ACADEMIA GREEN ENERGY

Research Article
Published: 2025-12-11
https://doi.org/10.20935/AcadEnergy8031

Variability and quality profiles of solid biofuels from standardized laboratory analyses

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Academic Editor: Halil Durak

Abstract

Solid biofuels, including forest residues, wood chips, wood pellets, briquettes, and sawdust, play a crucial role in sustainable energy production as renewable alternatives to fossil fuels. Understanding their physicochemical properties is essential for optimizing their utilization in energy recovery applications. This study presents a comprehensive characterization of these solid biofuels, focusing on parameters such as moisture content, ash content, low heating value, elemental composition, bulk density, mechanical durability, and fines content. The analysis was based on an extensive dataset collected by the Biomass Centre for Energy (CBE), from Portugal, and conducted following ISO standards. Forest residues show the largest variability: mean moisture of 36%, ranging from 3.6 to 70.1%, and a mean ash content of 11.9%, ranging from 0.6 to 31.4%, for example. This heterogeneity makes this fuel more suitable for energy recovery in large industrial furnace systems. Wood pellets, in turn, are markedly more uniform, with a mean moisture of 5.9%, ranging from 3.2 to 8.8%, and a mean ash content of 0.8%, ranging from 0.3 to 1.8%. Besides wood pellets, wood briquettes and wood chips also demonstrate superior fuel quality for commercial and residential applications due to their low moisture and ash content, high calorific values, and enhanced handling characteristics. The majority of these properties comply with ISO 17225-2, ISO 17225-3, and ISO 17225-4 standards.

Keywords: *solid biofuels, physicochemical properties, variability, energy recovery, quality standards, dataset*

Citation: Pires A, Cancela E, Alves N, Almeida T, Figo S, Gil L. Variability and quality profiles of solid biofuels from standardized laboratory analyses. *Academia Green Energy* 2025;2. https://doi.org/10.20935/AcadEnergy8031

1. Introduction

Biomass plays a pivotal role in the global transition towards sustainable energy systems, offering a renewable and carbon-neutral alternative to fossil fuels, since it does not contribute to the increase in greenhouse gas emissions (GHG) into the atmosphere. Among its diverse applications, solid biofuels have gained significant prominence due to their widespread availability, cost-effectiveness, and adaptability for various energy recovery systems. The utilization of these solid biofuels not only contributes to energy security but also aids in the reduction in GHG emissions, aligning with global efforts to mitigate climate change [1].

The physicochemical characteristics of solid biofuels are critical determinants of their performance in energy recovery applications. Parameters such as moisture content, ash content, low heating value, and elemental composition (e.g., carbon, hydrogen, oxygen, nitrogen, sulfur and chlorine) directly influence their combustion efficiency, emissions profile, and suitability for specific technologies, including combustion, gasification, and pyrolysis [2, 3]. Moreover, understanding the heterogeneity of these characteristics across different biomass types is essential for optimizing fuel quality, ensuring regulatory compliance, and enhancing the overall sustainability of the bioenergy sector.

Since its establishment, the Biomass Centre for Energy (CBE) has accumulated an extensive dataset of physicochemical analyses on various biomass products used for energy recovery, carried out by its laboratory, accredited by the Portuguese Institute of Accreditation (IPAC) in accordance with standard ISO/IEC 17025—General Requirements for the Competence of Testing and Calibration Laboratories [4]. This dataset, encompassing years of meticulous testing and characterization of mainly Portuguese samples, provides a unique opportunity to systematically assess the ranges and variability of key physicochemical properties. Such an assessment is of vital importance not only for the bioenergy sector but also for policymakers and researchers seeking to develop standards and guidelines that promote the sustainable use of biomass resources.

This study aims to analyze and present the physicochemical characteristics of solid biofuels commonly utilized in energy recovery, including forest residues (FR), wood chips (WC), wood pellets (WP), wood briquettes (WB), and sawdust (SD). By evaluating statistical parameters such as mean values, medians, standard deviations, and ranges, this work seeks to elucidate the heterogeneity inherent in these biomass types. Furthermore, the findings are expected to inform decision-making processes, facilitate the optimization of biomass utilization, and support the development of regulatory frameworks tailored to the specific needs of the sector.

2. Materials and methods

2.1. Dataset description

Routine laboratory results generated by CBE's accredited laboratory between 2013 and 2023 were collected, resulting in a dataset

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that covers the main solid biofuel categories handled by Portuguese producers and users—FR, WC, WP, WB, and SD. Samples were submitted for testing by CBE's lab clients from across Portugal; specific regions for individual samples were not recorded.

Two species dominate commercial forest biomass flows in Portugal—*Eucalyptus globulus* (eucalyptus) and *Pinus pinaster* (maritime pine)—and therefore, the samples tested, as well. However, their proportion in this dataset is unknown, as species was not recorded per sample. Pellets and briquettes were received without certification metadata (e.g., ENplus), so certification status is unknown.

The parameters analyzed for biomass characterization, as well as the number of samples available in the dataset per parameter to characterize each biomass fuel, are shown in **Table 1**.

2.2. Samples testing

The samples preparation, consisting of homogenization, dividing, drying, and milling processes, was carried out according to ISO 14780 "Solid Biofuels—Sample Preparation" [5].

The parameters were then analyzed according to the ISO standards shown in **Table 2**.

Table 1 • Number of samples used per parameter and per biomass fuel.

	FR	WC	WP	WB	SD
Total moisture (as received)	2906	77	795	10	7
Ash content (dry)	2918	77	802	8	7
Total carbon (dry)	194	56	260	8	7
Total Hydrogen (dry)	194	56	260	8	7
Total nitrogen (dry)	194	56	256	8	7
Total oxygen (dry)	188	52	259	8	7
Total sulfur (dry)	195	55	261	8	7
Total chlorine (dry)	196	59	246	7	7
Lower heating value (dry) (LHV_d)	194	56	259	8	7
Lower heating value (as received) (LHV_{ar})	194	56	259	8	7
Bulk density (as received)	28	20	211		
Mechanical durability of pellets (as received)			203		
Fines content in pellets (as received)			194		

Table 2 • ISO standards for the analysis of each parameter.

Property	Standard
Total moisture	ISO 18134-1 [6]
Ash content	ISO 18122 [7]
Carbon, hydrogen, and nitrogen total	ISO 16948 [8]
Oxygen total	ISO 16993 [9]
Sulphur and chlorine total	ISO 16994 [10]
Lower Heating Value	ISO 18125 [11]
Bulk density	ISO 17828 [12]
Mechanical durability of pellets	ISO 17831-1 [13]
Fines content in pellets	ISO 5370 [14]

2.3. Derived quantities

Oxygen (dry) was calculated by difference as O = 100 − (C + H + N + S + Cl + Ash) [15]. H/C and O/C atomic ratios were obtained by converting mass fractions to molar fractions using atomic weights (C 12.011, H 1.008, O 15.999, N 14.007, S 32.065) [16]. The stoichiometric oxygen requirement (kg O_2 per kg fuel) was computed from ultimate analysis, assuming complete oxidation to CO_2, H_2O and SO_2, with fuel nitrogen inert to N_2 and chlorine forming HCl [17]:

$$n_{O_2} = n_C + \frac{n_H}{4} + n_S - \frac{n_O}{2}, \qquad (1)$$

where $n_i = w_i/M_i$ for $i \in \{C, H, O, S\}$. Stoichiometric kg O_2 per kg fuel is $m_{O_2} = n_{O_2} \cdot 31.998$.

The stoichiometric air–fuel ratio (kg air·kg^{-1} fuel) was determined as $A/F = m_{O_2}/Y_{O_2,\mathrm{air}}$ with $Y_{O_2,\mathrm{air}} = 0.232$ (mass fraction of O_2 in dry air). Results are given on dry (d) and as-received (ar) basis (for ar, dry-basis mass fractions are scaled by $1 - \text{moisture}_{ar}$ before applying the formula).

2.4. Data processing and statistical analysis

After samples testing, outliers were excluded from the results according to the interquartile range (IQR) calculation method, i.e., values that lied beyond the superior and inferior limits, which are 1.5 times the IQR (Q3 − Q1) above the third quartile (Q3) or below the first quartile (Q1), respectively [18]. Where helpful for practice, ISO 17225 [19–22] class thresholds (e.g., WP A1/A2/B) were overlaid as dashed horizontal lines and annotated class labels on the right margin of figures.

3. Results and discussion

Firstly, it is crucial to consider that different characteristics of different types of solid biofuels may serve different applications. Qualitative, physical, and chemical properties of biomass raw materials are essential to decide for which energy recovery system/technology this biomass is more suitable, and thus, the following results were analyzed accordingly [23].

The results are now shown for each characteristic.

3.1. Total moisture

Figure 1 shows the results regarding the total moisture of the analyzed samples.

Moisture content is a key factor influencing combustion efficiency, storage stability, and indicating the suitable type of conversion process. The results indicate substantial variability across different biomass types. The moisture of forestry biomass in natural conditions is directly associated with climate conditions, showing variations along a year, which can be seen in **Figure 2** [24]. Therefore, FR exhibited the highest moisture content, with a mean of 36.0% and a maximum of 70.1%, which is significantly higher compared to WP with a mean of 5.9% and a maximum of 8.8%. Reference [25] shows a narrower variation in wood pellets, between 5.4 and 7.0%, although drawing results from only 12 samples, which demonstrates the greater variability existent within an extensive dataset such as the one analyzed, even within standardized fuels. The high moisture content in FR and WC suggests a need for pre-treatment before utilization to enhance storage stability, minimizing risks such as microbiological activity, composting, and self-ignition [23]. It also suggests that these feedstocks are more suitable for energy recovery in large industrial furnace systems such as thermoelectric plants or industrial boilers. Conversely, WP and WB showed low moisture variability, ranging within the ISO 17225 standards, making them more suitable for small furnace systems usually utilized in commercial and residential applications.

3.2. Ash content

Figure 3 shows the results regarding the ash content of the analyzed samples.

	FR	WC	WP	WB	SD
Mean (%)	36.0	35.3	5.9	10.2	11.0
Standard Deviation (%)	12.0	13.6	1.0	1.2	2.4
Maximum (%)	70.1	57.2	8.8	11.4	14.3
Minimum (%)	3.6	8.4	3.2	7.4	7.0
First quartile (%)	26.9	23.7	5.3	9.7	9.1
Third quartile (%)	45.1	46.4	6.6	11.0	12.6

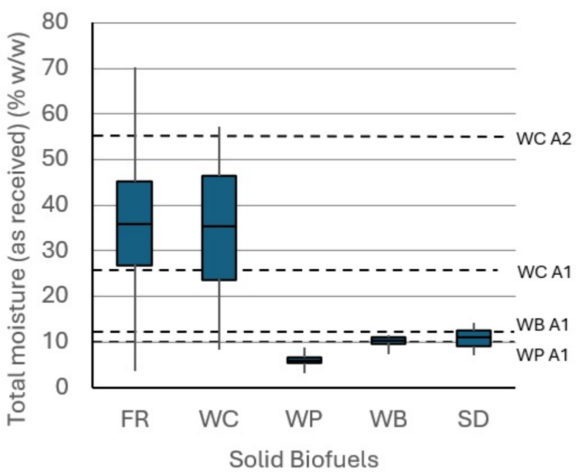

Figure 1 • Results and Box and whiskers plot of total moisture (as received) (% w/w). References [20–22] quality requirements are presented in the graph as dashed lines (WC A1 $\leq$ 25%; WC A2 $\leq$ 55%; WP A1 $\leq$ 10%; WB A1 $\leq$ 12%).

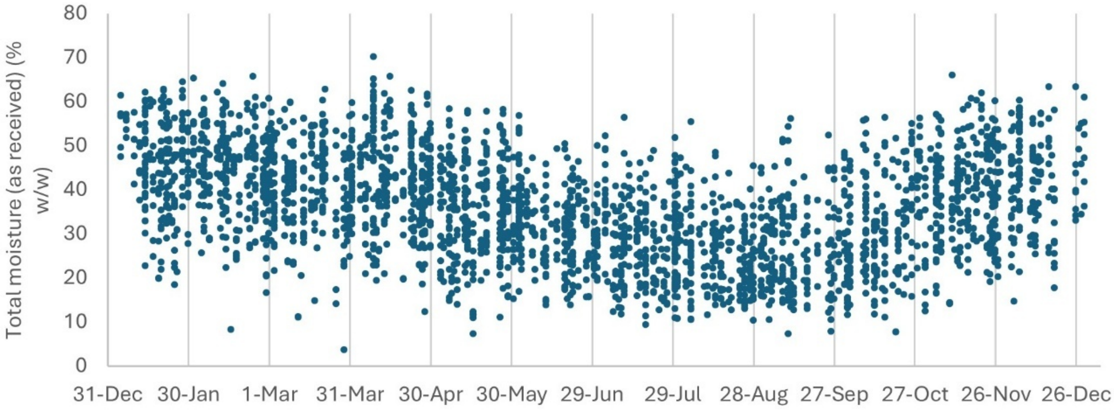

Figure 2 • Total moisture variation along a year. The samples represented were received throughout the timespan between 2013–2023.

	FR	WC	WP	WB	SD
Mean (%)	11.9	0.8	0.8	1.9	0.8
Standard Deviation (%)	6.7	0.4	0.3	1.5	0.4
Maximum (%)	31.4	1.9	1.8	4.9	1.3
Minimum (%)	0.6	0.3	0.3	0.4	0.4
First quartile (%)	6.7	0.5	0.6	0.7	0.4
Third quartile (%)	16.0	0.9	1.0	2.8	1.1

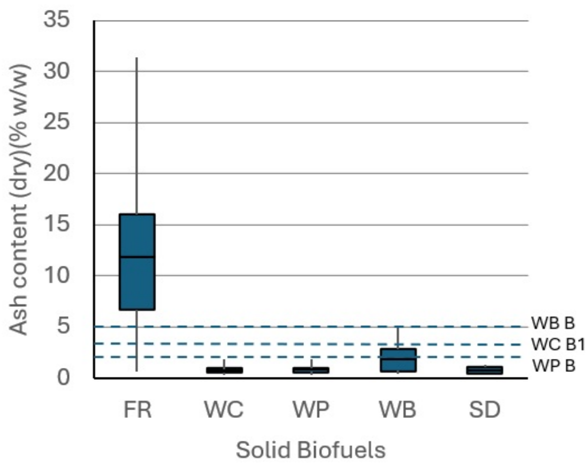

Figure 3 • Results and Box and whiskers plot of ash content (dry) (% *w/w*). References [20–22] quality requirements are presented in the graph as dashed lines (WC B1 $\leq$ 3%; WP B $\leq$ 2%; WB B $\leq$ 5%).

Ash content affects both the efficiency of biomass combustion and the maintenance requirements of energy systems. WC, WP, and SD demonstrated low ash contents, with mean values of 0.8%. These results align with the ISO 17225 standards for solid biofuels and indicate favorable combustion performance. Furthermore, WP range (0.3–1.8%) matches the one showed for debarked wood, of different species, by [26].

The presence of ash-forming inorganics requires thermal energy for breakdown and phase transitions, which otherwise could contribute to the heating value of the biomass. As a result, higher ash content reduces the net energy yield [1]. Moreover, excessive ash can lead to more frequent cleaning operations, slagging, fouling, and potential corrosion of combustion system components [2].

WB also complied with ISO standards but exhibited a higher mean ash content (1.9%) and standard deviation (1.5%), which can be attributed to differences in plant species and amounts of bark and soil [2]. The highest mean ash content was observed in FR (11.9%) and exhibited a large range of values (0.6% to 31.4%). This wide range is known to be related to the conditions of material harvesting in the field. However, in this case, it is much greater than the typical variation in ash content for logging residues presented in [19], which varies from <1 to 10%, evidencing once more the heterogeneity inherent to such an extensive dataset.

3.3. Elemental analysis

Figure 4, **Figure 5**, **Figure 6**, **Figure 7**, **Figure 8** and **Figure 9** show the results regarding the elemental analysis of the analyzed samples.

	FR	WC	WP	WB	SD
Mean (%)	45.4	49.9	50.1	48.9	49.7
Standard Deviation (%)	4.0	1.2	0.6	0.6	1.0
Maximum (%)	53.7	52.7	51.7	50.0	51.1
Minimum (%)	34.7	47.7	48.6	48.3	48.6
First quartile (%)	42.3	48.9	49.7	48.4	48.6
Third quartile (%)	48.5	51.0	50.6	49.4	50.6

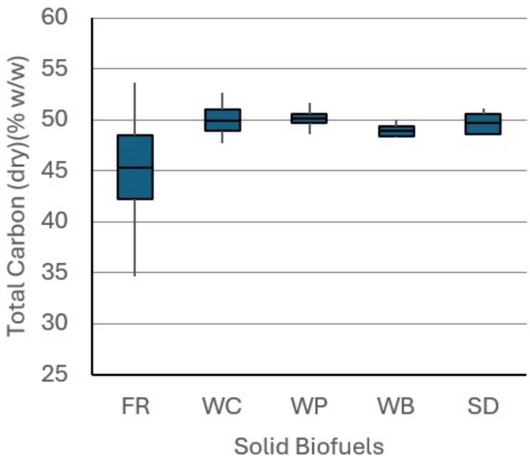

Figure 4 • Results and Box and whiskers plot of total carbon (dry) (% *w*/*w*).

	FR	WC	WP	WB	SD
Mean (%)	5.5	6.2	6.2	6.1	6.0
Standard Deviation (%)	0.5	0.2	0.1	0.1	0.2
Maximum (%)	6.8	6.6	6.6	6.3	6.3
Minimum (%)	4.1	5.8	5.9	6.0	5.8
First quartile (%)	5.1	6.0	6.1	6.0	6.0
Third quartile (%)	5.9	6.3	6.3	6.2	6.1

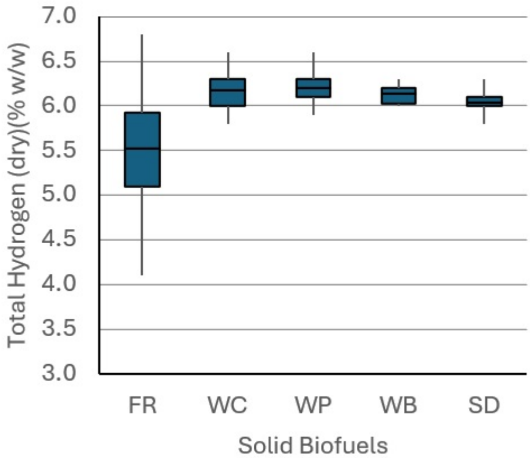

Figure 5 • Results and Box and whiskers plot of total hydrogen (dry) (% *w*/*w*).

	FR	WC	WP	WB	SD
Mean (%)	0.53	0.19	0.15	0.56	0.16
Standard Deviation (%)	0.21	0.07	0.04	0.62	0.05
Maximum (%)	1.10	0.50	0.32	1.90	0.20
Minimum (%)	0.14	0.10	0.10	0.10	0.10
First quartile (%)	0.40	0.16	0.10	0.20	0.10
Third quartile (%)	0.69	0.20	0.20	0.90	0.20

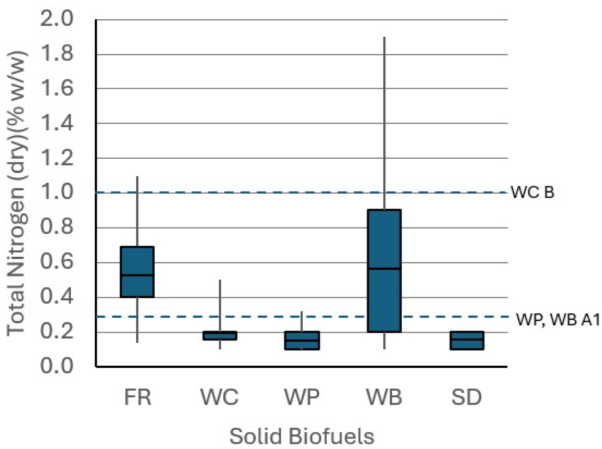

Figure 6 • Results and Box and whiskers plot of total nitrogen (dry) (% *w*/*w*). References [20–22] quality requirements are presented in the graph as dashed lines (WC B $\leq$ 1%; WP A1 $\leq$ 0.3%; WB A1 $\leq$ 0.3%).

	FR	WC	WP	WB	SD
Mean (%)	36.30	42.93	42.69	42.47	43.27
Standard Deviation (%)	4.05	1.34	0.57	0.92	1.14
Maximum (%)	44.70	45.30	44.28	43.37	44.90
Minimum (%)	26.30	39.80	40.80	40.60	41.90
First quartile (%)	33.23	41.80	42.37	41.97	41.99
Third quartile (%)	39.38	43.88	43.00	43.24	44.35

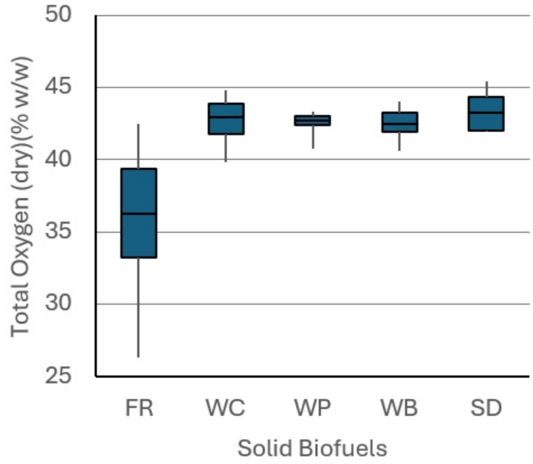

Figure 7 • Results and Box and whiskers plot of total oxygen (dry) (% *w*/*w*).

	FR	WC	WP	WB	SD
Mean (%)	0.038	0.012	0.012	0.025	0.014
Standard Deviation (%)	0.015	0.003	0.003	0.009	0.005
Maximum (%)	0.080	0.023	0.026	0.040	0.020
Minimum (%)	0.010	0.010	0.003	0.010	0.010
First quartile (%)	0.030	0.010	0.010	0.020	0.010
Third quartile (%)	0.050	0.012	0.014	0.030	0.020

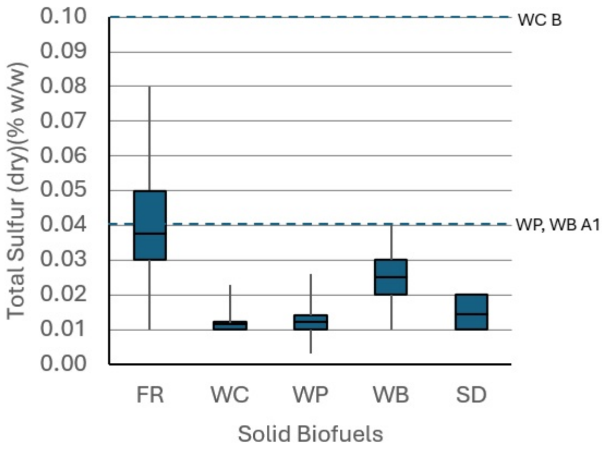

Figure 8 • Results and Box and whiskers plot of total sulfur (dry) (% *w*/*w*). References [20–22] quality requirements are presented in the graph as dashed lines (WC B ≤ 0.1%; WP A1 ≤ 0.04%; WB A1 ≤ 0.04%).

	FR	WC	WP	WB	SD
Mean (%)	0.080	0.027	0.014	0.019	0.023
Standard Deviation (%)	0.062	0.024	0.008	0.019	0.020
Maximum (%)	0.240	0.110	0.040	0.060	0.060
Minimum (%)	0.002	0.004	0.005	0.010	0.005
First quartile (%)	0.034	0.010	0.010	0.010	0.005
Third quartile (%)	0.120	0.040	0.020	0.020	0.030

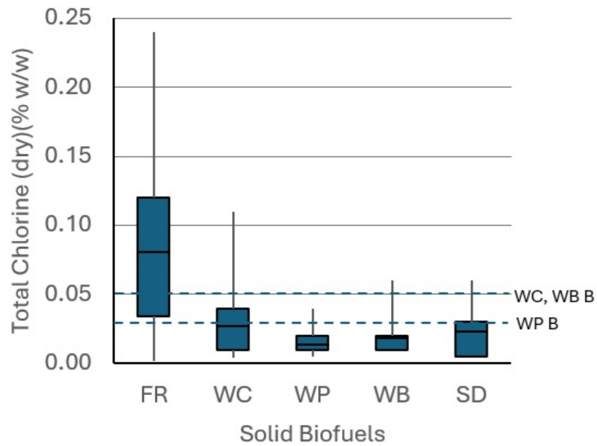

Figure 9 • Results and Box and whiskers plot of total chlorine (dry) (% *w*/*w*). References [20–22] quality requirements are presented in the graph as dashed lines (WC B ≤ 0.05%; WP B ≤ 0.03%; WB B ≤ 0.05%).

The elemental composition (total carbon, hydrogen, nitrogen, sulfur, and chlorine) of solid biofuels determines their energy potential [27, 28] and emissions behavior. Carbon content was highest in WP, WC, and SD (mean: ~50%), reinforcing their suitability as high-energy-density fuels. Hydrogen content remained relatively stable across all samples, with mean values between 5.5% (FR) and 6.2% (WC). Nitrogen and sulfur contents were low across most biomass types, reducing concerns about NO_x and SO_x emissions [29]. However, FR and WB exhibited higher nitrogen levels (0.53% mean) compared to other biomass types, which could contribute to increased NO_x emissions during combustion. Chlorine content, which raises concern regarding high-temperature corrosion of super-heater tubes in boilers [30, 31], was highest in FR with a mean value of 0.08% (much higher than the typical value of 0.01% featured in [19]) but remained low across the other biomass types. Apart from chlorine content across all fuels, and nitrogen content in WB, these results align with references [20–22] requirements, confirming the low emissions potential of the solid biofuels with commercial applications.

3.4. Lower heating value

Figure 10 shows the results regarding the lower heating value (LHV) on a dry basis of the analyzed samples.

Figure 11 shows the results regarding the LHV on an as-received basis of the analyzed samples.

On a dry basis, WP displayed the highest mean LHV at 18.80 MJ/kg, followed closely by SD (18.64 MJ/kg) and WC (18.62 MJ/kg). The lowest values were observed in FR (mean of 16.83 MJ/kg), indicating a lower energy yield per unit of dry mass.

The variation in LHV_d largely mirrors differences in elemental composition and ash content. Fuels richer in carbon and hydrogen generally possess higher energy densities, while elevated oxygen or mineral fractions reduce LHV_d through chemical and inert-mass dilution effects [32]. The lower LHV_d of FR, despite its relatively low O/C ratio, results from ash and mineral dilution and feedstock heterogeneity, which counteract its chemically favorable composition.

When expressed on an as-received basis, the influence of moisture content becomes dominant. The high moisture of FR and WC substantially decreases their effective energy yield. Conversely, the low-moisture fuels (WP, WB, SD) retain most of their dry-basis potential, yielding stable LHV_{ar} values well above 16 MJ/kg.

Overall, these findings reinforce that moisture control—through drying, storage management, or process integration—is the most effective lever for maximizing as-received energy efficiency. Both WP and WB comply with references [20, 21] threshold for solid biofuels.

3.5. Bulk density and mechanical durability

Figure 12 shows the results regarding the bulk density of the analyzed samples.

Figure 13 shows the results regarding the mechanical durability of the analyzed pellets' samples.

	FR	WC	WP	WB	SD
Mean (MJ/kg)	16.83	18.62	18.80	18.32	18.64
Standard Deviation (MJ/kg)	1.56	0.56	0.25	0.34	0.47
Maximum (MJ/kg)	19.98	19.76	19.43	18.90	19.20
Minimum (MJ/kg)	13.25	17.57	18.08	17.90	18.18
First quartile (MJ/kg)	15.78	18.17	18.61	18.02	18.18
Third quartile (MJ/kg)	18.01	19.06	19.00	18.61	19.16

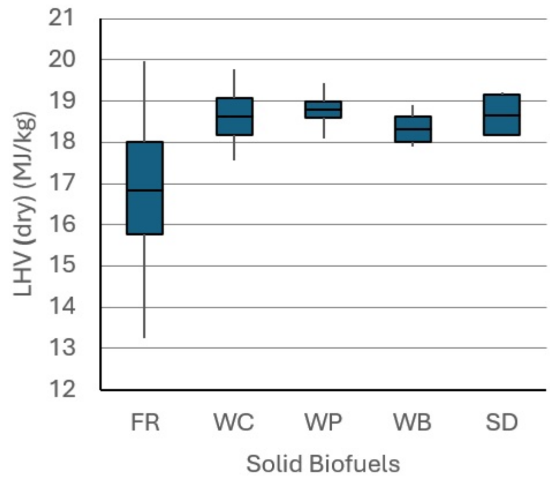

Figure 10 • Results and Box and whiskers plot of LHV (dry) (MJ/kg).

	FR	WC	WP	WB	SD
Mean (MJ/kg)	9.52	10.96	17.62	16.20	16.33
Standard Deviation (MJ/kg)	3.03	2.71	0.35	0.47	0.75
Maximum (MJ/kg)	17.75	17.67	18.61	17.00	17.64
Minimum (MJ/kg)	3.86	6.64	16.64	15.58	15.23
First quartile (MJ/kg)	7.09	8.99	17.36	15.79	15.95
Third quartile (MJ/kg)	11.69	12.08	17.89	16.54	16.62

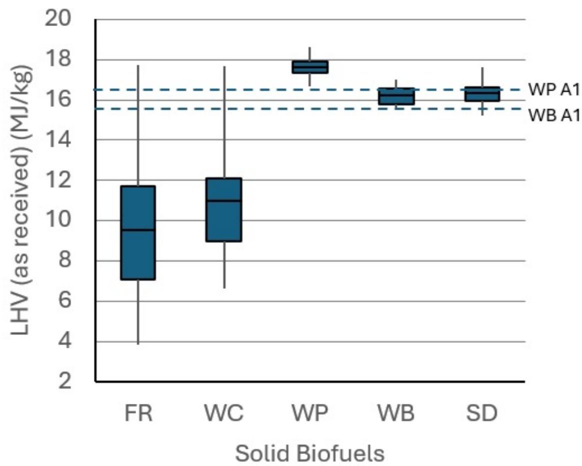

Figure 11 • Results and Box and whiskers plot of LHV (as received) (MJ/kg). References [20, 21] quality requirements are presented in the graph as dashed lines (WP A1 ≥ 16.5 MJ/kg; WB A1 ≥ 15.5 MJ/kg).

	FR	WP	WC
Mean (kg/m^3)	251	670	265
Standard Deviation (kg/m^3)	62	19	75
Maximum (kg/m^3)	380	720	420
Minimum (kg/m^3)	140	620	140
First quartile (kg/m^3)	203	660	203
Third quartile (kg/m^3)	290	681	335

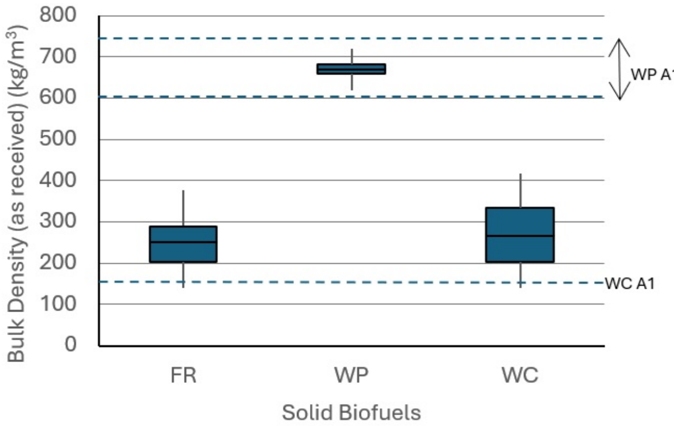

Figure 12 • Results and Box and whiskers plot of bulk density (as received) (kg/m^3). References [20, 22] quality requirements are presented in the graph as dashed lines (WC A1 $\geq$ 150 kg/m^3; 600 $\geq$ WP A1 $\geq$ 750 kg/m^3).

	WP
Mean (%)	98.5
Standard Deviation (%)	0.4
Maximum (%)	99.5
Minimum (%)	97.3
First quartile (%)	98.4
Third quartile (%)	98.8

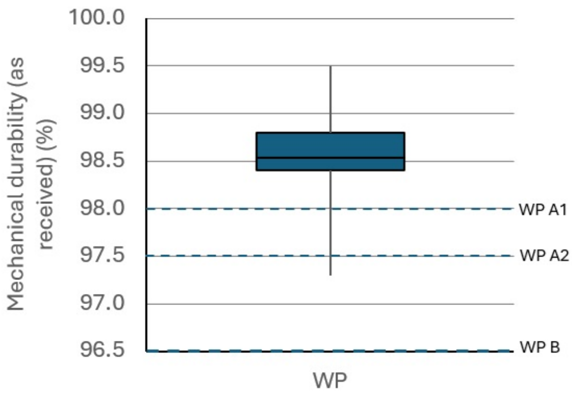

Figure 13 • Results and Box and whiskers plot of mechanical durability of pellets (as received) (% w/w). Reference [20] quality requirements are presented in the graph as dashed lines (A1 $\geq$ 98.0%; A2 $\geq$ 97.5%; B $\geq$ 96.5%).

Bulk density and mechanical durability are critical parameters for handling, storage, and transportation [33]. WP exhibited the highest bulk density (mean: 670 kg/m^3), ensuring efficient packing and storage. Mechanical durability of WP was also high, with values exceeding 97% (w/w), confirming their robustness during transport and handling. These findings align with reference [20] requirements, which recommend a bulk density between 600 and 750 kg/m^3 for pellets, indicating that the tested samples meet international standards. They also align with the results observed by [34], who found that, in pellets produced with residual biomass of pine, bulk density exceeded 600 kg/m^3 for ash contents below 2.18%, and that the mechanical durability exceeded 95% (w/w) for ash contents below 1.21%. In contrast, FR and WC had much lower bulk densities, indicating higher transportation costs and storage requirements.

3.6. Fines content in pellets

Figure 14 shows the results regarding the fines content of the analyzed pellets' samples.

	WP
Mean (%)	0.16
Standard Deviation (%)	0.09
Maximum (%)	0.47
Minimum (%)	0.04
First quartile (%)	0.10
Third quartile (%)	0.20

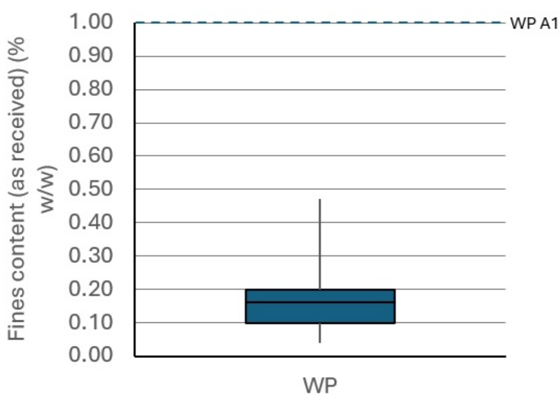

Figure 14 • Results and Box and whiskers plot of fines content in pellets (as received) (% w/w). Reference [20] quality requirement is presented in the graph as a dashed line (A1 $\leq$ 1.0%).

Fines content in pellets is a crucial quality parameter that affects handling, storage, and combustion efficiency. Excessive fines can lead to dust formation, reduced combustion efficiency, and operational issues in pellet-fed systems. The results show that fines content in WP ranged from a minimum of 0.04% to a maximum of 0.47%, with a mean of 0.16%. The relatively low fines content suggests that the analyzed pellets have good mechanical integrity, reducing material losses and improving overall system efficiency. Moreover, the observed values comply with reference [20] standards, which set the fines content limit at ≤1.0% in mass, as received, for commercial and residential applications. This confirms that the studied WP samples meet international quality requirements, ensuring optimal performance in biomass boilers.

3.7. Cross-property quality indicators (H/C, O/C, and A/F)

Figure 15 shows a Van Krevelen (VK) diagram plotting H/C versus O/C ratios of the five fuel types.

Atomic ratios occupy a compact but informative range across fuels (H/C ≈ 1.45–1.49; O/C ≈ 0.60–0.65). Mean values position FR at H/C = 1.453 and O/C = 0.601; SD shows H/C = 1.449 and the highest O/C = 0.654; WB exhibit the highest H/C = 1.494 with O/C = 0.651; WP and WC cluster near H/C ≈ 1.47–1.48 and O/C ≈ 0.64–0.65. Elliptic envelopes containing mean, IQR (Q1 and Q3), and extrema values partially overlap within the standardized fuels (WC, WP, and WB) region. In contrast, FR and SD sit outside this cluster and do not overlap either the standardized group or each other: FR centers at lower O/C (more reduced), while SD is shifted toward higher O/C (more oxygenated). This geometry shows that industrial processing and specifications compress compositional variability, whereas heterogeneous feedstocks (FR) and by-products (SD) retain distinct chemistries.

According to fuel chemistry, higher O/C aligns with lower LHV_d [29]. However, FR's favorable (lower) O/C ratio does not align with its lower LHV_d, suggesting that ash/mineral dilution and feedstock heterogeneity cause great deviations to this rule [32]. SD's O/C ratio helps explain why its LHV_d sits with the upper standardized cluster, especially when ash content is low.

Figure 16 compares the stoichiometric air–fuel ratio (A/F) between the five fuel types, on a dry and as-received basis.

On a dry basis, A/F is compact for all fuels (≈5.5–6.0 kg air·kg^{-1}), reflecting the modest spread in H/C and O/C. On an as-received basis, the A/F gap (A/F (dry) − A/F (as-received)) discriminates logistics rather than chemistry. FR and WC show large gaps due to moisture, while WP, WB, and SD remain close to dry-basis values [35].

The combined use of H/C and O/C ratios and A/F ratio (dry vs. as-received) provides a clear diagnostic: VK position reflects intrinsic fuel chemistry; the A/F gap captures logistics and handling (mainly moisture). Therefore, fuels with low moisture and tight VK clustering exhibit stable air requirements near the dry-basis values and are easier to use in small-scale appliances. On the other hand, fuels with high moisture and wider VK envelopes require conditioning (drying, screening, debarking) to lift LHV_{ar}, narrow the A/F (as-received) − A/F (dry) gap, and reduce risks associated with mineral content (e.g., slagging).

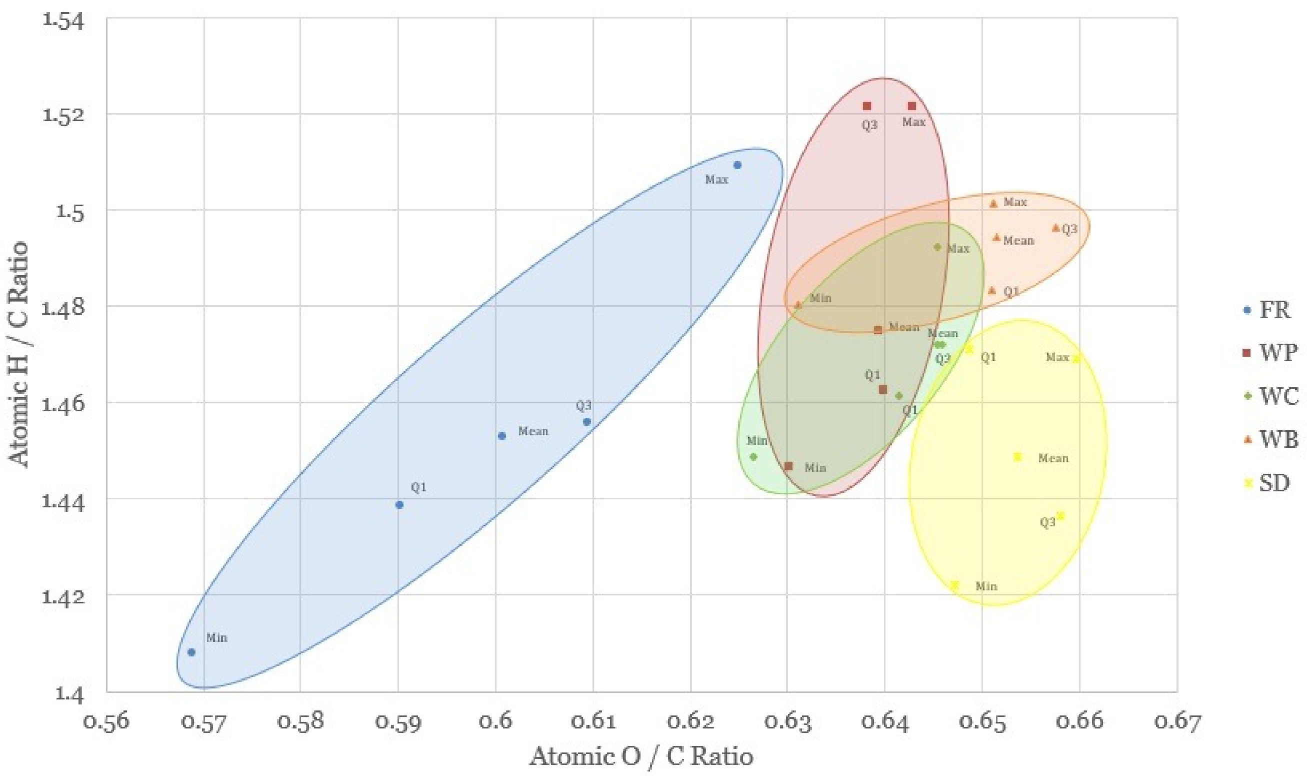

Figure 15 • Van Krevelen plot (H/C vs. O/C atomic ratios, dry basis), using mean, IQR (Q1 and Q3), minimum, and maximum values, grouped under colored shade areas by fuel type (blue—FR, red—WP, green—WC, orange—WB, yellow —SD).

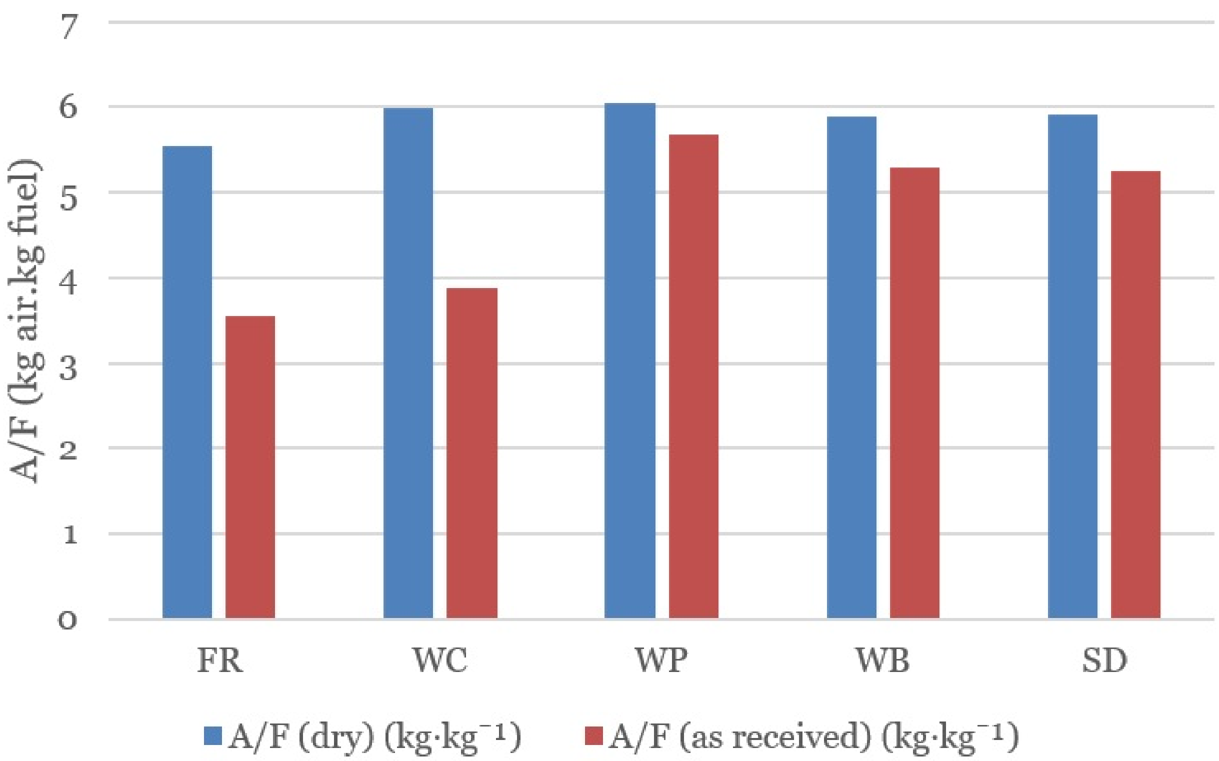

Figure 16 • Stoichiometric air–fuel ratio (A/F, kg air per kg fuel) derived from ultimate analysis for each fuel class, shown on a dry basis and on an as-received basis.

Despite the robustness of this study, a few limitations should be acknowledged. The dataset, while extensive, is composed mainly of samples collected in Portugal, which may not fully represent the variability of solid biofuels in other geographical contexts. In addition, the dataset aggregates materials without distinguishing plant species, harvesting methods, or supply chain practices, all of which can significantly influence physicochemical properties. Finally, while ISO standards were followed, factors such as storage conditions or pre-treatment history of the samples were not systematically recorded, which could contribute to some of the observed variability.

4. Conclusions

This study provided a comprehensive analysis of the physicochemical properties of various solid biofuels, highlighting their heterogeneity and its implications for energy recovery applications. The Van Krevelen diagram shows that standardized/processed products exhibit overlapping envelopes (H/C $\approx$ 1.47–1.49; O/C $\approx$ 0.64–0.65), whereas FR and SD occupy distinct, non-overlapping domains. This geometry reflects the constraining effect of industrial preparation (drying, densification, screening) on composition, versus the heterogeneity of field residues and by-products. The A/F results reinforce this picture: A/F (dry) is compact for all fuels (~5.5–6.0 kg air·kg^{-1}), but A/F (as-received) diverges where moisture is high, producing large gaps between the two ratios for FR and some WC, and minimal gaps for WP, WB, and SD.

Energy and handling performance mirror these indicators: mean LHV_d spans 16.83–18.80 MJ·kg^{-1} (FR lowest; WP highest) and pellets show high bulk density (670 kg·m^{-3}) and low fines (mean 0.16%), supporting robust logistics and small-scale appliance use.

One important takeaway is the fact that ash dilution and feedstock heterogeneity cause great deviations to the chemistry rule that states that greater O/C ratios mean lower LHV_d, as FR had the lowest O/C ratio, which does not align with its lower LHV_d mean of 16.83 MJ·kg^{-1}, compared to 18.3–18.8 MJ·kg^{-1} for WC, WP, WB, and SD.

The results confirm that WP and WB exhibit superior fuel quality due to their low moisture and ash contents, high calorific values, and favorable handling characteristics. In contrast, FR and WC, while widely available, often require additional preprocessing to improve combustion efficiency and storage stability. Nevertheless, it is important to highlight that WC also exhibit low ash contents, high carbon and low nitrogen contents, and high heating value on a dry basis, showing great fuel quality as long as optimal conditions are met.

Compliance with ISO 17225-2, ISO 17225-3, and ISO 17225-4 standards was verified for key parameters, demonstrating that the tested solid biofuels meet international quality requirements. These findings support the development of regulatory frameworks that ensure solid biofuels' sustainability, efficiency, and performance.

Future research should focus on refining the characterization of biomass fuels by further differentiating the solid biofuel categories. This could include distinguishing samples by plant species, source certification (e.g., FSC-certified vs. non-certified), quality certification (e.g., ENplus-certified vs. non-certified), degree of preprocessing (e.g., dried and calibrated vs. raw), and intended application (e.g., industrial vs. residential use). Building upon the extensive dataset presented in this study, these future efforts can contribute to the development of more tailored quality standards and optimized utilization pathways for each solid biofuel type. The results of this study provide valuable insights for policymakers, industry stakeholders, and researchers working towards a more efficient and sustainable bioenergy sector.

Funding

This research received no external funding.

Author contributions

Conceptualization, E.C., N.A., T.A., and S.F.; methodology, E.C. and N.A.; validation, E.C., N.A., T.A. and S.F.; formal analysis, A.P.; investigation, E.C. and N.A.; resources, L.G.; data curation, E.C. and N.A.; writing—original draft preparation, A.P.; writing—review and editing, E.C., N.A., T.A., S.F. and L.G.; visualization, A.P., E.C., N.A., T.A. and S.F.; supervision, L.G.; project administration, T.A., S.F. and L.G. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that they have no competing interests.

Data availability statement

The data supporting the findings of this publication can be made available upon request.

Additional information

Received: 2025-09-25

Accepted: 2025-11-21

Published: 2025-12-11

Academia Green Energy papers should be cited as *Academia Green Energy 2025*, ISSN 2998-3665, https://doi.org/10.20935/AcadEnergy8031. The journal's official abbreviation is *Acad. Energy*.

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