



Research Paper

Gasification of wood packaging waste and valorization of char in polymer composites

Vittoria Benedetti^{a,b,*}, Stefano Piazzi^b, Marco Scatto^c, Elisabetta Santello^d, Markus Kollmer^e, Grigorios Itskos^f, Konstantinos Atsonios^f, Francesco Patuzzi^b, Marco Baratieri^b

^a University of Trento, Department of Civil, Environmental and Mechanical Engineering (DICAM), Via Mesiano 77, 38123 Trento, TN, Italy

^b Free University of Bozen-Bolzano, Faculty of Engineering, Via B. Buozzi 1, 39100 Bolzano, BZ, Italy

^c University of San Marino, Department of Economics, Science, Engineering and Design, Via Consiglio Dei Sessanta, 99, Dogana, Republic of San Marino

^d TYMOTHEUS Srl, Via Villafranca 20E, 30035 Mirano, Venezia, Italy

^e Burkhardt GmbH, Kreutweg 2, 92360 Mühldorf, Germany

^f Centre for Research & Technology Hellas /Chemical Process and Energy Resources Institute (CERTH/CPERI), 6th Km. Charilaou-Thermis, GR 570 01 Thermi, Greece



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ABSTRACT

This study explores the possibility of repurposing wood packaging residues (WPR) through gasification, adopting a polygenerative approach yielding not only gas, but also char to be valorized as a filler/pigment in polymers. A commercial biomass gasifier was used to test standard pellets (PS) and WPR-derived pellets (PW). Pretreatment was needed to limit metal contaminants in PW, which nonetheless showed higher ash (15.7 vs. 11.1 wt%), and metal content (especially Fe, Cu, and Pb) than PS, affecting the resulting char composition. While feedstock variations primarily affected the inorganic composition and the porosity of the char, operating conditions were found to play a dominant role only in influencing char porosity (with the specific surface area reaching the maximum value of 1006 m²/g). Under standard conditions, PW gasification yielded slightly less char (1.1 vs. 1.3 wt%) but achieved higher cold gas efficiency (60.7 % vs. 56.6 %). The resulting char was tested in polymer matrices, performing well as a black pigment with minimal reduction in tensile properties, thus offering a sustainable alternative to carbon black.

1. Introduction

Wood is one of the most widely used materials in the packaging industry due to its remarkable versatility, inherent strength, durability, and ability to be reused (Besserer et al., 2021). Its natural antibacterial properties, combined with the fact that it often does not require chemical treatments, make it a preferred choice for various applications. Additionally, wood is considered to have a relatively low environmental impact when sourced sustainably, further enhancing its appeal in an era of increasing environmental awareness (Höglmeier et al., 2014). Common wood-based packaging solutions include crates, boxes, drums, reels, cages, and pallets. These are employed across industries to handle, store, load, and transport a wide range of goods. Indeed, wood packaging is particularly suitable for both fragile and heavy items, such as machinery and industrial equipment, as well as for products in the food sector where hygiene and strength are critical factors. However, despite its durability and reusability, wooden packaging is not immune to wear

and tear (Höglmeier et al., 2014). Over time and after extended use, defects or damages may accumulate, rendering it unsuitable for repair or further reuse. Once wooden packaging is considered unfit for its original purpose, it is often discarded and treated as waste. This stage in its lifecycle raises important considerations for waste management and recycling, as well as opportunities for repurposing or alternative applications to minimize environmental impact (Pazzaglia and Castellani, 2023; Taskhiri et al., 2019).

One promising approach to valorizing unrecoverable wood packaging waste is through its exploitation for energy purposes (Andrade et al., 2024), for instance via gasification. This process converts wood waste into a combustible mixture of gases, which can be used for heat and power generation, making it an efficient and environmentally friendly energy source (Patuzzi et al., 2021). Additionally, gasification yields valuable byproducts such as char, a carbon-rich material with a plethora of applications for instance, in soil enhancement, carbon sequestration, and as an industrial feedstock (Abdelal et al., 2023). By

* Corresponding author.

E-mail address: vittoria.benedetti@unitn.it (V. Benedetti).

adopting a polygenerative approach, which maximizes the utilization of both energy and byproducts, this method not only reduces waste and greenhouse gas emissions, but also contributes to a circular economy by turning an environmental liability into a resource (Klavins et al., 2020).

These goals are closely aligned with the broader objectives of the Horizon 2020 FRONTSHIP project, which has supported this work (The FRONTSHIP project). FRONTSHIP aims to develop four Circular Systemic Solutions (CSSs) for the sustainable valorization of various waste streams, with a strong focus on replicability across different contexts. Specifically, CSS1 targets the valorization of wood packaging waste through gasification, enabling the production of thermal energy and char, the latter intended for applications in the plastics industry. In parallel, the CO₂ captured after gas combustion can be repurposed in other industrial processes, contributing to a more integrated, circular, and resource-efficient value chain.

The dynamic availability of biomass and fluctuations in its pricing can impact both the financial viability and long-term stability of a gasification plant (Kamaruzaman et al., 2023). Therefore, adopting a diversified biomass feedstock portfolio, including wood packaging residues, can serve as an effective strategy to enhance resilience and reduce dependency on a single source resource. Moreover, energy production through the gasification of residual wood effectively reduces particulate emissions from uncontrolled combustion and limits the release of toxic organic compounds commonly found in treated wood (Littlejohns et al., 2020). Harnessing waste biomass for energy not only decreases reliance on fossil fuels but also prevents methane emissions from the natural decomposition of waste, contributing to a lower carbon intensity in the energy supply chain.

Arena et al. (Arena et al., 2010) tested wood packaging residues in a pilot scale bubbling fluidized bed gasifier with a maximum feeding capacity of 100 kg/h. In particular, sawdust from wood packaging industry was used with a Lower Heating Value (LHV) of 20.3 MJ/kg. Although the characterization of wood packaging residues revealed differences compared to natural wood (as expected), the results confirmed the technical feasibility of the process, producing syngas of sufficient quality for energy applications following appropriate downstream cleaning. With an equivalence ratio (ER) of 0.3 (corresponding to a bed temperature of 925 °C), a syngas with a LHV of 4.8 MJ/m³ and a cold gas efficiency (CGE) of 0.69 were achieved.

Littlejohns et al. (Littlejohns et al., 2020) investigated the use of landfill-diverted wood wastes, including pallet residues, in a pilot-scale downdraft gasifier coupled with an internal combustion engine generator operating at 10 kWe. Their study demonstrated that waste wood can effectively be utilized in gasification, achieving a CGE of 0.67 and a LHV of 5.5 MJ/Nm³. The hydrogen concentration remained consistent across most trials, except for dry pallets, which exhibited lower average CO levels and, consequently, a reduced LHV. This disparity was linked to system instability during the run, which caused issues like bridging and slugging in the pyrolysis zone, resulting in insufficient residence time for the wood chips. While instability influenced producer gas composition and increased tar production, it did not significantly affect system efficiency. The study emphasized that the stability of gasifier operation is closely tied to the bulk properties of the feedstock, suggesting that improvements in solids handling and gasifier design could help prevent issues like bridging and channeling. Furthermore, preprocessing methods, such as pelletizing, could standardize the bulk properties of waste wood and improve overall gasifier performance, as demonstrated in similar systems.

One of the primary challenges in utilizing wood packaging waste as a raw material lies in the logistics associated with its collection, transportation, and treatment since an inadequate supply chain can significantly limit the environmental and economic benefits (Garcia and Hora, 2017). Greenhouse gas emissions increase significantly with longer transportation distances for wood collection. Additionally, despite strict controls, non-wooden materials such as metals and plastics are often present in the residues (Garcia and Hora, 2017). As a result, further

sorting and treatment processes are necessary to address these residual contaminants and ensure the efficient use of wood packaging waste. Magnets are commonly employed to remove metallic components; however, their efficiency is often limited, leaving residual metal fragments in the wood. These remnants can subsequently enter the sawing machine or the gasifier, potentially causing operational issues.

Therefore, for the successful implementation of wood residues gasification, it is crucial to evaluate not only the technology itself, but also the entire value chain, including feedstock treatment, key stakeholders, and plant infrastructure. A comprehensive assessment is necessary to identify potential challenges and optimize process efficiency, ensuring both economic feasibility and environmental sustainability. Understanding the interactions between these factors can support informed decision-making, drive innovation, and enhance the overall viability of biomass gasification as a renewable energy solution.

Regarding char valorization, in line with the FRONTSHIP objectives, this study explores the potential of gasification char as a sustainable alternative to traditional fossil-based carbon materials, such as carbon black (CB), in polymer composites. Carbon materials are widely used as fillers and pigments to enhance the tensile, thermal, and electrical properties of composites while providing a black coloration (Byrne and Guin'Ko, Y.K, 2010; Kasgoz et al., 2014; Sengupta et al., 2011). However, their production relies on fossil fuel-based feedstocks, involves high costs, and requires chemical-intensive synthesis, making them less desirable from both economic and environmental perspectives (Hau Hau Xin, 2016).

As a sustainable alternative to fossil-based fillers, biochar derived from biomass pyrolysis has been successfully used in similar applications (Das et al., 2015; Nan et al., 2016; Peterson et al., 2015). However, it is typically produced for specific purposes rather than repurposed as waste. In contrast, gasification char is a byproduct that has not been extensively optimized for targeted applications, leaving its full potential largely unexplored.

In a previous study, the authors compared char-filled SEBS (styrene-ethylene-butylene-styrene) polymers with CB-filled counterparts demonstrating the ability of both fillers to improve the thermal stability of the composite (Benedetti et al., 2020). Char well-developed porosity led to a good adherence of the SEBS matrix to the char walls. Moreover, char addition (44 % by weight) improved the electrical properties leading to an electrical conductivity of $2 \times 10^{-3} \text{ S cm}^{-1}$. Values in the same range were obtained adding 20 % by weight of CB.

Despite the growing body of literature on the gasification of wood waste and char valorization, further research is needed to demonstrate the full potential of this integrated approach in real-world applications.

This paper aims to bridge this gap by presenting a comprehensive study on the valorization of wood packaging waste through gasification, explored as a dual-purpose process yielding both renewable syngas and char, building upon the development of CSS1 within the FRONTSHIP project. Unlike traditional approaches, char is treated as a valuable co-product rather than a mere by-product, with its potential application in polymer composites thoroughly examined. Additionally, this study explores the entire value chain from waste to energy and materials, demonstrating the feasibility of a circular economy model centered on wood packaging waste.

2. Materials and methods

2.1. Materials

Standard softwood pellets (6 mm in diameter, 30 mm in length), denoted as PS in the manuscript, were purchased from Beikircher Grünland GmbH, Italy. The pellets purchased were classified with the ENplus® certification standard as A1 class, according to ISO 17225-2. Among the different parameters that qualify pellets in the A1 class, one of the most important is related to the ash content, which must be below 0.7 wt% (Mack et al., 2024).

Wood packaging residues (i.e., discarded pallets denoted as WPR) were supplied in chipped form by Lamafer SrL, a leading waste collection operator in the South Tyrol region, Italy.

The residual wood collected by the company includes not only packaging waste, but also wood from construction, demolition, and discarded furniture. Therefore, the untreated wood was first separated from foreign materials such as plastic and large metal pieces, and then from treated wood. This process was carried out both manually and using material handling machines. As a result, the provided material may not have consisted solely of pure untreated wood, though the majority originated from the wood packaging industry. Moreover, although the pallet scraps had been initially processed through a magnetic separator to eliminate the largest and most accessible metal contaminants, some debris, including visible nails and various metallic objects, were still present. Consequently, it was essential to manually remove the most prominent metal debris to protect downstream equipment from potential damage. However, it should be mentioned that this manual removal process was not entirely effective.

Afterwards, the chipped material was sent for pelletization to a local industrial processor specialized in the pelletization of virgin biomass for domestic heating. Following processing, a total of 3.5 tonnes of pellets (denoted as PW) was produced.

2.2. Gasification tests

Gasification tests were conducted in a commercial rising co-current stationary fluidized bed gasifier provided by Burkhardt GmbH, Germany.

The gasifier (length: 3.45 m, width: 1.49 m, height: 2.90 m) operates at atmospheric pressure with biomass pellets (mass flowrate of

approximately 40 kg/h) and air as gasifying agent. The uniform pellet size allows the fluidized bed to self-stabilize without the need for inert materials like sand. The process is autothermal, using heat from the partial combustion of the fuel to drive pyrolysis and gasification. Since this study focuses on the waste wood conversion process, the gasification system was not provided with the typically coupled cogeneration unit (Burkhardt GmbH), and the producer gas was directly sent and burnt in an open flare.

The core of the gasification plant is the reactor, in which the thermochemical process takes place. However, the gasification system also includes: a pellet storage tank coupled with a screw conveyor pellet dosing system, jacket tube heat exchangers, useful to cool down the producer gas and produce hot water in a primary water circuit, a gas filter for gas entrained particulate matter removal, a screw conveyor for char/ash removal, a gas flare and a control cabinet (see Fig. 1).

The integrated controlling and measuring systems allowed for continuously monitoring the system operation and recording data on biomass and air flows, pressures, temperatures and gas composition. In particular, ten temperature sensors (k-type thermocouples) were located at different heights of the reactor wall to monitor the different reaction zones. Pressure sensors in the range 0–10 mbar and 0–50 mbar were installed in different locations of the plant to measure the pressure drops in the gasifier bed, in the heat exchanger and in the gas filter. The gas composition was measured with an in-line gas analyser able to detect carbon monoxide, carbon dioxide, methane and hydrogen through TCD (Thermal Conductivity Detector) and NDIR (Non-Dispersive Infrared) sensors. In-line measurements were validated through comparison with data obtained using a calibrated micro-GC (Micro-GC 490, Agilent Technologies). Although minor deviations were observed, the in-line analyzer showed overall consistency with the micro-GC results and

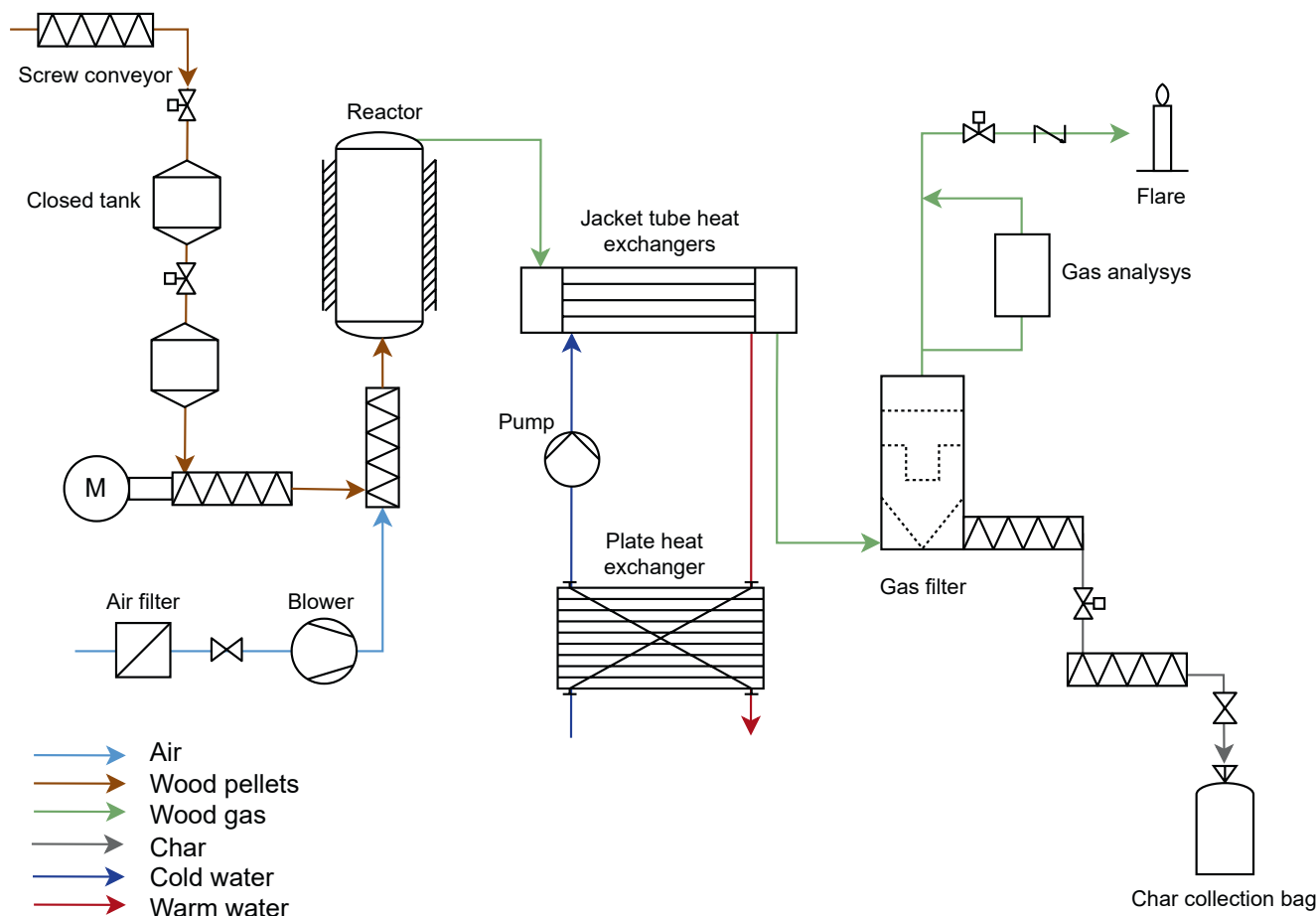


Fig. 1. Scheme of the gasification plant by Burkhardt GmbH.

proved to be reliable for continuous monitoring.

The entire module was completely piped, wired, pre-assembled and placed inside a transportable 40' HC commercial shipping container (12 m long), extensively modified to meet specific operational requirements. These modifications include the addition of a secondary entrance to facilitate ease of access and compliance with safety standards. Furthermore, the container has been equipped with an electrical utility supply system, ensuring reliable power delivery for all integrated components, and with a water-to-air heat exchanger, which was used to cool down the hot water produced in the primary circuit of the system. These alterations transformed the container into a fully functional, secure, and versatile enclosure, suitable as a lab, tailored to the needs of the experimental campaign.

Before each startup, the entire system was flushed with air. Once ignition was achieved, the gas was directed through the flue and burned in the gas flare.

Each test was conducted under steady-state conditions for a minimum duration of 6 h to ensure the collection of reliable and representative data. This time frame allowed the system to stabilize fully, minimizing transient effects and ensuring that the measured parameters accurately reflected the operational performance. By maintaining steady-state operation, the data obtained provided a robust basis for analysis, enabling consistent comparisons across trials and ensuring the validity of the experimental outcomes. During the tests, the system is operated in such a way as to maintain a constant biomass bed height. This is achieved by continuously monitoring the bed height using a pressure sensor and feeding biomass pellets from the bottom of the gasifier whenever needed. The pellet feed rate, in turn, regulates the amount of air supplied to the gasifier via an air blower. This unique gasification configuration eliminates the need for a dedicated char extraction system. Instead, the char is entrained in the syngas stream and collected in the gas filter, as the particles become small enough to be carried away by the flow.

Initial tests were run using PS to identify the optimal trade-off in terms of gas composition, operational stability, and char yield. Three operating conditions (called A, B, C) were investigated. Condition A corresponded to the standard one, suggested by the gasifier manufacturer, while conditions B and C were selected to increase the char yield (and thus the amount of char available for subsequent applications), varying the reactor vibration settings and the char bed height. Subsequently, the gasifier was operated under the chosen conditions using PW.

During the tests, operating parameters, gas yield and composition were continuously monitored to ensure the correct operation of the system. Moreover, a mass balance and an energy performance assessment were carried out after each test. The char was collected, characterized and further exploited in composites production. In order to accurately measure the char produced, the char container was emptied as soon as the plant reached steady-state and, from that point on, the char production was considered constant for the overall duration of the test. The char mass flow rate was then calculated as the average over the entire test.

The mass balance of the gasification system was calculated with Equation 1.

$$\dot{m}_{biomass} + \dot{m}_{air} = \dot{m}_{pg-wb} + \dot{m}_{char} \quad (1)$$

where:

$\dot{m}_{biomass}$ is the biomass flow rate, as received (ar) – measured by the plant control system;

\dot{m}_{air} is the gasification agent flow rate: air – measured by a flowmeter integrated in the plant;

\dot{m}_{pg-wb} is the producer gas flow rate on wet basis (wb) – calculated from Equation 1;

\dot{m}_{char} is the char flow rate – estimated by the char weight at the end of the test.

Equation 1 was used to evaluate \dot{m}_{pg-wb} , while total nitrogen balance equation (Equation 2) was used to obtain the dry gas flow rate (\dot{m}_{pg-db}):

$$\begin{aligned} \dot{m}_{biomass-db} \cdot Y_{N_{biomass-db}} + \dot{m}_{air} \cdot Y_{N_{2\ air}} \\ = \dot{m}_{pg-db} \cdot Y_{N_{2\ pg-db}} + \dot{m}_{char-db} \cdot Y_{N_{char-db}} \end{aligned} \quad (2)$$

where:

$Y_{N_{biomass-db}}$ is the mass fraction of nitrogen in the biomass on a dry basis (db) – obtained from the elemental analyzer;

$Y_{N_{2\ air}}$ is the mass fraction of nitrogen present in air – assumed equal to 0.75 kg_{N2}/kg_{air};

$Y_{N_{2\ pg-db}}$ is the mass fraction of nitrogen present in the gas on a dry basis – derived from the in-line gas analyzer;

$Y_{N_{char-db}}$ is the mass concentration of nitrogen present in char on a dry basis – obtained from the elemental analyzer.

Producer gas lower heating value (LHV_{pg-db}) and cold gas efficiency (CGE) were calculated through Equation 3 and 4, respectively:

$$LHV_{pg-db} = \sum_i (X_i \cdot LHV_i) \quad (3)$$

$$CGE = \frac{\dot{m}_{pg-db} LHV_{pg-db}}{\dot{m}_{biomass} LHV_{biomass}} \quad (4)$$

where:

X_i is the molar or volumetric fraction of gas component i - measured by the in-line gas analyzer,

LHV_i is the lower heating value of component i (expressed in MJ/Nm³) – according to the literature (Armstrong and Jobe, 1982).

2.3. Compounding

In order to test char suitability as filler/pigment in polymers, low-density polyethylene (DOW LDPE) was selected as polymeric matrix.

Three distinct char samples were examined: char derived from PS under standard condition A (Char_PS), char from PS produced under conditions corresponding to the maximum char yield (denoted as Char_MCY), and char from PW obtained under optimal conditions which, as discussed in the following sections, correspond to the standard ones (Char_PW). Each char sample was incorporated into the polymer matrix at a concentration of 1 % by weight. For comparative analysis, a currently utilized LDPE-based black compound provided by K-Flex, a company operating in the plastic industry partner of the FRONTSH1P project, was also characterized (denoted as KF).

A co-rotating twin-screw extruder equipped with a mixing function (Micro-compounder 15 cc, DSM) was used for melt compounding ensuring fine dispersion of char within the polymer matrix.

To prepare the samples for melt flow index (MFI) testing, melt compounds were cooled in air, and subsequently ground using a blade mill (TRIA) designed for polymer recycling.

Samples for mechanical characterization were obtained via injection-molded using a Micro Injection Moulding Machine 10 cc, DSM.

The operating conditions used during melt compounding and moulding are reported in Table 1. Parameters were adjusted according to the different viscosity of the samples.

2.4. Characterization

Before the analyses, biomass samples (PS, WPR, PW) and chars produced during the tests (Char_PS, Char_MCY, Char_PW) were pre-treated according to ISO 14780. Subsequently, proximate analysis was performed according to ISO 18134 (reference method TO_16 for determination of total moisture, TO_12 for ash content, and TO_03 for volatile matter), while elemental analysis (for determining C, H and N content) was conducted in a Perkin Elmer Series II instrument according to ASTM D5291. S and Cl were determined via X-Ray Fluorescence using a Bruker S8 TIGER instrument, by application of standard ISO/TS 16996, and O

Table 1
Operating conditions used during melt compounding and moulding.

	LDPE and KF	1 % Char_PS and 1 % Char_MCY	1 % Char_PW
Melt compounding			
Mixing time [s]	60	75	60
T profile [°C]	150–165–180	150–165–180	170–180–190
T melt [°C]	176	176	185
Screw rotation speed [rpm]	50	39	50
Moulding			
T mould [°C]	25	25	28
T injection [°C]	185	185	195
P injection [bar]	11	11	9
Injection time [s]	19	19	10

was then calculated by difference. The bulk density of the samples was determined according to ISO 17828 and the calorific value was determined using a PARR 6400CL bomb calorimeter according to ISO/DIS 18125. The major and trace element composition of the biomass and char samples was determined via Atomic Absorption Spectroscopy (AAS), using a Shimadzu AA-6300 instrument, by application of standard ISO16967 and ISO16968, respectively. Major elements here refer to: Al, Ca, Fe, Mg, P, K, Si, Na, and Ti, while trace elements refer to Cd, Co, Cr, Cu, Mn, Ni, Pb, V, and Zn. Regarding char porosity, specific surface area, pore volume, and pore size were measured using a 3Flex Surface Characterization Analyzer (Micromeritics Co.) operating with N₂ at –196 °C. Before analysis, samples were degassed ex situ with N₂ at 300 °C for 24 h and subsequently vacuum degassed in situ at the same temperature for 3 h. The specific surface area was determined by the Brunauer-Emmett-Teller (BET) method (Brunauer et al., 1938), while the total pore volume and the average pore size were obtained by the Barret-Joyner-Halenda (BJH) desorption analysis (Barrett et al., 1951).

Polymer compounds were characterized via tensile and MFI tests to assess their mechanical and rheological properties. Tensile tests were performed using a universal dynamometer with a 30 K load cell (LLOYD INSTRUMENT). Samples were tested in compliance with ISO 527, following a type 1BA geometry, with a traverse speed of 50 mm/min and an initial distance between vices of approximately 50 mm. Tests were conducted until rupture, which occurred after limited plastic deformation across all samples.

The MFI test was conducted according to ISO 1133 using an MFI 452 device by MP Strumenti, at a temperature of 190 °C and a weight of 2.16 kg. The time interval between cuts for weighing each sample was set to 60 s for a total of 10 min. Sample weights were measured using a precision balance (accuracy: 0.01 mg, Kern ABT-5DM). For each sample type, at least seven samples were tested to ensure a minimum of five results with good repeatability.

3. Results

3.1. Biomass characterization

Table 2 reports the results of the characterization of PS, WPR and PW. As expected, PW exhibits a higher ash content (1.6 wt%) compared to PS (0.5 wt%). This aligns with the findings of Littlejohns et al., who reported that wood pallet residues show double ash content compared to pure wood, either spruce or pine (Littlejohns et al., 2020). The increased ash content is primarily attributed to residual metallic particles in the pallet waste. During the milling process, these metallic bodies are partly pulverized and subsequently incorporated into the new pellets. Elemental compositions and heating values are comparable, with both PS and PW showing a carbon content of 49.9 wt% and a HHV around 19.5 MJ/kg.

However, the key difference lies in metal content, which aligns with the ash composition. PW contains nearly twice the amounts of Al, Ca, K,

Table 2
Biomass characterization results – ar: as received, db: dry basis.

Sample	Unit	PS	WPR	PW
Proximate analysis				
Moisture	wt% _{ar}	8.7	10.1	7.6
Ash	wt% _{db}	0.5	0.6	1.6
Volatiles	wt% _{db}	81.2	82.6	79.3
FC	wt% _{db}	18.3	16.8	19.1
Ultimate Analysis				
Carbon	wt% _{db}	49.95	49.88	49.96
Hydrogen	wt% _{db}	6.05	5.89	5.93
Nitrogen	wt% _{db}	0.12	0.30	0.41
Sulfur	wt% _{db}	0.01	0.01	0.02
Chlorine	wt% _{db}	0.01	0.02	0.02
Oxygen	wt% _{db}	43.86	43.90	43.66
Bulk density	kg/m ³	687	77	584
Heating value				
Higher Heating Value (HHV)	MJ/kg _{db}	19.63	19.48	19.42
	MJ/kg _{ar}	17.92	17.99	17.46
Lower Heating Value (LHV)	MJ/kg _{db}	18.31	18.19	18.13
	MJ/kg _{ar}	16.51	16.62	16.05
Major Element concentration				
Al	ppm	43	124	366
Ca	ppm	1697	1648	3795
Fe	ppm	69	347	541
K	ppm	591	533	1038
Mg	ppm	199	300	399
Na	ppm	27	395	119
Si	ppm	210	168	914
Trace Element concentration				
Cd	ppm	0.11	0.07	0.06
Co	ppm	0.08	0.08	0.13
Cr	ppm	0.39	1.17	1.94
Cu	ppm	1.11	3.16	5.53
Mn	ppm	121.0	88.6	60.2
Ni	ppm	0.2	0.8	0.9
Pb	ppm	0.2	0.9	2.4
V	ppm	0.87	0.14	0.30
Zn	ppm	12	21	44

and Mg, along with significantly higher concentrations of Na (4x), Si, Zn, Cr (5x), Cu, Fe (7x), and Pb (12x) compared to PS (see Table 2 for numerical values). Only V and Mn are present in lower quantities in PW.

Overall, PW also exhibits a higher metal and ash content than WPR. This is not only due to the pulverized metallic residues inside the PW (accurately removed in the case of WPR), but also likely as a result of metal wear from the milling and pelletizing equipment during processing, further intensified by the presence of metallic fragments.

3.2. Gasification tests

Initial tests were conducted using PS to determine the optimal operating conditions for the subsequent PW experiments. Results in terms of mass balance, LHV, CGE and gas composition are reported in Table 3, while Fig. 2 shows gas composition trends in steady-state operation. When using PS, comparable results in terms of mass balance were observed across all three operating conditions (A, B, and C). Among them, condition B resulted in the highest char yield (1.6 wt%), but this was accompanied by reduced operational stability, with fluctuations closely following the vibration intervals (see Fig. 2). Condition C, associated to the lowest char yield (0.9 wt%) and the lowest CGE (53.7 %), also showed clear signs of instability and was therefore excluded from further consideration. As a result, condition A was selected for the subsequent tests with PW, as it provided the best compromise between gasifier stability and char yield (1.3 wt%).

Tests with PW were initially run for a total of 24 h to fully replace the material in the gasifier bed and to ensure that the produced char originated exclusively from PW. Following this, eight full-day tests were run using PW under operating condition A. Results including the standard

Table 3

Results of the gasification tests using standard pellets (PS) and pellets from wood packaging waste (PW): mass balance, char yield, equivalence ratio (ER), gas composition, heating value (LHV) and cold gas efficiency (CGE) – ar: as received, wb: wet basis, db: dry basis.

Condition	Unit	PS			PW
		A	B	C	A
Biomass	kg _{ar} /h	42.4	44.6	42.9	42.8 ± 1.7
Air	kg/h	65.0	65.0	65.0	63.3 ± 1.5
Char	kg _{ar} /h	0.6	0.7	0.4	0.4 ± 0.1
Producer gas	kg _{wb} /h	106.9	108.9	107.5	105.6 ± 2.7
Char yield	wt%	1.3	1.6	0.9	1.1 ± 0.1
ER	–	0.27	0.25	0.27	0.30 ± 0.01
Gas composition					
H ₂	%vol. db	18.95	19.29	16.16	19.97 ± 1.98
CO	%vol. db	20.37	20.01	19.13	20.17 ± 1.32
CO ₂	%vol. db	9.18	9.33	9.26	8.93 ± 0.25
CH ₄	%vol. db	1.46	1.62	2.93	2.17 ± 0.16
N ₂ *	%vol.db	50.05	49.74	52.52	48.83 ± 1.22
LHV gas	MJ/Nm _{db} ³	5.24	5.19	5.20	5.47 ± 0.13
CGE	%	56.6	55.0	53.7	58.7 ± 3.8

*calculated as the difference from 100.

deviations are presented in Table 3. Performances were comparable to that of PS (condition A), although a slightly lower char yield of 1.1 wt% was observed.

Regarding producer gas properties, the LHV is relatively consistent

for both PS and PW, in line with the findings reported in the literature (Arena et al., 2010; Littlejohns et al., 2020). Only slight variations between the two samples were detected: 5.24 MJ/Nm³ in case of PS and 5.47 MJ/Nm³ in case of PW. This difference in LHV suggests that the gas produced from PW is slightly higher in energy content, which could be due to the higher volatiles content in PW, as indicated by its proximate analysis.

Also CGE values for both PS and PW align with previous findings (Arena et al., 2010; Littlejohns et al., 2020) and show a similar trend across the conditions, with PW typically exhibiting slightly higher CGE values (58.7 %) compared to PS (56.6 %). This is a direct consequence of the slightly higher LHV of the PW producer gas. However, it is worth mentioning that the CGE values presented here are lower than those measured by the gasifier manufacturer (e.g., CGE = 73.5 %). This is likely due to the plant being operated on a daily basis rather than continuously over extended periods.

3.3. Char characterization

Char characterization revealed significant differences in composition, heating value, trace element concentration, and textural properties especially between Char_PS and Char_PW (see Table 4). In terms of proximate analysis, Char_PW exhibits the highest ash content (15.7 wt %) and volatiles (32.0 wt%), while having the lowest fixed carbon (52.3 wt%), suggesting a less carbon-rich material compared to Char_PS and

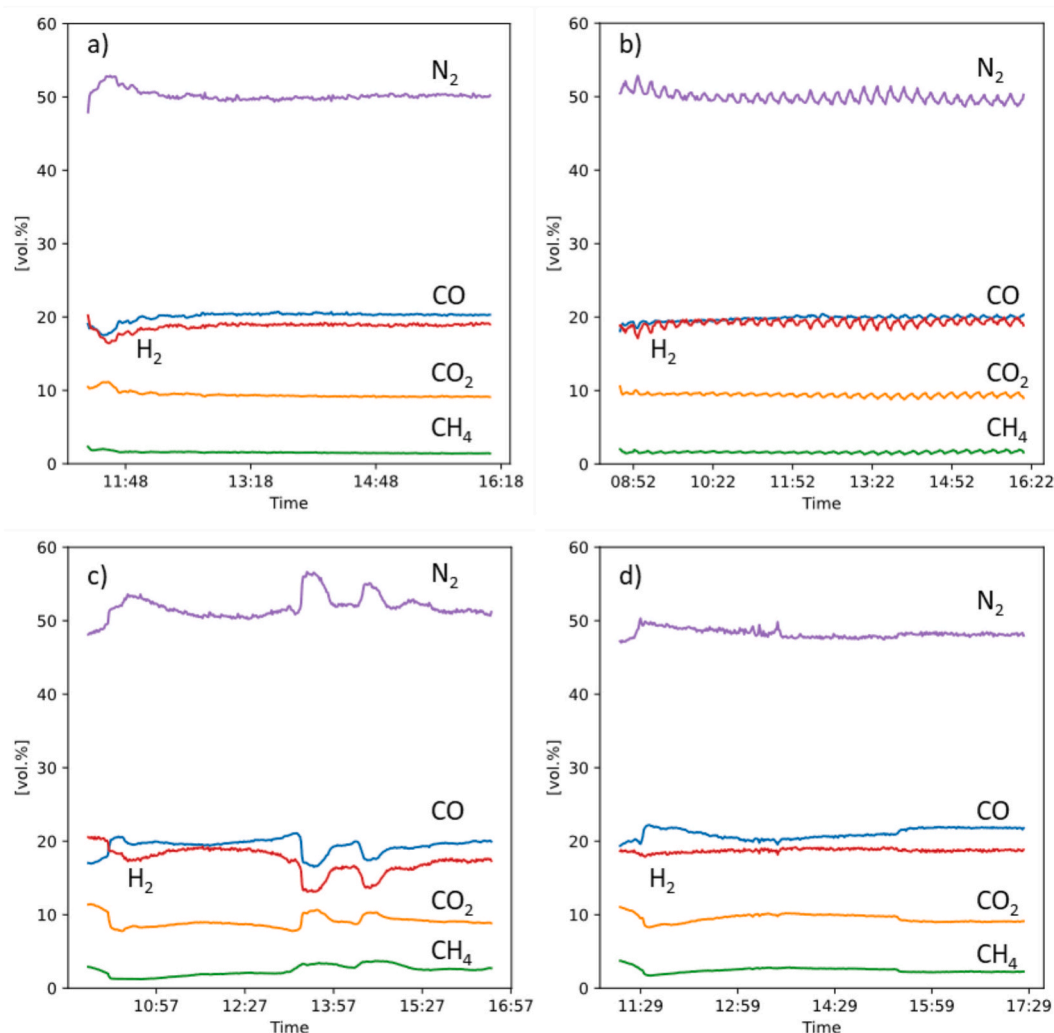


Fig. 2. Gas composition trend in steady-state operation a) PS condition A, b) PS condition B, c) PS condition C, d) PW condition A.

Table 4

Char characterization results – ar: as received, db: dry basis.

Sample	Unit	Char_PS	Char_MCY	Char_PW
Proximate analysis				
Moisture	wt% _{ar}	3.2	3.4	2.6
Ash	wt% _{db}	11.1	12.4	15.7
Volatiles	wt% _{db}	19.0	16.3	32.0
FC	wt% _{db}	69.9	71.3	52.3
Ultimate Analysis				
Carbon	wt% _{db}	81.20	83.70	67.40
Hydrogen	wt% _{db}	0.68	0.50	1.16
Nitrogen	wt% _{db}	0.41	0.66	0.47
Sulfur	wt% _{db}	0.10	0.07	0.32
Chlorine	wt% _{db}	0.15	0.15	1.01
Oxygen	wt% _{db}	17.46	14.92	29.61
Heating value				
Higher Heating Value (HHV)	MJ/kg _{db}	27.62	28.38	23.86
	MJ/kg _{ar}	26.73	27.40	23.23
	MJ/kg	27.48	28.27	23.57
Lower Heating Value (LHV)	MJ/kg _{db}	26.52	27.21	22.93
	MJ/kg _{ar}			
Trace Element concentration				
Cd	ppm	41.90	37.50	21.24
Co	ppm	2.03	1.74	12.17
Cr	ppm	33.80	9.64	157.27
Cu	ppm	222.00	234.00	430.75
Mn	ppm	4.90	4.50	3.30
Ni	ppm	42.60	21.80	123.70
Pb	ppm	50.10	53.50	403.90
V	ppm	1.25	0.43	12.71
Zn	ppm	1847	1832	7279
Concentration of major oxides in char				
Al ₂ O ₃	wt% _{db}	0.66	0.32	3.05
CaO	wt% _{db}	38.32	39.49	46.17
Fe ₂ O ₃	wt% _{db}	1.52	0.85	4.81
K ₂ O	wt% _{db}	14.45	16.71	11.70
MgO	wt% _{db}	4.84	4.50	7.93
Na ₂ O	wt% _{db}	0.64	0.53	2.62
SiO ₂	wt% _{db}	4.97	1.92	11.57
Physorption				
Specific surface area	m ² /g	587	1006	210
Pore volume	cm ³ /g	0.7	0.8	0.5
Pore size	nm	8.7	7.3	10.0

Char_MCY. This is further supported by the ultimate analysis, where Char_PW shows the lowest carbon content (67.4 wt%) and highest oxygen content (29.61 wt%), which likely contributes to its lower values of HHV (23.86 MJ/kg) and LHV (23.57 MJ/kg) compared to the other samples. This is in line with the previous findings on PS and PW, where PW showed higher metal content due to the presence of metallic foreign bodies in the starting wood packaging residues, which have been pulverized during processing.

Indeed, Char_PW reflects these differences in its trace element concentrations, with significantly elevated levels of metals such as Cr (157.27 ppm), Cu (430.75 ppm), Ni (123.70 ppm), Pb (403.9 ppm), and Zn (7279 ppm). This increased metal presence is further corroborated by the major oxide content, including higher Al₂O₃ (3.05 %), Fe₂O₃ (4.81 %), and SiO₂ (11.57 %), which indicates a greater accumulation of inorganic compounds.

The high metal concentration in the char could pose potential toxicity risks in polymer applications, with Pb being the most critical element. However, assuming a 1 % Char_PW loading in the polymer matrix, the resulting Pb concentration in the final plastic would be approximately 4 ppm. This value remains well below the regulatory limits established by European directives, including the most stringent threshold of 23 ppm for consumer products (Turner and Filella, 2021). Nonetheless, further efforts to reduce the Pb content in char would be beneficial and proposed applications should be limited to non-food-

contact and non-toy products, for which less restrictive regulations apply. The lower carbon content and higher metal content also influence the textural properties of Char_PW, as shown in Table 4. In particular, Char_PW exhibits the lowest specific surface area (210 m²/g vs. 587 m²/g of Char_PS) and pore volume (0.5 cm³/g vs. 0.7 cm³/g of Char_PS), while having the largest pore size (10.0 nm vs. 8.7 nm of Char_PS). This can be attributed not only to the reduced availability of carbonaceous material for porosity development, but also to the higher concentration of inorganic components, which may hinder pore formation or contribute to pore blockage, ultimately limiting the development of a finer porous structure (Benedetti et al., 2018).

Regarding char samples obtained from the same pellet type (PS) but under different operating conditions, the most noticeable difference is the significantly higher surface area of Char_MCY (1006 m²/g). This is likely a result of the vibration effects during the gasification process. As a matter of fact, the vibration moves the char bed affecting the residence time of the particles in the reactor, which in turn could influence the structure and porosity development of the material, enhancing its surface area (Zhang et al., 2020).

3.4. Compound characterization

The compounds formulated with Char_PS, Char_MCY, and Char_PW underwent comprehensive characterization to assess their properties in detail. Fig. 3a provides a visual representation of their appearance, highlighting the pigmenting effect of the char, which imparts a black coloration to the material, while Fig. 3b shows some specimens used for tensile tests after fracture.

The mechanical properties, in terms of yield stress (σ_y) and strain (ϵ_y), fracture stress (σ_{br}) and strain (ϵ_{br}), as well as Young's modulus (E) and MFI of the materials are reported in Table 5.

The data dispersion is minimal for σ_y and ϵ_y , whereas a slight increase is observed for ϵ_{br} and E. This variation is likely due to the heterogeneous nature of the materials, despite several optimization attempts, and is attributed to the limited chemical compatibility between the char and the polymer matrix. Generally, when a molten polymer lacks good compatibility between different phases, polymer compatibilizers can help enhance interfacial interactions and improve the wettability of the polymer with the filler (Song and Hong, 2020).

The addition of char generally results in a decrease in σ_{br} , ϵ_{br} and MFI compared to the pristine polymer. Among the yield properties, the most significant difference is observed in ϵ_y , where the highest value (12.13 %) is recorded for the 1 % Char_PW compound, which also corresponds to the lowest E (242 MPa). This behavior is likely related to the limited chemical compatibility between the char surface and the polymer matrix, which weakens interfacial adhesion and reduces stress transfer, ultimately leading to lower stiffness and higher deformability. While the larger pore size of Char_PW may also influence this behavior, chemical compatibility remains the dominant factor.

The highest plastic deformation before breakage was observed for KF, whereas char-containing compounds exhibited a significant reduction in this property. However, plastic deformation before breakage was generally limited for all the materials analyzed, despite the use of LDPE as the base matrix.

Regarding fluidity, KF exhibited the highest fluidity (MFI 2.40 g/10 min), followed by LDPE (MFI 1.92 g/10 min). Char-based compounds showed a slight decrease in fluidity compared to the pure matrix, with reductions of 13.5 %, 16.7 %, and 2.6 %, respectively, for the polymers containing Char_PS, Char_MCY, and Char_PW. This decrease in fluidity can be attributed to the increased viscosity of the samples, which was expected for filled compounds.

4. Conclusions

WPR are valuable resources and should therefore be properly valorized. This study applied a polygenerative approach involving

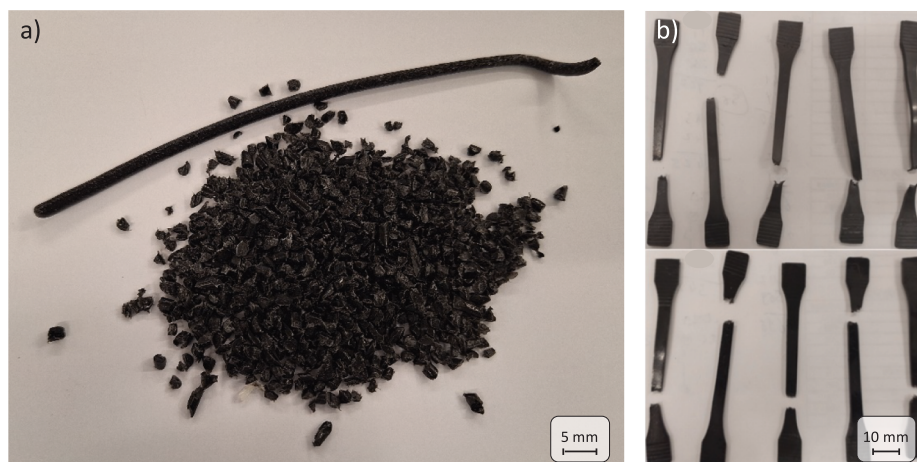


Fig. 3. A) compound obtained adding 1 wt% of Char_PW to a LDPE matrix, b) char-based specimens used for tensile tests after fracture.

Table 5
Mechanical properties and MFI.

Sample	σ_y (MPa)	ϵ_y (%)	σ_{br} (MPa)	ϵ_{br} (%)	E (MPa)	MFI (g/10 min)
LDPE	10.77 ± 0.31	3.33 ± 0.10	17.95 ± 0.30	70.72 ± 2.35	325.13 ± 10.68	1.92 ± 0.03
KF	9.94 ± 0.51	3.45 ± 0.11	19.25 ± 0.97	81.53 ± 7.01	294.90 ± 25.65	2.40 ± 0.03
1 % Char_PS	11.02 ± 0.42	3.37 ± 0.20	16.75 ± 1.22	46.90 ± 3.58	326.18 ± 28.00	1.66 ± 0.03
1 % Char_MCY	11.03 ± 0.55	3.50 ± 0.29	17.14 ± 0.45	47.52 ± 3.38	314.62 ± 20.96	1.60 ± 0.01
1 % Char_PW	10.57 ± 0.59	12.13 ± 1.39	14.63 ± 0.45	55.11 ± 1.46	242.06 ± 20.16	1.87 ± 0.03

gasification to WPR, aiming to achieve both energy recovery and material valorization in the context of a real-scale application.

Experiments were conducted using a commercial air-blown gasifier operating with pellets. Three operating conditions (A, B, C) were tested with PS to increase char yield while maintaining gas stability. Condition A, representing standard operation, offered the best trade-off and was thus selected for PW testing. To produce PW, it was first necessary to remove residual metallic components from the WPR to prevent damage to the milling and pelletizing equipment. However, some metallic residues remained, influencing the final composition of PW showing higher ash (11.1 wt% vs 15.7 wt%) and metal content than PS.

PW gasification was successfully performed for over 90 h. Compared to PS, it showed slightly lower char yield (1.1 wt% vs. 1.3 wt%), but higher CGE (60.7 % vs. 56.6 %). Mass balance and gas composition remained similar, confirming the suitability of PW for gasification with minor performance differences.

The char obtained from PS and PW was characterized and tested as filler and pigment in a LDPE matrix showcasing its potential for value-added applications in the plastics industry as a substitute for carbon black.

In conclusion, this study demonstrates the technological feasibility of waste gasification systems. However, to enable their broader adoption, enhance economic viability, and support integration into wider sustainability strategies, a supportive policy framework comprising targeted measures such as financial incentives and regulatory adjustment, should be implemented.

CRediT authorship contribution statement

Vittoria Benedetti: Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Stefano Piazzi:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Scatto:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation,

Conceptualization. **Elisabetta Santello:** Writing – review & editing, Investigation, Formal analysis. **Markus Kollmer:** Writing – review & editing, Supervision, Methodology. **Grigorios Itskos:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Konstantinos Atsonios:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Francesco Patuzzi:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Marco Baratieri:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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