GIFFT

Sustainable Glass Industry

Gasification ash for glass production: Characterization

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Table 1.1 Document information

Document Information	
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Table 1.2: Dissemination level of this report

Dissemination level of this report	
PU	Public

Table 1.3: List of Abbreviations

Abbreviation	Definition
XRD	X-ray Diffraction
XRF	X-ray Fluorescence
TGA-MS	Thermogravimetric Analysis-Mass Spectrometry
EFG	Entrained flow gasifier
LOD	Loss on Drying
LOI	Loss of Ignition

ACKNOWLEDGMENT & DISCLAIMER

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EXECUTIVE SUMMARY

This deliverable D5.1 presents the raw material resources and characterises their properties in respect of glass making. The treated and untreated biomass and ash samples were received from Lithuania, Germany and Sweden over the period of 10 months. The biomass samples were combusted at Sheffield Hallam University via double combustion techniques. The received treated and untreated biomass samples, combusted ash samples and as received ash samples were thoroughly characterised via proximate and ultimate analysis. Chemical compositions were determined via analytical techniques and then compared with basic glass making raw materials. The D5.1, entitled " Characterization of raw, pre-treated and gasified biomass ashes regarding the usage in glass-making " is prepared in the framework of Task T 5.1, " Characterization of raw, pre-treated and gasified biomass ashes with supply chain engagement " which is part of the work package five (WP5). This GIFFT project deliverable is developed based on the Horizon FAIR DMP template provided by the European Commission.

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1 INTRODUCTION

The GIFFT project aims to create a Flexible Hybrid Furnace operation for optimal use of low value developing the next biogenic residues and wastes. The GIFFT collaboration includes nine entities, representing four European countries. Organizations participating in the project are: Lithuanian Energy Institute (LEI, Lithuania), Chalmers University of Technology (CTH, Sweden), Technical University of Munich (TUM, Germany), Vytautas Magnus University (VMU, Lithuania), WIP Renewable Energies GmBH & Co, KG (WIP, Germany), AB Panevezio stiklas, Schott AG (SCHOTT AG, Germany), PlasmaAir AG Oxidative Abgasbehandlung und Plasmasysteme (PlasmaAir AG, Germany), Sheffield Hallam University (SHU, UK).

This study evaluates and compares ashes derived from various biomass sources with the gasification ash produced within the GIFFT project. The GIFFT project aims to valorise ash generated from plasma-assisted gasification and combustion processes by assessing its suitability for use in glass production. The reuse of gasification ash as a partial substitute for conventional glass-making raw materials would support resource efficiency, circularity, and contributing in reduction in overall energy consumption within the glass manufacturing process. Treated (Torrefied) and untreated biomass were received from Lithuania and ash samples were received from Germany and Sweden over the period of 10 months. Real industry-based samples were also collected by SHU, UK. As shown in Table 1.1, The samples are grouped into four main categories (A–D). Group A consists of torrefied and untreated (untorrefied) biomass fuels, including lignin, straw, sunflower residues, and wood chips supplied by LEI, Lithuania. These samples represent typical biomass feedstocks used in thermochemical conversion processes and provide a baseline for assessing the influence of fuel type on ash composition.

Group B includes bottom ash and slag samples generated from entrained flow gasification (EFG) at TUM, Germany. These materials are directly relevant to the GIFFT project, as they represent gasification residues with potential application as glass-making raw materials. Group C comprises fly ash and bottom ash samples produced in fluidised bed systems using feldspar and silica sand bed materials at CTH, Sweden. These samples enable evaluation of the impact of bed material and process conditions on ash chemistry. Group D consists of samples collected from industries generation different types of ashes such as coal-based fly and bottom ashes sourced from SHU, UK, serving as reference materials for comparison with biomass-derived ashes. Overall, the samples capture a broad spectrum of ash types, supporting a comprehensive assessment of compositional variability and suitability for glass-making applications.

Table 1.1: List of treated and untreated biomass samples, ashes collected from consortium partners.

	Sample Code	Sample Name	Country of Origin	Same type
A	**LE01**	Torrefied Lignin	LEI, Lithuania	Fuel
	LE02	Lignin	LEI, Lithuania	
	LE03	Torrefied straw	LEI, Lithuania	
	LE04	Torrefied sunflower	LEI, Lithuania	
	LE05	Torrefied wood chips	LEI, Lithuania	
B	**DE01**	Bottom ash	TUM, Germany	Ash from EFG
	DE02	Slag	TUM, Germany	Slag From EFG
C	**CTH-F-FA**	Feldspar fly ash	CTH, Sweden	Ash from fluidised bed
	CTH-F-BA	Feldspar Bottom ash	CTH, Sweden	
	CTH-S-FA	Silica Sand fly ash	CTH, Sweden	
	CTH-S-BA	Silica Sand Bottom sample	CTH, Sweden	
	CTH-FS	Sample code (20160311)	CTH, Sweden	
D	**TH1**	Coal based ash site 1	SHU, UK	Ash
	TH3	Coal based ash site 3	SHU, UK	
	SFA	Fly Ash	SHU, UK	
	SBA	Bottom Ash	SHU, UK	
	IFA	Fly ash	SHU, UK	
	IBA	Bottom ash	SHU, UK	

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2 Experimental and analytical Methods.

The biomass samples received from LEI were prepared via double combustion at SHU premises. For this moisture free biomass sample weighing between 1.5–3.0 kg is used. The samples were placed inside the stove on a metal tray, as shown in the image (Figure 2.1). Ignition was achieved using a fire starter (1-2 square), matchsticks and fine biomass powder. Combustion is allowed until the entire sample is fully combusted to an ash/char form. After the combustion, ash temperature was measured using a thermal sensor to ensure it is within the range of 30-40°C. Water spray could be used for cooling down the ash temperature. The samples were kept for 24 hr in the drying oven at 105 °C.

Figure 2.1: Double combustion method to prepare ashes collected from LEI, Lithuanian partners.

The combusted samples were then further combusted using ASTM standard: D7348 – 21 at 750̊ C (Adeleke et al., 2020). This protocol was slightly modified to ensure full decarbonisation of the sample, which was validated using TGA-MS analysis. According to this protocol, approximately 50 g of combusted samples were placed in a thin layer on a ceramic tray (15X 25 cm) and placed in the furnace. The temperature was gradually raised at a rate that the furnace temperature reaches 500 °C ± 10 °C at the end of 1 hr, and then the temperature is again raised from 500 °C to 750 °C ± 15 °C at the end of 1 hr (at 500 °C hold for 5 hrs). The samples were then held at 750 °C for 12 hrs. The prepared ash samples are then analysed using TGA-MS analysis to ensure complete burn off of carbonaceous content. In case of incomplete combustion, the samples could be heated again at 750 °C ± 15 °C for 2- 5 hrs. The final ash samples were then ground and characterised.

Sample Preparation: Upon receiving the ash sample, the sample details are recorded, including source, date, and any other relevant information. The samples were sieved into size fractions and analysed via the instruments below. All the characterisation was conducted using a representative moisture-free sample, which was ground using mortar and pastel (after sieving) to ensure homogeneity. Ensuring the homogeneity of a sample is critical in analytical procedures to guarantee the results are representative of the entire bulk sample. A quartering sampling procedure was used for this project. The bulk samples were thoroughly mixed and spread out into four equal parts (quarters) into a circular or square shape. Two opposite quarters were discarded, then the remaining two quarters were mixed. This process was repeated until the desired sample size was achieved.

2.1 Proximate and Ultimate analyses

Loss on drying (LOD) and loss on ignition (LOI) determine the moisture content and the weight loss associated with low molecular weight gases such as H_2O, CO_2, SO_2, Cl_2 in a sample. The standard protocols ISO 18134:2015 and ISO 18122:2015 were used for LOD and LOI determination (Dej et al., n.d.; Garcia et al., 2018), respectively. 4- 6 g of representative samples were placed in an appropriate glass beaker, and the combined weight of the beaker and samples was measured using a precision balance (PX 323). The sample beaker was then heated in an oven at 105 ± 5°C for 24 hours. The weight after 24 hrs was recorded using a precision balance. The samples were then returned to the desiccator to maintain a moisture-free environment. For LOI, an empty crucible was heated at 550 ± 10 °C, cooled in a desiccator, and weighed to ±0.1 mg. A 1–2 g sample was heated to 250 °C for 60 min and then to 550 °C for at least 120 min, with reheating as needed until the mass change was <0.5 mg. The calorific value of the biomass was measured using a bomb calorimeter (Brand: Ika, Model: C200) following the ASTM D240-02 standard. For this experiment, 1 g of sample was placed in a crucible and used as the test sample. Carbon, Hydrogen, Nitrogen, and Sulphur content of biomass and ash was analysed using a CHNS analyser (Brand: Elementar, Model: Micro) in accordance with the ISO 16948:2015 (E) protocol. The Oxygen content was calculated by difference.

2.2 Thermogravimetric Analysis with Mass Spectrometry (TG-MS)

This instrument is used to measure the change in mass as a function of temperature to assess the amount of mass loss due to decomposition/loss of low molecular weight molecules/ gases such as H_2O, CO_2, SO_2, Cl_2 etc. Mass spectroscopy (MS) is coupled with the TGA instrument to predict the gases/mass fragments evolved/decomposed at elevated temperatures. 30-40 mg of the sample (using quartering method) is sufficient. The sample could be pre-dried, however, this is not crucial for TGA-MS analysis. Heating rate of 10° C/min for temperatures up to 1000 ° C was used.

2.3 X-Ray Fluorescence (XRF) Spectrometry

To determine the elemental composition X-ray fluorescence was used. Compositional analysis was performed using a PANalytical MagiX Pro XRF spectrometer equipped with a Rh anode x-ray tube. A representative moisture free 1-2 g of sample (using quartering method) was ground using mortar and pastel to ensure homogeneity. Each sample were tested at least 3 times to reduce uncertainty associated with the sample. XRF samples was prepared using thin film method without diluting the sample with cellulose. For this method, sample was compacted in an even layer on a plastic disk and then placed on top of plastic cup. A polypropylene film (a thin-film plastic as it has large % transmittance for both light and heavy elements) was used to cover the disk which was secured with a plastic cap.

2.4 X-Ray Diffractometry (XRD)

X-ray diffraction was used to identify and semi-quantify the mineralogical phases. All data was collected using a Philips X'Pert Pro X-Ray diffractometer with a Cu Kα source (λ=1·5406 Å). The operating voltage was 40 kV and the operating current was 40 mA. Powdered samples were placed on a spinner stage rotating at 15 rpm, with diffraction patterns collected over a 2θ range of 5–90° with a step size of 0·02°. Moisture free 5-6 g of sample (using quartering method) was ground using mortar and pastel to ensure homogeneity and placed onto an XRD sample holder for analysis. Phase identification was performed using Hi Score plus software.

3 Ash quality assessment for glass making.

Biomasses are characterised by their thermochemical properties, such as moisture, ash content and ash melting point, particle size and shape, volatile compounds, chemical composition, energy content, bulk density, and the homogeneity of all properties (Molino et al., 2016) and (McKendry, 2002).

3.1 Influence of feedstock on ash quality

Ash constituents may come from the biomass itself or be introduced during the collection and pretreatment process (Vassilev et al., 2013). Therefore, understanding ash constituents is critical for reusing as a raw material in glass making, selecting appropriate feedstocks, and designing ash management or recovery strategies. Table 3.1 represents the proximate and ultimate analysis of biomass samples collected from LEI partners. This characterisation was essential to understand the overall ash composition and variations associated with ashes depending on the origin of biomass.

Table 3.1: Proximate and Ultimate analysis of biomass samples collected from LEI, Lithuanian partners.

This section cannot yet be disclosed. The information will become publicly available after the journal publication.

3.1.1 Proximate and Ultimate Analysis of Biomass Samples

The moisture content of biomass is one of the important parameters influencing the energy balance of the gasification and combustion process. All torrefied materials (LE01, LE03–LE05) show very low moisture contents, reflecting the effectiveness of torrefaction in removing physically bound water. In contrast, untreated lignin (LE02) exhibits significantly higher moisture, which would increase energy consumption during thermal processing and may promote incomplete combustion or variable ash formation (Vamvuka et al., 2020). LOI indicates the combustible organic fraction, while the residual mass corresponds to ash. LE01 and LE02 (lignin-based samples) have relatively low LOI values, resulting in high ash yields. This indicates that lignin contains a substantial mineral fraction, which is beneficial when targeting ash-derived raw materials for glass production. In contrast, the agricultural and woody biomasses, especially torrefied wood chips (LE05), show extremely high LOI and very low ash contents, demonstrating that their inorganic content is minimal. Torrefied sunflower and straw show intermediate behaviour, reflecting their higher intrinsic mineral content compared with wood.

The ultimate analysis further reflects the degree of carbonisation and the nature of the feedstocks. Carbon contents are comparable among the biomass samples, confirming their high organic and energy-rich character before combustion. In addition, the nitrogen and sulphur contents suggest that their ashes are likely to be chemically simpler and more favourable for reuse in glass formulations, where excessive volatiles such as NO_x and SO_x emissions would be minimal.

3.1.2 Thermal Analysis of Biomass Samples

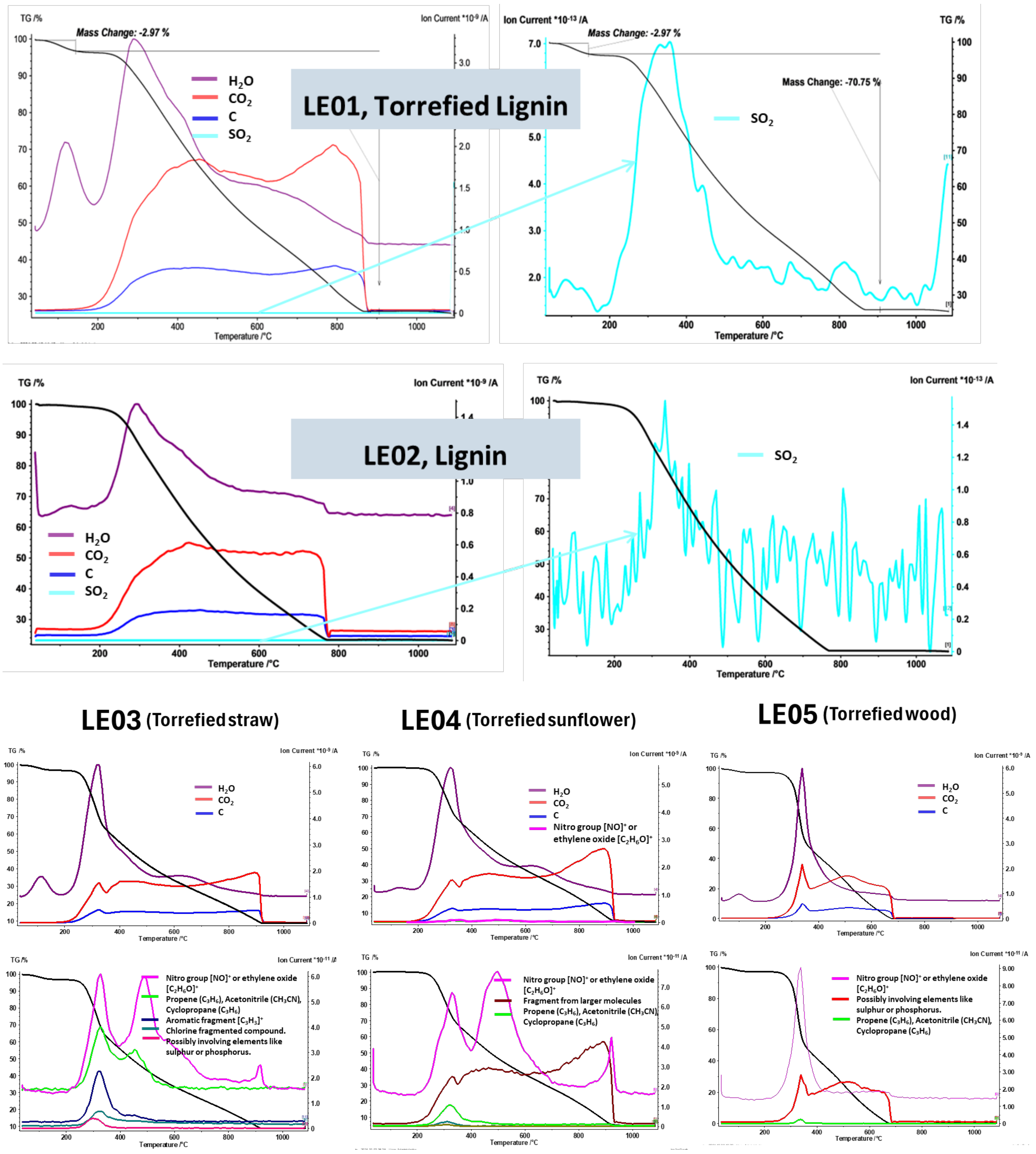

Figure 3.1: TGA-MS analysis of biomass samples to understand decomposition behaviour.

The TGA–MS analysis in Figure 3.1 shows the combustion behaviour of the biomass samples governed by their relative contents of hemicellulose, cellulose, and lignin. Minor mass loss below 150 °C corresponds to moisture removal and is more evident for untreated lignin. Complete combustion was achieved for LE01, LE02 and LE05 samples below 800 ˚C temperature. However, Straw (LE03) and sunflower (LE04) samples demonstrated complete combustion at 900˚C. The decomposition between 200° and 400°C is associated with hemicellulose (200–300 °C) and cellulose (300–370 °C) (Pasangulapati et al., 2012), which dominate the profiles of torrefied straw, sunflower, and wood chips, leading to rapid mass loss and low char formation. In contrast, lignin samples decompose slowly over a wider temperature range (200–750 °C), producing more char and higher ash yields (Sharma et al., 2004). These differences explain the higher ash contents of lignin-based feedstocks and the lower ashes from torrefied wood and herbaceous biomasses.

3.1.3 Characterisation of Ashes from LEI Biomass Samples

The physical appearance of the ashes is feedstock dependent (see (Table 3.2 and Figure 3.2). Lignin-derived ashes (A-LE01 and A-LE02) are brown and heterogeneous, reflecting incomplete mineral homogenisation and the presence of iron-rich phases (see XRF in Table 3.3). In contrast, torrefied straw (A-LE03) produces an off-white, fine powder, typical of silica and alkali-rich (see XRF in Table 3.3) agricultural ashes. Torrefied sunflower ash (A-LE04) appears greenish-white and loosely agglomerated, suggesting high alkali and calcium contents (see Table 3.3). Torrefied wood ash (A-LE05) is a fine grey powder, consistent with its calcium-rich but silica-poor composition. In glass production, the chemical composition of raw materials plays a critical role in determining the glass composition and final glass properties. Glass formers such as SiO_2 and P_2O_5 constitute the primary glass network, while modifiers and intermediates including Na_2O, K_2O, MgO, CaO, Al_2O_3, and ZnO disrupt or reinforce the network, thereby influencing key parameters such as melt viscosity, melting temperature, thermal stability, refractive index, and density (Shelby, 2020). Additionally, transition metal oxides such as Fe_2O_3, SO_3, Cr_2O_3, MnO_2, NiO, and CuO and other elements such as sulphur and low concentrations of carbon serve as colouring agents, influencing redox properties. However, their excessive presence can adversely affect glass colour and chemical durability (Deng et al., 2020; Shelby, 2020).

Table 3.2: The physical appearance of the ashes prepared at SHU, UK from LEI based biomass.

Sample code	Colour	Physical properties
A-LE01	**Brown**	Mixed particle sized powder
A-LE02	**Brown**	Mixed particle sized powder
A-LE03	**Off White**	Fine powder
A-LE04	**Greenish white**	Loosely agglomerated form
A-LE05	**Grey**	Fine powder

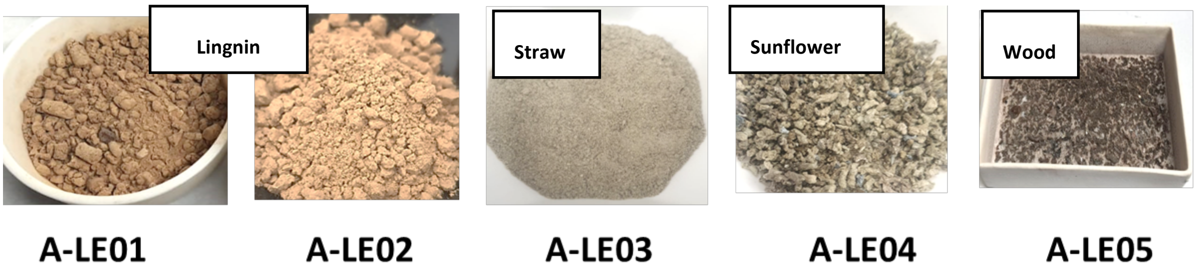

Figure 3.2: Physical appearance of ashes from different biomass sources collected from LEI partners.

XRF analysis (Table 3.3) shows that combustion significantly concentrates inorganic oxides in all ash samples relative to the parent biomasses. Silicon, calcium, potassium, magnesium, phosphorus, and sulphur are the dominant ash-forming elements, but their relative proportions vary strongly with feedstock. Lignin-based ashes (A-LE01 and A-LE02) are dominated by SiO_2, CaO and Fe_2O_3, giving them a darker colour and more refractory character and suggest higher melting temperatures, which would be disadvantageous due to higher weight % of Fe responsible in changing glass colour and melting profile. However, using optimised concentrations would still be favourable as a substitute for glass raw material. Furthermore, lignin ashes exhibited relatively high concentrations of SO_3 content. The elevated sulphur oxide concentration could be due to Kraft pulping process where use of sulphate-based chemicals (e.g., Na_2SO_4, $CaSO_4$) are employed in the pulping and bleaching processes (Jansson, 2022). The presence of these residual sulphates in the paper waste likely contributed to the observed sulphur enrichment in the ash composition. On the contrary, agricultural residues show very different behaviour. A-LE03 (torrefied straw) is rich in K_2O, SiO_2 and CaO, a combination typical of herbaceous biomass ash (Maj et al., 2025). Similarly, sunflower ash (A-LE04) contains high K_2O and CaO but very low SiO_2, which could aid in lowering the melting temperature of the glass by reformulating and partial or complete substitution of glass making raw materials such as limestone, potassium carbonate, and dolomite. In contrast, torrefied wood ash (A-LE05) is dominated by CaO and MgO, with very low SiO_2 and K_2O. This composition is typical of woody biomass and produces a more refractory, lime-rich ash, suitable to partially substitute limestone/dolomite, which is heavily used in glass manufacturing.

Table 3.3: XRF analysis of Biomass and ash generated from respective biomass sources.

This section cannot yet be disclosed. The information will become publicly available after the journal publication.

3.2 Characteristics of Bottom Ash and Slag Generated from Entrained Flow Gasifier (EFG)

The samples obtained from the entrained flow gasifier (EFG) operated with logging residues (torrefied wood chips, LE05) consist of two visually and physically distinct portions. A granular bottom ash and slag, as shown in Figure 3.3. The bottom ash appears as black, moist and powdered, while the slag forms dense, dark, chunky agglomerates, indicating partial melting and fusion of minerals during high-temperature gasification. These two samples were mechanically separated and characterised.

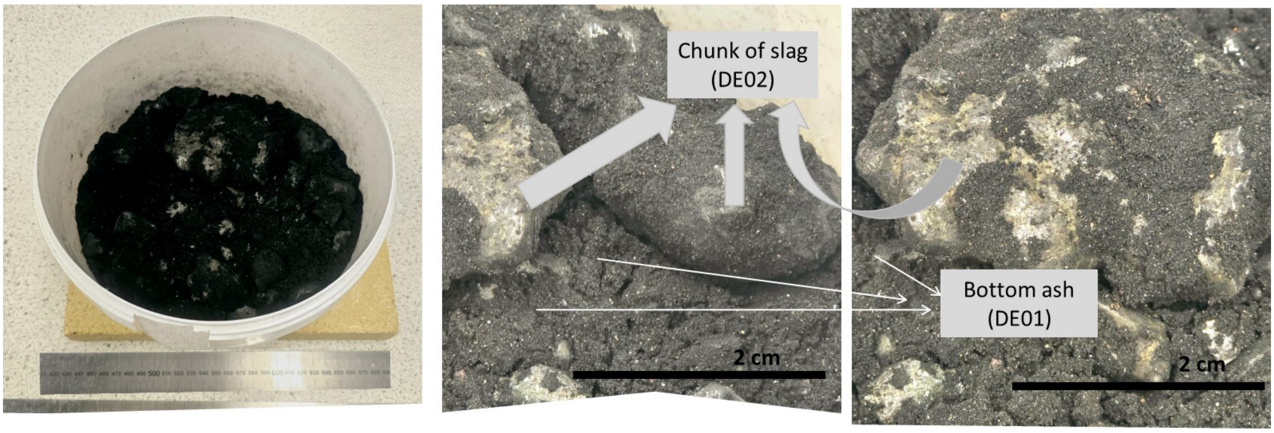

Figure 3.3: Physical appearance of sample collected from entrained flow gasifier (EFG) from logging residues (wood chip LE05) from TUM, Germany partners.

Figure 3.4 shows the mechanical separation of bottom ash and slag by sieving and milling, which allows the coarse, vitrified slag to be isolated from the finer ash fraction. Furthermore, the samples contained contamination from previous trials and refractory linings. This separation is essential for subsequent characterisation because the two fractions differ not only in particle size but also in chemistry and reactivity. 14% and 1% of ash and contamination, respectively, were separated and collected via mechanical separation and named DE01 for bottom ash and DE02 for slag sample.

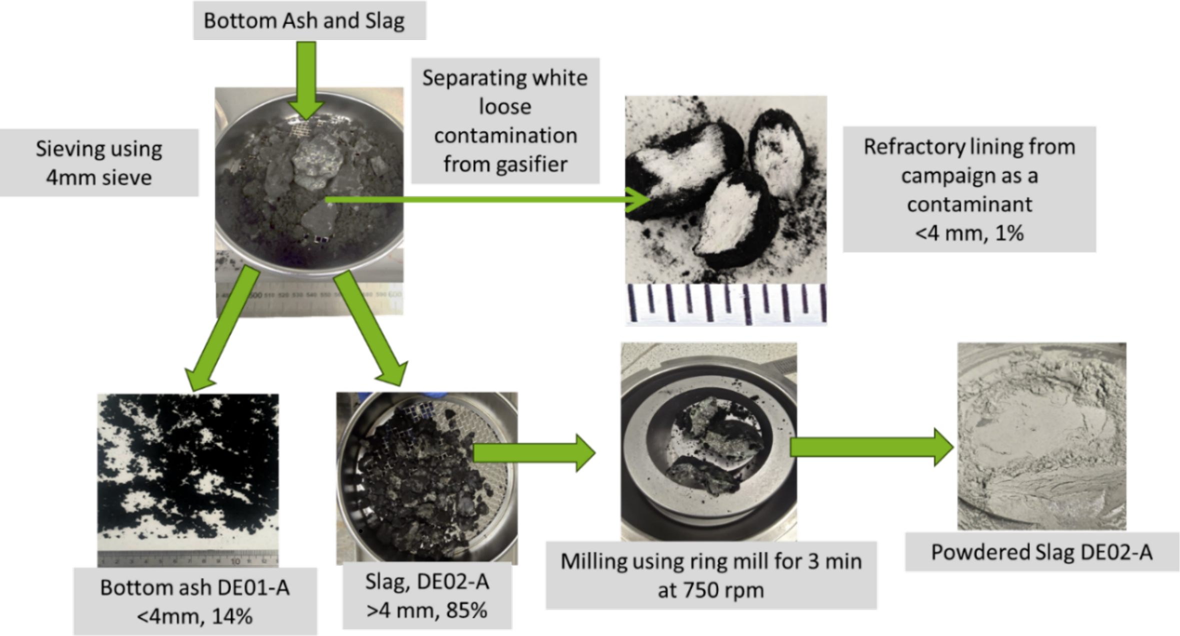

Figure 3.4: Separation of bottom ash and slag via sieving and milling operations.

Table 3.4 highlights fundamental differences between the bottom ash (DE01) and the slag (DE02) generated in the entrained flow gasifier (EFG) from torrefied wood (LE05). The bottom ash contains measurable residual carbon, as indicated by its LOI and carbon content, confirming incomplete conversion of char and entrained carbon during gasification. However, from a glass manufacturing perspective, it is generally desirable to maintain carbon content below 1 wt%, particularly in amber glass production, where controlled reducing conditions are used to develop the characteristic coloration. Excess carbon can create highly reducing conditions, promote metallic phase formation, and introduce defects during melting (e.g., seed formation, blistering) (Johnson, 1986; Shelby, 2020). In contrast, the DE02, slag shows negligible LOI and carbon content, demonstrating that it is fully melted/ vitrified inorganic residues. The slightly higher moisture content of DE01 reflects its porous and hydrophilic nature, particulate nature, whereas the slag is dense and non-porous. To ensure complete removal of unburnt carbon, the samples were subjected to secondary combustion following British standard (BS:) at 750 °C for a duration adjusted to sample mass. This step ensured that the ash analysed represented suitable for glass making raw material.

Table 3.4: Fundamental characteristics of bottom ash (DE01) and the slag (DE02) generated in the entrained flow gasifier (EFG) from torrefied wood (LE05).

This section cannot yet be disclosed. The information will become publicly available after the journal publication.

Gasified ash (DE01) and slag (DE02) samples exhibited distinct distributions of glass formers, modifiers, and colour influencing oxides. The slag (DE02) is strongly enriched in Al_2O_3 and contains lower CaO and alkali oxides than DE01 (Table 3.5), indicating preferential incorporation of alumina into the molten phase. In contrast, DE01 retains higher CaO, K_2O and Fe_2O_3, which are less readily incorporated into the molten slag and therefore remain in the bottom ash. After complete combustion at 750˚C of DE01 (A-DE01), the oxide composition remains broadly similar, but SO_3, P_2O_5 and transition metal oxides become more concentrated, confirming that residual carbon in the raw bottom ash had previously diluted the mineral fraction. The Fe_2O_3 concentration for DE01 is higher compared to DE02. This was significantly exceeding that of the LE05-A, wood ash, which served as the precursor fuel during gasification. This indicates iron contamination originating from the gasification process, likely due to abrasion and erosion of metallic reactor components (Ramadhani et al., 2022). Similarly, the Al_2O_3 concentration was noticeably higher in both A-DE01 and DE02, suggesting contamination from refractory lining material during high-temperature operation. In contrast, the gasified ash (A-DE01) and slag (DE02) exhibited lower levels of volatile oxides such as SO_3 and Cl. This could be attributed to volatilisation during combustion and gasification processes, respectively at elevated temperatures.

Table 3.5: XRF results of DE01, bottom ash and DE02, slag from TUM partners at two different temperatures.

This section cannot yet be disclosed. The information will become publicly available after the journal publication.

X-ray diffraction (XRD) analysis was performed on the samples to identify crystalline phases and assess whether additional treatment was required before glass production (see Table 3.6). Attention was given to the detection of magnetic iron bearing phases, as these can be magnetically separated from the ash quality. The DE01 ash primarily contained iron oxides (Fe_2O_3, Fe_3O_4), silicon oxide (SiO_2), calcium oxide (CaO), and calcium phosphate ($Ca_3(PO_4)_2$), indicating partial fusion and complete removal of organic phases after combustion at 750 ˚C. The DE02 slag showed dominant crystalline phases of calcium silicate (Ca_2SiO_4), aluminum oxide (Al_2O_3), silicon oxide (SiO_2), and iron oxide (Fe_2O_3), reflecting exposure to intense thermal conditions that promoted ash fusion and interaction with refractory materials. A similar compositional pattern is typically observed during slagging in gasifiers, where iron, calcium, and silica rich silicate and aluminosilicate phases are formed through mineral coalescence and melt solidification (Ramadhani et al., 2022; Zhang et al., 2024).

Table 3.6: Crystalline phases identified in ashes and slag samples via XRD after loss on ignition (LOI) at 750˚C.

Crystalline Phases Identified	
DE01-LOI	• Iron Oxide (Fe_2O_3) • Silicon Oxide (SiO_2) • Calcium Oxide (CaO) • Iron Oxide (Fe_3O_4) • Calcium phosphate $Ca_3(PO_4)_2$
DE02	• Calcium Silicate (Ca_2SiO_4) • Aluminum Oxide (Al_2O_3) • Silicon Oxide (SiO_2) • Iron Oxide (Fe_2O_3)

3.3 Characteristics of Ash Samples Collected from Fluidised Bed System (FBS)

GIFFT ash and slag samples collected from TUM were then compared with fly ash and bottom ash collected from fluidised bed system (FBS), CHT, Sweden partners. Proximate and ultimate analyses were conducted as shown in Table 3.7. The ashes produced in the fluidised bed system (FBS) differ fundamentally from the GIFFT residues generated in the entrained flow gasifier (EFG), both in physical form and in chemical form. All FBS-derived ashes have extremely low moisture contents (<0.2 wt%), reflecting the dry, well-fluidised operating conditions of the reactor and the efficient separation of solids from the gas stream. The loss on ignition (LOI) values were also very low, compared to GIFFT, DE01 bottom ash samples. This is since gasification process requires the use of steam and final ashes were quenched using water.

Table 3.7: Proximate and ultimate analysis of the ashes produced in the fluidised bed system (FBS).

Sample code	Sample description	Moisture (%w/w), 105° C for 24 h	Loss on ignition dry basis, LOI (%w/w), 750° C , 4h
CH-F-FA	Feldspar fly ash	0.2 ± 0.001	4.4 ± 0.2
CH-F-BA	Feldspar Bottom sand	0.2 ± 0.001	0.1 ± 0.02
CH-S-FA	Silica Sand fly ash	0.02 ± 0.001	0.5 ± 0.05
CH-S-BA	Silica Sand Bottom sample	0.01 ± 0.001	0.04± 0.001
CH-FS	Sample code (20160311)	0.01 ± 0.001	0.01 ± 0.001

Table 3.8: XRF analysis using semi quant method to analysis ash samples collected from CTH, Sweden partners.

XRF analysis	**CTH-F-BA (Feldspar Bottom Ash)**	**CTH-F-FA (Feldspar Fly Ash)**	**CTH-FS (Sample code 20160311)**	**CTH-S-BA (Silica Bottom Ash)**	**CTH-S-FA (Silica Fly Ash)**
Element oxides (wt %)	**Normalized %, RU (4%)**	**Normalized %, RU (3%)**	**Normalized %, RU (3%)**	**Normalized %, RU (3%)**	**Normalized %, RU (4%)**
Na_2O	2.87	2.46	4.32	0.80	0.88
MgO	10.79	4.70	15.51	9.43	5.92
Al_2O_3	5.14	3.70	7.15	2.33	4.62
SiO_2	22.65	19.79	28.13	32.32	31.92
P_2O_5	6.92	2.93	5.99	7.17	4.13
SO_3	2.23	11.95	1.69	2.58	2.25
Cl	10.85	0.41	9.73	8.76	0.27
K_2O	35.21	7.71	24.80	32.69	9.72
CaO	0.04	42.14	0.03	2.14	36.48
TiO_2	1.83	0.10	1.34	0.94	0.20
Cr_2O_3	0.76	0.03	0.88	0.03	1.83
MnO_2	0.01	2.33	0.02	0.37	1.28
Fe_2O_3	0.04	1.25	0.01	0.08	0.02
NiO	0.33	0.02	0.18	0.16	0.25
CuO	0.01	0.01	0.12	0.00*	0.08
ZnO	0.16	0.45	0.09	0.00*	0.15
Rb_2O	0.15	0.00*	0.01	0.18	0.00*
Total	100.00	100.00	100.00	100.00	100.00

* Below the limit of detection (LoD), RU=relative uncertainty.

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The XRF results in Table 3.8 demonstrate compositional analysis of FBS ashes, which is strongly controlled by the type of bed material (feldspar or silica sand) and by the separation between bottom ash and fly ash. Feldspar-based bottom ash (CTH-F-BA) is dominated by K_2O (35.2 wt%), SiO_2 (22.7 wt%) and MgO (10.8 wt%), reflecting interaction between biomass ash and feldspar minerals. In contrast, feldspar fly ash (CTH-F-FA) is highly enriched in CaO (42.1 wt%) and SO_3 (12.0 wt%), indicating preferential volatilisation and re-condensation of calcium and sulphur species onto fine particles. The silica sand systems show much higher SiO_2 contents, exceeding 32 wt% in both bottom ash and fly ash due to silica bed material. Silica bottom ash (CTH-S-BA) also contains substantial K_2O (32.7 wt%) and P_2O_5 (7.2 wt%), demonstrating strong alkali–silica interaction during fluidisation. Silica fly ash (CTH-S-FA) is also enriched in CaO (36.5 wt%), again confirming that calcium preferentially partitions into the finer, entrained fraction. The ashes contain significantly high concentrations of Cl in bottom ash samples (8.76-10.75 wt. %) and sulphur in flyash samples. This is considerably higher compared to GIFFT gasification ashes and slag samples. The presence of sulphur in low concentrations influences redox during glass melting, which thereby influences the glass colour. However, their excessive presence can adversely affect glass colour and glass chemistry.

3.4 Characteristics of Ash Samples Collected from UK-based Industries

Figure 3.5 shows that the UK industrial ashes collected by SHU partners exhibit a wide range of moisture contents and LOI values. In general, these ashes have higher LOI than GIFFT slag but are comparable to GIFFT bottom ash, indicating that they contain residual unburnt carbon.

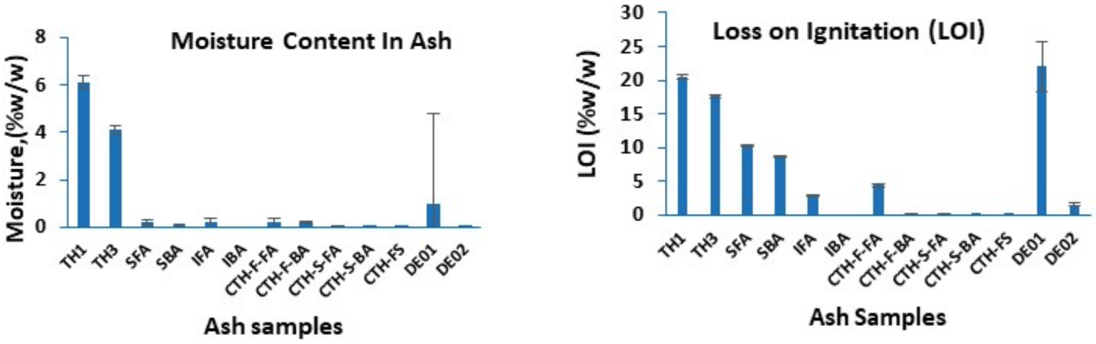

Figure 3.5: Comparison of a) moisture content and b) Loss on ignition of ashes collected by SHU, UK partners with GIFFT ash samples .

XRF data (Table 3.9) reveal strong compositional differences between the different UK ashes and the GIFFT residues. The TH1 and TH3 samples are highly enriched in SiO_2 (≈50 wt%) and Al_2O_3 (≈28 wt%), with moderate Fe_2O_3, indicating that they are aluminosilicate-rich ashes similar in chemistry to coal-derived fly ashes (Das, D., & Rout, P. K. 2023). These compositions resemble of GIFFT slag, which is also dominated by aluminosilicate phases. In contrast, the SFA and SBA samples are rich in CaO (60–70 wt%). These ashes could be utilised as a substitute for limestone or dolomite for glass making. However, the fly ash contains a considerable amount of chlorine, which could cause refractory lining corrosion issues during glass raw material melting. Hence, post-treatment of the ashes will be required. IFA and IBA samples containing significant SiO_2 (32–37 wt%), CaO (24–35 wt%) and Al_2O_3 (6–8 wt%), making them suitable candidates for replacing calcium-rich portions in glass. However, consideration should be given to the high content of Fe in the ash samples, as these could interfere with glass redox, thereby affecting glass colour.

Table 3.9: XRF analysis of ashes showing composition of ashes collected from different UK based industries.

Element oxides	TH1	TH3	SFA	SBA	IFA	IBA
(wt %)	(RU 3%)	(RU 2%)	(RU 2%)	(RU 2%)	(RU 3%)	(RU 3%)
Na_2O	0.62	0.54	2.48	0.47	1.14	0.83
MgO	0.98	1.01	1.31	1.42	3.56	7.72
Al_2O_3	28.30	28.27	4.88	7.55	8.17	6.09
SiO_2	51.82	49.85	6.08	6.94	36.53	32.01
P_2O_5	1.06	1.04	2.35	2.71	3.73	5.17
SO_3	0.78	0.66	6.32	3.71	4.94	0.08
Cl	0.00*	0.00*	11.61	2.36	0.88	0.08
K_2O	2.89	2.83	1.13	0.32	8.92	3.48
CaO	2.64	3.08	60.39	70.03	23.86	35.06
TiO_2	1.36	1.28	1.78	2.52	1.02	0.35
Cr_2O_3	0.03	0.03	0.05	0.04	0.04	0.04
MnO_2	0.17	0.25	0.08	0.12	0.75	1.29
Fe_2O_3	9.25	11.06	1.15	1.64	6.25	7.51
NiO	0.03	0.03	0.01	0.00*	0.02	0.00*
CuO	0.02	0.02	0.08	0.06	0.04	0.05
ZnO	0.03	0.03	0.31	0.11	0.13	0.24
Rb_2O	0.02	0.02	0.00*	0.00*	0.03	0.01
Total	100	100	100	100	100	100

* Below the limit of detection (LoD), RU=relative uncertainty.

4 Diversity and Potential of Biomass Ash for Glass Manufacture

The production of commercial soda-lime silica (SLS) flat and container glass is recognised as one of the highly energy-intensive industries, contributing approximately 86 million tonnes of CO_2 annually, which is about 0.3% of global CO_2 emissions. According to the Glass Decarbonization Roadmaps 2050 and Glass sector Net zero strategy 2050, 75%−85% of CO_2 emissions arise from the combustion of fuel, primarily natural gas and 15%−25% from the decomposition of carbonate raw materials (Dang et al. 2024). In 2021, the European glass industry alone released 17 million metric tonnes of CO_2 into the environment. This is closely linked to the energy demand of glass production, which involves prolonged exposure to high temperatures. Energy consumption of SLS glass ranges from 5 to 9 GJ per tonne, with EU averages closer to 7–9 GJ/t. Compared to the theoretical minimum (2.7 GJ/t), the current industrial processes are far from ideal values (Atzori et al., 2025). With global net-zero targets gaining traction, the glass industry is approaching a transformative era. Over the next 20 to 30 years, the established glass industry will face significant challenges as it enters a transitional phase.

As efforts to reduce emissions intensify, existing production methods and raw materials are expected to evolve, driven by innovation and sustainability goals. A promising approach involves utilising biomass ashes from different biomass based powerplants that could potentially reduce emissions by partially or completely replacing carbon intensive raw materials such as carbonates in glass making. This opportunity is further reinforced by the increasing global availability of biomass ash. In 2022, global bioenergy generation from solid biomass and municipal solid waste (MSW) reached 10 EJ and 3 EJ, respectively, sourced from an estimated 460 million dry metric tonnes (Mt(dry)) of biomass and 1 billion Mt (dry) of MSW, collectively producing 103 Mt of ash, of which 15 Mt came from biomass alone. In the UK, around 16 Mt (dry) of solid biomass was used in heat and power generation, resulting in approximately 450,000 tonnes of ash. Achieving this goal will require 15% of total energy to come from biomass, translating to roughly 27 Mt(dry) annually expected to produce over 1 Mt of biomass ash

(Prasittisopin, 2024). This growing ash stream presents a timely and abundant resources that could be redirected for industrial use, including low-carbon glass manufacturing. One of the aims of WP5 was to explore and develop the use of a broad range of biomass ashes as raw materials to reduce energy consumption and environmental impact of several different types of glass product including amber, green and colourless container glasses, float glass, and mineral wool.

Figure 4.1 shows two ternary diagrams summarising different ashes processed, collected from consortium partners in terms of their glass-making functionality, a) glass formers-mainly SiO_2 and P_2O_5 b) glass modifiers & intermediates -CaO, MgO, Na_2O, K_2O, Al_2O_3, etc. and c) Glass colourants Fe_2O_3, SO_3, Cr_2O_3, MnO_2, NiO, CuO, etc. (Shelby, 2020).

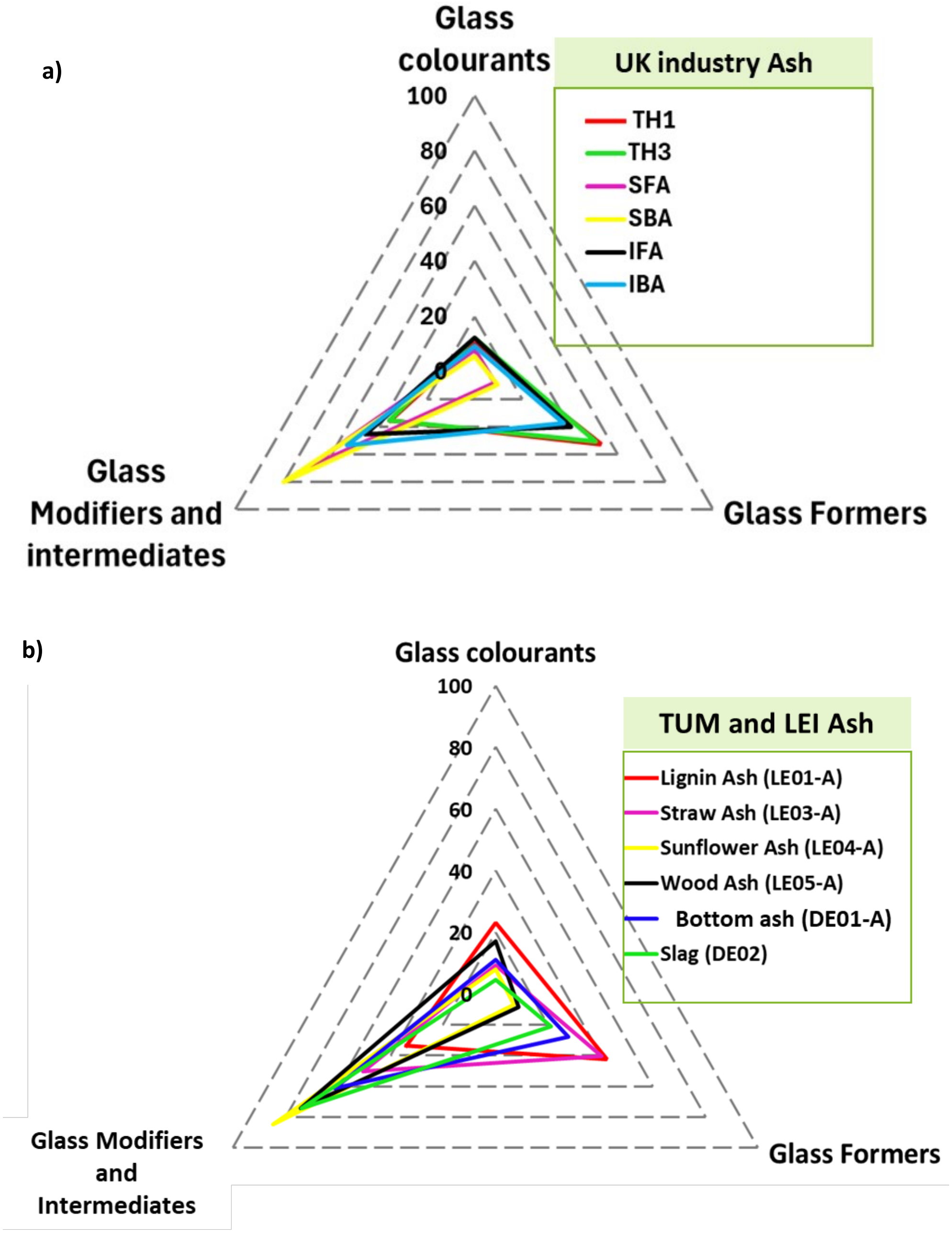

Figure 4.1: a) Comparison of ashes collected by SHU, UK partners with b) GIFFT ash samples in terms of glass formers, modifiers, intermediates and glass colourants.

4.1.1 UK Industrial Ashes

TH1 and TH3

Both ashes contain a higher amount of glass former, showing they are dominated by SiO_2 and Al_2O_3. This makes them suitable for formulating high alumina content glasses as a raw material (sand + alumina). However, their relatively low modifier content would require balancing the proportions with alkaline and alkaline earth oxides to reduce the melt temperatures that would be due to increased SiO_2 and Al_2O_3. Otherwise, only a fraction (less than 5%) could be used.

IFA and IBA

Both fly ash and bottom ashes contain a good number of modifiers & intermediates and the lowest amount of glass colourants. However, even after achieving a balanced glass composition (SiO_2–Na_2O–CaO–MgO), much closer attention should be paid to reducing chlorine and sulphur emissions by utilising appropriate beneficiation, separation and consolidation techniques to avoid refractory corrosions, NO_x and SO_x emissions.

SFA and SBA

Similar to IFA and IBA ashes, these ashes also have a good amount of glass modifier, due to their high CaO and volatile salts (SO_3, Cl) contents. They contain more fluxes (see Table 3.9) than glass formers as a result, these ashes could be a suitable substitute for limestone and/or dolomite, which are mostly used in glass industries.

4.1.2 Comparing UK Industry-based Ashes with TUM & LEI (GIFFT)Ashes

Lignin ash (LE01/LE02-A)

The ternary plot shows that LE01/LE02 ashes contain an elevated amount of glass colourant due to more than 10 wt% Fe_2O_3 and high SO_3 contents. This would largely impact the redox during melting, thereby influencing the glass colour (green/brown). Hence, a limited weight % of these ashes could be used as a raw material substitute.

Straw, sunflower ashes and wood ash (LE03-A, LE04-A, LE05-A)

These ashes have a considerable amount of glass modifier their very high K_2O and CaO. Glass modifiers act as powerful fluxes, lowering the melting temperature. On the other hand, LE05-A ashes contain both glass modifiers and intermediate and considerably high amount of glass colourants such as Fe_2O_3. Thus, replacement of traditional glass-making raw material would be dependent on the amount of Fe_2O_3 concentration (considering unburned carbon/char content is below 1%).

GIFFT bottom ash (DE01-A) and slag (DE02)

This ash sits in an intermediate position, showing a mix of glass formers, modifiers and colourants. However, because it still contains residual carbon and a considerable number of colorants including more than 10 weight % of Fe_2O_3, it would require further treatments to completely remove unburnt residual carbon and reduce concentrations of element oxides responsible for glass colour and changes in chemical properties such as glass durability. Slag samples hold maximum promise according to the diagram. It has more glass modifiers with low colourant content. However, the aluminium concentrations are very high (<50 weight %). Although this initial high concentration of aluminium is due to contamination of refectory linings and previous runs. TUM partners are currently optimising the gasification process with the aid of a plasma torch. The samples collected from TUM partners were from the very first run without the addition of plasma touch. It is expected that the residual carbon and alumina content would be minimal with assisted plasma touch.

5 Summary of the Potential

5.1 Role of Residual Carbon and Unburned Content in Determining Ash Suitability for Commercial Glass Manufacture

Among all parameters evaluated in this study, the residual carbon (unburned material, char or carbon) content of ash is identified as the single most critical factor governing its suitability for glass-making applications. While oxide composition and its variability also plays a role, and influences the substitution of glass raw material with ash, excessive carbon content fundamentally compromises furnace stability and glass melting chemistry.

Residual carbon impacts the redox conditions in the glass melt. Carbon-rich ashes promote reducing environments, leading to the partial reduction of multivalent oxides, particularly Fe_2O_3 to FeO or metallic iron (Johnson, 1986; Shelby, 2020). Iron, which is always present in silica sand and other raw materials, can be reduced from Fe^{3+} (yellowish) to Fe^{2+} (greenish), changing the glass colour and making it difficult to control in products like clear containers or float glass. Excessive carbon promotes defects such as foaming, blisters, seeds, and inhomogeneities (Johnson, 1986; Shelby, 2020). Furthermore, carbon monoxide from the incomplete combustion of carbon can also promote foaming and increase gas content in the glass, raising the risk of seeds and bubbles (Connors, 2004). For this reason, controlled carbon contents above approximately 1 wt% are generally considered unacceptable for direct use in glass batch formulations, particularly for colour-sensitive products.

Loss on ignition (LOI) and CHNSO elemental analysis together provide a robust assessment of residual carbon and unburned content in ashes. LOI reflects the total mass loss during heating, largely associated with the oxidation of residual carbon and the release of volatile species, while CHNSO analysis directly quantifies elemental carbon remaining in the ash. When interpreted together, these results allow clear differentiation between fully mineralised ashes and carbon-rich residues that are unsuitable for glass production.

The GIFFT, EFG bottom ash (DE01) shows substantially elevated LOI, which correlates directly with its high elemental carbon content measured by CHNSO analysis. This unequivocally confirms that DE01 contains significant quantities of unburned char. This is directed towards the incomplete conversion of carbonaceous material during gasification. As a result, despite its potentially favourable oxide composition, DE01 is unsuitable for direct use in glass making without mandatory post-combustion or carbon removal treatment. The GIFFT slag sample (DE02) exhibits zero LOI and zero measurable carbon, confirming complete oxidation and vitrification of inorganic material during high-temperature gasification. This clearly demonstrates that when residual carbon is eliminated, the ash chemistry becomes stable and predictable, making slag inherently far more suitable for glass-making applications than bottom ash in terms of carbon content.

In contrast, the fluidised bed system (FBS) ashes (CH-F-FA, CH-F-BA, CH-S-FA, CH-S-BA, and CH-FS) exhibit very low LOI values, ranging from 0.01 to 4.4 wt%. Their extremely low moisture contents (<0.2 wt%) and negligible LOI confirm that these ashes contain minimal unburned carbon. Although CHNSO data are not reported for these samples, the low LOI values strongly indicate that residual carbon is well below critical thresholds. From a glass-making perspective, such ashes are inherently suitable from a carbon standpoint, allowing their chemical composition to be assessed without the confounding effects of reduction reactions during melting.

Importantly, within this work package, a viable pathway for reducing residual carbon and unburned char was established through the application of a double-combustion process. CHNSO analysis of the double-combusted biomass-derived ashes (A-LE01 to A-LE05 and DE01-A) demonstrated carbon contents below 0.26 wt%, confirming near-complete oxidation of residual carbon (see Table 5.1). These results show that appropriate thermal treatment can reliably convert unburnt/residual carbon into ashes that meet the stringent requirements for use in glass batch formulations. This finding reinforces that carbon content rather than ash origin or oxide composition is the dominant limiting factor, and that effective carbon burnout is a critical enabling step for the circular use of biomass- and gasification-derived ashes in glass manufacture.

Table 5.1: LOI and CHNSO analysis of ashes generated via double combustion process.

Sample code	**Sample Name**	**Loss on ignition dry basis, LOI (%w/w)**	**Ultimate Analysis (%w/w)****			
			N	**C**	**H**	**S**
A-LE02	Torrefied Lignin pellet ash	0.00 ± 0.00	0.00*	0.00*	0.18	0.01
A-LE03	Torrefied straw pellet ash	0.00 ± 0.00	0.00*	0.02	0.21	0.00*
A-LE04	Torrefied sunflower pellet ash	0.00 ± 0.00	0.02	0.00*	0.23	0.00*
A-LE05	Rice husk ash	0.00 ± 0.00	0.00*	0.26	0.45	1.06
DE01-A	DE01 ash after post-processing	0.00 ± 0.00	0.02	0.20	0.35	0.10

*Below the detection limit

5.2 Other Factors Determining Ash Suitability for Glass Manufacture

This study demonstrates that the quality and suitability of biomass-derived ashes for glass-making applications are strongly governed by both the original feedstock and the thermal conversion route. Effective utilisation of ashes requires careful control of several critical parameters. Residual carbon content is a primary concern, as elevated levels can disrupt furnace redox conditions, promote defect formation, and adversely affect glass quality. Similarly, high concentrations of volatile components such as chlorine and sulphur pose risks of refractory corrosion, increased NO_x/SO_x emissions, and instability during melting. Transition metal oxides (notably Fe_2O_3, MnO_2, CuO, and TiO_2) and excessive alumina can significantly influence the colour, viscosity, melting behaviour, and chemical durability of glass, necessitating optimisation or selective removal.

Among the materials assessed, GIFFT slag exhibits the highest immediate potential due to its low carbon content and favourable balance of glass formers and modifiers. However, elevated alumina levels, largely attributed to refractory contamination during early gasifier trials, need to be addressed. Biomass ashes (LE01-A to LE05-A) rich in CaO and alkali oxides show strong promise as fluxing agents capable of partially replacing limestone, dolomite, and alkali carbonates, thereby reducing both energy demand and process-related CO_2 emissions.

While biomass ashes represent a viable and abundant secondary raw material for glass production, their successful implementation depends on appropriate pre-treatment and beneficiation strategies, such as post-combustion, thermal treatment, magnetic separation, or selective blending. When suitably processed and formulated, these ashes can meaningfully contribute to improved resource efficiency, enhanced circularity, and reduced CO_2 emissions in the glass industry, directly supporting the objectives of the GIFFT project.

6 Concluding Remarks

This WP has characterised raw, pre-treated and gasified biomass for use as secondary raw materials in glass manufacture, with particular emphasis on their physical properties, chemical composition, and residual carbon content. Ashes from entrained flow gasification (EFG), fluidised bed systems (FBS), and UK industrial sources were characterised using moisture analysis, loss on ignition (LOI), CHNSO elemental analysis, XRF, and phase identification techniques.

Many ashes exhibited oxide compositions containing significant proportions of SiO_2, CaO, Al_2O_3, and alkali and alkaline earth oxides, which are potentially attractive for glass manufacture. However, their suitability is governed primarily by their residual carbon content rather than bulk chemistry. Carbon-rich ashes, such as the GIFFT, EFG bottom ash (DE01) and other industrial ashes, exhibit elevated LOI and elemental carbon levels, indicating substantial levels of unburned material or char. Such ashes would pose significant risks in commercial glass manufacture due to their propensity to cause redox instability, iron reduction, colour variability, foaming, and defect formation, rendering them unsuitable for direct batch incorporation without further treatment. In contrast, GIFFT slag (DE02) and FBS-derived ashes exhibited very low LOI, indicating near-complete carbon burnout and inherently more stable behaviour during melting. However, the replacement of traditional glass raw materials would require looking into individual ash compositions to balance the glass formula and to ensure low NOx and SOx emissions. For example, although GIFFT, DE02 slag has no/minimal amount of residual carbon, its high aluminium content would limit how much slag would be suitable to replace traditional glass raw materials. Finally, this work demonstrated that residual carbon can be effectively eliminated through a double-combustion processing pathway. CHNSO analysis of treated biomass ashes (A-LE01 to A-LE05) confirmed carbon contents below 0.26 wt%, well within acceptable limits for glass manufacture. This highlights that residual carbon content is the primary gatekeeper for the circular integration of ash into glass production. Addressing efficient carbon burnout would transform ash from a problematic residue into a viable, low-carbon secondary raw material for the glass industry.

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HISTORY OF CHANGES		
VERSION	DATE	CHANGE
1.0	19.01.2026	Initial version
1.1	27.01.2026	The first version was sent to all partners
1.2	29.01.2026	Revised version
1.3	30.01.2026	Comments from key partners have been taken into account.