ENVIRONMENTAL PROBLEMS

Vol. 10, No. 2, 2025

USE OF THERMALLY MODIFIED WOOD AFTER THE END OF ITS SERVICE LIFE AS A RAW MATERIAL FOR FUEL PELLET PRODUCTION

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https://doi.org/10.23939/ep2025.02.182

Received: 30.04.2025

Abstract. The growing demand for environmentally sustainable materials with improved performance has led to a notable rise in the production of thermally modified (TM) wood, including ash wood (*Fraxinus excelsior* L.). Although TM wood offers enhanced functional properties and durability, it still has a finite service life. Comprehensive experimental investigations have revealed that prolonged environmental exposure (over 24 months) significantly affects the surface quality of thermally modified ash (TM-Ash) wood. Scanning electron microscopy (SEM) identified surface degradation, while water contact angle measurements of indicated a shift from hydrophobic to hydrophilic behavior and accelerated water permeability. As one of the strategies for recycling TM wood at the end of its service life, the potential use of this material as a raw feedstock for solid biofuel production has been explored. The comprehensive thermal analysis of biomass sample (Biom-TM-Ash^{24}) obtained by grinding TM-Ash wood, exposed outdoors for 24 months, revealed its characteristic mass loss behavior across different temperature intervals. The intensive decomposition of hemicellulose, cellulose, and the less stable lignin components, occurring between 200 and 398 °C, was accompanied by the most substantial mass loss (62.9 %) and was expressed by a broad extremum on the DTA curve due to the pronounced exothermic reactions, indicating a high calorific value of the biomass. The high calorific value of the biomass (19.7 MJ/kg), which exceeds that of unmodified ash wood biomass (18.8 MJ/kg), along with favorable ash content (0.5–7 wt. % d.m.) and an optimal moisture level (6.8 ± 0.5 %), indicates its potential for use as feedstock in solid biofuel production.

Keywords: thermally modified (TM) wood, surface degradation, thermograms, calorific value, biofuel production.

1. Introduction

Currently, there is a marked increase in the production of thermally modified (TM) wood, driven by growing consumer demand for environmentally sustainable materials with enhanced performance characteristics – namely, improved dimensional stability, hydrophobicity, and increased resistance to fungal decay (Jones and Sandberg, 2020). These properties are developed through thermal treatment of wood at elevated temperatures (typically between 160 °C and 240 °C) in a low-oxygen environment, which prevents oxidative degradation (Zelinka et al., 2022). This process results in significant alterations in the chemical structure of wood, particularly partial degradation of hemicellulose and cellulose, as well as the redistribution of lignin components. The extent of these transformations depends on factors such as wood species, treatment parameters, processing time, atmospheric composition (Herrera-Díaz et al., 2019; Jones & Sandberg, 2020). What is important is that thermal modification enhances the wood throughout its entire structure, unlike chemical impregnation, which only affects the outer surface.

Research studies (Bahrami et al., 2023; Humar et al., 2020; Tsapko et al., 2021) demonstrate that TM wood retains superior physical and mechanical properties compared to untreated wood when exposed to

For citation: Kindzera, A., Kshyvetskyy, B., Kindzera, D. (2025). Use of thermally modified wood after the end of its service life as a raw material for fuel pellet production. *Journal Environmental Problems*, *10*(2), 182–190. DOI: https://doi.org/10.23939/ep2025.02.182

environmental conditions expanding its areas of use. However, practical application shows that over time, TM wood also undergoes deterioration – evidenced by discoloration and structural degradation, including microcracking. Consequently, in addition to technological advancements in thermal modification, contemporary research focuses on the comprehensive assessment of surface degradation mechanisms in TM wood under environmental influences, with the goal of predicting its long-term durability.

Given the increasing production and use of TM wood, the volume of post-consumer waste from materials that have lost their functional properties is expected to rise. This trend underscores the necessity of developing scientifically grounded approaches and strategies for the effective disposal and recycling of such materials.

Potential pathways for the post-service utilisation of thermally modified (TM) wood can be identified through a critical review of existing strategies and best practices for managing post-consumer wood (PCW). Given the potential of PCW as a renewable and sustainable resource, its efficient utilisation is a key objective in the context of circular economy development. Reusing and recycling PCW significantly contributes to reducing the demand for virgin wood resources, lowering environmental impacts, and promoting more sustainable production cycles (Navare et al., 2022). The adoption of circular economy principles in waste wood management is part of the EU's strategy and is also relevant for Ukraine. However, several issues remain unresolved, hindering the effective handling of such waste. These challenges include the variation in collected wood and wood materials and the high variability of chemically active additives they contain (Pazzaglia & Castellani, 2023), the lack of proper assessment of the quality and composition of wood waste materials (Faraca et al., 2019), and the lack of a unified approach to classifying wood waste (Besserer et al., 2021).

Nonetheless, several waste wood utilisation trends have become increasingly established and implemented. A significant portion of waste wood is combined with plastic to produce insulation panels for the construction sector (Grigoriadis et al., 2019). Studies on the physical and mechanical properties of post-consumer wood (PCW), presented in article (Gayda & Kiyko, 2023), have laid the groundwork for its rational application in woodworking technologies (Gayda & Kiyko, 2020). PCW post-consumer wood can be processed into dimensionally appropriate blanks, which serve as the basis for manufacturing carpentry boards of various designs (Medvid, L., 2021). However, the most common use of wood waste, generated at th e end of wood product life and during the wood processing, remains its recycling into particle boards (Iždinský et al., 2020) as well as into noise and thermal insulating cement-bonded particleboards (Hou et al., 2022). Moreover, waste wood is repurposed into pulp for diverse industrial uses or converted into wood powders and fibres, which are incorporated into cement mortars (Ince et al., 2021), thus enabling the transformation of waste into value-added construction products. Various types of wood waste, as a source of organic matter, can be incorporated into horticultural substrates as compost (Pizzeghello, et al., 2021; Schroeter-Zakrzewska & Komorowicz, 2022; Wróblewska et al., 2009) and may serve as a substitute for peat. In practice, however, the use of wood waste as a raw material for compost production – a key component in the horticultural industry – is primarily limited to waste derived from forests, green areas, as well as the technological processes that do not involve chemical additives (Schroeter-Zakrzewska & Komorowicz, 2022).

In this regard, TM wood may follow similar reuse pathways as post-consumer wood. These include its use in the production of composite materials, insulation panels, particleboards, and as a feedstock for bio-based materials or compost production.

Amid the depletion of traditional fossil fuels and their rising costs, solid biofuels are emerging as a viable alternative, largely owing to the wide variety of raw materials suitable for their production. Among them, woody biomass is especially valued for its high energy content, primarily due to its composition of cellulose, hemicellulose, and lignin. However, it is important that solid biofuels can only be produced from waste wood originating from technological processes that do not involve the use of chemical additives. This restriction is essential to ensure environmental safety during combustion.

Within this context, aged thermally modified (TM) wood can be considered a viable alternative feedstock for the production of briquetted fuels, owing to its lignocellulosic composition, growing availability, and environmentally benign nature, as it is produced without the use of chemically active additives. Consequently, briquettes and pellets derived from such raw material are more likely to comply with ISO standards concerning emissions, user safety, and environmental impact, thereby representing a reliable and sustainable biofuel option.

Statement of the problem and its solution

Ash wood (*Fraxinus excelsior* L.), a species categorized as hardwood, is one of the principal forest-forming tree species in Europe (Meger et al., 2024). However, it remains underutilized in the woodworking and furniture industries. This is primarily due to its susceptibility to abiotic and biotic damaging factors, as well as the technical difficulties associated with its drying and machining processes. To broaden its scope of application, particularly for outdoor use where durability and dimensional stability are critical, it is advisable to thermally modify ash wood. Thermal modification significantly enhances the material's resistance to biological degradation, reduces moisture absorption, and improves dimensional stability. As a result, thermally modified ash (TM-Ash) wood becomes a more viable and sustainable alternative for outdoor construction, decking, cladding, and other high-performance wood applications.

However, environmental factors such as UV radiation, moisture, cyclic temperature-humidity fluctuations, wind forces, and abrasive elements like dust have a detrimental effect on the surface of wood (Tomak, et al., 2018). These influences lead to changes in the physical and mechanical properties of the material and significantly impact its service life. Given this, it is advisable to conduct a comprehensive study on the surface changes in TM-Ash wood exposed to variable environmental conditions. The findings of this study can provide a valuable foundation for increasing both manufacturer and consumer interest in TM-Ash wood. Moreover, the insights gained may contribute to the development of more effective surface protection coatings, ultimately helping to extend the durability and functional lifespan of TM wood products used in outdoor environments.

Although TM-Ash wood offers enhanced functional properties and durability, it still has a finite service life. Considering its potential reuse as a raw material for solid biofuel production, it is important to evaluate its suitability for this application. Thermal modification, combined with natural aging due to weathering, alters the chemical composition of the wood – specifically its hemicellulose, cellulose, and lignin content. Therefore, to assess the feasibility of using aged TM-Ash wood as biofuel feedstock, it is essential to investigate its thermal decomposition behavior and determine its calorific value and ash content.

The aim of this study is to analyze the surface condition of thermally modified ash wood after prolonged exposure to environmental factors, and to evaluate its thermal decomposition patterns, calorific value and ash content.

2. Experimental part

2.1. Materials

Ash wood (*Fraxinus excelsior* L.) was thermally modified at a temperature of 195 °C for 12 hours to produce TM-Ash wood. To evaluate the impact of environmental factors on the surface condition of TM-Ash wood, a batch of 25 test samples (150 × 20 × 10 mm) was installed on an outdoor test rack in November and exposed to natural environmental conditions for 24 months in a moderately continental climate (Lviv, Ukraine: 49°50′17″ N, 24°01′23″ E), characterized by mild winters and warm summers. The average annual air temperature is +8 °C, with approximately 740 mm of precipitation falling throughout the year. On average, precipitation occurs on 206 days annually. The average relative humidity is 79 %. Seasonal variations are clearly reflected in fluctuations of average temperature, humidity, precipitation, and solar radiation (Table 1). Additionally, rapid weather changes are common in all seasons, often accompanied by sudden shifts in meteorological parameters such as air temperature and humidity, precipitation, wind direction and speed, and atmospheric pressure.

Table 1

Average seasonal values of air temperature, relative humidity, precipitation, and solar radiation

Season	Average seasonal values of indicators			
	Temperature,°C	Relative humidity, %	Precipitation, mm	Solar radiation, kW·h/m²
autumn	from +14 to +5	80–85	55.7–28.8	2.5–2.0
winter	from +1 to –3	85–90	41.8–36.5	0.6–1.2
spring	from +10 to +17	70–75	38.7–92.9	2.5–3.5
summer	from +18 to + 22	65–70	95.3–51.7	4.5–5.5

After the exposure period, the samples were removed from the test rack for surface condition assessment and designated as TM-Ash^{24} (thermally modified ash wood exposed outdoors for 24 months).

2.2. Experimental procedure

2.2.1. Evaluation of surface condition

The condition of the TM-Ash and TM-Ash^{24} surfaces was evaluated using a scanning electron microscope (SEM, JEOL IT 500 LV, Japan). The SEM was operated under the following parameters: accelerating voltage (EHT) – 14.7 kV; working distance (WD) – 11–13 mm. SEM images were captured at a magnification of 2000×.

In addition, TM-Ash and TM-Ash^{24} samples were used to measure the time-dependent water contact angle. Contact angle (θ°) values were determined according to a standard method, based on digital photographs of water droplets placed on the sample surface at regular time intervals.

2.2.2. Fuel characteristics research

For the experiments, biomass was prepared from TM-Ash^{24} samples by grinding. Biomass test samples (Biom-TM-Ash^{24}), each weighing 50 mg, were formed for analysis. A comprehensive thermal analysis was used to investigate the high-temperature behavior of Biom-TM-Ash^{24}. Thermal analysis was conducted using a Q-1500 derivatograph (Paulik – Paulik – Erdey system), connected to a computer for recording analytical signals of mass loss and thermal effects. The Biom-TM-Ash samples were placed in a platinum crucible and heated at a rate of 5 °C/min from room temperature to 600 °C in an air atmosphere. Aluminum oxide was used as an inert reference material in the comparison crucible.

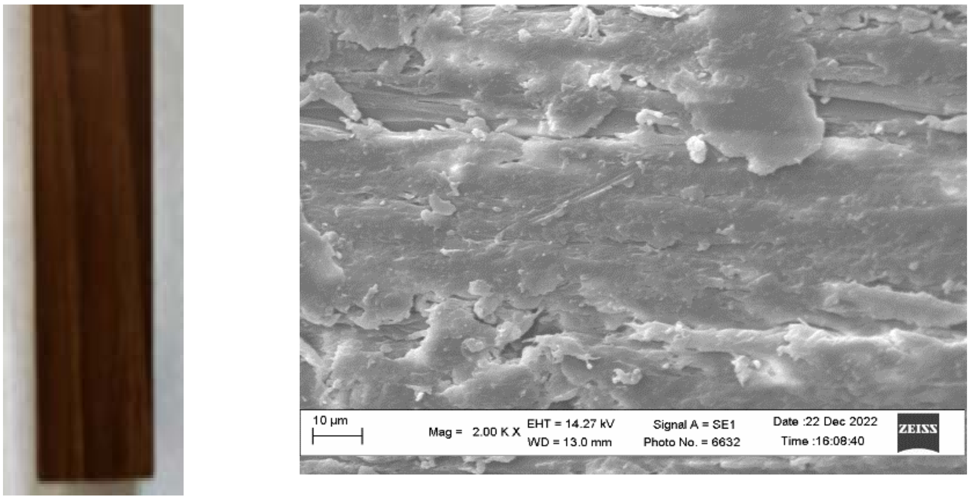
Standard methods for determining the calorific value of biomass samples and ash content were used. The calorific value of the Biom-TM-Ash^{24} samples was determined using a B-08-MA bomb calorimeter equipped with an isothermal jacket (Esteves et al., 2023; Kindzera & Kochubei, 2025) and the ash content was determined according to ISO 18122 (E) standard "Solid biofuels – determination of ash content" – by carbonization the material (1 g) in an oven (at 550 °C for 3 hr).

To ensure data reliability, all experiments were performed in replicates.

3. Results and discussion

3.1. Surface condition evaluation results

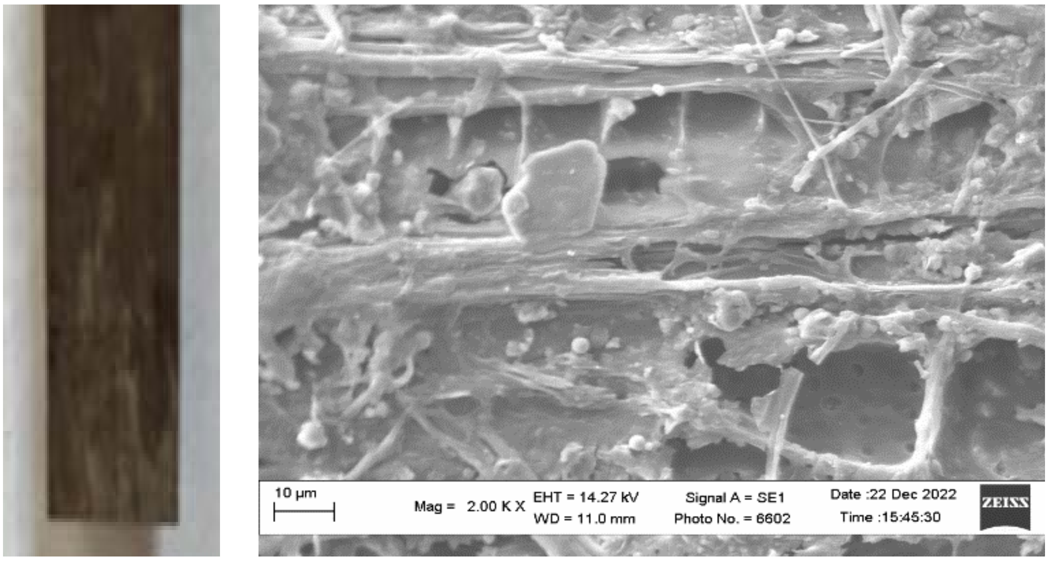
The TM-Ash wood surface, which appears brown in color (Fig. 1, *a*), is characterized by a relatively homogeneous, lignified smooth structure with reduced porosity, as observed in the SEM image (Fig. 1, *b*). This structure results from complex physicochemical transformations within the wood matrix induced by high-temperature thermal modification.



a b

Fig. 1. Thermally modified ash wood:
a – the condition of the TM-Ash surface; b – SEM image of TM-Ash surface at 2000× magnification

In contrast, significant changes in the surface condition was observed in the TM-Ash[24] sample (Fig. 2, *a*) following two years of environmental exposure. In general, degradation of the thermally modified wood surface was caused by prolonged exposure to intense ultraviolet (UV) radiation, fluctuations in humidity and temperature, precipitation like rain and snow (see Table 1), and wind carrying abrasive particles such as dust. UV radiation contributed to the photodegradation of lignin, resulting in surface discoloration and greying, as well as the erosion of surface fibers. The most significant impact was observed during the two summer exposure periods, when radiation doses were at their highest. Cyclic wetting and drying caused slight dimensional changes in the thermally modified wood samples. Additionally, temperature fluctuations and freeze-thaw cycles during the winter period accelerated microstructural damage. The SEM image in Fig. 2, *b* clearly illustrates the deterioration of the TM-Ash[24] surface.



a b

Fig. 2. Thermally modified ash wood following two years of environmental exposure: a – the condition of the TM-Ash[24] surface; b – SEM image of TM-Ash[24] surface at 2000× magnification

The water contact angles on both TM-Ash and TM-Ash[24] surfaces were observed to decrease over time, which is typical feature of wood materials. Consequently, time-dependent water contact angle measurements were conducted. Table 2 shows the contact angle values for the TM-Ash surface, measured from the moment of droplet contact at 1 second until near-complete absorption (575 seconds), where the angle decreased to θ = 17°. Initially, the contact angle slightly exceeded 90°, indicating hydrophobic behavior. This hydrophobicity is attributed to thermal modification, which reduces wood porosity and partially removes hydrophilic hydroxyl groups from hemicelluloses, thereby increasing the hydrophobic character of the wood cell walls.

Table 2

Values of the water droplet contact angles for TM-Ash surface

Sample	Contact angle, θ°						
	1s	100s	200s	300s	400s	500s	575s
TM-Ash	92	68	59	48	38	26	17

In contrast, the TM-Ash[24] surface exhibited an initial contact angle of less than 90° (Table 3), indicating a more hydrophilic nature. This behavior is associated with structural degradation due to prolonged environmental exposure. Additionally, the contact angle on TM-Ash[24] decreased more rapidly over time, confirming its reduced water resistance and susceptibility to further degradation under external factors. The contact angle reached θ = 17° after 480 seconds on this surface.

Table 3

Values of the water droplet contact angles for TM-Ash^{24} surface

Sample	Contact angle, θ°					
	1s	100s	200s	300s	400s	480s
TM-Ash^{24}	75	63	51	38	28	17

Thus, as complex experimental studies have demonstrated, environmental factors negatively impact the surface of TM-Ash wood, leading to surface collapse and loss of functional properties. It is evident that the surface condition will continue to deteriorate if TM wood is exposed to aggressive environmental factors over many years.

3.2. Fuel characteristics research results

Accordingly, the next phase of the research focused on investigating the fuel characteristics of biomass test samples (Biom-TM-Ash^{24}), which were obtained by grinding TM-Ash^{24} wood (Fig. 3).

Fig. 3. Finely dispersed biomass of thermally modified ash wood exposed in the natural environment (TM-Ash^{24}) wich was used to prepare biomass test samples (Biom-TM-Ash^{24})

The moisture content of the Biom-TM-Ash^{24} sample, determined by weight method, was 6.8 ± 0.5 %, indicating a low amount of sorbed moisture despite prolonged external exposure of TM-Ash^{24}, which reflects the moisture-resistant properties of TM-Ash wood (which initial moisture content was 6.0 ± 0.5 %). The low moisture content of this type of biomass is a significant advantage for solid biofuel production, as it eliminates the need for additional energy expenditure on drying – a mandatory step when using other plant biomass sources (Kindzera, et al., 2021; Hosovkyi, et al., 2016; Denysiuk et al., 2025).

The results of the comprehensive thermal analysis of the Biom-TM-Ash^{24} sample, presented in the form of thermograms, are shown in Fig. 4. The analysis was conducted at a low heating rate (5 °C/min), ensuring uniform heating of the material. Based on the thermogram analysis, data on mass loss across specific temperature ranges were obtained, and five stages of mass loss were identified (Table 4).

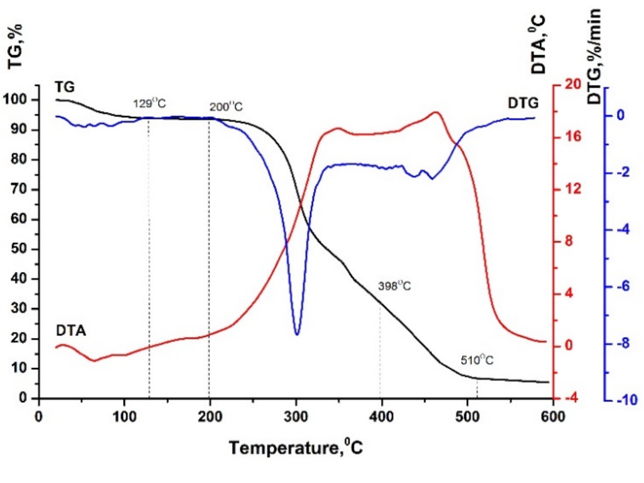


Fig. 4. Thermograms of the Biom-TM-Ash^{24} sample

Table 4

Results of complex thermal analysis of the Biom-TM-Ash^{24} sample

Sample	Degradation stage	Temperature range, °C	Mass loss, %
Biom-TM-Ash^{24}	I	20–129	6.0
	II	129–200	0.4
	III	200–398	62.9
	IV	398–510	26.0
	V	510–600	4.7

According to the thermal analysis results (Table 4), the first stage involved the dehydration of the sample in the low-temperature range. Endothermic processes associated with the moisture removal occurred without any structural degradation of the material. The mass loss at this stage for the Biom-TM-Ash^{24} sample was 6.0 %.

During the second stage, a slight mass loss of 0.4 % was observed in the temperature range of 129–200 °C. The onset of thermo-oxidative processes was indicated by the deviation of the DTA curve toward the exothermic region.

The third stage, representing the major thermal decomposition phase, occurred between 200 and 398 °C and resulted in a significant mass loss of 62.9 %. This stage corresponds to the low-temperature decomposition of organic matter, including the thermal degradation of hemicellulose (225–325 °C), cellulose (305–375 °C), and the less stable lignin components (starting at approximately 250 °C). These processes are accompanied by a pronounced exothermic effect on the DTA curve (Fig. 4).

In the fourth stage, under high-temperature conditions, the decomposition of cellulose and the more thermally resistant lignin fragments continued until the complete breakdown of all organic matter. The sample lost an additional 26.0 % of its mass in the temperature range of 398–510 °C, which also corresponded to an intense exothermic effec on the DTA curve. At the upper end of this range, the formation of pyrolytic residue was observed.

During the fifth and final stage, the pyrolytic residue underwent calcination, resulting in a m ass loss of 4.7 % between 510 and 600 °C.

The comprehensive thermal analysis of the Biom-TM-Ash^{24} sample revealed the characteristic behavior of thermally modified ash wood with respect to mass loss under different temperature intervals. Notably, the mass losses in the 20–129 °C and 129–200 °C ranges were low, which is attributed to the reduced initial moisture content and lower concentration of amorphous polysaccharides – primarily hemicelluloses, the most thermally unstable component – as a result of the thermal modification process. The thermograms revealed that the most substantial mass loss (62.9 %) occurred between 200 and 398 °C, coresponding to intensive decomposition of organic components. Based on the analysis of the DTA profile, a preliminary assessment of the biomass's calorific value was made. The broad extremum observed on the DTA curve indicates a h igh calorific value, resulting from the presence of energy-rich components in the biomass and the pronounced exothermic reactions associated with their decomposition.

Additionally, the calorific value of the Biom-TM-Ash^{24} sample was determined using the bomb calorimeter. The calorific value of 19.7 MJ/kg was obtained as an average of five measurements. A comparison of the calorific value of the Biom-TM-Ash^{24} sample was carried out with the calorific values of thermally modified oak and spruce wood samples, as well as with those of unmodified wood samples (Table 5).

Table 5

Comparison of calorific value

Wood species	Calorific value, MJ/kg		References
	Thermally modified (TM) wood	Unmodified wood	
Oak wood	19.3	18.8	Todaro, et al., 2015
Spruce wood	19.6	18.6	Todaro, et al., 2015
Ash wood	19.7	18.8	The results obtained by the authors

The results indicated that calorific value of Biom-TM-Ash[24] sample was higher than for the unmodified ash wood and, in general, the calorific values of TM wood off all species are higher compared to the values obtained for unmodified wood of the same species. The ash content of the Biom-TM-Ash[24] sample after combustion corresponds to an ash level within the range of 0.5–7.0 wt. % d. m, which is a typical value for wood (Zevenhoven, et al., 2012).

Thus, thermally modified end-of-life ash wood can be effectively used as a raw material for solid biofuel production, as it demonstrates efficient thermal decomposition, a high calorific value, and acceptable ash and moisture content.

4. Conclusions

Complex experimental studies have demonstrated that environmental factors negatively impact the surface of thermally modified ash wood exposed to external conditions over 24 months, leading to color loss – specifically, graying. Surface degradation was observed using scanning electron microscopy, and the loss of functional properties was indicated through time-dependent water contact angle measurements. The initially hydrophobic surface tended to become hydrophilic, with the contact angle decreasing more rapidly over time, confirming reduced water resistance and increased susceptibility to further degradation under environmental exposure.

A comprehensive thermal analysis was conducted on biomass test samples (Biom-TM-Ash[24]), obtained by grinding thermally modified ash wood that had been subjected to prolonged natural exposure for 24 months. Thermograms provided data on mass loss across various temperature intervals. Mass losses in the 20–129 °C and 129–200 °C ranges were low (6.0 % and 0.4 %, respectively), which corresponds to the reduced initial moisture content and the lower concentration of amorphous polysaccharides – primarily hemicelluloses – resulting from the thermal modification process. The most substantial mass loss (62.9 %) occurred between 200 and 398 °C, corresponding to the intensive decomposition of hemicellulose, cellulose, and the less stable lignin components. These processes were accompanied by a pronounced exothermic effect, which was expressed by a broad extremum on the DTA curve, indicating a high calorific value of the biomass due to the presence of energy-rich components and the strong exothermic reactions associated with their decomposition.

The calorific value of the biomass test sample (Biom-TM-Ash[24]) was determined to be 19.7 MJ/kg. It was established that thermally modified ash wood exposed to natural conditions possesses a higher calorific value than unmodified wood (18.8 MJ/kg), along with a favorable ash content ranging from 0.5 to 7 wt. % d. m., which is significant for its energy suitability. Additionally, the biomass exhibited an appropriate moisture content of 6.8 ± 0.5 %, which is optimal for densification and contributes to the production of high-quality pellets. Therefore, thermally modified ash wood, after the end of its service life, can be effectively utilized as feedstock for solid biofuel production, contributing to a circular economy model and minimizing environmental impact.

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