Perera, P.; Bandara, R.; Amarasekera, H.; Vlosky, R. Insights into Properties of Biomass Energy Pellets Made from Mixtures of Woody and Non-Woody Biomass: A Meta-Analysis. *Energies* **2024**, *17*, 54. [CrossRef]
77. Larsson, S.H.; Thyrel, M.; Geladi, P.; Lestander, T.A. High Quality Biofuel Pellet Production from Pre-compacted Low Density Raw Materials. *Energies* **2024**, *17*, 123. [CrossRef]
78. Miranda, T.; Montero, I.; Sepúlveda, F.J.; Arranz, J.I.; Rojas, C.V.; Nogales, S. A review of pellets from different sources. *Materials* **2015**, *8*, 1413–1427. [CrossRef] [PubMed]
79. Larsson, E.; Thyrel, M.; Geladi, P.; Lestander, T.A. Durability and breakage characteristics of biomass pellets. *Fuel* **2008**, *87*, 885–896. [CrossRef]
80. Tumuluru, J.S.; Wright, C.T.; Kenny, K.L.; Hess, J.R. The influence of process parameters on the physical properties of biomass pellets. *Fuel Process. Technol.* **2010**, *92*, 373–379. [CrossRef]
81. Stelte, W.; Holm, J.K.; Sanadi, A.R.; Barsberg, S.; Ahrenfeldt, J.; Henriksen, U.B. Mechanical durability and strength of pellets from biomass feedstocks: Effect of raw material characteristics and density. *Biomass Bioenergy* **2011**, *35*, 4685–4690. [CrossRef]
82. Miranda, M.A.; Almeida, A.A.; Nascimento, R.A.; Ribeiro, A.J. Influence of bulk density and moisture content on the durability of pellets obtained from agroindustrial waste. In Proceedings of the 17th International Scientific Conference on Engineering for Rural Development, Jelgava, Latvia, 23–25 May 2018; pp. 1835–1841.
83. Jiang, Y.; Wu, H.; Liu, H.; Zhao, M.; Yang, L. Moisture content in pellet making. *BioResources* **2020**, *15*, 557–573. [CrossRef]
84. Bhatia, R.K.; Sakhuja, D.; Mundhe, S.; Walia, A. Renewable Energy Products through Bioremediation of Wastewater. *Sustainability* **2020**, *12*, 7501. [CrossRef]
85. Chang, D.; Li, Q.; Wang, Z.; Dai, J.; Fu, X.; Guo, J.; Zhu, L.; Pu, D.; Cuevas, C.A.; Fernandez, R.P.; et al. Significant chlorine emissions from biomass burning affect the long-term atmospheric chemistry in Asia. *Natl. Sci. Rev.* **2024**, *11*, nwae285. [CrossRef]
86. Lachman, J.; Lis, M.; Baláš, M.; Matúš, M.; Lisá, H.; Milčák, P. Spent coffee grounds and wood co-firing: Fuel preparation, properties, thermal decomposition, and emissions. *Renew. Energy* **2022**, *193*, 464–474. [CrossRef]
87. Limousy, L.; Jeguirim, M.; Dutournié, P.; Kraiem, N.; Lajili, M.; Said, R. Gaseous products and particulate matter emissions of biomass residential boiler fired with spent coffee grounds pellets. *Fuel* **2013**, *107*, 323–329. [CrossRef]
88. Solowiej, P.; Neugebauer, M.; Esmer, O. Coffee Grounds as an Additive to Wood Pellets. *Energies* **2024**, *17*, 4595. [CrossRef]
89. Park, S.; Kim, S.J.; Oh, K.C.; Cho, L.; Kim, M.K.; Jeong, I.S.; Lee, C.G.; Kim, D. Investigation of agro-byproduct pellet properties and improvement in pellet quality through mixing. *Energy* **2020**, *190*, 116380. [CrossRef]