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Sustainable Insulation Panels Made of Tree Bark Fibers: Thermal and Fire Performance

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Abstract

The growing demand for sustainable solutions stimulates the building sector to develop environmentally friendly building materials. However, innovative natural-based options used in residential buildings must also comply with safety standards. This study examines the thermal and fire performance of insulation boards produced from tree bark fibers of two hardwood species, *Tilia* spp. (Lime) and *Robinia pseudoacacia* (Black Locust). The samples were fabricated using a wet process without adhesives and fire retardants, achieving thermal conductivity coefficient values of 0.055–0.057 W/m·K at densities ranging from 218 to 231 kg/m^3. Density profiling revealed a characteristic vertical gradient associated with wet processing, while wettability measurements indicated hydrophobic surface behavior. Fire tests showed species-dependent behavior: Black Locust panels exhibited smaller damaged zones and lower maximum temperatures, whereas Lime panels showed deeper thermal degradation. No board ignition was observed, and smoke release remained moderate and consistent. Overall, these findings highlight the potential of bark-based insulation boards as sustainable alternatives in building applications. However, further optimization with larger sample sets and the integration of natural flame retardants is recommended to improve performance and safety.

Keywords: bark fiber; bio-based material; thermal insulation; fire performance; density profile

1. Introduction

The construction sector is one of the largest contributors to global CO_2 emissions, accounting for almost 40%. As a mitigation strategy, the transition toward bio-based construction materials is recommended [1]. Wood and wood-derived materials are naturally based resources, acting as natural carbon stores, temporarily sequestering CO_2 and reducing emissions when used in buildings [2,3]. Moreover, during wood processing, a large amount of by-products are generated that can be used for building material purposes [4–6]. According to Eurostat, the total amount of wood waste treated was around 41 million tonnes for 2020 (data reported by Eurostat or other relevant agencies) for all EU countries. Despite the recovery, around 400,000 tons of wood waste are still disposed of through landfill or incineration [7].

Tree bark is one of the main wood by-products that finds utilization in different ways, including its potential use as thermal insulation in the building sector [8]. Several studies have explored the use of bark as an additive in particleboards [9] or MDF [10,11] showing improvements in thickness swelling [12].

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Tree bark is generally obtained as a by-product in sawmills, where it can be further processed for board fabrication within a hammer mill [13,14] or collected after high-pressure debarking and produce insulation material [15]. Oak tree bark pieces have been used as a filler material in wall frames in bungalows [16] showing U-values 0.29 $W/m^2 \cdot K$.

The utilization of bark in insulation materials can be approached from the perspective of waste management and circular economy principles. Additional processing steps require LCA, since they may increase energy consumption and CO_2 emissions [17]. At the end of the life cycle, adhesive-free [18–20] or natural-based adhesives [21] in tree bark, building panels are more favorable, as they facilitate the recycling process [22]. Species such as *Robinia pseudoacacia* (used for durable outdoor furniture, siding, and posts) and *Tilia* spp. (used for pulp, crates, and carving) are widely used in industrial applications, generating significant residual bark biomass as a byproduct of their established processing flows [23–27].

The development and use of innovative insulation materials for residential buildings require compliance with international standards and regulations that ensure human safety, including fire safety. The EU's CPR, Regulation (EU) No 305/2011 (now updated to Regulation (EU) 2024/3110), is a key regulatory document governing fire safety, waste as secondary raw materials usage, and other requirements, setting the framework for these requirements [28]. European standards for fire tests define two main types of tests for insulation materials: reaction-to-fire testing and fire-resistance testing. However, when conducting tests and interpreting their results, it is necessary to consider not only the material classification but also other factors, building large-scale test systems [29].

To evaluate the behavior of materials and the construction's integrity during fire exposure, classification tests, laboratory-based or large-scale experiments are used. As an example of a classification test, *Eucalyptus globulus* bark fiber insulation boards were tested for fire response according to ASTM D 4986-03, with the addition of 1% *w*/*w* of a commercial flame retardant, based on ammonium salts [14]. The test is horizontal, measuring the local fire reaction of foamed plastics. Conceptually, it is similar to EN ISO 11925-2:2011, a vertical ignitability test, which was applied to thermal insulation panels made from larch and poplar bark, with clay added as an ecological flame retardant [30]. The small flame test (EN ISO 11925:2011) is acceptable to determine class E but insufficient to prove higher fire resistance classes.

The protection of tree bark against fire is a complex system of physical (bark thickness, bark density, and moisture content), anatomical, and chemical adaptations. The bark of certain tree species, such as conifers, is rich in phenolic compounds and tannins. Upon intense heating, these substances effectively convert into a carbonaceous, graphite-like residue, which is a poor heat conductor and inhibits further combustion, acting as a fire-retardant layer. Anatomical protection involves a high percentage of sclerenchyma (stone cells), especially near the cambium, which further minimizes thermal damage to the underlying tissues [31–35].

Fiberboards made from French Guiana bark species, produced using the air-laid technology, were evaluated using laboratory techniques such as TGA and PCFC. Results show that the thermal stability of bark is greater compared to wood-based fiber panels [36]. Binderless panels were tested within TGA in a study on thermal insulation made of spruce bark fibers [20], where it is shown that the percentage of mass loss increased with longer pressing time. Laboratory methods, such as TGA, PCFC, and cone calorimeter measurements, are primarily used to evaluate the effectiveness of flame retardants [37]. Gebke et al. [38] reported the efficacy of starch-based phosphate/urea reaction system flame retardants on commercial wood fibers at an industrial scale, showing that efficiency depends on phosphate content, solubility, reaction time, and the form of the additive (physical mixture, unpurified or purified synthesis products).

Bark-based panels bonded with non-flammable construction material (cement) in the study by Pacher et al. [39]. According to it, the specimens were tested for fire resistance within a built-in furnace, in accordance with EN 1363-1:2020, which is part of the Fire Resistance of Structures series. The study showed that spruce and larch bark contain tannins that serve as protective layers and charring agents.

Samples of wood dust from hard and soft wood species with 50% bark, tested in the study by Renner et al. [40], showed that samples made with beech, oak, and spruce bark exhibited lower heat release properties compared to those made with fir and pine bark, which showed higher heat release.

Pine bark, when used with other forest waste (such as cones) in a honeycomb thermal insulation panel structure, demonstrated good fire-resistant properties. However, these panels contained formaldehyde additives for bonding and boric acid for enhanced fire resistance, achieving a minimum thermal conductivity coefficient of 0.121 W/(m·K) [41].

Although the general trend in wood panel production is toward eliminating synthetic adhesives or replacing them with environmentally friendly binders, current bark research predominantly uses synthetic adhesives such as phenol formaldehyde (PF) [14] or urea formaldehyde (UF) [11] as binders. However, it leads to the release of harmful compounds, such as formaldehyde, during combustion [42,43]. While adhesive-free options exist for producing bark panels, such as particle boards made from gelam [44,45] or spruce bark [19,20], comprehensive data on the specific thermal and fire properties of fiber bark materials produced by hydromechanical processes remains scarce. Therefore, the novelty of this study lies in providing comprehensive data on the thermal and fire resistance of hardwood bark treated entirely without external binders, which is an important step towards confirming its potential as an environmentally friendly insulation material.

For fire protection, additives are still necessary, and a recent review by Liu et al. [46] summarized options for improving the fire resistance of lignocellulosic materials, highlighting phosphorus-, nitrogen-, boron-, and silicon-based compounds, inorganic fillers and nanomaterials, as more environmentally friendly flame-retardant alternatives.

In this study, the bark of two wood species, *Tilia* spp. (Lime) and *Robinia pseudoacacia* (Black Locust) was selected as raw material due to its availability and widespread use in construction and woodworking. Investigating the properties of bark from deciduous tree species is particularly important, as these trees may gain increased attention in the near future amid the projected drop of several coniferous species under climate change [47].

As a result of the increasing interest in utilizing deciduous bark within circular-economy strategies and the shifting strategy toward low-carbon construction materials, this study aimed to: (1) fabricate insulation panels from hydro mechanically processed Lime and Black Locust bark fibers; (2) examine the fire behavior of these bark materials; and (3) evaluate performance characteristics of the resulting panels that are critical for their use in building applications. The data obtained from this pilot study expands current knowledge on fire behavior, density profile, and wettability of adhesive-free insulation panels made from hardwood bark fibers.

2. Materials and Methods

2.1. Raw Material Preparation

Bark obtained after debarking of *Robinia pseudoacacia* and *Tilia* spp., sourced from sawmills located in the Bakony Mountains region (Franciavágás, Hungary), was used as raw material. The air-dried bark was mechanically processed in a laboratory grinder

(Laszlo Medicago, Budapest, Hungary) equipped with a 12 mm sieve on the bottom to obtain the final bark fraction for later fiber extraction (Figure 1).

Figure 1. (**a**) Milled bark before the defibration process for insulation board production. (**b**) Example of the fabricated panels after sanding (upper panel made of *Robinia pseudoacacia* (Black locust) bark fibers, lower; lower panel made of *Tilia* spp. (Lime)).

2.2. Production of Thermal Insulation Panels

The milled bark was soaked in water for several days to soften fibers and improve defibration efficiency. Defibration was performed in a laboratory defibrator (Valmet Oyj, Espoo, Finland) using water as the processing medium. A 1.5% wax solution was introduced during the defibration cycles to enhance water resistance. The bark fiber pulp was poured into a drainage mold (diameter 500 mm) for gravitational dewatering. After 24 h, the material was transferred to a drying chamber and dried at 60 °C (±5) for 3–5 days. The target thickness was adjusted during the sanding stage after the sample had dried, to ensure even and flat sample surfaces (Table 1). The target board density was controlled by adjusting the mass of bark used for each board while keeping the mold dimensions and water volume constant. From every panel type, up to two 500 mm diameter boards have been selected for further investigation.

Table 1. Basic characteristics of fibers and binderless insulation boards produced from tree bark fibers (*Tilia* spp. and *Robinia pseudoacacia*).

Wood Species	Board		Fiber Longitudinal Slenderness (Length-to-Width Ratio)
	Density, kg/m^3	Thickness, mm	
Tilia spp. (Lime)	218 ± 4	47	17.8
Robinia pseudoacacia (Black Locust)	231 ± 9		11.3

2.3. Determination of Fiber Size

The length and width of bark fibers were determined using the L&W Fiber Tester (AB Lorentzen & Wettre, Kista, Sweden), which operates based on optical analysis of fiber suspensions in water. A defined amount of fiber particles was suspended in water and passed through the instrument, where they were analyzed by the built-in software using image recognition and measurement algorithms. The following properties of the fibers have been calculated: mean fiber length (µm), mean fiber width (µm), fines content (%)–defined as the percentage of material shorter than 0.2 mm in relation to the number of fibers longer than 0.2 mm, and mean shape (%), i.e., the projected length divided by the actual length. From each panel sample, 1 g of fiber material was taken and dispersed in 1 L of water to prepare the suspension.

2.4. Determination of Apparent Density

The apparent density of the samples was determined using a gravimetric method, based on the ratio of mass to volume (ρ = m/V). Rectangular specimens were cut from the panels, and length, width, and thickness were measured using a digital calliper. The mass of each specimen was measured with a balance (±0.01 g). Density was then calculated as ρ = m/V, where m is the mass of the test specimen (kg), and V is the volume of the test specimen (m^3). Ten specimens from each material type were conditioned at 20 ± 5 °C and 65 ± 5% RH. The mass was considered to be at equilibrium when the variation was less than 0.1%.

2.5. Determination of Thermal Conductivity

Thermal conductivity of the bark-based insulation panels was evaluated using the steady-state heat flow meter method, following the EN 12667:2002 [48] and ISO 8301:1991/Amd 1:2002 [49]. Measurements were carried out with a heat flux sensor system (sensor area: 120 mm × 120 mm; accuracy: ±0.1 W/m^2) positioned at the center of the heating plate. For each test, the temperature gradient across the sample was maintained at a constant 10 °C, while the average specimen temperatures on the cold and warm sides were 5 °C and 15 °C, respectively. The thermal conductivity coefficient (λ, in W/m·K) was calculated based on the one-dimensional heat flow Equation (1):

$$\lambda = \frac{q}{\frac{dT}{dx}} \tag{1}$$

where q is the measured heat flux (W/m^2), dT/dx is the temperature gradient across the sample thickness (K/m). The diameter of the measured samples was 45 cm, and the thickness was 47 mm. The measurement was started only when the steady state condition was achieved. After that, a hundred measurements were performed every minute, and the results were generated by averaging the hundred measurements.

2.6. Density Profile Determination

For the DP measurements, specimens measuring 50 mm × 50 mm were analysed using a Grecon DA-X device (Fagus-GreCon Greten GmbH & Co. KG, Alfeld/Hannover, Germany) with direct X-ray densitometry, scanning the panel thickness in 0.02 mm increments. For the 47 mm thick specimens, measurements were performed in two directions, across and along the layer formation direction, using 5 samples per panel type. For the 20 mm thick specimens, measurements were performed in duplicate, but only along one direction. For the presentation in the plots, the representative density profiles have been selected after preliminary evaluation of the individual results.

2.7. Determination of Wettability

Water contact angle measurements were used to evaluate the wettability of the panel surfaces with the PHOENIX 300 goniometer (SEO-Surface & Electro Optics Co., Gyeonggi-do, Ltd., Suwon City, Republic of Korea). For each material type, 15 specimens were tested. A droplet of distilled water was placed on both surfaces of each specimen, and images were recorded immediately at deposition and after 60 s. The contact angle was determined using open-source image processing and analysis software ImageJ 1.54p (National Institutes of Health and the Laboratory for Optical and Computational Instrumentation, University of Wisconsin, Madison, WI, USA). The measurement was performed based on images in side view, where only two contact angles can be determined. To minimize the effect of surface heterogeneity, both sides were measured, and the average value was calculated for each side.

2.8. Determination of Fire Performance

The fire performance of bark-based insulation boards was evaluated using a modified small flame test (EN ISO 11925-2:2011). Specimens (250 mm × 90 mm × 20 mm) were conditioned to a constant mass at 23 ± 2 °C and 66 ± 5% RH, clamped in a frame in a vertical orientation, and a wide surface exposed to a 20 mm long gas burner flame for 10 min. Six thermocouples were fixed on the back surface to record temperature dynamics during three continuous exposure phases (5 min without ventilation, 5 min with ventilation, 10 min after the flame turned off). The thermocouples were placed in the centre of the sample width, with the following distances from the sample bottom edge: T1—30 mm, T2—60 mm, T3—90 mm, T4—120 mm, T5—150 mm, and T6—220 mm (Figure 2). Board ignition and smoke development were evaluated visually throughout the test. Burn height and burn width were quantified based on image analysis using ImageJ software for the video-recorded burning process. Individual frames were extracted and calibrated using a reference scale visible within the recorded scene.

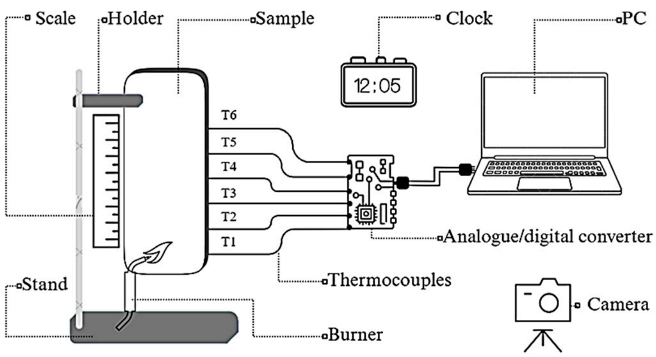


Figure 2. Experimental setup for the fire performance test of bark-based insulation boards. T1–T6 indicate thermocouple positions at different heights within the sample.

The burning area was assessed after the completion of the burning test. Each sample was cut along the line of the thermocouple locations to expose the internal charred profile. The cross-sections were photographed and subsequently analyzed using image-processing software (ImageJ) to determine the depth and distribution of thermal degradation.

3. Results

3.1. Characterization of Tree Bark Fiber Morphology

The length and width distributions of the bark fibers obtained after wet defibration are shown in Figure 3a,b, and the main morphological parameters are listed in Table 2. Both samples consist mainly of short phloem-derived fragments, which are typical for outer bark tissues [50]. Despite the predominance of small particles shorter than 0.2 mm, both materials contain elongated elements that can be classified as a fiber, allowing the formation of a fiber network in the wet-laid mats.

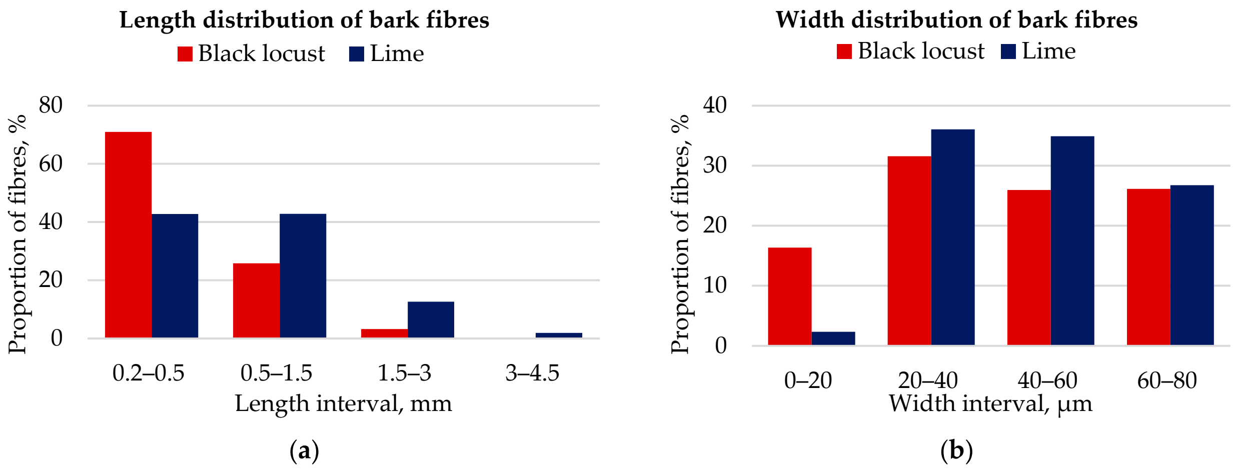


Figure 3. Bark fiber size distributions for Black locust and Lime. (**a**) Length distribution; (**b**) width distribution. Values are proportions calculated from the mean frequency of replicate measurements.

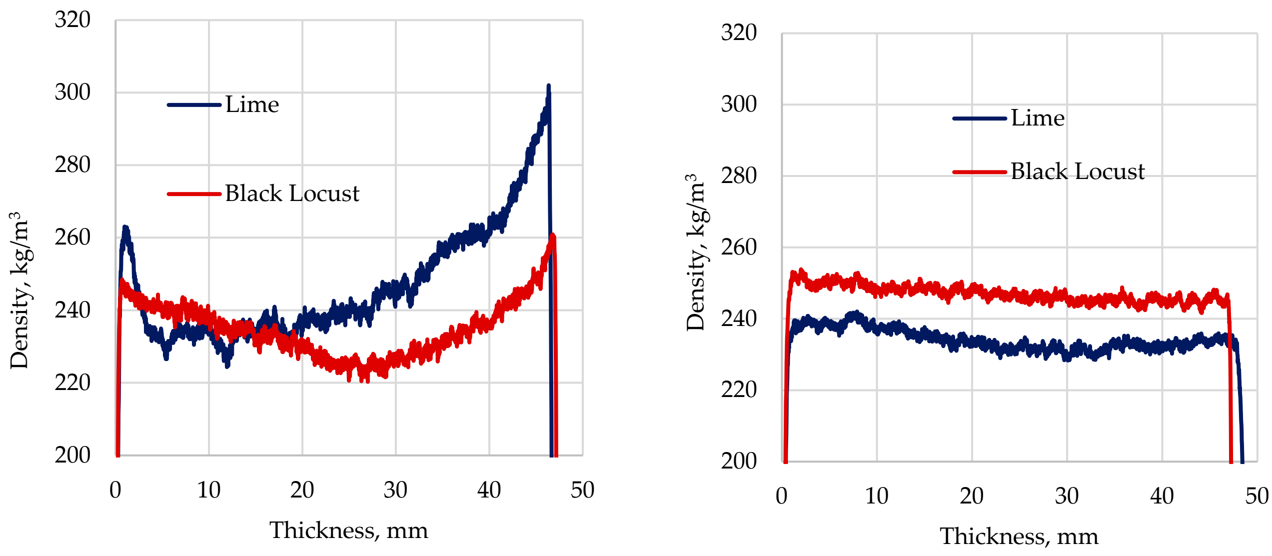
Table 2. Morphological characteristics of bark fibers obtained after wet defibration.

Fiber	Mean Fiber Length, µm	Mean Fiber Width, µm	Fines, %	Mean Shape, %
Bark Black locust	474.8	42.5	96.6	85.8
Bark Lime	834.8	46.9	85.3	85.6

3.2. Characterization of Tree Bark-Based Panels

The density differences between the two board types, 218 and 231 kg/m^3 for Lime and Black Locust bark-based panels, respectively, manufactured under identical forming and drying conditions, are primarily determined by the species-specific properties of the bark. Lime bark fibers after defibration contain a slightly higher proportion of elongated fibers, which interlock into a more open network and create additional internal voids, while Black Locust bark fibers generate a larger share of fine particles that behave as filler within the composite, packing more tightly and increasing consolidation [51].

The density profile analysis was performed both through the thickness (top to bottom) and along the layers of the panels (Figure 4a,b). The density distribution across the thickness of Lime and Black Locust bark boards showed a clear asymmetry, characterized by lower densities near the top surface and up to 25% higher values at the bottom layers. During wet mat formation, gravity drives an uneven settling of fibers, producing a denser structure at the bottom and a lighter one at the top. Depending on their rigidity, flexible fibers bend and interlock to create compact, low-porosity layers that block fluid transport, while stiffer fibers deform less and generate more permeable networks [52]. Similar asymmetric density profiles were studied by [15] for bark fiber-based composites, where vertical heterogeneity strongly influenced thermal conductivity and sound absorption due to the interplay between porosity and localized densification. The U-shaped vertical density profile in wet-formed boards is closely linked to internal bonding and strength, remaining a decisive factor even after hot pressing of the wet-formed mat [53]. Optimizing drainage and pressing conditions could reduce vertical asymmetry and improve the overall homogeneity of insulation performance.



(**a**) (**b**)

Figure 4. Density profiles of bark fiberboards made from *Robinia pseudoacacia* (Black Locust) and *Tilia* spp. (Lime): (**a**) vertical density distribution through the thickness; (**b**) in-plane density distribution along the layers.

The vertical density gradient in wet-formed lignocellulosic boards appears due to uneven moisture removal, since the surface layers dry and shrink faster, while the core preserves water for a longer time [54–56]. The in-plane density distribution remained relatively stable for both species, with minor variations around the average density, with CV for Lime ≈ 2.8% and ≈1.8% for Black Locust, indicating a relatively homogeneous fiber arrangement within the layers.

3.3. Thermal Conductivity of Tree Bark Based Panels

Thermal conductivity (λ) directly measures a material's ability to resist heat flow, with lower thermal conductivity values indicating better insulation performance [57]. The mean λ for binderless bark fiber-based Black Locust and Lime insulation panels was 0.055 W/m·K and 0.057 W/m·K, respectively (Table 3). No significant difference was observed between the two panel types. To compare the results obtained in this study with other research reported in the literature, it is important to consider that thermal conductivity depends on several factors, including density, moisture content, fiber orientation, and temperature [58]. Table 3 summarizes data for different bark-based insulation materials produced from fibers or residues, where the manufacturing method is also considered. The values of λ obtained in this study correspond with the range for bio-based insulation materials (0.03–0.10 W/m·K) [59]. When compared to synthetic insulators such as expanded or extruded polystyrene (0.029–0.040 W/m·K) and polyurethane foams (0.020–0.025 W/m·K), bark-based boards show higher thermal conductivity, but remain competitive with mineral wool (0.035–0.045 W/m·K) and conventional wood fiber insulations can be found in the market, however the majority contains adhesive.

Table 3. Thermal conductivity of bark-based insulation panels compared with data from the literature, including density, fabrication method, and bark source.

Bark Source	Thermal Conductivity, W/m·K	Density, kg/m^3	Fabrication Method	Fiber obtaining	Reference
Black Locust *Robinia pseudoacacia*	0.055	218 ± 4	Wet	Defibration	Current study
Lime *Tilia* spp.	0.057	231 ± 9	Wet	Defibration	Current study
Spruce	0.044	162.00	Wet	After debarking by high-pressure water jets	[19]
C. Obtusa *V. Surinamensis* (French Guiana species)	0.04–0.06	120–250	Air-laid	Impact milling	[36]
Eucalyptus globulus	0.071–0.076	200–250	Wet	Hammer mill, defibration	[14]
Eucalyptus	0.042–0.062	50–220	Bulk fibres	Mill grinder	[13]
Pinus sylvestris L., *Picea abies* L., *Quercus robur* (Alpine tree species)	0.068–0.079	170–330	Wet	After debarking within high-pressure water jets, sieving	[60]

3.4. Wettability of Tree Bark-Based Panels

According to the wettability test, contact angles above 90° indicate a hydrophobic surface [61]. All samples tested in this study showed contact angles exceeding this value, indicating hydrophobic surfaces (Figure 5). The wettability of boards made of Lime and Black Locust bark fibers was comparable, with no observable species-related and surface orientation differences. The sessile drop method provides only indirect information on surface free energy and should be considered mainly as a qualitative assessment of surface properties [62].

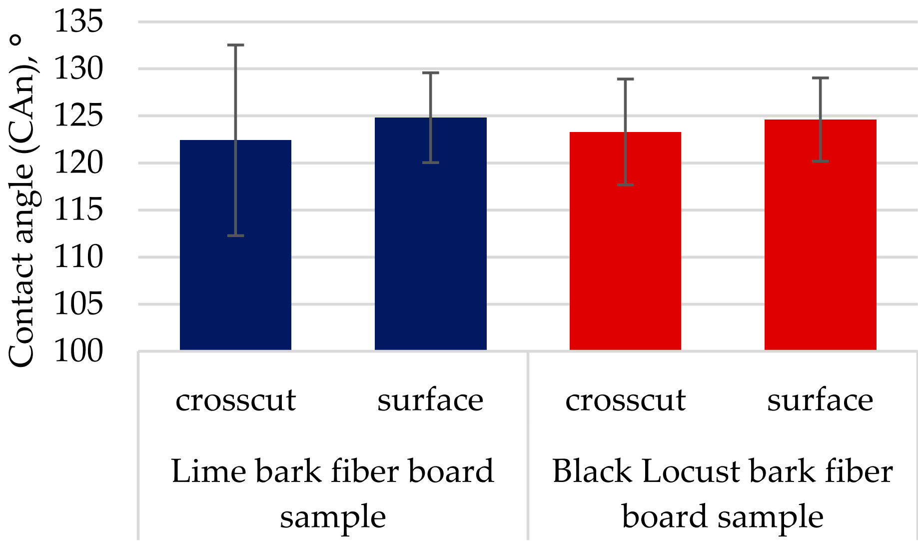


Figure 5. Average water contact angle on crosscut and surface of Lime and Black Locust bark-based insulation boards.

3.5. Fire Test Performance

The inside area of Lime bark fibers boards after fire test completion was affected more deeply compared to Black Locust bark fiber boards (Figure 6), with significant differences. No internal charring was observed at thermocouple T6 position, which recorded temperatures of 21.5–36.0 °C for Lime bark fiber board and 23.1–33.5 °C for Black Locust bark fiber board. Thermocouples installed near the fire (T1–T3) showed similar temperature ranges, indicating a larger damaged zone (Table 4).

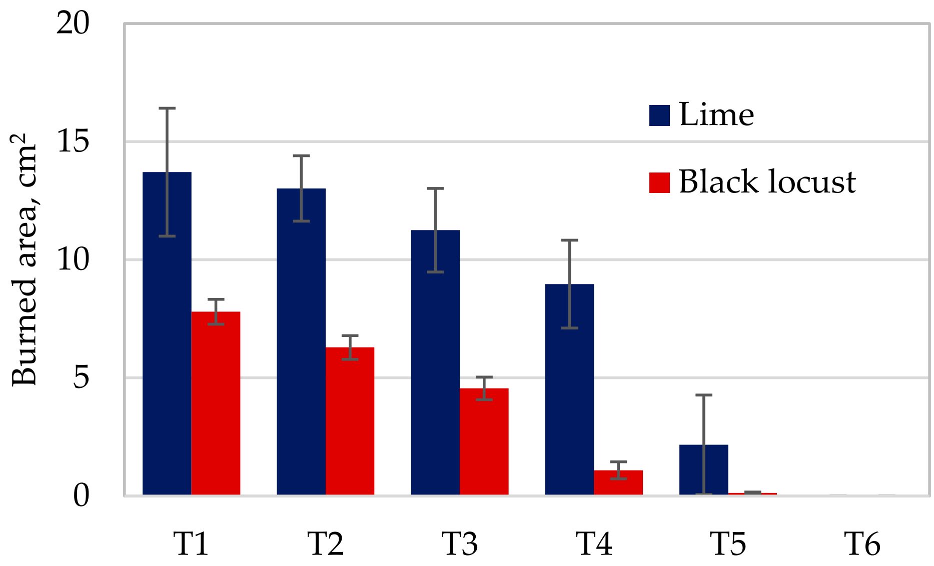


Figure 6. Burning areas in the cross-section of *Tilia* spp. (Lime) and *Robinia pseudoacacia* (Black Locust) bark fiber boards at T1–T6 thermocouple positions.

Table 4. Maximum temperatures recorded by thermocouples (T1–T6) during the 20 min fire test of bark-based insulation boards.

Thermocouple	Lime Bark Fiber Board	Black Locust Bark Fiber Board
	Max Temperature, °C	
T1	115.3	78.0
T2	120.9	91.3
T3	81.8	76.1
T4	96.1	67.1
T5	81.9	42.2
T6	36.0	33.5

During fire exposure, even after the visible flames are extinguished, smouldering can remain inside the material and potentially cause delayed ignition and further fire spread [63]. The results of smouldering behavior showed that thermal degradation continued in some cases and spread below the initial flame application line (Figure 7). After 20 min, the width spread of damage in Lime boards was considerably greater than in Black Locust, whereas no significant differences were observed in vertical flame height. In our study, the smouldering time has not been registered for the complete temperature decay, as it was performed with a similar approach by Gebke et al. [38] study for loose-fill material, but it shows only the early stage of post-flame smouldering, limited to a 10 min observation window. Steen-Hansen et al. [64] in their study show that smouldering is more strongly for low density loose-fill wood fiber insulation material, with higher temperatures and greater mass loss, because oxygen moves more easily through the pores.

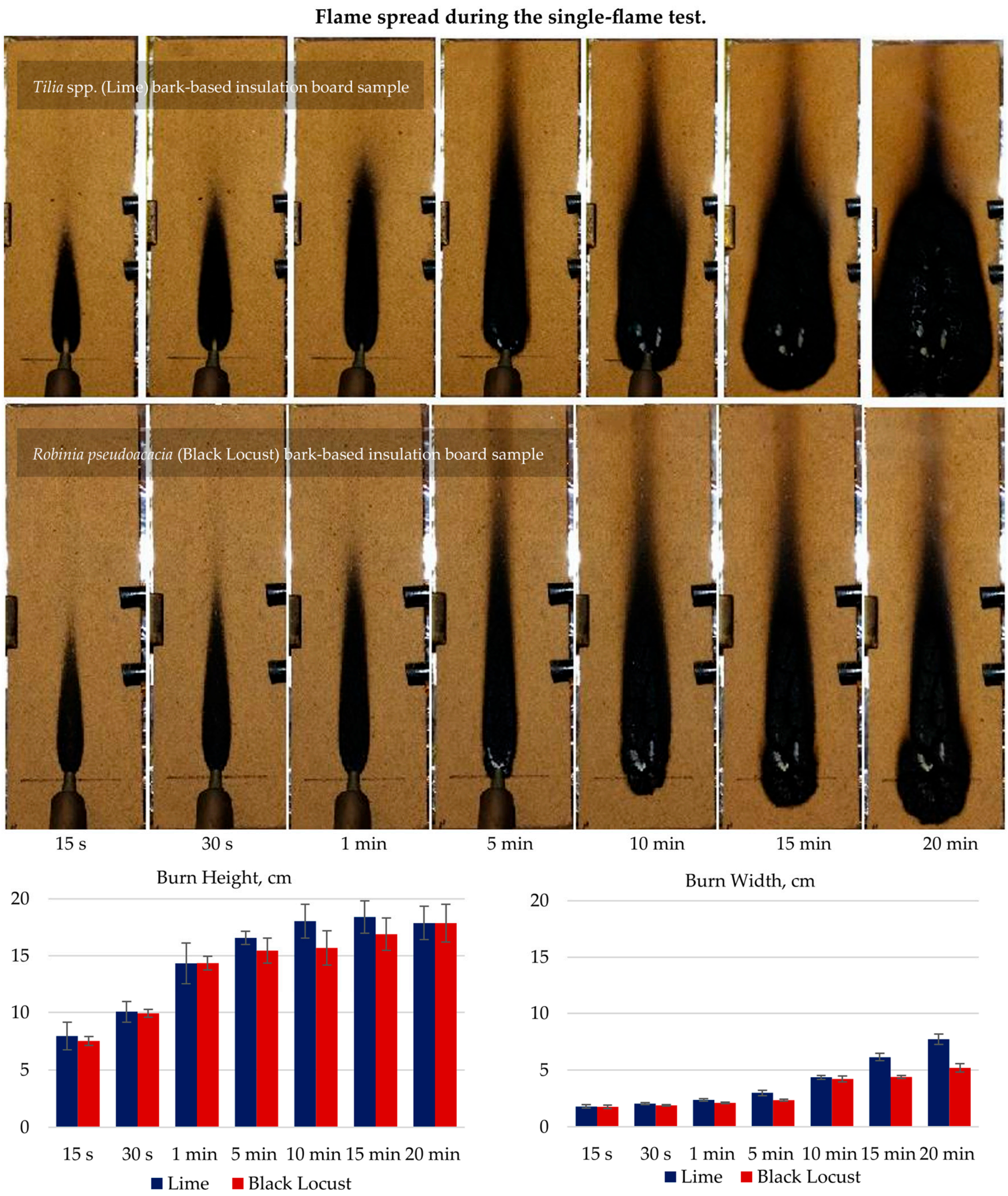


Figure 7. Flame spread development (burn width and burn height) of Lime (upper images) and Black Locust (lower images) bark-based insulation boards during small flame exposure.

No board ignition or filter paper ignition was observed during the tests. Smoke development was assessed visually from the recorded videos. The first signs of active smoke appeared after about 2 min in both cases, and from the 5th minute, smoke became more intense and clearly visible. After 5 min, the exhaust system was switched on, and the resulting airflow influenced the smoke behaviour. Smoke release continued until the end of the 20 min observation period. External airflow is known to facilitate the transition from smouldering to flaming in solid wood, making it easier and faster [65]. However, in our study, this effect was likely minor and did not significantly affect the formation of flame or smoke.

4. Discussion

The panels produced in this study were manufactured using a wet-forming process, a technologically simple and cost-effective method compatible with low-grade raw materials, although it is currently less common in commercial wood-based insulation manufacturing. Most bio-based insulation materials available on the market, such as wood fiberboards, hemp mats or agricultural-fiber composites, are fabricated either by dry air-forming followed by hot pressing or via thermoplastic or biopolymer bonding, both of which enable tight control over density, mechanical strength, and thickness stability [66–68]. Only a limited number of research works have explored wet-formed insulation panels made of spruce bark fibers [19], cardboard and plant fibers [69–71], rice husk [72] or hemp shive [73]. By using water to evenly suspend fibers, the wet process forms stable adhesive-free mats that can be easily recycled since no chemical binders are added [15].

The thermal conductivity results obtained in this study (0.055–0.057 W/m·K) align with the range reported for bio-based insulation composites [13,19,36]. While they do not reach the low values characteristic of expanded polystyrene or PUR foams, they remain comparable to mineral wool and commercial wood fiber insulation boards. This means that binderless bark panels could supplement the portfolio of natural insulation products, especially where the design criteria prioritize circularity, local sourcing, and recyclability over maximum insulation efficiency.

While commercial products often demonstrate excellent results, this is often dependent on the manufacturing process, which requires the addition of synthetic adhesives or binders such as dry hot-pressing technology. The thermal performance of the panels produced in this study demonstrates competitive results without the use of any adhesives. The key potential of this material lies in its ability to deliver acceptable thermal performance using a simple, environmentally friendly, adhesive-free wet process, representing a major environmental and technological breakthrough in this research.

However, future industrial implementations could integrate closed-loop water recirculation, which would significantly reduce water consumption and improve the overall environmental profile of wet-formed panels.

The obtained average thermal conductivity value is favorable, but it requires critical contextualization. The applied fabrication methodology, based on wet laying and uncontrolled gravity drying, compromises the homogeneity of the lignocellulosic matrix. This process leads to significant density gradients across the panel thickness. As a consequence, the density heterogeneity raises serious engineering concerns regarding the long-term performance and reliability of the insulation product. The potential anisotropy associated with this problem can be further investigated by relating it to mechanical properties, such as compressive strength. Thermal conductivity in low-density lignocellulosic panels is governed by porosity, density gradients, and fiber alignment [74,75]. Further research should focus on advanced techniques such as optimized mechanical pressing or vacuum filtration to ensure uniform mass distribution and, hence, predictable thermal stability.

For material characterization, to overcome the limitations of conventional sessile-drop measurements on porous and fibrous materials, there are several approaches, such as correcting for absorbed drop volume [76], analyzing the menisci formed between parallel fibers [77] minimizing evaporation effects through controlled environments [78], or performing standardized advancing and receding angle protocols to quantify hysteresis [79]. These methods improve accuracy and provide detailed insights into surface energy and heterogeneity. To minimize variability in the current study, contact angles were determined on both sides of the droplet in side view and averaged. The difference between left and right angles, averaging 4.81° for Lime and 5.45° for Black Locust, was taken as an indicator of surface heterogeneity, though part of this variation likely reflects measurement uncertainty. All contact angles remained above 90°, confirming the hydrophobic character of both bark-based boards. In this study, the bark fibers were obtained by water mechanical processing. Thermomechanical pulp fibers change in their wettability and structure from the origin [80]. In our case, wax granules were also added; however, their influence on wettability remains unconfirmed, as the granules were largely embodied within the fiber-based biomass. During the mechanical decomposition of bark, lignin can migrate to the surface, and the amount of insoluble lignin has been shown to partly correlate with the initial CA_n [81]. According to the literature [82,83], Black Locust and Lime bark are characterized by 22%–45% and 41%–50% wt. lignin content, respectively. However, both ranges are sufficiently wide and overlap with each other, which is why they do not provide a stable foundation for explaining how the lignin difference affects the behaviour of the samples.

Wood resists ignition mainly due to its surface properties, thermal behavior, and the formation of a protective char layer during pyrolysis, which slows down heat transfer. These processes, together with factors such as moisture content and density, influence ignition resistance [84]. The density of panels made from Lime and Black locust bark fibres is quite similar, at 218 ± 4 kg/m^3 and 231 ± 9 kg/m^3, respectively. This finding aligns with a review of studies by Albert et al. [85], which showed that differences in fire behaviour between low- and high-density materials are often small. This means that the different fire behavior of the two barks is more likely caused by their chemical composition. In our case, no flame retardants or additives were used, so the results reflect only the natural structure and chemistry of the bark. Kinetic charring models for solid wood suggest only small species differences [86], studies on natural fibers show that higher lignin content leads to more char, higher activation energy, and a lower CO/CO_2 ratio [87], lower heat release, and longer burning.

Fire performance remains a central criterion for material acceptance in building applications. The small-flame test in the current study was extended; however, the initial phase of the test still allowed the material to be assessed according to the standard, focusing on the presence of ignition after 15 and 30 s, as well as the flame-affected zone. The absence of ignition and the limited flame spread (less than 150 mm) indicate that the investigated materials could meet the requirements for Class E under EN 13501-1 when evaluated with the EN ISO 11925-2 test. To achieve Class D, an additional test, SBI, is needed. Integrating mineral flame retardants such as clay [30], phosphorus–nitrogen systems [38], or silicate-based additives [88] may further reduce temperature rise, limit smouldering, and improve classification. However, any modification must remain compatible with the sustainability goals of adhesive-free bark panels, ensuring that circularity principles are followed.

Considering resource availability, bark is an abundant and underutilized by-product of the wood industry across Central Europe [8]. In Hungary, hardwood processing generates substantial amounts of bark from species such as *Robinia pseudoacacia*, one of the most widespread deciduous trees in the region. The valorization of this bark into functional insulation materials aligns directly with circular-economy principles: diverting material from low-value uses such as combustion, reducing waste, and creating opportunities for local production of bio-based building products.

5. Conclusions

- This pilot study of binderless insulation boards produced from bark fibers of *Tilia* spp. (Lime) and *Robinia pseudoacacia* (Black Locust) shows promising thermal and fire-related properties, providing a foundation for further improvement and potential real-world application in sustainable construction.

- Thermal conductivity values of both investigated insulation boards for hardwood tree bark fibers are in the range of 0.055–0.057 W/m·K, which complies with the typical range of bio-based insulation materials. These results confirm their potential as environmentally friendly alternatives to conventional synthetic products.
- Density profile analysis revealed a characteristic vertical gradient of wet-formed boards, with denser bottom layers and lighter top layers. This highlights the need for optimization of processing parameters to enhance structural uniformity and improve overall insulation performance.
- Wettability tests confirmed that both board types are hydrophobic, with contact angles above 90°, likely influenced by the relatively high lignin content of bark fibers. This property may contribute to improved durability by reducing moisture sensitivity.
- The fire performance evaluation showed species-specific differences: Black Locust boards showed greater thermal stability, with smaller affected zones and lower internal temperatures, while Lime boards were more prone to deeper thermal degradation. No board ignition or filter paper ignition was observed, and smoke development followed a similar pattern in both cases, remaining consistent during the test.

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Abbreviations

The following abbreviations are used in this manuscript:

CO_2	Carbon dioxide
CO	Carbon monoxide
EU	European Union
LCA	Life Cycle Assessment
CPR	Construction Products Regulation
TGA	Thermogravimetric Analysis
PCFC	Pyrolysis Combustion Flow Calorimetry
DP	Density Profile
RH	Relative Humidity
CA_n	Contact Angle
CV	Coefficient of Variation
SBI	Single Burning Item
PUR	Polyurethane
MDF	Medium-Density Fibreboard
PC	Personal Computer

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