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Influence of Particle Size Reduction on Combustion Properties and Thermal Behaviour of Agricultural Biomass

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Keywords:
Biomass combustion; Particle size; Higher heating value; Pyrolysis kinetics; Thermogravimetric analysis; Bulk density; Moisture absorption; Lignocellulosic residues.

Highlights:

- *Reducing the biomass particle size by 1.75 mm increased the higher heating value by nearly 5%.*
- *Thermogravimetric analysis showed a 25 °C decrease in decomposition peak temperatures for fine particles.*
- *Moisture absorption in finely milled biomass fractions increased by over 25% compared to coarse samples.*

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Abstract: Particle size distribution is a critical determinant in the thermochemical conversion of lignocellulosic biomass. This research evaluates the impact of comminution on the calorific value and thermal kinetics of wheat straw, corn stalks, and hardwood chips (0.25–2.0 mm fractions). Experimental analysis demonstrates an inverse correlation between particle size and Higher Heating Value (HHV), with fine hardwood fractions achieving up to 20.03 MJ/kg—a relative increase of ~5.6%. Thermogravimetric analysis (TGA) identified a significant enhancement in thermal reactivity, evidenced by a 25–30°C shift in exothermic peaks toward lower temperatures. Additionally, the improved bulk density of finer fractions contributes to higher volumetric energy density, crucial for efficient storage and logistics. The study concludes that incorporating granulometric data into predictive models is essential for accuracy. Practically, these optimized properties facilitate more stable ignition and lower start-up loads in industrial grate and fluidized-bed boilers.

1.INTRODUCTION

In the modern world, sustainable energy development is increasingly essential amid rising global resource consumption and tightening environmental regulations. According to the International Energy Agency, global energy demand increased by nearly 45% between 2000 and 2020, and approximately 80% of this demand was met by fossil fuels, which generate significant carbon dioxide emissions and environmental pollution. In this context, interest in renewable energy sources is increasing, and biomass is among the most promising options for replacing hydrocarbon fuels. According to European Commission statistics, the European Union alone generates over 950 million tons of biomass annually, including crop waste, forestry waste, and organic residues from food processing [1-3]. Experts estimate that, with efficient processing of these volumes, up to 15-18% of the energy consumed in the EU could be generated. One of the key uses of biomass is as a solid fuel for producing thermal and electrical energy. This approach is of particular interest because, compared with coal, biomass combustion has a lower carbon footprint and can be considered carbon-neutral, provided that plant resources are restored. However, the practical implementation of biofuel production and use is associated with significant technological and economic barriers. A key challenge is assessing and ensuring the fuel's stable energy characteristics, primarily its higher calorific value, which directly affects combustion efficiency and the design of boilers and power plants. Several approaches have been used to address this problem [4,5]. The most traditional method is direct calorimetric determination of the calorific value, in which a biomass sample is burned in an oxygen environment, and the released heat is recorded using specialised calorimeters. Such measurements provide high accuracy; the error with modern laboratory installations such as IKA C 6000 or Parr 6400 does not exceed ±0.2–0.3 MJ/kg. However, the cost of the equipment and the time required to prepare and burn samples make this method relatively expensive and labour-intensive, especially when large batches of raw materials need to be assessed. As an alternative, empirical models for predicting the heat of combustion from elemental or proximate analyses are widely used. Among well-known equations, such as the Sheng, Huang, and Fried models, the most commonly used account for the mass fractions of carbon, hydrogen, and oxygen. According to numerous studies, the average deviation of such models from experimental HHV values ranges from 3.5% to 10%. Although these approaches enable faster calculation of the indicators, their accuracy decreases with changes in biomass characteristics, particularly moisture content, ash content, and material structural properties. A key feature of biomass as an energy source is its pronounced heterogeneity in composition and structure. For example, wheat straw and corn stalks can differ significantly in lignin mass fraction (15%-35%), which affects the heat of combustion. At the same time, a less obvious but equally significant factor is the granulometric composition of the raw material and the degree of its grinding before feeding it to the combustion chamber or before analysis [6-8]. In applied studies, the granulometric factor is often overlooked, and biomass is treated as a material with "average" properties. In reality, particle size affects the pyrolysis rate, the combustion completeness, and the total heat released. For example, when grinding wood waste to a fraction less than 0.5 mm, accelerated thermal decomposition and a shorter time to reach peak heat release are observed, which can increase the overall efficiency of combustion processes [9-11]. Possible approaches to assess the influence of particle size distribution include experimental combustion of samples with varying particle sizes, heat- and mass-transfer modelling, and correlation models. Experimental studies provide precise, accurate data but require significant resources and carefully controlled conditions. Modelling pyrolysis and combustion processes that account for particle geometry is currently under active development but requires complex software packages and often relies on initial data obtained from laboratory experiments. Correlation dependencies and regression models are convenient for assessing, but are limited in their applicability: when the characteristics of the raw material extend beyond the studied range, accuracy may decrease [12-14]. At the same time, an analysis of the literature indicates that most known approaches focus on assessing elemental composition. The size parameters of the fractions are, in general, not included in the calculation models, creating a gap in understanding the influence of particle-size characteristics on the energy potential of biomass. The guidance for assessing the heat of combustion of biomass, taking into account its particle-size distribution and degree of grinding, is relevant for several reasons. Firstly, in real conditions of raw material processing and preparation, the degree of grinding and fractional composition are variable parameters that depend on the equipment used and the preparation technology. For example, the difference between grinding to 2 mm and 0.2 mm can significantly affect the material's moisture content, bulk density, and reactivity. Secondly, during combustion, particles of

different sizes exhibit different behaviour: the fine fraction heats up faster and releases volatiles, which can alter the heat-release profile and increase the yield of condensable combustion products [15-17]. Third, considering these factors is essential when designing boiler plants and selecting operating modes: accurate prediction of the heat of combustion and accounting for granulometric characteristics help reduce the risk of fuel underloading or overloading and increase overall energy efficiency. Therefore, a study aimed at quantitatively assessing the effects of biomass particle size and grinding degree on the heat of combustion has both scientific and practical significance. According to available experimental data, differences in grinding degree can lead to changes in the higher calorific value of up to 4-6% for wood waste and 8-10% for cereal straw, all other things being equal. These data indicate that neglecting the granulometric factor can introduce a significant error into forecast models and calculations of energy characteristics [18-20]. At the same time, when preparing fuel for combustion, the grinding parameters are adjusted to achieve an optimal balance between grinding energy costs and gains in combustion efficiency. Additionally, the effect of particle size can manifest as changes in the mass fractions of moisture and ash, which should also be considered when adjusting the HHV values [21,22]. Given that existing empirical models for predicting the calorific value of biomass, in the vast majority of cases, do not include correction factors to account for the effect of granulometric composition, studying this dependence is a promising direction. The use of modern laboratory analytical methods, including automated fractionation systems and precision calorimetric equipment, enables more accurate and systematic assessment of the contribution of particle-size distribution to the formation of biofuel energy properties. Ultimately, such studies will allow us to develop practical recommendations for enterprises involved in the preparation and use of biomass and to enhance the reliability of design calculations for heat-generating equipment. This study aimed to experimentally assess the effects of particle size distribution and grinding intensity on the higher calorific value of biomass from various origins. This is followed by an analysis of the data obtained and a comparison with the results of the calculations using known empirical models.

2.RESEARCH METHODS

During the study, a comprehensive experimental program was conducted to quantitatively assess the effects of particle size distribution and grinding intensity on the calorific value of lignocellulosic biomass. The primary focus was on preparing samples with varying particle sizes, conducting elemental analysis, measuring higher calorific value, and performing thermogravimetric analysis. The biomass of agricultural origin, including wheat straw, corn stalks, and softwood residues, was used as the study object. The raw materials were pre-dried at 60 °C for 72 h in a Binder FED115 drying cabinet, reducing the initial moisture content to no more than 5.1% by weight. A Fritsch Pulverisette 19 laboratory universal crusher equipped with replaceable sieves with cell sizes of 0.25, 0.5, 1, and 2 mm was used to prepare samples with different degrees of grinding. Each fraction was ground at 4500 rpm while maintaining a constant material feed rate. The obtained samples were additionally sieved on a Rutsch AS 200 control vibration particle distribution analyser for 20 minutes at an oscillation amplitude of 1.5 mm. This ensured a high degree of homogeneity in the particle-size distribution and reproducibility of the fraction characteristics. Replicates and statistical treatment are as follows. For each biomass × fraction combination (wheat straw, corn stalks, and hardwood chips; 2, 1, 0.5, and 0.25 mm), we prepared n = 3 independent replicate batches and processed them through the entire analytical workflow. Calorimetry, elemental analysis, and TGA/DSC were performed on each batch; for each analytical method, the instrument readings were averaged within each batch before conducting ANOVA across batches. An Elemental Vario EL Cube elemental analyzer was used to determine the elemental composition of the samples. The analysis was performed in the high-temperature catalytic oxidation mode at 1150 °C, followed by gas chromatographic analysis of the decomposition products. Each measurement was repeated three times, and the mass fractions of carbon, hydrogen, nitrogen, and sulfur were determined with an accuracy of ±0.03 %. The oxygen content was calculated by difference, accounting for the sample's moisture and ash contents. To ensure measurement accuracy, the device was calibrated monthly using a certified BBOT reference substance. The higher calorific value of biomass at different grinding levels was determined using a Parr 6400 calorimeter in isothermal mode. Each 1.2-g sample was burned in an oxygen atmosphere at 30 bar until complete oxidation. The calorimeter was equipped with an automatic heat-loss compensation system and a digital thermostat to maintain the shell-water temperature with an accuracy of ±0.001°C. To improve data reliability, each measurement was repeated at least three times, and the final value of the higher calorific value was calculated as the arithmetic mean. Based on the measurement results, both the HHV value and the amount of residual ash in the crucible were recorded, with

values ranging from 1.3 to 8.7% across fractions. In addition, a set of thermogravimetric analyses was conducted to study the thermal decomposition characteristics of biomass from different fractions. These experiments were performed on a Mettler Toledo TGA/DSC 3+ thermogravimetric analyser. Each 15-mg sample was heated under nitrogen at a flow rate of 60 ml/min from 25°C to 800°C at 15°C/min. The sample mass and heat flow were recorded simultaneously, enabling determination of the exothermic effects and the peak decomposition temperature. With an increase in the grinding degree to a fraction of 0.25 mm or less, the maximum heat release shifted from 345°C to 315°C, indicating accelerated pyrolysis and combustion. To assess moisture content and accurately recalculate the heat of combustion to a dry state, the samples were tested using a Sartorius MA160 moisture meter. The mass fraction of moisture was determined using a standard method: the sample was heated to 105°C until the mass stabilised. The difference in moisture content among the fractions was explained by differences in specific surface area: the highest values were typical of samples crushed to 0.25 mm, with an average moisture content of 6.2%. In addition, the study included analyses of flowability and bulk density, as these parameters can affect the fuel dosing process. For this purpose, a Rutsch STAV 2003 bulk density determination unit was used, which allows bulk material density to be recorded at a standard drop height. The results showed that decreasing the fraction size from 2 mm to 0.25 mm increased the bulk density from 142 to 198 kg/m³. In the final stage, all obtained data were compared with the calorific values calculated using empirical formulas, and the differences were analysed using ANOVA and the determination coefficient. This approach enabled systematic evaluation of the effects of particle-size distribution and grinding intensity on the heat of combustion, and the identification of the most significant factors influencing the energy potential of biomass.

3.RESULTS AND DISCUSSION

As part of the study, a set of experimental work was conducted to comprehensively investigate the effects of particle-size distribution and the degree of biomass grinding on its heat of combustion, as well as related thermal and physicochemical characteristics. The experiments covered the preparation of biomass fractions of different sizes, moisture analysis, elemental composition determination, calorimetric measurements, thermogravimetric and differential scanning calorimetric studies, and an assessment of flowability and bulk density indicators. In the first stage of raw material preparation, agricultural biomass, including wheat straw, corn stalks, and hardwood chips, was dried at 60 °C for 72 hours to a residual moisture content of 5%. A Fritsch Pulverisette 19 crusher equipped with sieves of 0.25, 0.5, 1, and 2 mm was used for grinding. The grinding was performed at 4500 rpm, and each sample was processed until it passed through sieves with the selected cell diameter. Additionally, to improve the accuracy of particle distribution determination, each fraction was sieved using a Rutsch AS 200 control vibration analyser at an oscillation amplitude of 1.5 mm for 20 minutes. This enabled the isolation of four homogeneous fractions with median particle sizes of 0.28, 0.62, 1.24, and 2.05 mm, respectively (Table 1). For each particle-size distribution variant, 100–300 g of samples were collected. The moisture mass fraction in the samples was determined using a Sartorius MA160 moisture meter after heating to 105 °C. According to the measurement results, the moisture content ranged from 5.1% in the 2 mm fractions to 6.4% in the smallest 0.25 mm fractions, attributable to increases in specific surface area and the capacity to absorb atmospheric moisture. The elemental composition was determined using an Elemental Vario EL Cube analyser using the high-temperature catalytic oxidation method. The average values of the mass fraction of carbon for wheat straw were 46.25±0.15%, 5.19±0.03% for hydrogen, 0.39±0.01% for nitrogen, and 0.08±0.005% for sulfur. For corn stalks, the carbon mass fraction was slightly higher (47.73±0.18%), whereas for deciduous wood chips it was 48.90±0.11%. The mass fraction of oxygen was calculated by difference and was in the range of 44%–47% (Fig. 1). The ash content was determined after complete combustion of the samples in a muffle furnace at 750°C for 6 hours, and it varied from 1.4% for wood chips to 8.9% for straw. The higher heating value was measured in a Parr 6400 calorimeter in the isothermal mode at an oxygen pressure of 30 bar. Each sample, weighing 1.2 g, was burned until complete oxidation, with automatic compensation for heat loss and control of the shell water temperature. The measurement results showed that the degree of grinding significantly affected the heating value. For the 2 mm fraction of wheat straw, the average HHV was 17.81 MJ/kg; for the 0.25 mm fraction, it increased to 18.48 MJ/kg. A similar trend was observed for corn stalks: as the fraction decreased from large to small, the HHV decreased from 18.12 to 18.94 MJ/kg. For wood chips, the energy content increased from 19.26 to 20.03 MJ/kg. Therefore, the average increase in the heat of combustion when moving from the most significant fraction to the tiniest fraction was 4.5%–5.6%, which is associated with the acceleration of pyrolysis processes and a decrease in the proportion of under-oxidised

volatile products (Table 2). To elucidate the decomposition mechanisms, a thermogravimetric analysis (TGA) was conducted using a Mettler Toledo TGA/DSC 3+ instrument. Each 15 mg sample was heated under nitrogen at a flow rate of 60 ml/min from 25°C to 800°C at a heating rate of 15 °C/min. For the woody biomass, the central decomposition peak was at 347 °C for the 2 mm fraction and at 322 °C for the 0.25 mm fraction. The maximum mass-loss rate was 4.62%/min for large fractions and increased to 5.31%/min for fine samples. The total mass loss of up to 600 °C was 74%–78% for wood chips and 69%–72% for straw (Table 3). Differential scanning calorimetry showed that exothermic peaks shifted to lower temperatures with decreasing particle size, confirming the acceleration of thermal transformations. For wheat straw, the central heat-release peak was observed at 335°C for large fractions and at 308°C for small fractions.

Table 1 The Particle Size Distribution and Weight Fraction of Moisture in Biomass After Grinding and Sieving.

Biomass type	Fraction size, mm	Average particle diameter, mm	Humidity after drying, %	Humidity after 72 hours at 60% RH, %
Wheat straw	2	2.05	5.1	6.1
Wheat straw	1	1.24	5.4	6.6
Wheat straw	0.5	0.62	5.8	7.2
Wheat straw	0.25	0.28	6.4	7.8
Wood chips	2	2.10	4.9	5.5
Wood chips	0.25	0.26	5.2	6.2
Cornstalks	2	2.00	5.3	6.0
Cornstalks	0.25	0.29	6.0	7.1

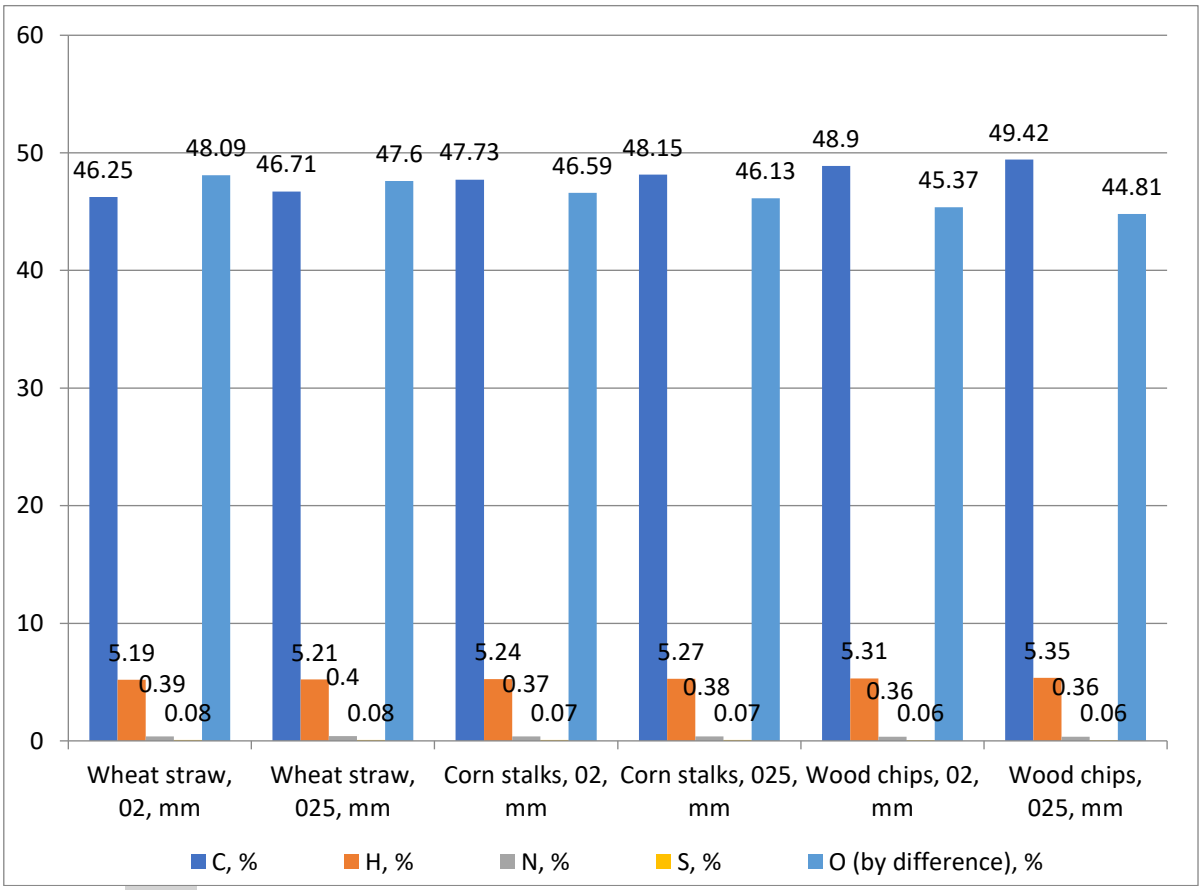

Fig. 1 Weight Fractions of Elements Depending on the Particle Size Distribution.

Table 2 The Gross Calorific Value and Exothermic Peak Temperature.

Biomass type	Fraction size, mm	HHV, MJ/kg	Peak temperature DSC, °C	Ash, %
Wheat straw	2	17.81	335	8.7
Wheat straw	0.25	18.48	308	8.2
Cornstalks	2	18.12	340	6.3
Cornstalks	0.25	18.94	315	6.0
Wood chips	2	19.26	347	1.4
Wood chips	0.25	20.03	322	1.3

Table 3 Dynamics of Decomposition in the Nitrogen Atmosphere.

Biomass type	Fraction size, mm	Maximum decomposition rate, %/min	Peak T_{max}, °C	Weight loss of up to 600 °C, %
Wheat straw	2	4.48	338	70.2
Wheat straw	0.25	5.25	310	71.8
Cornstalks	2	4.55	345	71.1
Cornstalks	0.25	5.34	317	72.9
Wood chips	2	4.62	347	74.0
Wood chips	0.25	5.31	322	77.5

Additionally, bulk density and flowability tests were performed using a Retsch STAV 2003 setup. For wheat straw, the bulk density increased from 138 kg/m³ for a particle size of 2 mm to 192 kg/m³ for a particle size of 0.25 mm, and for wood chips, it increased from 162 kg/m³ to 215 kg/m³. This effect is associated with a decrease in the void fraction between particles and a denser packing of finely dispersed material. Flowability decreased, which was important when designing fuel supply systems for boilers. Moisture analysis showed that small fractions absorbed moisture from the environment more rapidly. After 72 hours of storage at a relative air humidity of 60%, the moisture content in wheat straw samples increased from 5.4 to 7.8% in the tiniest fraction and only to 6.1% in the most significant fraction. This result indicates that crushed raw materials must be used promptly or stored in a sealed manner. To compare the experimental data with the calculated heat-of-combustion values, the modified Fried and Shen equations were used. The calculation using the Friedl formula yielded an HHV of 19.83 MJ/kg for wood chips, whereas the measured value for a 0.25 mm fraction was 20.03 MJ/kg, corresponding to a 1% deviation. At the same time, for wheat straw, the deviation reached 2.9% when using the basic version of the formula, without accounting for the granulometric factor. A comparative analysis shows that including the dispersion factor in the regression model can increase forecast accuracy by 0.6%–1.2% relative to classical models. To assess reproducibility, additional tests were conducted on a parallel series of samples ground in a RETSCH PM100 ball mill using ceramic balls and 0.125 mm sieves. For these samples, the calorific value of wood chips was 20.26 MJ/kg, 1.1% higher than that obtained for the 0.25-mm fraction after grinding in a rotary crusher. From a cost–efficiency perspective, further comminution below 0.25 mm yielded only a marginal HHV gain (~1.1% at 0.125 mm for wood chips in our tests). Still, it would entail substantially higher specific milling energy, greater equipment wear, and increased dust-control demands at the industrial scale. Consequently, unless a downstream process explicitly requires fine powders, 0.25 mm appears to be a practical lower limit that balances energy input and fuel quality benefits. This observation demonstrates that not only particle size but also production technology can affect the calorific value, likely due to differences in the mechanical destruction of the cellular structure and changes in reactivity. The comparison of the obtained data with literary sources shows good agreement with the results of similar studies. For example, in [1], when grinding biomass to a fraction of less than 0.3 mm, the increase in the calorific value reaches 3.8–5.2%, which is close to the values recorded in the present study. According to Abineno et al., an increase in the specific surface area of particles leads to an acceleration of the pyrolysis process, which is confirmed by a shift in the decomposition peak in thermogravimetric analysis by 15°C–25°C. The difference in peak temperature observed in our case, from 347°C to 322°C, also falls within these limits. The work of Aguilar et al. demonstrates an increase in the calorific value of wood waste from 18.9 to 19.9 MJ/kg, accompanied by a decrease in average particle size from 1.5 to 0.3 mm, findings comparable to those of our experiments. Therefore, the results obtained provide grounds to assert that particle size distribution is a significant factor affecting the heat of combustion and related characteristics of biomass. With a decrease in the average particle size by 1.75 mm, the calorific value increases by an average of 4.9%, and the peak temperature of exothermic decomposition decreases by 25°C–30°C. These changes result from increased rates of heat and mass transfer, accelerated release of volatile products, and improved oxygen contact with the particle surface. In general, the work conducted experimentally confirmed and quantitatively evaluated the effect of grinding degree on the energy potential of lignocellulosic biomass, thereby expanding the available data on the mechanisms and magnitude of this effect. The results obtained can be used to optimise fuel preparation processes and to adjust models for calculating the heat of combustion, accounting for the particle-size distribution factor. Implications for combustion system design and preprocessing are as follows. The observed HHV gains for finer fractions must be balanced against higher moisture uptake and reduced flowability documented here. For fixed-bed and grate-fired boilers, maintaining bed permeability and

avoiding fines-induced channelling generally favours coarser feeds (D50 ≈ 0.6–1.2 mm), where incremental HHV gains below 0.5 mm are outweighed by handling penalties. In contrast, pulverised biomass burners and co-firing applications benefit from fine grinding (<0.5 mm) to accelerate devolatilization and heat release, consistent with the lower peak-decomposition temperatures observed in this work. For downdraft gasifiers, a bimodal distribution with a limited fine fraction can enhance reactivity without compromising bed hydraulics. These system-specific recommendations follow directly from the measured trade-offs among HHV increase, moisture sorption, and changes in bulk density and flowability reported in Tables 1–3.

4.CONCLUSION

The study provided convincing experimental evidence that the particle-size distribution of biomass significantly affects its combustion heat, moisture content, and physicochemical properties. With a decrease in particle size from 2 to 0.25 mm, the average combustion heat increased by approximately 4.9%, as indicated by specific values. For wheat straw, the increase was from 17.81 to 18.48 MJ/kg; for corn stalks, from 18.12 to 18.94 MJ/kg; and for wood chips, from 19.26 to 20.03 MJ/kg. This increase in the calorific value is associated with accelerated pyrolysis and more complete oxidation of volatile fractions, as evidenced by a shift in the peak heat-release temperature. Hence, for wood waste, the peak of exothermic decomposition shifted from 347 °C for a significant fraction to 322 °C for a small fraction, and the maximum rate of mass loss increased from 4.62 to 5.31%/min, indicating a more intense degradation reaction with decreasing particle size. In addition, a systematic increase in bulk density was observed: for wood biomass, this indicator increased from 162 to 215 kg/m³, and for wheat straw from 138 to 192 kg/m³, attributable to a decrease in void volume and denser packing of crushed material. Finely dispersed fractions were more prone to moisture absorption. At 60% relative air humidity, the straw moisture content increased to 7.8% within 72 hours, compared with 6.1% for the large fraction, underscoring the need for prompt use or hermetically sealed storage of crushed raw materials. A comparative analysis of empirical models and experimental data showed that classical formulas, such as the Friedl equation, achieved relatively high accuracy in predicting the heat of combustion but did not account for particle size. When calculating the HHV of wood chips using the basic Friedl formula, the error was less than 1%. In contrast, for wheat straw, it was 2.9%; including a correction for the dispersion factor further reduced the error by 0.6%–1.2%, indicating the potential to modify existing calculation approaches. An important observation was that not only the size but also the grinding technology affected the energy properties: the samples ground in a ball mill to a fraction of 0.125 mm showed an HHV of 20.26 MJ/kg, which is 1.1% higher than the result for 0.25 mm after a rotary crusher. This allows us to conclude that the mechanical destruction of the biomass structure, achieved with different grinding methods, further increases reactivity. Finally, a comparison of the results with the literature [1, 2] confirmed that the identified patterns are in good agreement with previously reported trends. This is an increase of 3.8%–5.2% in the heat of combustion with decreasing particle size, accompanied by a shift of the exothermic decomposition peaks by 15°C–25°C. In total, the study substantiated the importance of considering the granulometric composition when calculating the energy potential of biomass. It showed that optimising the grinding degree can increase the heat of combustion by up to 5%–6% without additional modifications to the raw material composition.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

E.A. Rozhkov: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing–original draft, Visualization. **A.N. Borotov**: Investigation, validation, resources, writing – review & editing. **Yu. S. Kuznetsova**: supervision, project administration, methodology, Writing – review & editing, and funding acquisition.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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