

Biomass Diversification for District Heating: Trade-Off between Biomass Sustainability and Heat Production Efficiency

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Abstract – Biomass diversification in district heating is driven by resource constraints and sustainability requirements under European Union policy, yet variability in fuel properties complicates procurement and operational planning. This study evaluates nine biomass fuels available on the local market, including wood chips, residues from intensified forest harvesting, and alternative biomass blends, to link fuel quality with economic and environmental performance. Fuels were characterized by proximate and ultimate analysis, calorific value, ash melting temperature, and chemical composition, and ash utilization potential was assessed through oxide mapping and heavy-metal analysis. Combustion tests were conducted in a large-scale moving-grate boiler under real operating conditions, with flue-gas measurements used to calculate efficiency and heat losses. WC3 achieved the highest net calorific value due to low moisture, also the highest combustion efficiency and lowest particulate matter concentration in flue gas, while WM3 and WM4 showed severe CO peaks and combustion efficiency losses under tested conditions. WM3 had the highest ash content and lowest melting point, while WM4 contained a large fines fraction, raising dust and segregation concerns. Heavy-metal concentrations were lowest in WC3 and highest in WR2.

Keywords – Alternative biomass; combustion performance; district heating; ICP-OES; proximate analysis; SDG 12; solid fuel; ultimate analysis.

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1. INTRODUCTION

Biomass is a highly versatile resource that occurs in multiple forms and exhibits significant variability in its properties. It originates from forestry, agriculture, and industrial sectors, including the food industry, and is utilized for energy generation, food production, animal feed, and as a raw material in manufacturing. Globally, solid biofuels represent the smallest share of biomass consumption, whereas animal feed accounts for the largest portion [1]. The inherent heterogeneity of biomass (reflected in its chemical and physical characteristics) creates challenges for maintaining consistent quality and limits its efficient application for thermal energy production through combustion. Combustion technology selection is not only a technical decision but also a regulatory and operational constraint, as illustrated in Fig. 1.

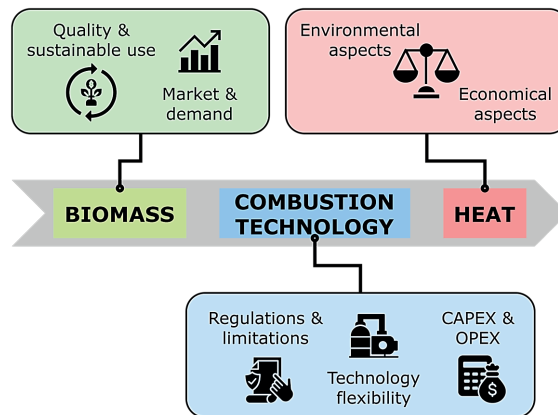


Fig. 1. Key factors influencing biomass combustion for thermal energy production.

Combustion technology selection is influenced not only by technical considerations but also by regulatory and operational constraints. Biomass boilers with thermal energy capacities of 1–50 MW fall under the Medium Combustion Plant Directive (MCPD), which establishes emission limit values and monitoring requirements, while allowing European Union (EU) Member States to impose stricter limits in areas with poor air quality [2]. This makes fuel quality control essential for compliance and stable operation. Procurement and burner configuration should be based on graded wood chip classes under ISO 17225, which define origin categories and testable property ranges [3].

Beyond combustion performance and MCPD compliance, EU policy increasingly links market access and financial support to sustainability and traceability. The recast Renewable Energy Directive strengthens sustainability criteria for forest biomass and recognizes voluntary certification schemes (e.g., Sustainable Biomass Program) that verify conformity through supply-chain audits [4]. In parallel, the EU Deforestation Regulation replaces the EU Timber Regulation and introduces due-diligence obligations for wood and derived products, including chips, requiring proof of legality and deforestation-free origin [5].

In practice, EU markets differentiate high-grade wood chips from those accompanied by credible sustainability and chain-of-custody certification rather than informal labels [6]. While quality certification improves transparency and standardization, harmonization across Member States remains incomplete, and empirical evidence on operational benefits versus certification costs is limited. This highlights the need for comparative, standardized field data

linking chip classes, boiler technologies, and MCPD compliance under real-world operating conditions.

While certification frameworks and ISO grading provide theoretical assurance of fuel quality and sustainability, their practical implications for combustion performance remain largely unverified under real-world conditions. District heating plants operate under dynamic load profiles, variable ambient temperatures, and site-specific control strategies that cannot be replicated in laboratory settings. These factors influence flue-gas composition, thermal efficiency, and maintenance requirements, which are critical for compliance with emission limits and cost optimization. Investigating operational performance with fuels that meet emerging sustainability criteria is therefore essential to determine whether such fuels deliver tangible benefits beyond regulatory conformity. Empirical evidence from large-scale installations will inform procurement strategies, technology adaptation, and policy development, ensuring that sustainability objectives align with technical and economic realities in the district heating sector.

Although biomass fuel properties, combustion emissions, and ash composition have each been widely investigated, these aspects are often assessed separately. Consequently, there is limited field-based evidence linking laboratory fuel quality indicators with combustion efficiency, regulated emissions, ash-related environmental risks, and fuel-to-heat cost under real district heating conditions. This study addresses this gap by integrating these aspects into a single comparative assessment framework.

1.1. The Role of Chemical Composition of Biomass Ash

Biomass contains various metal ions, predominantly macronutrients such as calcium (Ca), potassium (K), iron (Fe), manganese (Mn), magnesium (Mg), and sodium (Na) [7]. These macronutrients are basic components that play an essential role in the quality of biomass from a nutritional point of view, but only Fe and Mg count as heavy metals (HMs), and they are generally non-toxic. In contrast, trace concentrations of hazardous HMs, including carcinogenic chromium (Cr), neurotoxic lead (Pb), bioaccumulative cadmium (Cd), and nickel (Ni), which is associated with respiratory disorders, can also be present in biomass [8]–[11].

Despite extensive research on the influence of biomass properties on combustion, significant uncertainties remain regarding HMs accumulation, their release during combustion, and potential capture strategies. Current studies highlight critical knowledge gaps in understanding HM formation mechanisms and in developing effective pollution control measures [12]–[14]. Similar to biogeochemical cycles such as carbon, nitrogen, and phosphorus, as well as the hydrological cycle, HMs also circulate through various environmental compartments – soil, water, and air [15]–[17].

Given the continuous circulation of HMs in the environment and their persistence throughout the biomass life cycle, determining the chemical composition of biomass is crucial. This is particularly important because, at the end of the life cycle, biomass ashes are often released into the environment, enabling further redistribution of HMs [18]. Consequently, accurate characterization of these elements is essential for assessing environmental impacts, ensuring compliance with sustainability standards, and developing strategies to mitigate HM emissions.

Beyond emissions, the oxide composition of biomass provides a quantitative basis for screening end-use pathways. Ternary compositional plots (commonly referred to as Vassilev diagrams) locate ash within domains indicative of pozzolanic potential, glass-ceramic precursors, fluxing behavior for cement raw meals, or agronomic reuse, while simultaneously flagging slagging propensity during combustion [19]–[21]. Systematic placement of sample ash on the Vassilev diagram thus supports evidence-based, compliant utilization strategies and reduces the likelihood of environmentally adverse disposal.

1.2. Nature of the Study

The aim of this study was to evaluate the suitability of locally available wood-based and mixed biomass fuels for use in a medium-scale district heating boiler by linking fuel quality indicators, combustion performance under real operating conditions, emission compliance, ash composition, and fuel-to-heat conversion cost. The specific objectives were to: (1) characterize fuel properties; (2) evaluate combustion performance under real conditions; (3) assess emissions relative to regulatory limits; (4) analyze ash composition and environmental implications; and (5) integrate technical, environmental, and economic indicators into a comparative assessment.

2. METHODOLOGY

Fig. 2 shows nine biomass fuels represent the local market. The samples are divided into two groups: the upper row includes five wood-based fractions (WC1–WR2), differing in origin and particle size (wood chips from roundwood and branches, as well as small and large wood residues). The lower row presents four mixed compositions (WM1–WM4), where wood chips were blended with alternative biomass components: reeds (20 % and 40 %), bark, sunflower husk pellets, and wood sawdust. The photographs illustrate the visual structure of each sample, highlighting differences in color, texture, and heterogeneity, which reflect the diversity of biomass types considered in the study.



Fig. 2. Biomass fuel samples used in the study.

The experimental activities were conducted at two locations. The first location was the Environmental Monitoring Laboratory (EML) at the Institute of Energy Systems and Environment (IESE), Riga Technical University (RTU), where the characterization of fuel samples was performed. This included proximate and ultimate analyses, determination of energy and physical properties, and particle size distribution. The second location was a district heating boiler house in Ādaži municipality, Latvia, where the prepared biomass samples were combusted in a large-scale solid-fuel boiler under controlled conditions, and the corresponding operational and emission parameters were measured. The overall experimental scheme is presented in Fig. 3, illustrating the complete workflow of the study.

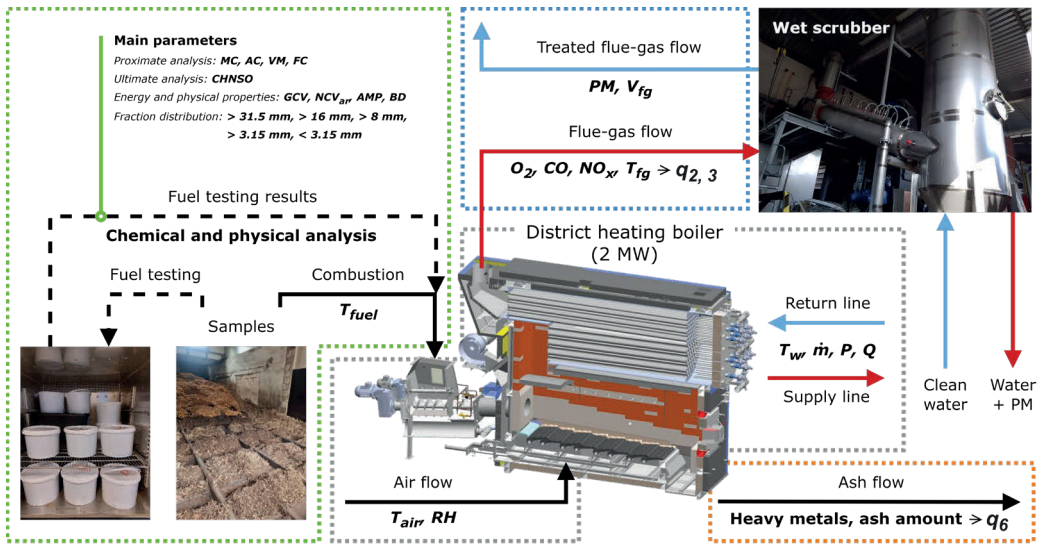


Fig. 3. Experimental setup and measurement scheme of this study.

2.1. Fuel Testing

Fuel characterization is a critical prerequisite for accurate emission assessment and comparability of results. The chemical and physical properties of biomass fuels strongly influence combustion behavior and efficiency, as well as flue gas content. Therefore, prior to combustion tests in the boiler house, all samples were analyzed in an accredited laboratory equipped with modern instrumentation, ensuring compliance with internationally recognized standards. This approach guarantees data reliability and reproducibility, enabling a robust interpretation of emission indicators across different biomass types. Table 1 summarizes the activities carried out during fuel testing and the parameters that were measured or determined.

From all types of biomass used in this study, immediately after bringing into the laboratory, a representative mass was directed for the sample preparation according to LVS EN ISO 14780:2017 [22]. At first, the sample was mixed and then divided into several equal parts and used for the determination of the MC according to LVS EN ISO 18134-2:2017 [23]. After the MC tests, the dried sample was milled into a powder using a hammermill with a mesh size of 1 mm and used for other parameter testing. AC and VM were determined according to the methodologies described in LVS EN ISO 18122:2022 [24] and LVS EN ISO 18123:2023 [25], respectively. The FC content was determined by subtracting the sum of the VM and the AC from 100 wt% on dry basis, according to methodology from scientific literature [26], [27]. The CHNSO elemental composition was determined by combining methodologies from LVS EN ISO 16948:2015, LVS EN ISO 16994:2016, and LVS EN ISO 16993:2016 [28]–[30]. The GCV and NCV_{ar} were determined according to LVS EN ISO 18125:2017 [31]. The AMP was determined according to LVS EN ISO 21404:2020 [32]. The BD was determined according to LVS EN ISO 17828:2016 [33]. The PSD was determined in accordance with LVS EN ISO 17827-1:2024 [34].

TABLE 1. FUEL CHARACTERIZATION ACTIVITIES AND CORRESPONDING EQUIPMENT

Activity/measurements	Equipment
Sample preparation	Hammermill Vibrotechnik PM120
Moisture content (MC)	Scales Precisa XB 120A
	Dryer Ecocell 55
Ash content (AC), combustible fraction in the ash	Scales Precisa XB 120A
	Muffle furnace Nabertherm L3/11/P320
	Muffle furnace SNOL 7.2/1300
Volatile matter content (VM)	Scales Precisa XB 120A
	Muffle furnace SNOL 7.2/1300
Fixed carbon (FC)	– (determined)
Chemical composition of fuel (CHNSO)	Costech ESC 4010
Gross calorific value (GCV) Net calorific value, as received (NCV _{ar})	Calorimeters IKA-Werke C 2000
	Pellet press IKA-Werke C 21
	Oxygen supply station IKA C 248
Ash melting point (AMP)	Calorimetric bomb IKA C 5010
	Carbolite CAF DIGITAL
Bulk density (BD)	Metal measuring cup, 5 L
Particle size distribution (PSD)	Sieve shaker Retsch AS 400

2.2. Combustion Tests

The boiler used is a series model comprising a slightly inclined moving-grate furnace integrated with a three-pass water boiler and a multicyclone. The unit is custom-adapted for the specific site; the model family covers nominal heat outputs from 0.75 to 4 MW. The integrated design reduces footprint and assembly time. Eight combustion tests were performed in two stages. Each stage included one reference test using the boiler's regular fuel (wood chips supplied via the on-site conveyor) and three tests with blended fuels representing higher- and lower-quality biomass. All tests were conducted under real district heating operating conditions at part-load, corresponding to the actual heat demand during the measurement period. Flue-gas parameters were recorded at 10 s intervals. Each test included a stabilization period after fuel changeover, and only steady-state operation data were used to calculate mean values. Transient phases, including start-up and fuel switching, were excluded from the analysis. Table 2 summarizes the activities carried out during combustion tests and the parameters measured.

Two main instruments were employed during the experimental measurements: the Testo 350 flue-gas analyzer and the Testo 380 particulate matter measurement system. The Testo 350 is a modular industrial-grade analyzer designed for high-accuracy monitoring of combustion processes which perform measurements according to EN 14789:2017, EN 15058:2017 and ISO 10849:2022 [35]–[37]. It consists of a control unit and an analyzer module, enabling flexible configuration and remote operation. The system supports multi-parameter measurements and is suitable for large-scale boilers under real operating conditions. The Testo 380 is a compact system for direct particulate matter determination in flue gases which perform measurements according to VDI 4206-2 [38]. It integrates a dedicated probe with a control module, allowing real-time measurements and simultaneous

monitoring of key combustion indicators. The device is optimized for solid-fuel applications and provides reliable data for compliance and research purposes.

TABLE 2. COMBUSTION TEST ACTIVITIES AND CORRESPONDING EQUIPMENT

Activity/measurements	Equipment
	Boiler KAPAK2000N
Samples combustion	Chip feed conveyor
Air temperature (T_{air})	Boiler monitoring system
	Fuel bunker
Oxygen content in flue gas (O_2)	
Carbon monoxide content in flue gas (CO)	
Carbon dioxide content in flue gas (CO_2)	Testo 350
Nitrogen oxides content in flue gas (NO_x)	
Flue gas temperature (T_{fg})	
Particulate matter content in flue gases (PM)	Testo 380
Thermal heat losses in the flue gas (q_2)	– (determined)
Chemical heat losses in the flue gas (q_3)	– (determined)
Combustion efficiency calculation (ζ)	– (determined)

The combustion efficiency indicator was calculated using a simplified indirect method $\zeta = 100 - q_2 - q_3$, where ζ is the combustion efficiency (%), q_2 represents heat losses with flue gas, and q_3 represents losses due to incomplete combustion. In combustion systems, most of the released energy is associated with the chemical energy of the fuel, while sensible heat contributions from fuel and air are negligible. Determining full boiler efficiency requires accounting for multiple loss components and is typically complex. Detailed analysis is not essential for comparative emission assessment. Therefore, this study focuses on the dominant loss terms q_2 and q_3 , while other losses were assumed proportional. The q_2 losses represent the largest share of total heat losses and are primarily influenced by flue-gas temperature and excess air ratio. These parameters depend strongly on fuel characteristics and combustion control. The q_3 losses are associated with incomplete combustion and are typically reflected by CO concentration in flue gas. Under optimal conditions, q_3 losses remain below 1 % of the total heat balance. Losses were calculated using a combined approach in accordance with LVS EN 12952-15 and LVS EN 16510-1:2023 [39], [40].

2.3. Ash Composition

Accurate determination of the elemental composition of biomass ash requires the use of reliable analytical techniques. One of the most common composition analysis method is wet chemical analysis, which mainly includes titration or gravimetric techniques, are sometimes applied for specific components, but they are labor-intensive and lack the capability for multi-element detection [41]. Another group of techniques is based on spectroscopy, including X-ray Fluorescence (XRF), Atomic Absorption Spectroscopy (AAS), and Inductively Coupled Plasma (ICP) methods – mass spectrometry (ICP-MS) and optical emission spectroscopy (ICP-OES) – which offer higher sensitivity and multi-element capability.

Among these techniques, XRF is rapid and non-destructive but has limited sensitivity for light and trace elements, which restricts its applicability for comprehensive HM analysis in biomass ash [41]. AAS provides accurate measurements for individual elements but operates sequentially, resulting in low efficiency for multi-element determinations [42]. ICP-MS achieves superior detection limits for trace metals, yet its high cost and susceptibility to matrix interferences

complicate routine analysis of ash digests [43]. ICP-OES offers simultaneous multi-element detection, broad dynamic range, and robust performance for samples containing both major and minor elements, making it well suited for biomass ash characterization [44]. Compliance with ISO standards for solid biofuels further supports the selection of ICP-OES as the analytical method for this study.

Elemental determinations were performed using a Thermo Scientific iCAP 7400 ICP-OES, operated under manufacturer-recommended conditions for routine multi-element analysis and stable plasma performance. Instrument configuration and sample introduction parameters are summarized in Table 3.

TABLE 3. METHOD PARAMETERS AND SAMPLE INTRODUCTION SETUP USED

Parameter	Setting
Pump Tubing (Standard Pump)	Sample: TFS® white /white Drain: TFS® yellow/blue
Pump Speed	50 rpm
Center Tube	2 mm, ceramic
Spray Chamber	PTFE cyclonic Nebulizer Burgener Mira Mist®
Nebulizer Gas Flow	0.65 L·min ⁻¹
RF Power	1150 W
Exposure Time	Axial: UV 15 s, Vis 10 s Radial: UV 15 s, Vis 10 s

All acids and auxiliary reagents used for digestion were of the highest purity. Ultrapure water was produced on with a Barnstead MicroPure system to minimize background contamination and ensure reproducibility in calibration and sample dilution. Ash collected was mineralized in closed vessels using a MARS 6 microwave digestion system equipped with EasyPrep vessels. The digestion program employed elevated temperatures appropriate for silicate-containing matrices, using acid mixtures based on HNO₃ and HF, with H₂O₂ as oxidant; post-digestion complexation with boric acid was applied to bind residual fluoride prior to analysis. The use of sealed microwave vessels enables higher temperatures and faster kinetics than open digestion, improving dissolution of refractory ash phases while maintaining safety and reproducibility; HF is included for complete attack of silicates, and boric acid mitigates HF-related interferences in subsequent ICP measurements. External calibration was established using Multielement Standard Solution V (p/n 54704) and Multielement Standard Solution VI (p/n 43834), covering the analyte suite and concentration ranges expected in biomass ash; cysteic acid monohydrate served as the reference standard for sulfur. Instrument performance verification and blank checks were performed at the beginning and end of each batch to confirm drift control and contamination levels consistent with best practice. Major elements and minor/trace elements were quantified according to LVS EN ISO 16967:2015 [45] and LVS EN ISO 16968:2015 [46], respectively. These standards define target analyte lists, sample decomposition guidance, and suitable instrumental methods for solid biofuels and their ashes, providing traceability and international comparability of results. Selected analytical wavelengths and plasma view settings are provided in Table 4.

TABLE 4. DETECTION WAVELENGTHS

Element	Wavelength, nm	View
Al	167.079 {502}	Axial
Ba	455.403 {74}	Axial
Ca	393.366 {86}	Radial
Cd	214.438 {457}	Axial
Co	230.786 {446}	Axial
Cr	267.716 {126}	Axial
Cu	324.754 {104}	Axial
Fe	259.940 {130}	Axial
K	766.490 {44}	Axial
Li	670.784 {50}	Axial/Radial
Mg	279.553 {120}	Radial
Mn	257.610 {131}	Axial
Mo	202.030 {467}	Axial
Na	589.592 {57}	Radial
Ni	231.604 {445}	Axial
P	178.284 {489}	Axial
Pb	220.353 {453}	Axial
Rb	780.023 {43}	Axial
S	182.034 {485}	Axial
Sb	206.833 {463}	Axial
Si	251.611 {134} / 212.412 {459}	Axial
Sr	407.771 {83}	Axial
Ti	323.452 {104}	Axial
V	292.402 {115}	Axial
Zn	213.856 {457}	Axial

Method fidelity was ensured using reagent blanks, calibration verification solutions, and replicate digestions. The microwave digestion protocol and vessel selection were chosen to minimize contamination and ensure complete dissolution of ash constituents; manufacturer documentation emphasizes vessel recognition, temperature monitoring, and safety interlocks, which were used throughout to maintain consistent conditions.

3. RESULTS

Based on the developed methodology, all planned tests were performed. All measurements were performed repeatedly. The values presented in the results section represent arithmetic mean values of the repeated measurements. A detailed statistical uncertainty analysis was not conducted – the results should be interpreted as indicative mean values rather than statistically evaluated parameters.

3.1. Fuel Testing Results

Fuel testing results are shown in Table 5. MC varied significantly among samples. The lowest value was in WC3 (17.9 wt%), which explains its highest NCV_{ar} and makes it the most energy-efficient option on an as-received basis. The highest MC occurred in WC2 (52.1 wt%), with similarly high values in WM3 and WM4 (50 and 51 wt%, respectively). Such MC reduce practical heat output and increase latent heat losses during evaporation in the boiler, negatively affecting combustion stability and efficiency. Differences in MC are linked to storage and drying conditions of chip batches and pellet composition. Alternative pellet blends tend to be more hygroscopic, and their mechanical integrity can vary, leading to uneven moisture absorption.

AC was highest in WM3 (6.2 wt%), which is consistent with the sunflower husk pellet admixture that increases mineral fraction and ash yield. This composition raises concerns about slagging and fouling during combustion. The lowest AC was found in WC1 (1.0 wt%), corresponding to clean wood chips with minimal inorganic impurities, which is favorable for stable combustion and low ash handling requirements.

VM was lowest in WM3 (74 wt%), aligning with its higher ash and lower H content, typical for biomass with a larger mineral fraction. Low VM reduces the intensity of the devolatilization phase and slows ignition, requiring careful air staging to avoid incomplete combustion. Wood-chip samples such as WC1 and WC2 exhibited VM values above 80 wt%, indicating a more pronounced volatile release and faster ignition, which can improve combustion stability but may increase oxidation of volatiles in the flue gas if not properly controlled.

FC ranged between 16–20 wt%, with the highest value in WM3 (20.1 wt%). Elevated FC in WM3 implies a longer burnout phase on moving grates. Combined with low VM and high AC, this composition increases the risk of slagging and deposit formation if air distribution and load are not optimized.

CHNSO patterns reveal distinct group characteristics. WC samples are compositionally uniform and close to typical woody biomass, with WC3 combining favorable elemental composition and lowest MC, making it the most efficient sample in practical terms. WR2 sample shows higher N content (2.05 wt%), which indicates a greater potential for NO_x formation under high-temperature conditions. WM samples are the most heterogeneous: WM3 combines lower H, higher O, and elevated AC, explaining its lower VM and higher slagging risk. WM4 maintains a favorable energy composition despite high MC, while WM2 exhibits low BD and moderate CHNSO, implying easier ignition but more demanding handling and feeding. S remains negligible (0.01 wt%) across all samples.

GCV ranged between 19.3–20.6 MJ/kg, with the highest value in WM4 (20.6 MJ/kg) and the lowest in WM3 (19.3 MJ/kg). These differences are minor because GCV is measured on a dry basis and primarily reflects elemental composition. NCV_{ar} strongly depends on MC: WC3 delivers the highest NCV_{ar} (14.8 MJ/kg), while samples with high MC show significant reductions in usable heat. AMP was lowest in WM3 (1133 °C), typical for agriculture biomass, increasing slagging and sintering risk under hot grate operation. The highest AMP was observed in WC3 (1353 °C), reducing slagging susceptibility in district heating boilers. BD ranged between 109–240 kg/m³; low BD, as in WM2 (109 kg/m³), requires larger storage volume and increases the risk of bridging and uneven flow in feeding systems, while high BD, as in WC2 (240 kg/m³), improves transportability and ensures steadier fuel supply.

The PSD reveals distinct structural characteristics among the biomass samples tested. The coarse fraction (> 31.5 mm and > 16 mm in total) is dominant in WR1 (64.9 %) and remains high in WR2 (46.2 %) and WM3 (40.1 %). Such composition indicates a requirement for

extended residence time and slower grate movement in boiler combustion chamber to ensure complete burnout. WC1 also exhibits a relatively coarse structure (47.0 %), whereas WC3 (18.9 %) and WM2 (22.4 %) are markedly finer, favoring rapid ignition. Intermediate fractions (> 8 mm) are most prevalent in WC2 (40.9 %), WC3 (32.7 %) and WC1 (32.6 %), suggesting well-sieved chips with predictable combustion behavior and stable airflow through the grates. WR samples contain substantially less material in this range (WR1 – 11.5 %, WR2 – 23.5 %), consistent with their coarse-dominant profile. WM samples show moderate variability (15.6–24.9 %), reflecting heterogeneity in pellet size and integrity. Fine material (< 3.15 mm) is particularly critical for operational performance. WM4 exhibits an exceptionally high proportion of fines (48.3 %), which poses significant challenges related to dust emissions, fuel segregation, and uneven combustion. WM2 (22.3 %) and WM1 (19.5 %) also present elevated fine content, whereas WC samples remain comparatively clean, minimizing dust-related issues.

TABLE 5. FUEL TESTING RESULTS SUMMARY

Parameter	Unit	WC1	WC2	WC3	WR1	WR2	WM1	WM2	WM3	WM4
Proximate analysis										
MC	wt%	47.9	52.1	17.9	41.2	35.2	37.7	33.9	50.9	51.3
AC	wt%	1.0	1.5	2.2	3.7	4.5	2.8	3.4	6.2	3.3
VM	wt%	83.1	82.3	81.1	78.8	77.6	80.8	80.2	73.7	78.9
FC	wt%	15.9	16.2	16.7	17.5	17.9	16.4	16.4	20.1	17.8
Ultimate analysis										
C	wt%	53.22	52.21	52.08	52.47	53.25	50.59	52.01	50.06	52.02
H	wt%	5.31	5.32	5.32	5.51	5.25	5.2	5.16	4.72	5.05
N	wt%	1.03	1.21	1.52	1.6	2.05	1.66	1.54	1.47	1.00
S	wt%	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
O	wt%	40.43	41.25	41.07	40.41	39.44	42.54	41.28	43.74	41.92
Energy and physical properties										
GCV	MJ/kg	20.5	19.9	19.9	19.4	19.5	19.5	19.5	19.3	20.6
NCV _{ar}	MJ/kg	8.8	7.6	14.8	9.6	10.9	10.4	11.2	7.6	8.1
AMP	°C	1251	1265	1353	1198	1192	1179	1187	1133	1225
BD	kg/m ³	226	240	184	174	215	133	107	216	189
Particle size distribution										
> 31.5 mm	%	10.9	3.9	5.2	12.9	18.1	5.1	5.0	11.0	5.9
> 16 mm	%	36.1	26.7	13.7	52.0	28.1	24.2	17.4	29.1	17.9
> 8 mm	%	32.6	40.9	32.7	11.5	23.5	24.9	21.7	22.0	15.6
> 3.15 mm	%	15.6	19.9	34.8	12.3	18.2	26.3	33.6	28.1	12.3
< 3.15 mm	%	4.9	8.5	13.7	11.3	12.1	19.5	22.3	9.8	48.3

3.2. Combustion Tests Results

All results presented in this study correspond to mean values calculated for each individual combustion test. During each test, the boiler was operated under real operating conditions at part-load to meet the actual heat demand of the site. Consequently, instantaneous process parameters and flue-gas concentrations exhibited natural temporal variations, reflecting realistic

fluctuations in fuel feeding, air supply, and combustion dynamics typical for industrial-scale biomass boilers.

Results of combustion tests are shown in Table 6. The measured O_2 ranged from 9.0–11.8 %, indicating operation with substantial excess air across all tests. Higher O_2 coincided with larger q_2 losses: WM3 and WM4 (highest O_2) exhibited the 20.3 and 20.1 %, respectively, whereas WC3 (lowest O_2) achieved the lowest q_2 – 10.8 %. The strong anti-correlation between efficiency and q_2 confirms that air–fuel ratio control is the dominant lever for thermal performance.

The lowest CO was observed for WR1 and WR2 (288 and 301 mg/Nm³, respectively), while WM3 and WM4 produced extremely high CO (8017 and 4541 mg/Nm³, respectively). This trend aligns with q_3 losses: WM3 and WM4 showed the highest q_3 (6.2 % and 4.2 %, respectively), driving the lowest ζ . Conversely, WC3 combined low q_3 with low q_2 to reach the highest ζ , despite its mid-range CO, indicating that further improvement is available by strengthening secondary-air mixing and burnout without materially increasing q_2 .

NO_x ranged from 139 mg/Nm³ for WC2 to 416 mg/Nm³ for WR1. A positive correlation between ζ and NO_x and a negative one between NO_x and CO illustrate a classical trade-off (in case of WR1 and WR2): more complete and better-mixed combustion suppresses CO but tends to increase NO_x .

PM ranged 52–180 mg/Nm³, lowest for WC3 and highest for WM3. In case of WM4, high PM is consistent with high < 3.15 mm fraction content, which promotes mechanical entrainment from the bed and through the convective pass. By contrast, WM3 has low < 3.15 mm fraction content, so its high PM is better explained by high CO, large q_3 losses. Low AMP further supports ash disintegration into fine aerosols in this case.

TABLE 6. COMBUSTION TESTS RESULTS SUMMARY

Parameter	Unit	WC1	WC2	WC3	WR1	WR2	WM1	WM2	WM3	WM4
Flue gas composition										
O_2	%	10.4	9.6	9.0	10.5	9.9	11.1	11.6	11.8	11.8
CO	mg/Nm ³	1526	2405	2453	288	301	542	752	8017	4541
NO_x	mg/Nm ³	156	139	224	340	416	329	321	273	142
PM	mg/Nm ³	59	81	52	102	153	109	112	180	172
Boiler performance										
q_2	%	18.0	18.5	10.8	15.7	14.4	16.6	17.6	20.3	20.1
q_3	%	1.1	1.7	0.9	0.2	0.2	0.2	0.4	6.2	4.2
ζ	%	80.9	79.7	88.2	84.1	85.4	83.2	82.0	73.5	75.7

3.3. Ash Composition Results

Four main HMs content in sample ashes are shown in Fig. 4. Cr and Pb exhibit the largest inter-sample variability and co-vary strongly, with maximum in WR2 and WR1. WM1 also shows elevated Cr and Pb, while WM2 and WM4 are intermediate. The WC group and WM3 are consistently low in these two HMs. WC3 is the cleanest; Cr is 0.026 mg/kg and Pb is 0.039 mg/kg. Ni is highest in WM1 and WC1, Cd is uniformly low across all samples studied, with the minimum in WC3 and maximum in WC1.

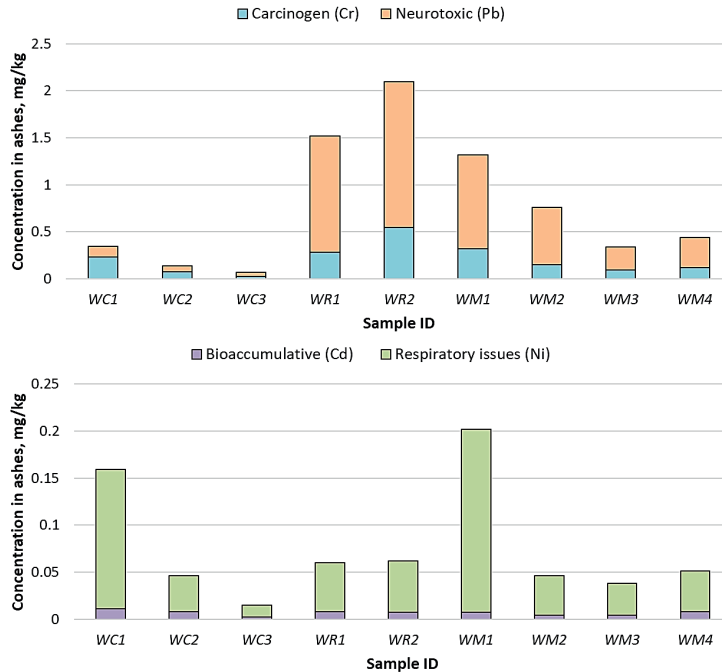


Fig. 4. Heavy metal concentrations in biomass ash samples after combustion tests.

The Vassilev diagram categorizes biomass ash into compositional zones that reflect both operational behavior and utilization potential. The calcareous zone (C) represents calcareous matrices dominated by CaO , MgO , and MnO , which are typically associated with high liming potential and reduced slagging risk during combustion. The siliceous zone (S) corresponds to siliceous matrices rich in SiO_2 , Al_2O_3 , Fe_2O_3 , Na_2O , and TiO_2 , favoring pozzolanic properties and generally exhibiting higher ash melting temperatures, making these ashes suitable for cementitious applications. In contrast, the alkali-rich zone (K) is characterized by alkali components such as K_2O , P_2O_5 , SO_3 , and Cl_2O , which promote fluxing behavior, lower melting points, and increase the likelihood of slagging and fouling in thermal systems. Intermediate fields, including calcareous matrices (C-MA), siliceous matrices (S-MA), and alkali-rich matrices (K-MA), represent mixed matrices where the relative dominance of calcareous, siliceous, and alkali oxides determines both combustion performance and the feasibility of ash utilization strategies.

The distribution presented in Fig. 5 indicates that samples WC2 and WC3 fall within the C zone, which is dominated by Ca and Mg oxides. The C-MA zone comprises WC1, WM4, and WR1, where Ca and Mg oxides remain prevalent but are accompanied by notable amounts of Si and Al oxides. The S-MA zone includes WR2, WM1, WM2, and WM3, characterized by a predominance of Si oxides, although significant concentrations of Ca oxides are still present. Alkali components, typically associated with the K zone, are negligible across all analyzed samples.

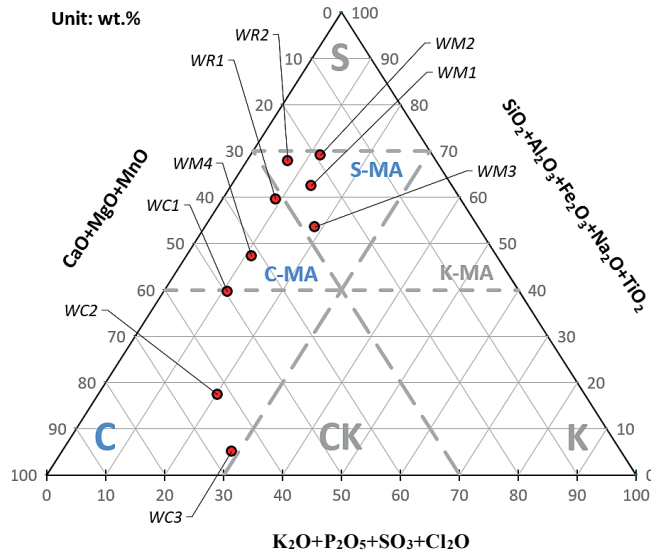


Fig. 5. Oxide mapping results according to Vassilev diagram.

3.4. Discussion

The results demonstrate clear linkages between fuel properties, combustion performance, emissions, and ash composition. Moisture content and calorific value influence efficiency, ash content and particle size influence PM emissions, nitrogen content influences NO_x formation, and incomplete combustion reflects air-fuel mixing quality. These relationships form the basis for integrated fuel suitability assessment. A simplified economic appraisal was carried out to characterize the tested fuels from a fuel-to-heat conversion perspective. For each fuel, the fuel conversion cost was computed as the ratio of the as-received fuel price to the ζ obtained in the corresponding combustion test (see Table 7). Fuel prices were taken from the boiler-house operator and/or current supplier quotations for the tested batches. The ζ values are arithmetic means from each test, as described earlier. The indicator intentionally excludes all non-fuel cost components (e.g., staff, electricity consumption, routine O&M, ash handling, taxes, profit). It therefore does not represent a heat tariff; rather, it isolates the fuel-to-heat conversion component to enable like-for-like comparison between fuels with different prices and combustion performance.

TABLE 7. MARKET PRICES AND CONVERSION COSTS OF FUEL TESTED

Parameter	Unit	WC1	WC2	WC3	WR1	WR2	WM1	WM2	WM3	WM4
Fuel price	EUR/MWh	30	35	30.0	28.0	26.0	27.0	25.0	25.0	23.0
Fuel costs (including ζ)	EUR/MWh	37	44	34.0	33.3	30.4	32.4	30.5	34.0	30.4

The study was conducted under real operating conditions; therefore, the results represent indicative field-based values rather than strictly controlled laboratory data. Consequently, the regression analyses presented below should be interpreted as exploratory and not predictive. CO (see Fig. 6A) was elevated at low moisture (<25 %) and at high moisture (>45 %), exceeding 2000 mg/Nm³ and 4000 mg/Nm³, respectively. A second-order regression shows a minimum near 35 % moisture ($R^2 = 0.5567$), indicating moderate explanatory power of

moisture alone. The pattern is empirical within the tested range; other varying parameters influence CO formation. Operating near the intermediate-moisture minimum reduces CO and q_3 losses under the tested conditions. NO_x (see Fig. 6B) increased linearly with fuel nitrogen, with strong correlation ($R^2 = 0.8855$). The association is empirical because temperature, air distribution, and load were not independently controlled. For NO_x reduction, prioritize low-nitrogen fuels; when using higher-nitrogen fuels, additional measures (e.g., staged air, furnace temperature control, flue-gas recirculation) may be required, to be evaluated case by case given boiler design and control strategy. PM (see Fig. 6C) increased with fuel ash content, with substantial correlation ($R^2 = 0.6945$). The relationship is empirical under real operation with co-varying fuel properties and conditions. Fuel selection alone is insufficient for PM control, especially with alternative or higher-ash biomass. Focus on furnace ash handling and removal (moving grate, ash discharge), and gas-air flow organization to limit entrainment. Assess the adequacy and optimization of PM abatement systems (e.g., scrubbers), recognizing that alternative biomass can alter flue-gas composition, temperature, and flow and thereby affect removal efficiency.

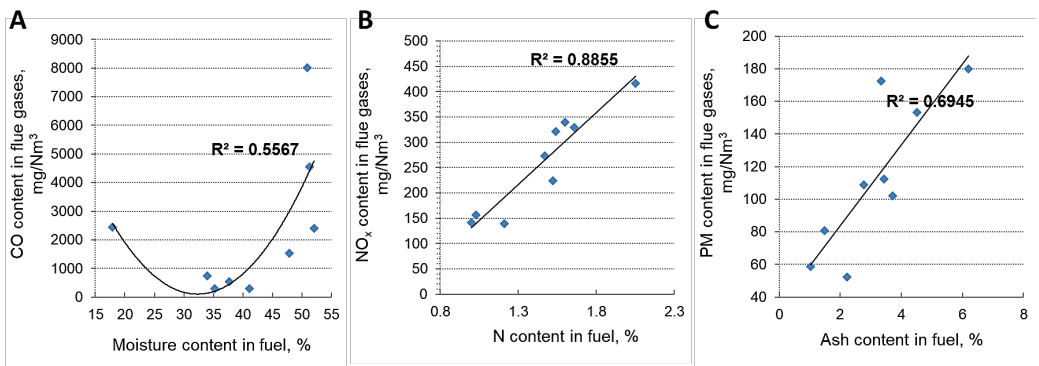


Fig. 6. Relationships between fuel properties and flue-gas pollutants under real boiler operation: (A) CO dependence on moisture content in fuel (second-order); (B) NO_x dependence on nitrogen content in fuel (linear); (C) PM dependence on ash content in fuel (linear).

The nominal capacity of boiler used is 2 MW and it corresponds to a medium solid fuel combustion plant based on Decree No. 17 of Cabinet of Ministers of the Republic of Latvia [47]. From 1 January 2030, the emission limits for solid fuels boilers of this capacity will be 50 mg/Nm³ for PM, 650 mg/Nm³ for NO_x , and 1000 mg/Nm³ for CO. At present, the applicable limits are higher, namely 1000 mg/Nm³ for PM, 600 mg/Nm³ for NO_x , and 2000 mg/Nm³ for CO. Under these current requirements, WC1, WR1, WR2, WM1 and WM2 comply. However, given the planned tightening of emission limits, it is important to evaluate how the tested fuels will perform under the future regulatory framework.

Fig. 7 presents the summary of CO, NO_x and PM of for tested fuels against the applicable limits from 2030. All fuels are below the NO_x limit, with a clear safety margin. Within the CO-compliant subset, WR2 offers the lowest conversion cost, followed by WM1, WR1, and WC3. For these fuels, PM is the only binding pollutant; compliance depends on particulate abatement rather than fuel switching. In contrast, the lowest-priced CO-exceeding fuels (WM4, WM2) are cost-attractive on a fuel-to-heat basis but require substantial combustion-side CO reduction in addition to PM control. The highest-cost options (WC1, WC2) combine large CO exceedances with high PM removal needs and are therefore unattractive under the stated limits.

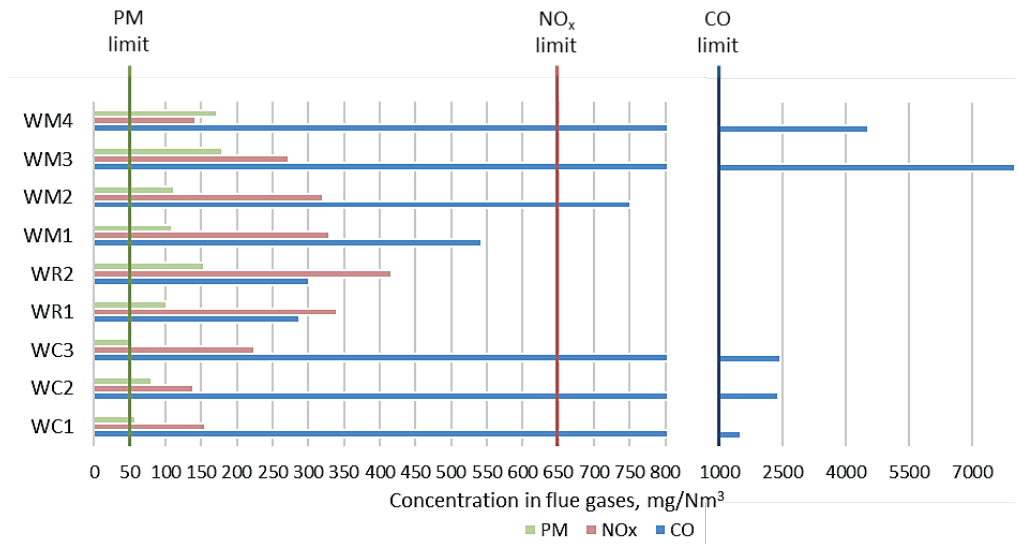


Fig. 7. Measured PM, NO_x, and CO for tested fuels and comparison with planned emission limits for a 2 MW boiler in Latvia from 2030.

Across the set, achieving the PM limit requires overall capture efficiencies of 40–85 %, with the lower end associated with cleaner-ash cases and the upper end with ash-rich fuels. The relevant decision variable is therefore not whether PM control is needed, but which fuel minimizes total cost once realistic PM capture performance and operational measures are internalized. Under existing high-efficiency PM control, WR2 delivers the strongest cost-compliance balance, with WM1, WR1, and WC3 as close substitutes at slightly higher conversion cost. If available PM control achieves less than 70 %, no fuel meets the PM limit without upgrades; higher-efficiency capture and furnace-side entrainment reduction become prerequisites.

A near-term strategy is to select from the CO-compliant group and ensure high-efficiency PM control, prioritizing WR2 on cost and using WM1, WR1, or WC3 where supply, handling, or operational stability favor them. Adoption of low-priced but CO-exceeding fuels should proceed only after demonstrated, stable CO reduction via combustion optimization; otherwise, the nominal price advantage is offset by non-compliance risk and added operational burden. High-cost and CO-noncompliant options should be deprioritized.

4. CONCLUSION

Laboratory results reveal clear trade-offs between physical quality and economic attractiveness. WC group deliver the most consistent CHNSO and lowest AC, minimizing slagging risk and ensuring stable combustion. WC3 stands out with the lowest MC and highest NCV_{ar}, making it the most energy-efficient option. However, chip prices remain high, and MC variability indicates a need for controlled drying and logistics to justify cost. WR group offer intermediate quality: higher AC and coarse PSD increase handling complexity, while *N* content raises NO_x potential. Yet, their market price and acceptable NCV_{ar} position them as cost-effective alternatives if ash management and screening are applied. WM group are the cheapest and improve BD, but heterogeneity introduces operational risks. WM3 shows the

highest AC and lowest AMP, indicating potential slagging and fouling issues. WM4 contains high amount of < 3.15 mm fraction, increasing dust and segregation risk. WM1 and WM2 exhibit moderate properties and competitive prices, making them suitable for blending strategies.

For district heating operation, the most robust option is WC3 with highest ζ and lowest PM, however, WR1 and WR2 also could be used as good alternatives due to low CO. WM1 and WM2 are acceptable with routine optimization and ash management. WM3 and WM4 are operationally challenging under the tested settings. The dataset demonstrates the expected sensitivities: efficiency decreases strongly with both q_2 and q_3 , while pushing CO down without raising NO_x requires targeted air distribution rather than a simple increase in total excess air.

Analysis of HMs content in ashes shows that WR2 and WR1 have the highest combined concentrations of hazardous elements, followed by WM1 and WM2 with concentration above 1 mg/kg, while WC1, WM4, WM3, WC2 and WC3 exhibit the lowest overall levels below 1 mg/kg. This pattern indicates that WR2 and WR1 pose the greatest environmental risk if ashes are released untreated. Conversely, WC2 and WC3 are the cleanest samples, with minimal HM burden. From a utilization standpoint, ashes in the C and C-MA zones are generally suited for agronomic applications because of their strong neutralizing capacity, but their suitability is conditional on heavy-metal leachability. For WC2 and WC3, low HM content supports direct use as agents for lime. WC1 and WR1 require stricter compliance checks, and WR1 may need blending or immobilization before soil application. In contrast, ashes with high HM loads should not be used in agriculture or open systems; instead, they should be directed to processes that immobilize metals (as incorporation into cementitious matrices, geopolymer binders, or vitrification) where heavy metals are chemically bound and prevented from further environmental circulation. S-MA ashes remain promising for cementitious applications, but WR2 and WM1 demand rigorous leachability control and possibly reduced substitution rates to ensure compliance.

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