



An experimental study to investigate the impact of solar drying on emission products of woody biomass in the torrefaction process

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Abstract

Biomass torrefaction is a thermochemical process that transforms biomass into a more energy-dense fuel, producing solid biochar, volatile organic compounds, and gases such as carbon dioxide (CO₂), carbon monoxide (CO), and nitrogen oxides (NO_x). In this study, the effects of solar drying, as a sustainable preprocessing method, and subsequent torrefaction were evaluated under varying initial moisture content levels of 5%, 10%, 15%, and 20%. The drying conditions of wood chips and the torrefaction process were documented for a sustainable biomass drying system using solar energy. Comprehensive proximate and final analysis and flue gas monitoring analyzed the torrefied biomass's emission characteristics and combustion efficiency. Results showed that higher initial moisture content increased hydrogen and volatile matter, decreased fixed carbon, and marginally raised the higher heating value. This study shows that solar drying optimizes biomass pretreatment and is a cost-effective and environmentally friendly alternative to conventional drying. This work sheds light on the relationship between initial moisture content, emission characteristics, and combustion behavior, aiding bioenergy development.

Keywords Torrefaction · Wood-biomass · Emission characteristics · Combustion efficiency · Solar drying

1 Introduction

World-level institutions such as the United Nations (UN), the World Energy Forum, and the Organization for Economic Co-operation and Development recognize the potential of biomass from wood fuels as a crucial component of the global sustainable energy landscape as an alternative to fossil fuels (Ajmi and Inglesi-Lotz 2020). Biomass, including wood-based fuels, is a renewable energy source that can mitigate climate change, promote energy security, and foster

rural development. According to the United Nations FRA (Forest Resource Assessment) study, the total carbon stored in forests fell from 668 gigatons in 1990 to 662 gigatons in 2020 (FRA 2020). Natural biomass from forests, such as wood and other plant materials, often requires pretreatment before it can be effectively and efficiently used for various applications. Compared to coal, biomass found in nature has a higher moisture and volatile content, lower energy density, fast biological degradation, and limited product consistency.

However, a comprehensive assessment of its environmental impact requires a balanced evaluation of both its benefits and drawbacks, for which life cycle assessment (LCA) studies may come in handy (Costa et al. 2024). While LCA analyses indicate that woody biomass can achieve net reductions in greenhouse gas (GHG) emissions compared to coal or natural gas. One way to do this is to use CO₂ impulse response functions (IRF) from C cycle models to come up with atmospheric decay functions for CO₂ releases from biomass (CHERUBINI et al. 2011), the process, however, is not without challenges. One major drawback is particulate matter (PM) emission during combustion, which can adversely affect air quality and human health. PM emissions are influenced by feedstock characteristics, combustion

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conditions, and the absence of advanced emission controls, particularly in small-scale applications. Furthermore, the transportation and processing stages of biomass can contribute additional GHG emissions, reducing its overall environmental advantage. These pollutants highlight the need for improved transportation and supply chain optimization (Delcourt et al. 2024). To build comprehensive long-lasting bioenergy plans, we must weigh the merits and downsides of using woody biomass as an energy source, taking into account human health and the environment.

Thus, to enhance the biomass's physical, chemical, structural properties, thermo-chemical procedures, such as gasification, liquefaction, pyrolysis, and combustion, have drawn a lot of interest in recent years (Chen et al. 2024; Director and Sinelshchikov 2019; Li et al. 2024; Mendoza-Martinez et al. 2023; Shahbeik et al. 2024). A thermochemical technology for producing a conditioned solid biofuel is mild pyrolysis, known as torrefaction, which entails raising the feedstock's temperature to 200–300 °C, mainly in an oxygen-free atmosphere. The end product is a solid biomass that is, compared to the raw feedstock, hydrophobic, brittle, and has a higher calorific value. The removed oxygen during torrefaction results in a solid material with a lower molar ratio of oxygen to carbon than the original biomass (van der Stelt et al. 2011). Furthermore, some of the raw materials are liberated as gases during the process, such as water, volatiles like acetic acid, and permanent gases like CO₂. These challenges may occur due to the inherent characteristics of natural wood biomass, including a high moisture content field (Kumar, Raj, Szepesi, et al., 2023a), a low energy density (Yu et al. 2019), and a complex lignocellulosic structure. Additionally, the presence of inhibitory compounds, variable composition, and mineral content can hinder its suitability for various applications. Pretreatment processes are performed to enhance the performance of wood biomass in different applications such as energy production, biofuel manufacturing, and animal feed. These processes aim to modify the wood biomass properties, making it better suited for conversion. For instance, pretreatment methods can reduce moisture content, increase energy density, and break down the complex lignocellulosic structure to facilitate efficient enzymatic hydrolysis (Da Silva et al. 2020). They can also minimize inhibitory compounds and improve overall homogeneity, ensuring consistent quality. Biomass from forests can contain minerals and inorganic materials. High ash content can lead to slagging and fouling during combustion. Pretreatment methods can help reduce ash content, improve combustion efficiency, and reduce maintenance needs.

Moreover, pretreatment can lead to environmental benefits by reducing transportation emissions, increasing mechanical strength (Klement et al. 2022), and enabling

more efficient storage. The char formation can be of two categories. First, Hydrochar is produced through hydrothermal carbonization (HTC), where biomass is subjected to hot compressed water under subcritical conditions (180–250 °C), mimicking natural coal formation but within hours rather than millions of years. In contrast, normal char (torrefied char or biochar) is generated through pyrolysis (> 400 °C) or torrefaction (200–300 °C) in an oxygen-deficient environment, where biomass undergoes thermal degradation to form a more carbon-dense and energy-rich solid product. Among these pretreatment methods, torrefaction has gained prominence for its ability to significantly enhance the characteristics of biomass, preparing it for a range of applications while minimizing its inherent limitations. Torrefaction is often divided into two types: dry and wet. Conventional dry torrefaction (DT) takes place in an oxygen-free environment with low heating rates (below 50 °C per minute) and durations ranging from 15 to 60 min (Kostyniuk and Likożar 2024). Wet torrefaction (WT), also known as hydrothermal torrefaction, is a high-pressure thermal pre-treatment process carried out, typically at temperatures ranging from 180 °C to 265 °C. (Bach and Tran 2015; Ivanovski et al. 2023). This increases the energy requirements and costs of the process. As a result, for low-income industries, DT is a viable alternative that eliminates the cost of post-drying (Tu et al. 2022). Unlike fossil carbon, which remains locked in geological formations for millions of years, biogenic carbon cycles more rapidly between the atmosphere and living organisms. In the context of wood torrefaction, this concept is crucial because the biomass used in the process originates from renewable sources, making its carbon emissions potentially neutral when managed sustainably. Biogenic carbon refers to the carbon naturally absorbed and stored by biomass through photosynthesis during its growth phase. As biomass grows, it absorbs atmospheric CO₂, and during torrefaction, part of this carbon is retained in the solid char, while the rest is released as gaseous emissions. If torrefied biomass is used as biochar, it can act as a long-term carbon sink, helping sequester carbon and mitigate climate change.

However, the evaluation of biogenic carbon and carbon uptake remains controversial due to methodological challenges, climate policy implications, and standardization issues in carbon accounting (Thylmann and Kießer 2024). A key complexity arises from the difficulty in assessing net carbon uptake and accurately measuring biogenic emissions, leading to discrepancies in reporting. One major concern is biogenic carbon credit double counting, where the same carbon sequestration event might be accounted for more than once in different assessment frameworks. Moreover, life cycle assessments (LCA) of biogenic carbon are highly dependent on the methodology used, as different carbon accounting models yield varying results based

on time horizons, carbon storage assumptions, and decay rates. Another challenge is the lack of globally standardized biogenic carbon accounting methods. Existing frameworks, such as ISO-14067, CENEN-15804, and prEN18027, provide guidance on measuring and reporting greenhouse gas (GHG) emissions associated with products, including biogenic carbon considerations (BIC 2024). These ISO standards aim to enhance transparency in carbon accounting by ensuring consistent evaluation methodologies across different sectors. By establishing a standardized approach, these frameworks help stakeholders reduce inconsistencies in carbon reporting, facilitating more reliable assessments of torrefied biomass's role in carbon neutrality and monitoring industrial practices.

In an industrial setup, analytical methods play a crucial role in monitoring and controlling thermal treatment. The endurance of heat-treated wood at an industrial scale may be evaluated using various analytical techniques, such as spectroscopy, thermogravimetry, chemical analysis, color analysis, or mechanical nondestructive testing (NDT), which (Candelier et al. 2016) reviewed. A biomass batch's overall quality is estimated by monitoring the relative area indication of wood temperature, but not for specific boards of chunks. Combining these techniques offers a thorough way to evaluate the qualities and attributes of thermally treated wood. As a result of the biomass's increased lignin content and decreased moisture content, the torrefaction process increases bulk density and calorific (Saeed et al. 2015). Changes in the MC have varying effects on the polysaccharides; the most significant difference is observed between glucomannan and xylan. According to research, biomasses that have a high percentage of flexible polysaccharides are more susceptible to MC concentrations. This information improves our comprehension of the biomass's constituent parts and their relative contributions to the densification process (Frodeson et al. 2019). Understanding the influence of torrefaction temperature on biomass is vital due to its impact on yield, energy content, structure, and composition (Zheng et al. 2017). Several recent studies have investigated the torrefaction of wood biomass, aiming to enhance its properties for various applications. (Alizadeh et al. 2022) focused on torrefying wood sawdust from processing mills to improve fuel properties and densify it for more accessible transportation. They observed an increase in energy value by 40% under severe torrefaction conditions, with enhanced pellet strength through the addition of a binder. On the one hand, (Mutlu et al. 2022) investigated downstream torrefaction of wood pellets, highlighting the difficulty of assuring consistent product quality. While they discovered ideal torrefaction temperatures, the study did not delve further into the ultimate and proximal analyses required to comprehend biomass's chemical and physical changes. Similarly,

(Cahyanti 2024) studied the physiochemical parameters of torrefied biomass and discovered variations in lignin, hemicellulose, and cellulose concentration with torrefaction temperature. Furthermore, (Zhang et al. 2023) investigated thermogravimetric analysis and other parameters affecting industrial wood species during torrefaction, with an emphasis on temperature-induced changes. In their investigation of the impact of torrefaction temperature on wood pellet quality, Park et al. 2023 demonstrated enhanced hydrophobicity and heating values. The possibility of wet torrefaction to transform wet biomass into hydrochar solid fuel was investigated in a review by (He et al. 2018). While these studies also lacked a comprehensive evaluation of the ultimate and proximate properties of the resulting hydrochar.

On large-scale utilization, the moisture presence in woody biomass has a substantial influence on both the efficiency of combustion and the emission properties of these fuels. When any woody biomass has high amounts of moisture, it requires an extra amount of energy to vaporize the water before the real combustion process can begin. Consequently, the decrease in combustion temperature impedes the full combustion of the fuel, leading to elevated emissions of volatile organic compounds (VOCs) and particulate matter (PM) (Amaral et al. 2016; Paris et al. 2022; Price-Allison et al. 2019). Scientific studies suggest that increased moisture levels might result in incomplete combustion, which in turn affects the emission variables linked to different pollutants. The power industry often uses raw and moist biomass, which not only necessitates more energy but also leads to heat losses due to the energy expended in evaporating the moisture. This inefficient processing of woody biomass is especially noticeable in biomass that has a moisture content of more than 30%, resulting in a considerable drop in the net calorific value (Del Giudice et al. 2019) (Sahoo and Mani 2017). Studies have shown that when the moisture content of biomass increases, the amount of heat that can be extracted from it decreases by over 50%. This drop in heat extraction directly corresponds to a decrease in the efficiency of power production systems using woodchips or woody biomass at largescale (Sahoo and Mani 2017; Shen et al. 2013).

Another concern with high MC is that it might worsen the release of noxious chemicals. Studies have demonstrated that the combustion of biomass with high moisture content might result in elevated emissions of carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs), and other byproducts of incomplete combustion (Han et al. 2020). Moisture has a significant impact on both the combustion dynamics and the creation of certain pollutants, such as dioxins and furans. These pollutants are released when chlorine-containing biomass is burned (Grandesso et al. 2011; Gu et al. 2021). It is crucial because the emissions

have a significant environmental impact, leading to the deterioration of air quality and related health hazards. A few parameters which affect the process are shown in Table 1.

To mitigate these adverse effects and optimize both emissions and efficiency, regulating the moisture content to a range of 10–20% is critical. At this level, the energy required for water evaporation is minimized, allowing for a higher and more stable combustion temperature. As a result, toxic emissions such as CO and PM are significantly reduced, and thermal efficiency can increase beyond 85%. This moisture regulation can be achieved through pre-drying techniques, such as solar drying in appropriate storage conditions, or integrating drying processes in the combustion system. Careful moisture monitoring and control are necessary to balance environmental impact and fuel efficiency. By focusing on moisture content within this optimal range, wood biomass combustion systems can reduce toxic emissions, improve efficiency, and contribute to a more sustainable energy process.

Addressing biomass quality issues before large-scale use involves process optimization, thorough characterization, quality control protocols, feedstock selection, innovative technologies, and continuous monitoring. By considering these measures, producers can ensure consistent, high-quality torrefied biomass for practical energy production and industrial applications. Hence, to address the existing gaps, the present work focuses on the effect of solar drying pretreatment on the torrefaction of wood biomass through ultimate and proximate analysis of wood chips with different moisture contents in a lab-scale reactor. This approach will provide a detailed understanding of the chemical, physical, and thermal changes occurring during torrefaction. By systematically varying moisture content levels and

employing detailed analytical techniques, we aim to understand the influence of moisture on the torrefaction process and its impact on the ultimate and proximate properties of the resulting biomass.

2 Methodology

This torrefaction-based study of woody biomass investigates the effects of solar-dried initial moisture content on the torrefaction process and the subsequent gas composition, proximate, and ultimate analysis of biomass. Hungarian Beechwood logs, a common and readily available biomass source, are processed into Grade 14,969 wet wood chips to ensure uniformity in size and shape, as shown in Fig. 1. In the solar dryer, the drying chamber (LXBXH) was $80 \times 50 \times 45$ cm and featured three levels of trays with two kilograms of woodchip samples. Four 500-watt halogen reflector lamps were mounted above air collectors using wooden frames to maintain a consistent generation of 755 Wm^{-2} in outdoor areas with changing solar radiation. In Miskolc, Hungary, where trials are conducted, noon global radiation ranges from 250 to 600 Wm^{-2} throughout the winter months. Radiation values of 755 Wm^{-2} were reasonable throughout the summer season, which occurs between 600 and 1000 Wm^{-2} from April to September. The samples' initial moisture content was 45%, which dried to 20%, 15%, 10%, and 5%.

This variation allows for a comprehensive analysis of how initial moisture content influences the torrefaction process and product composition. Post-drying, the wood chips are categorized into samples based on their moisture content and stored under controlled conditions.

Table 1 Parameters affecting the combustion efficiency and the emission of woody biomass

Parameters	Findings	References
Moisture Content (%)	Higher moisture content (> 30%) significantly reduces combustion efficiency and increases toxic emissions (CO, VOCs). The ideal moisture content for optimal range combustion of woody biomass is between 10–15%.	(Paris et al. 2022; Roos and Roos 2008)
Combustion Temperature (°C)	Combustion temperature decreases with higher moisture, as more energy is used to evaporate water, lowering thermal efficiency. Torrefied biomass improves grindability and combustion by reducing the hemicellulose fraction binding the cellulose fibrils when heated to 200–300 °C in an inert atmosphere.	(Riaz et al. 2023)
Emission of CO (g/kg)	The CO emissions from wood chips with a higher moisture content were discovered to be an order of magnitude greater than those from chips with a lower moisture content under comparable conditions.	(He et al. 2019)
NOx Emissions (ppm)	Compared to those with lower moisture levels, wood pellets with a moisture content of approximately 30% exhibited lower NOx emissions. This could result in emissions exceeding 370 mg/m^3 under specific circumstances.	(Schön et al. 2019)
Thermal Efficiency (%)	Woody biomass that contain 40% moisture can ignite and fire rapidly at 800 °C; however, they require a significantly prolonged time to ignite and burn at 500 °C and do not ignite at 400 °C in boiler operations, thereby reducing the thermal efficiency.	(Orang and Tran 2015)
Particulate Matter (PM2.5)	The combustion of Eucalyptus globulus biomass demonstrates that the combustion efficiency decreased (93–49%) and the emission factors of total PAHs (5215.47ngg-1 to 7644.48ngg-1), gravimetric PM2.5 (2.01 g kg-1 to 22.90gkg-1), and the total number of measured micrometer-sized particles (3.15×10^{12} particles kg-1 to 1.33×10^{13} particles kg-1) increased due to incomplete combustion.	(Guerero et al. 2019)

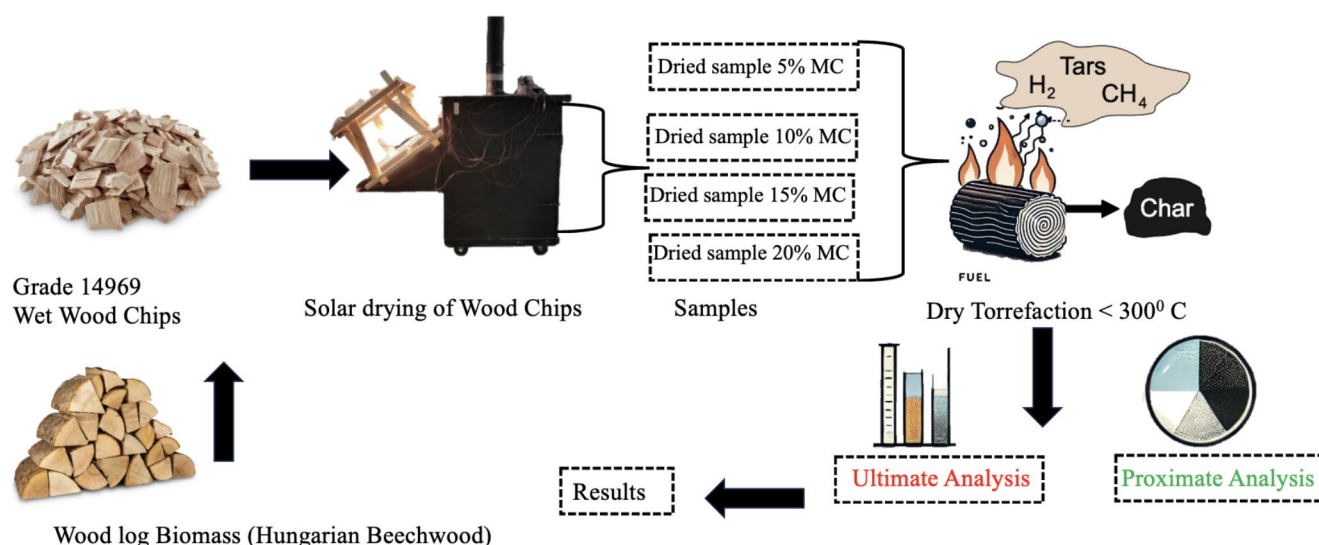


Fig. 1 Schematic of the methodology adopted for the study

After that, in order to maintain consistent heating and avoid combustion, these samples are exposed to dry torrefaction in a regulated setting at temperatures below 300 °C. The biomass is subjected to heat breakdown during torrefaction, which produces char and releases gases like methane (CH₄) and hydrogen (H₂). The solid (char) and gaseous fractions of the torrefied products are gathered for examination. The samples undergo proximate analysis to evaluate moisture content (MC), ash content (AC), volatile matter (VM), and fixed carbon (FC), as well as ultimate analysis to ascertain their elemental composition (N, C, and H). These studies helped explain the biomass's quality, energy potential, and thermal properties. This comprehensive method facilitates an in-depth analysis of the influence of initial moisture content on biomass torrefaction, providing essential insights for enhancing bioenergy production processes.

2.1 Materials

Wood chips (WC) of Grade 14969 (Hungarian Beechwood) and sizes (5–10) mm were carefully sourced from an industrial supplier in Miskolc to maintain consistency in biomass properties, ensuring reliability in subsequent analyses. An ultimate analysis was performed with a Carlo Erba EA 1108 elemental analyzer to accurately determine the elemental composition of the torrefied biomass. This evaluation followed the guidelines of EN ISO 16948:2015, which specifies the accepted procedure for measuring the combined levels of carbon, hydrogen, and nitrogen. The sulfur amount was measured with the MSZ 24051:2001 guideline, utilizing a combustion technique in a tube furnace operated at high temperature (Method 'C').

The HHV (High heating value) and LHV (Low heating value) were used to calculate the energy content of the WCs, both pre- and post-torrefaction. The HHV was ascertained according to the EN 14918:2009 standard method, utilizing an isoperibol bomb calorimeter (type: Parr 6200) with an applied oxygen bomb pressure of 3 MPa. This measurement provided insights into the maximum energy potential of the biomass. The LHV, which represents the net energy released during combustion when the water remains in the vapor state, was computed using Eq. (1):

$$LHV = HHV - 24.493 \cdot (9H + M) \quad (1)$$

where is H the hydrogen concentration (wt%) and M is the moisture content (wt%). This calculation allowed for a more practical estimation of the energy available from the biomass under typical combustion conditions, where moisture is not condensed.

The WCs were subjected to proximate analysis to determine the moisture (MC), volatile matter (VM) and ash contents (AC), according to EN 14774-217, EN 15148.18 and EN 14775.19 standards, respectively. Fixed carbon content (FCC) was calculated using Eq. (2)

$$FCC = 100 - (AC + VM) \quad (2)$$

The higher heating value (HHV) of the WC was determined following the DIN51900-1 standard.

Torrefied solid mass yield (MY) was obtained using the ratio between the dried mass of feedstock and dried mass of the torrefied by-product using Eq. (2):

$$MY = \frac{(M_{by-product})_{db}}{(M_{feedstock})_{db}} \times 100\% \quad (2)$$

The energy densification factor (EDF) indicates the elevation in HHV during the thermochemical process as shown in Eq. (3):

$$EDF = \left(\frac{HHV_{product}}{HHV_{feedstock}} \right)_{daf} \quad (3)$$

Energy densification does not indicate the total energy remaining in the product, since omits the mass losses. This is included in the energy yield EY Eqs. (4),

$$EY = MY \times EDF \quad (4)$$

2.2 Experimental setup

The torrefaction process was then systematically executed using a controlled lab-scale torrefaction reactor for each moisture-defined batch. Specific attention was given to maintaining uniformity in torrefaction conditions, precisely controlling temperature and residence time across all batches. Flue gases emitted during torrefaction were methodically collected in 50 ml gas syringes, setting the stage for subsequent ultimate analysis to understand the compositional changes induced by torrefaction. Post-torrefaction, a critical phase, involved carefully cooling and sampling the torrefied wood chips in a controlled environment this precautionary measure aimed to prevent additional reactions, preserving the torrefaction-induced modifications for subsequent proximate analysis. The experimental procedure was designed with meticulous precision to ensure reliability, consistency, and a comprehensive understanding of the torrefaction process on wood biomass under varying moisture content conditions, as shown in Fig. 2 which was prepared using SolidWorks software.

A design of experiment (DOE) was performed to evaluate the combined effect of temperature and moisture experiments by the response surface method on the thermochemical experimental treatments. A central composite design (CCD) was used for the DOE. As a result, total number of experiments conducted was 11. Table 2. shows the summary of the experimental ranges of independent variables. Each treatment was tested in duplicate. As the design considered two levels for each continuous factor, a quadratic regression model was used. The predictive polynomial quadratic equation in general form is Eq. (5)

$$Y = \beta_0 + \sum_{j=1}^k \beta_j X_j + \sum_{j=1}^k \beta_{jj} X_j^2 + \sum_{i < j} \beta_{ij} X_i X_j + \varepsilon \quad (5)$$

where Y is the response, β_0 is the intercept coefficient, β_i , β_{ij} , and β_{jj} are the interaction coefficients of the linear, second-order terms and quadratic terms, k is the number of independent parameters, X_j are the independent variables and

ε is the residual associated with the experiments. The significance of each term was evaluated based on analysis of variance (ANOVA) at significance level $\alpha=0.05$.

The independent variables were optimized by establishing targets for each response. A global desirability function (D) was applied concurrently to optimize the set of models derived from experimental statistical analysis. The two independent variables were encompassed in the optimization within their designated range. In simultaneous optimization, specific low and high values were assigned to each goal for every response. The temperature response aimed for a minimum goal. Consequently, an individual desirability function (D) was proposed for each response, with values expressed on a non-dimensional scale ranging from 0 to 1.

3 Results

3.1 Properties of biomass feedstock and torrefied material

The feedstock moisture plays an important role in the biomass-to-energy conversion. The lower the material's moisture in the environment where it will be used, the less energy will be consumed to evaporate the water, and the greater the efficiency of the equipment used to generate energy from biomass. At the same time, the material can be stored for long periods without compromising its energy qualities with hybrid solar drying facilities. WC initially reported a moisture content range of (5–20) wt% for the samples. After torrefaction, a decrease in moisture content was observed with a final equilibrium moisture content ranging from 1.25 to 3.11% for all the samples, mainly because the hemicellulose fraction of biomass is broken down to varying degrees depending on the increasing temperature. The hemicellulose degradation increases hydrophobicity since the main process through which water is absorbed by biomass is by attaching to polar sites, such as hydroxyl groups found in sugar molecules (Medic et al. 2012). Research conducted by (Lima et al. 2023) presented an increase in energy density and reduction on the moisture content of wood pellets after torrefaction treatment at temperatures of 200–300 °C, making them more efficient for energetic use compared to unprocessed biomass. Similarly, (Torres et al. 2023) found that torrefaction of woodchips resulted in a reduction of moisture content, leading to increased energy density and heating value.

Furthermore, the torrefaction process, as applied to WCs in this context, would aim to decrease the hydrophilic nature of the biomass, reducing its equilibrium moisture content and improving its grinding characteristics, which are essential parameters for subsequent bioenergy conversion

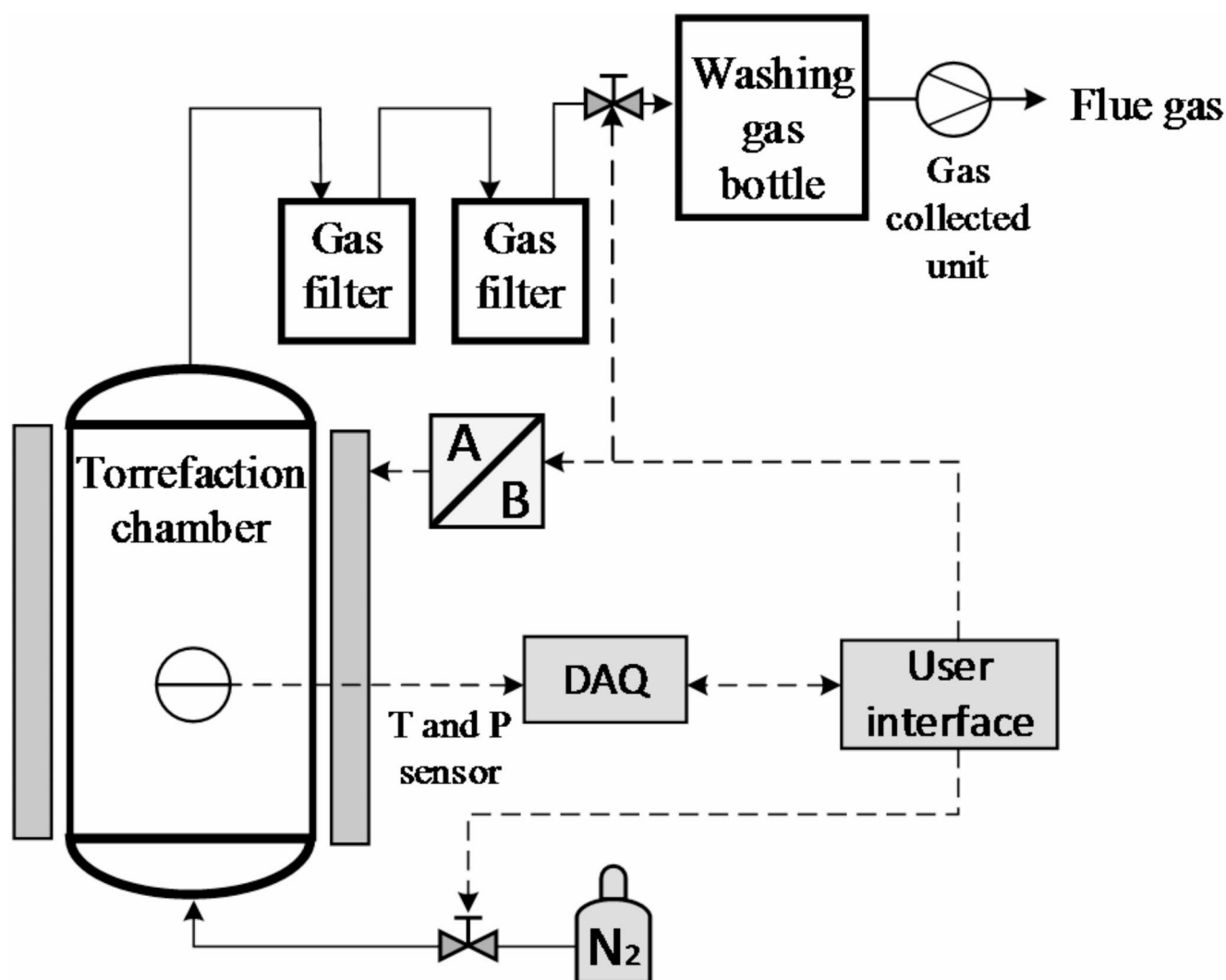


Fig. 2 System diagram of the experimental setup

Table 2 Experimental range and values of independent variables used in central composite design

Independent variable	- α	-1	0	+1	+ α
Torrefaction temperature [°C]	189.64	200	225	250	260.35
Feedstock moisture [%wt]	2.93	5	10	15	17.07

processes. The increase in biomass moisture content over the days preceding torrefaction could lead to a higher energy requirement for moisture evaporation, potentially impacting the efficiency and final quality of the torrefied product. In comparison, study developed by (Yan et al. 2020) reported a method using capacitive sensing and data-driven modeling to predict woodchips' moisture content with a relative error within $\pm 10\%$ for a range of 7–49% moisture content. This technique may offer a valuable tool for monitoring and controlling WC moisture content before and after torrefaction. Additionally, (Leoni et al. 2022), recommended the collection and analysis of multiple samples to achieve reliable

moisture-content results using portable NIR spectrophotometer, highlighting the variability inherent in bioenergy feedstocks and the need for meticulous sampling protocols.

High volatile matter (VM) indicates biomass fast burn, high reactivity, and easily ignited characteristics. Typically, VM values range from 76–86%wt for woody biomass (Mendoza Martinez et al. 2019). In the current work, VM concentration was 72% (maximum), which revealed a downward trend. The decrease in VM with torrefaction temperature increases the results of devolatilization and depolymerization during the thermal treatment. An opposing trend for the fixed carbon (FC) content showed values of 63.9% (maximum). The highest FC value was found for 63.92% observed in Trial 1, Sample S-3, which indicates that the sample would tend to burn more slowly, requiring longer residence time in comparison to the samples with low FC. The ash content represents the inorganic solid residue after complete combustion. High ash content, together with high

Table 3 Results of the proximate analysis

Trial	Samples	Ultimate elemental* [wt%]				C	H	HHV* [kJ/kg]
		AC*	VM*	FC*	N			
Trial 1	S-1 05/09	1.87	34.45	62.82	0.35	75.02	3.80	28,820
	S-2 05/09	2.21	33.86	62.99	0.41	73.43	3.91	29,353
	S-3 05/09	1.85	33.47	63.92	0.35	75.62	3.89	29,532
Trial 2	S-1 06/09	3.31	37.47	58.38	0.35	72.43	4.14	27,989
	S-2 06/09	2.58	38.10	58.47	0.40	72.97	4.10	28,660
	S-3 06/09	2.07	40.07	56.96	0.30	72.63	4.30	28,403
Trial 3	S-1 07/09	2.08	39.86	57.10	0.42	72.86	4.15	28,890
	S-2 07/09	4.70	42.05	52.46	0.47	68.97	4.19	27,059
	S-3 07/09	2.32	38.18	58.75	0.34	73.73	4.19	28,577
Trial 4	S-1 12/09	2.55	72.03	23.53	0.53	56.17	5.08	21,029
	S-2 12/09	1.09	67.82	28.87	0.27	59.88	5.04	23,064
	S-3 12/09	0.86	69.05	28.37	0.26	58.85	5.08	22,527

Table 4 Mean and standard deviation of the proximate parameters

Parameter	Mean	Standard Deviation
Ash Content (AC, %)	2.29	0.998
Volatile Matter (VM, %)	45.53	14.79
Fixed Carbon (FC, %)	51.05	14.93
Nitrogen (N, %)	0.371	0.080
Carbon (C, %)	69.38	6.92
Hydrogen (H, %)	4.32	0.471
Higher Heating Value (HHV, kJ/kg)	26,991.92	2,987.50

moisture content, negatively on high heating value because the proportion of combustible material decreases. Ash can interfere with combustion processes by forming clinkers, slag, or other deposits in combustion equipment, which can reduce combustion efficiency. Additionally, some elements present in ash, such as sulfur and chlorine, can contribute to emissions of harmful pollutants (Gani et al. 2021), for example, sulfur dioxide (SO₂) (Mendoza Martinez, Alves Rocha, et al., 2019). For the HHV, values between (21.02–29.53) MJ/kg (dry basis) were reported for wood chips. HHV represents the maximum amount of heat energy released per unit mass of the biomass when it undergoes complete combustion, as depicted in Table 3.

The mean values in Table 4 suggest that the biomass samples generally exhibit favorable characteristics for energy applications, including high carbon content, moderate hydrogen levels, and relatively low ash content. However, the significant standard deviations for certain parameters (e.g., volatile matter, fixed carbon, and HHV) reveal the sensitivity of these properties to variations in initial moisture content, feedstock composition, and torrefaction conditions.

The moisture content varies across the samples, with a general trend of decreasing MC with the progression of the torrefaction process. The MC ranges from 1.67 to 3.11%. Samples from Trial 4 (S-1 12/09, S-2 12/09, S-3 12/09) exhibit the highest moisture content, indicating the influence

of seasonal variation on the initial moisture content of the biomass. Ash content remains relatively low across all samples, ranging from 0.86 to 3.31%. The highest ash content is observed in sample S-2 06/09 (3.31%), while the lowest is in sample S-2 12/09 (1.09%). This variation indicates differences in the inorganic content of the biomass, potentially influenced by the initial feedstock composition. Volatile matter shows significant variation, ranging from 33.46 to 72.03%. Samples from Trial 4 exhibit higher volatile matter, particularly S-1 12/09 (72.03%), suggesting that higher initial moisture content leads to higher volatile matter retention post-torrefaction. Fixed carbon content inversely correlates with volatile matter, with values ranging from 23.53 to 63.92%. Samples with higher volatile matter (e.g., S-1 12/09) have lower fixed carbon, highlighting the trade-off between these two components during the torrefaction process. Nitrogen content varies slightly, ranging from 0.26 to 0.53%. The highest nitrogen content is observed in sample S-1 12/09 (0.53%), suggesting potential proteinaceous material presence in the feedstock. However, the variation is relatively minor, indicating consistent nitrogen levels across different samples. Carbon content is a critical indicator of the energy content of the biomass. It ranges from 56.17 to 75.62%, with the highest values observed in samples from May and June. This high carbon content corresponds to the higher fixed carbon content and lower volatile matter in these samples, reflecting more efficient torrefaction. Hydrogen content ranges from 3.80 to 5.08%. Higher hydrogen content is associated with samples having higher volatile matter (e.g., S-1 12/09). This indicates that higher moisture content in the feedstock leads to higher retention of hydrogen in the torrefied biomass. The higher heating value (HHV) is a crucial parameter for assessing the energy potential of the biomass. It ranges from 21,029 kJ/kg to 29,532 kJ/kg. Samples with higher carbon and fixed carbon content exhibit higher HHV, reflecting their superior energy potential. Notably, samples from Trial 1 and Trial

2 show the highest HHV, while Trial 4 samples show the lowest, indicating the significant impact of initial moisture content and seasonal variation on the energy potential of the biomass.

3.2 Effect of moisture on gas composition

The analysis of gas compositions for torrefied samples at varying initial moisture content levels (5%, 10%, 15%, and 20%) across three trials provides critical insights into the behavior of different gas components. The gas compositions evaluated include H_2 , O_2 , CH_4 , C_2H_4 , C_2H_6 , C_2H_2 , C_3H_8 , CO , and CO_2 .

In the first trial, as shown in Fig. 3, the gas compositions show a consistent pattern across different moisture content levels. The concentration of CO_2 remains relatively stable at around 60%, indicating its dominant presence in the gas mix, regardless of moisture content. CO levels also exhibit minimal fluctuation, maintaining a concentration of around 30%, suggesting that the formation of CO is less sensitive to changes in initial moisture. Moisture during torrefaction aids in the thermal disintegration of organic molecules, resulting in the release of volatile chemicals, such as hydrogen. Increased initial moisture levels can facilitate the degradation of hemicellulose and cellulose, leading

to a greater release of hydrogen as a consequence of both processes. The overall chemical composition alters during torrefaction; whereas hydrogen content may initially rise with moderate moisture levels, excessive loss of oxygen and other volatiles at elevated temperatures might result in a net reduction of hydrogen content in relation to carbon (Tumuluru 2016). Methane (CH_4) and other hydrocarbons such as ethylene (C_2H_4), ethane (C_2H_6), and propane (C_3H_8) exhibit low concentrations with minor variations, indicating that these hydrocarbons are less influenced by the initial moisture content in this trial.

The second trial presents a noticeable increase in gas concentrations compared to the first trial, particularly for hydrocarbons and oxygen (O_2) shown in Fig. 4. The concentration of CH_4 , C_2H_4 , C_2H_6 , and C_3H_8 increases significantly as the moisture content rises, reaching their peaks at 20% moisture. This trend suggests that higher moisture content enhances the breakdown of biomass into simpler hydrocarbons. The CO and CO_2 levels remain relatively stable, similar to the first trial, but with a slight upward trend in CO_2 concentration as moisture content increases. This stability in CO and CO_2 levels indicates that these gases are primary products of the torrefaction process and are less impacted by variations in initial moisture content.

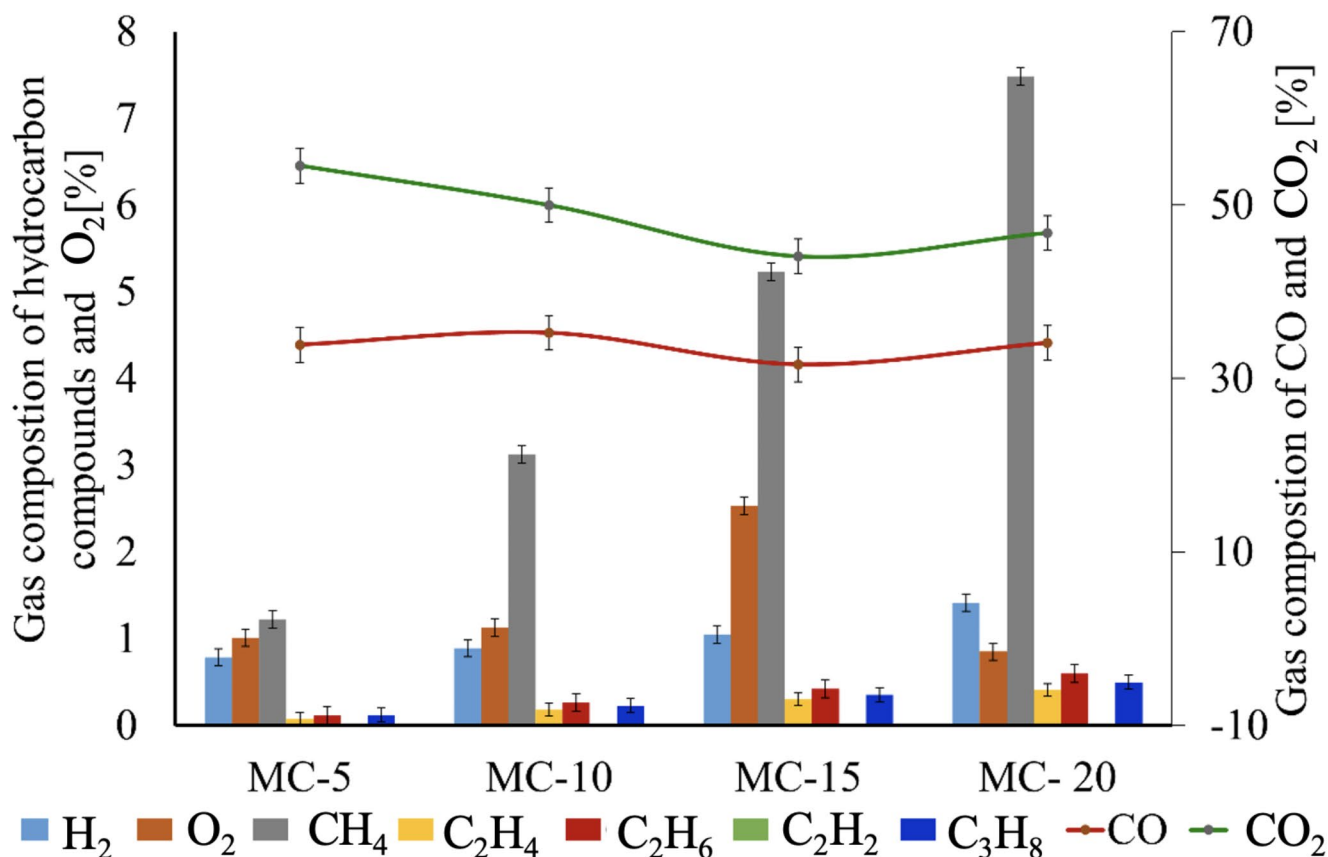


Fig. 3 Trial 1 results of the ultimate analysis

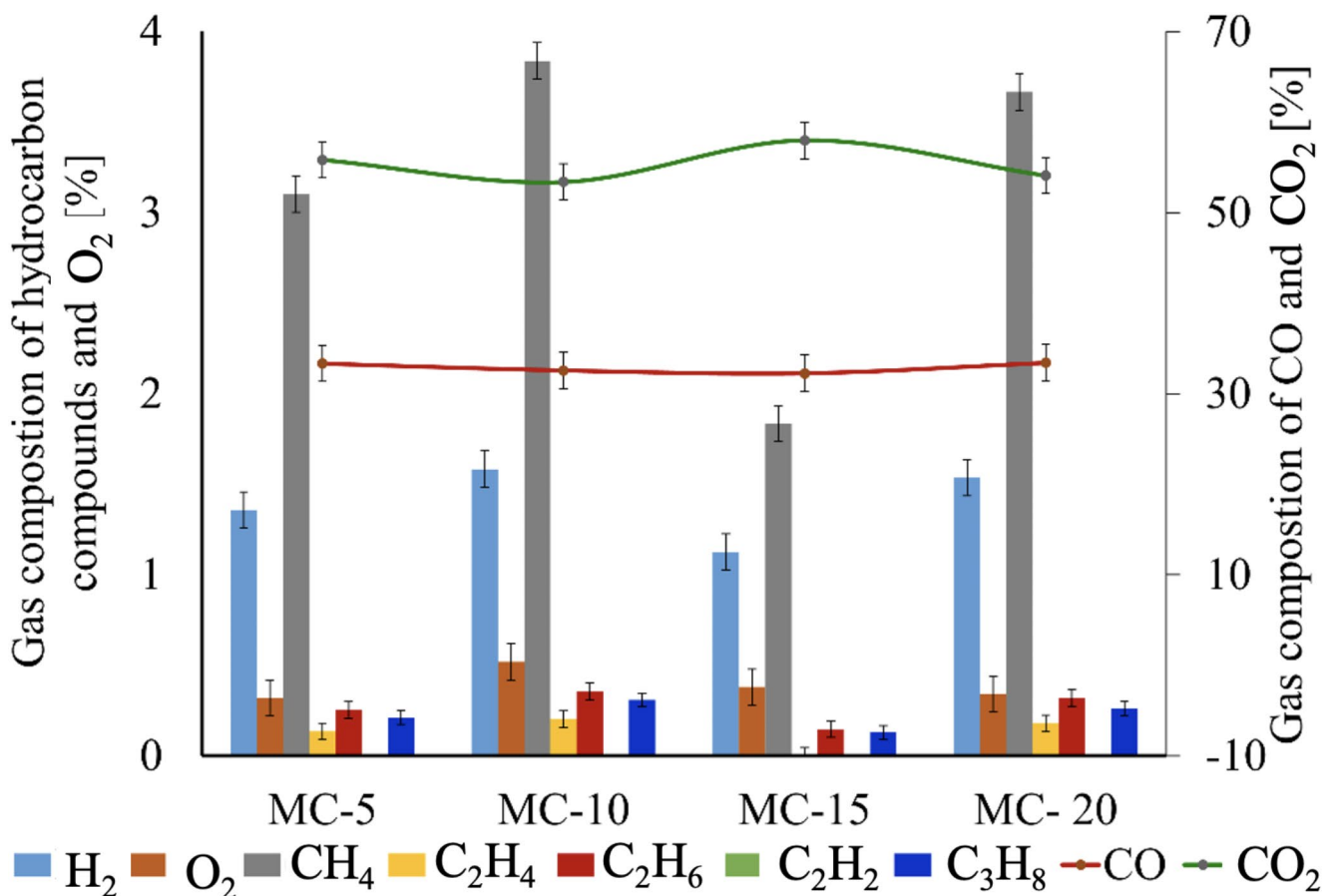


Fig. 4 Trial 2 results of the ultimate analysis

In the third trial, Fig. 5. Shows the gas compositions show a different pattern, particularly for the non-hydrocarbon gases. The concentration of H₂ continues to increase with moisture content, reaching its peak at 20% moisture. This further supports the observation that higher moisture levels facilitate the formation of hydrogen. O₂ levels decrease significantly as moisture content increases, which can be attributed to the higher consumption of oxygen in the formation of other gases. The CO and CO₂ levels in this trial exhibit a more pronounced fluctuation compared to the previous trials. CO₂ shows a decreasing trend with higher moisture content, while CO increases slightly, suggesting a shift in the gas formation dynamics with higher moisture. Hydrocarbons such as CH₄, C₂H₄, C₂H₆, and C₃H₈ maintain a consistent increase in concentration with higher moisture content, reinforcing the observation from the second trial that moisture promotes the formation of these gases.

The data from the three trials collectively indicate that initial moisture content has a significant impact on the gas composition during torrefaction. Higher moisture content generally promotes the formation of H₂ and hydrocarbons, while the concentrations of CO and CO₂ remain relatively stable, albeit with some fluctuations. The decrease in O₂

levels with higher moisture suggests increased oxygen consumption in the formation of other gases. These results imply that controlling moisture content can be a crucial parameter in optimizing the torrefaction process for desired gas compositions. The consistency in CO and CO₂ levels across trials highlights their primary nature in the torrefaction process, whereas the variation in hydrocarbons and H₂ concentrations provides insights into the secondary reactions influenced by moisture.

4 Discussion

4.1 Global industrial contrivances

Analyzing the characteristics of the torrefaction process and the properties and applications of torrefied biomass, torrefaction holds promising prospects as an alternative process to carbonization. Worldwide there are many torrefaction initiatives in development, mainly in Europe and North America. An overview is shown in Table 5.

In general terms, torrefaction does not require highly complex technologies, as it is carried out at relatively low

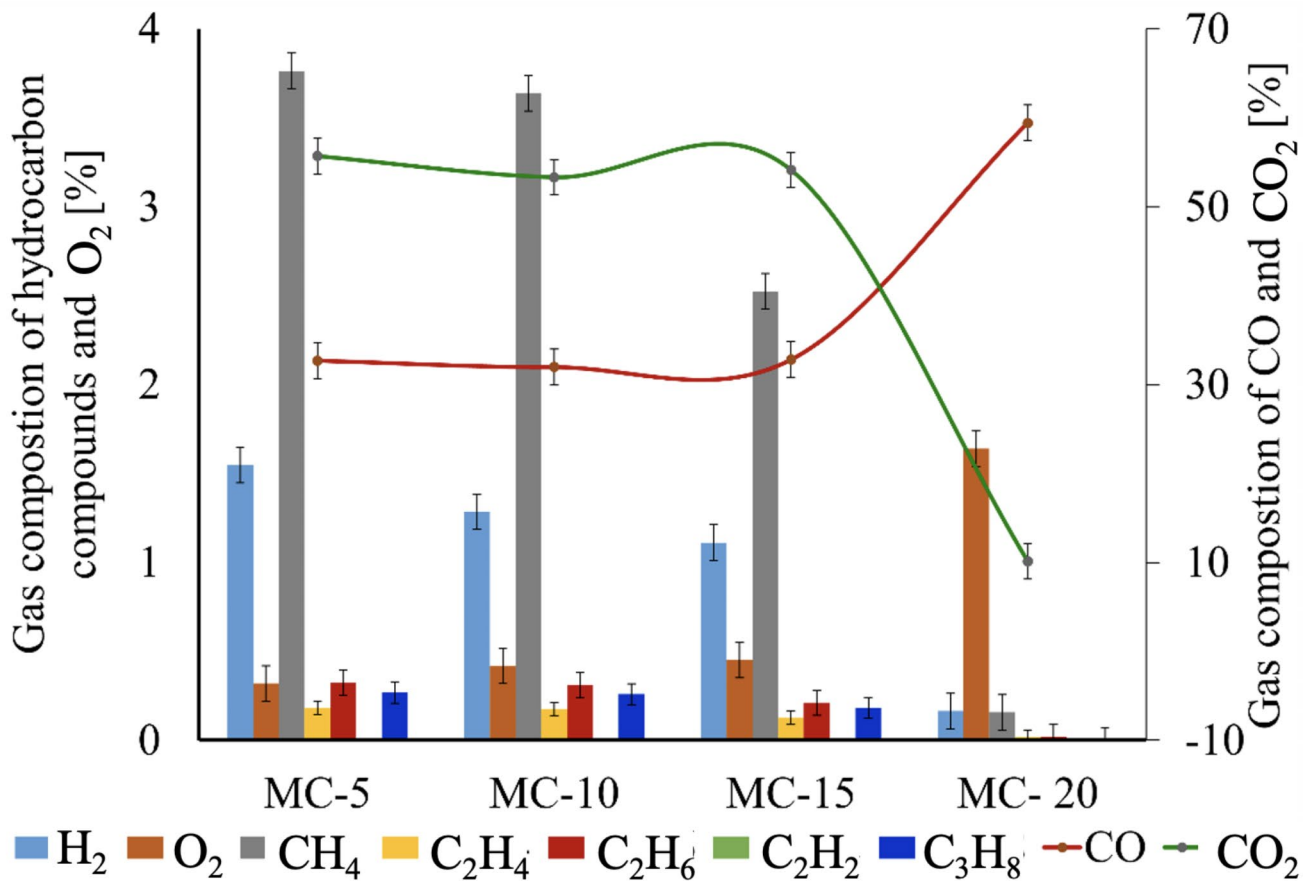


Fig. 5 Trial 3 results of the ultimate analysis

temperatures and atmospheric pressure. Companies reported equipment costs generally are not very high, and even the techniques used are well-known, as in the case of the Torricol B.V. (NL) (see: <https://www.torricol.com/torrefaction-technology/>), which employs a rotary drum as the torrefactor. This fact contributes to making torrefaction economically attractive compared to other conversion technologies that are more complex, costly, and less explored (Thran et al. 2016). Wood torrefaction, on a small and medium scale, has prospects to compete with traditional carbonization methods, mainly because torrefied biomass has sufficient capacity and flexibility to adapt to the technical requirements of different markets, being able to meet the demand for charcoal in both domestic and commercial markets, as well as in some industrial sectors that extensively use wood, such as the ceramics industry. Typical uses for torrefied biomass include co-firing with coal in power plants and cement kilns, dedicated combustion in pellet burners, and gasification in entrained flow gasifiers that typically employ pulverized coal (Huang et al. 2013).

Technical challenges of torrefaction include fuel flexibility due to feedstock inherent characteristics, such as moisture content, bulk density, and particle size. Torrefaction gas

may contain acids and primary tars that need to be cracked in an afterburner. Up-scaling and process validation are still challenging in terms of optimization. The independent process parameters are extremely important for good performance.

During torrefaction, water in WCs evaporates, under the influence of the thermal energy supplied for the process. This evaporation leads to a cooling effect within the biomass material, potentially affecting the uniformity and efficiency of the torrefaction process. Moreover, the presence of moisture influences the composition of the gases released during torrefaction. Water vapor interacts with other volatile compounds produced during biomass degradation, potentially leading to the formation of acids and primary tars. Acids and primary tars in torrefaction gas present operational challenges. These compounds can cause corrosion in equipment and require additional processing steps, such as cracking in an afterburner, to convert them into safer and less corrosive compounds (Cortazar et al. 2023). This necessity for gas cleaning and treatment adds complexity and potentially increases the operational costs of the torrefaction process. High level of moisture in the pre-torrefaction WCs can result in decreased energy efficiency and reduced

Table 5 Torrefaction initiatives worldwide on an industrial level

Developer	Technology	Location	Production capacity (ton/a)
Torrec (FI)	Moving bed	Mikkeli (FI)	10,000
Topell energy (NL)	Torbed	Duiven (NL)	60,000
Stramproy Green investment B.V. (NL)	Oscillating belt conveyor	Steenwijk (NL)	45,000
4Energy invest (BE)	Unknown	Amel (BE)	38,000
Torr-coal B.V. (NL)	Rotary drum	Dilsen-stokkem (BE)	35,000
Thermya (FR)	Moving bed	San Sebastian (SP)	20,000
FoxCoal B.V. (NL)	Screw conveyor	Winschoten (NL)	35,000
BioLake B.V. (NL)	Screw conveyor	Eastern Europe	5,000–10,000
EBES AG (AT)	Rotary drum	Frohnleiten (AU)	10,000
Atmosclear SA (CH)	Rotary drum	Latvia, New zeland, US	50,000
Bio energy development North AB and Metso (SWE)	Rotary drum	Ö-vik (SWE)	25,000–30,000
Rotawave, Ltd. (UK)	Microwave reactor	Terrace, British Coulmbia (CA)	110,000
Clean electricity generation (UK)	Oscillating bed	Derby (UK)	30,000
Solvay (FR)/New biomass energy (USA)	Screw reactor	Quitman (USA/MS)	80,000
Integro earth fuels LLC (US/NC)	Turbodryer	Roxboro (NC)	50,000
Agri-tech producers LLC (US/SC)	Screw reactor	Raleigh (USA/NC)	Unknown
Zilkha biomass energy (US)	Unnown	Crockett, Texas (US)	40,000
Airex (CAN/QC)	Cyclonic bed	Bécancour	16,000
Earth care products (USA)	Rotary drum	Independence (USA/SC)	20,000
Teal sales Inc (USA)	Rotary drum	White castle (USA/LA)	15,000

production of desired torrefied WCs. Controlling the biomass's moisture content prior to the torrefaction process is therefore necessary.

4.2 Potential of solar drying

Solar dryers advance wood biomass processing. They are essential for woodchip combustion efficiency and hazardous emission reduction. Because it directly influences biomass moisture, drying is crucial for combustion efficiency. High moisture in wood biomass might induce incomplete combustion. CO, NO_x, and PM emissions increase as a result (Choe et al. 2019; Schmidt et al. 2018). Solar dryers reduce woodchip moisture, improving calorific value and burning. The use of solar energy in drying processes improves the efficiency of moisture removal and supports the sustainability of biomass utilization. For example, experiments were conducted that showed the practicality of solar-enhanced drying of woody biomass (Kumar, Szepesi, Szamosi, et al., 2023). The results indicated that drying times could differ considerably, with final moisture contents ranging from 12 to 32% (Raitila and Tsupari 2020). The decrease in moisture content is important because it enables a greater calorific value for each unit of biomass weight, which is vital for effective combustion (Pryce et al. 2020). Installing solar dryers can decrease the energy necessary for combustion processes since less energy is required to remove moisture during combustion (Rizzo et al. 2019).

Standalone dryers are not highly effective, but the effectiveness of solar dryers can be enhanced by integrating hybrid systems that make use of both solar energy and

biomass energy. Research indicates that these systems yield higher-quality dried products when compared to traditional solar dryers (Kumar et al. 2021) that do not utilize auxiliary heating (Gebreegziabher et al. 2013). Traditional drying processes are available after wood chips are reduced in size. For instance, some common ways are Solar drying, which is relatively cheap, while vacuum, radiation, and freeze-drying use a lot of energy. Solar drying, especially in hybrid settings, needs more research because material porosity, humidity, temperature, and convective air conditions affect the variables (Gandia Ventura et al. 2024). Following typical drying procedures, (Dobele et al. 2007) found that drying wood at 200 °C and pyrolysis improves bio-oil quality by reducing water and acids. Research shows that drying at 240 °C reduces main product yield. We found the optimal drying conditions and wood pyrolysis temperature for bio-oil yields of 60% and calorific values of 17–20 MJ/kg. A review work (Jahirul et al. 2012) reveals that low-water woody biomass reduces overall costs and improves oil quality. The hybrid approach facilitates ongoing operation, even when solar irradiance is low, which helps maintain the biomass at optimal moisture levels consistently. It is especially crucial in areas where solar energy may not be consistently available, as this ensures that the biomass is prepared for combustion when required, thereby improving overall efficiency (Khouya 2021).

The drying process aided by solar thermal energy is crucial in reducing emissions associated with biomass burning and energy production. Reducing the moisture level of woodchips via solar drying significantly diminishes the production of smoke and other detrimental pollutants during

burning. In biomass gasification, pre-drying of biomass is essential. This technique can significantly enhance gasification by ensuring the feedstock retains the appropriate moisture content. Employing solar energy for pre-heating combustion air improves the combustion process, leading to more complete combustion and reduced emissions of CO and NO_x. Alongside enhancing combustion efficiency, solar dryers play a significant role in promoting the overall sustainability of biomass energy systems. Assistance of solar thermal energy helps to reduce the greenhouse gas emissions that are typically linked to conventional biomass drying methods, which often depend on fossil fuel combustion (Chuatrakool et al. 2020). Using solar energy can greatly decrease the carbon footprint associated with biomass processing, which supports worldwide initiatives aimed at moving towards more sustainable energy systems. Additionally, various studies have shown that solar dryers are economically viable. The initial investment in solar drying technology can be recovered by the long-term savings in energy costs and the enhancement of product quality (Pozzobon et al. 2018). The payback time for solar biomass hybrid dryer systems is favorable for small and medium industries (Kumar, Raj, Szepesi, et al., 2023b), which makes them an appealing choice for small-scale processing industries (Nzihou et al. 2012). There are limited industrial-scale computer simulations of integral drying systems in the literature. Thermal efficiency evaluations with dryer-specific models and simulations (Kumar et al. 2023) of dryer and solar collector temperature and velocity profiles have been found at a smaller production/industrial scale (Ortiz-Rodríguez et al. 2022). Effective techniques for the timely removal of wood debris from forests and their suitable valorization can help mitigate forest restoration expenses, decrease fire hazards, and enhance forest management. This makes solar dryers an important technology in the quest for cleaner and more efficient use of biomass.

5 Conclusion

The impacts of initial moisture content on the gas composition, proximate characteristics, and final properties of torrefied biomass, specifically for WCs, were thoroughly examined in this work. The outcomes of the conducted experiments show that the moisture content has variable effects on the torrefaction process and the physical properties of the biomass that is produced. Understanding the behavior of various gas compositions during torrefaction is crucial for optimizing biomass conversion processes. Higher initial moisture content generally promotes the formation of hydrogen and hydrocarbons while maintaining relatively stable levels of CO and CO₂. This indicates the importance

of moisture management in enhancing the efficiency of the torrefaction process. Furthermore, the proximate and ultimate analyses showed that higher moisture content leads to increased volatile matter and hydrogen content but reduced fixed carbon and higher HHV. These findings underscore the need for precise control over moisture content to maximize the energy potential of torrefied biomass. However, the sustainability benefits of integrating solar energy into biomass pretreatment processes, particularly in rural and off-grid regions, where energy access is often limited and biomass drying is crucial for fuel production, also need environmental evaluation. Recent research conducted in a rural Mexican community demonstrated that Life Cycle Assessment (LCA) effectively quantifies the environmental benefits of solar drying technology in biomass processing. The study revealed that the newly developed solar wood-dryer prototype has significantly lower environmental impacts across all assessed categories, with reductions of 5% or more compared to conventional biomass drying methods. These findings underscore the potential of solar-assisted drying systems in reducing the carbon footprint, energy consumption, and overall environmental burden associated with traditional drying techniques. (López-Sosa et al. 2019). Such evaluations can improve the sustainability and efficiency of biomass energy generation through the optimization of torrefaction conditions. Furthermore, the knowledge gathered from this research can help develop biomass processing technologies that are more efficient, which will further the larger objective of providing sustainable energy options. Opposing viewpoints might argue that the impact of initial moisture content on torrefaction is negligible or that other factors, such as feedstock type, play a more crucial role. However, the data presented in this study demonstrate the significant influence of moisture content on both gas composition and the proximate and ultimate properties of the biomass. Given the consistent trends observed across multiple trials and samples, it is evident that moisture management is a critical parameter in optimizing the torrefaction process. However, several limitations need to be acknowledged. One significant limitation is the scope of the experimental setup, which was designed to simulate specific drying conditions but may not fully capture the variability present in real-world applications. The regional applicability of solar drying is another concern, as its effectiveness is highly dependent on climatic conditions. In regions with limited solar radiation, the drying process may be less efficient or infeasible, potentially limiting its broader adoption. Future research should explore the interactions between moisture content and other variables, such as feedstock type and torrefaction temperature, to further refine and optimize the process. Additionally, long-term studies with large volume samples could investigate the environmental

and economic impacts of optimized torrefaction on a larger scale, providing a more comprehensive understanding of its potential benefits.

Abbreviations

UN	United Nations
FRA	Forest Resource Assessment
ISO	International Organization for Standardization
NDT	Nondestructive testing
HTC	hydrothermal carbonization
DT	Dry Torrefaction
WT	Wet Torrefaction
MC	Moisture Content
EMC	Equilibrium Moisture Content
VM	Volatile Matter
FC	Fixed Carbon
AC	Ash Content
N	Nitrogen Content
C	Carbon Content
H	Hydrogen Content
HHV	Higher Heating Value
IRF	Impulse Response Function
PM	Particulate Matter
LCA	Life Cycle Assessment
GHG	Greenhouse Gasses

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Data availability The dataset is available from the corresponding author on request.

Declarations

Competing interests The authors declare no competing interests.

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