Technical Performance Overview of Bio-Based Insulation Materials Compared to Expanded Polystyrene

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Abstract: The energy efficiency of buildings is well documented. However, to improve standards of energy efficiency, the embodied energy of materials included in the envelope is also increasing. Natural fibers like wood and hemp are used to make low environmental impact insulation products. Technical characterizations of five bio-based materials are described and compared to a common, traditional, synthetic-based insulation material, i.e., expanded polystyrene. The study tests the thermal conductivity and the vapor transmission performance, as well as the combustibility of the material. Achieving densities below 60 kg/m^3, wood and hemp batt insulation products show thermal conductivity in the same range as expanded polystyrene (0.036 kW/mK). The vapor permeability depends on the geometry of the internal structure of the material. With long fibers are intertwined with interstices, vapor can diffuse and flow through the natural insulation up to three times more than with cellular synthetic (polymer) -based insulation. Having a short ignition times, natural insulation materials are highly combustible. On the other hand, they release a significantly lower amount of smoke and heat during combustion, making them safer than the expanded polystyrene. The behavior of a bio-based building envelopes needs to be assessed to understand the hygrothermal characteristics of these nontraditional materials which are currently being used in building systems.

Keywords: bio-based; fire behavior; hemp; thermal conductivity; thermal insulation; vapor permeability; wood

1. Introduction

In industrialized countries, insulation is now an important tool for the improvement of a building's energy behavior. The degree of insulation achieved in a building is directly linked to the minimal thickness imposed by the national regulations that has been increasing over the years. As Papadopoulos [1] indicates, during the period of 1980 to 2000, the thickness of insulation for walls has doubled in some countries in Northern Europe, although it has remained stable for less prosperous countries like Greece. The choice of insulation materials should be based on multiple factors. A couple of decades ago, other than the building's energy behavior and the physical properties of the materials, the focus moved on the use of environmentally-friendly products in the construction industry. Indeed, different materials could be used to provide similar functions in buildings but the related energy-use and emissions could vary significantly.

A study by Grand View Research [2] stated that the North American building thermal insulation market size was valued at 7.09 billion USD in 2015. Higher energy costs have led to increases in the demand for insulation, and can explain the slow but stable growth witnessed in the market. In Canada, the National Energy Code of Canada for Building Code (NECB 2015) sets the requirements

for the energy efficiency of a building. In the U.S., an initiative called The Weatherization Assistance Program is funded by the U.S. federal government and has the goal of promoting more efficient thermal insulation. These programs are key to educating the population and industry about the necessity of achieving high-energy efficiency in buildings. The positive impacts are both economic and environmental in the long term. After glass wool, the most used insulation material in North America is expanded polystyrene (EPS), accounting for 23.5% of share by volume. Made of 98 to 98.5% air, the main component is polystyrol pearls blown with pentane as a propellant gas. Under heating, the pearls expand at 212 °F, i.e., the temperature at which the pentane evaporates. To further eliminate of the pentane by diffusion, the expanded pearls are stored for a few days, after which they are poured into molds and melted under controlled steam heating to bind with each other. A counterbalance to the high thermal resistance of this material is its poor fire behavior. Indeed, in the event of a fire, EPS melts and releases toxic fumes.

As Grand Review reported [2], current thermal insulation materials in the construction market are generally inorganic, e.g., extruded polystyrene (XPS), expanded polystyrene (EPS), polyisocyanurate and polyurethane foam with high performance in relation to heat transfer, but also with the highest environmental impact. As the International Energy Agency revealed, the building sector is responsible for 40% of energy use, one third of GHG emissions and the consumption of 30% of all resources [3]. There is a need to reduce this impact, and it could be linked with the choice of materials included in the envelope. In a study by Thormark [4], the embodied energy of an energy efficient building reached 40% of the total energy needed for a life expectancy of 50 years. His results showed that through material substitution, the embodied energy can be decreased by 17%.

Numerous studies have examined the use of bio-based or natural insulation materials with the aim of replacing conventional inorganic ones [5–9]. During photosynthesis, plants sequester atmospheric carbon dioxide, meaning that the use of crop-based materials in a building can reduce its embodied energy. Their transformation process also involves fewer steps and requires less energy than petrochemical or mineral insulation [10]. Nonetheless, the use of bio-based insulation materials is limited due to their thermal conductivity and density, which are usually higher than those of EPS. Reif et al. [11] showed that natural fiber insulation materials can achieve thermal conductivities of around 0.060 to 0.080 W/mK with densities ranging from 150 to 450 kg/m^3; EPS is known to have a thermal conductivity of 0.036 W/mK with an appreciably lower density of around 35 kg/m^3. It is also well known that synthetic-based insulation materials such as EPS do not let water vapor evacuate by diffusion in cases of water leakages in walls. The growth of mold which occurs in walls is often due to a mix of air tightness and the use of impermeable-to-vapor insulation materials. Hygroscopic materials like natural fibers can equilibrate indoor humidity through their ability to absorb, store and release water vapor from the air. The movement of vapor in the envelope is essential, as even an efficient design cannot ensure that a leakage will never occur.

Vink et al. [12] defined an ideal, environmentally sustainable product as providing the equivalent function of the product it replaces, and which is available at competitive cost. It also needs to be sourced from renewable raw materials and have a minimal negative impact on the environment and on human health. Despite critical embodied energy and a poor end-of-life behavior, organic foams can achieve high thermal resistance. Conventional natural insulations cannot achieve the same thermal performance due to their layered structures, as opposed to porous ones, limiting the transport of heat by trapping air inside. As Steen-Hansen, Mikalsen and Jensen [13] proposed, combustible insulation materials are likely to contribute to fires by their tendency to ignite from smoldering combustion as well as visible flame. Smoldering combustion can increase fire risk due to its starting point, i.e., a lower temperature than traditional flaming fire. The authors' results showed that with the same level of fire retardant, fire developed at lower temperatures for loose-fill insulation with smaller-sized fibers than with the larger ones.

The function of insulation is complex, and the materials from which it is made should not be strictly evaluated as independent entities, but rather, as a part of a complex system, i.e., the building

envelope. By blocking, limiting and controlling the transport of air, water and heat through the building, the shield needs to be designed according to different physical mechanisms. Furthermore, the quality of an insulation material is not restricted to its technical and environmental performance, but is related to local needs, i.e., adaptability to national regulations, traditional methods of building and the availability and use of the product in a defined area [10].

　　　　Our technical characterization included studying the thermal conductivity and vapor transmission, as well as the combustibility of the material. As a building material, insulation should be assessed in view of performance-based fire design. Therefore, this study assesses the technical performance of various bio-based insulation materials which may be able to replace EPS. The focus is on natural fiber materials and excludes other potential bio-based insulations like mycelium composite foam or bio-based polymeric foams.

2. Results

The density, thermal conductivity, vapor permeability and fire behavior for the studied insulation materials are presented in this section. The means and the coefficients of variation are included to illustrate the interval of distribution.

2.1. Density vs. Thermal Conductivity

Figure 1 establishes the relationship between the thermal conductivity and density of the six studied materials; the trend seems to be linear. In ascending order of density, the insulation materials are ranked as follows: EPS (21 kg/m^3), FHB (34 kg/m^3), FWBF (55 kg/m^3), FWB (55 kg/m^3), WF (143 kg/m^3) and RWF (231 kg/m^3). The expanded foam structure of EPS makes it less dense than the fiber composites, with an impressive ability to trap air inside its cavities, thereby limiting the transport of heat. It is difficult to make lightweight materials with natural fibers as the density of wood is typically higher than 300 kg/m^3. With the longest hemp fibers, it is possible to create a lighter, tridimensional network, and hence, to obtain a lower density and thermal conductivity. Also, here, due to its relatively low density, obtained through an innovative process, the thermal resistance of FWBF (0.039 W/mK) is in the same range as that of EPS (0.036 W/mK). With a gas injection step in the making of the FWBF, the formation of bubbles ensures better thermal resistance properties than conventional wood fiberboard, even at the same density. By changing the parameters in the process, it is possible to obtain a density ranging from 40 kg/m^3 to 100 kg/m^3 [14]. Here, the density is more than three time higher than that of EPS; the expected end-use is in the form of rigid insulation boards which could replace conventional oriented strand board (OSB) panels. This recycled fiberboard (0.057 W/mK) competes with OSB in terms of its insulation properties; the thermal conductivity of OSB is around 0.13 W/mK [15]. With an average density and thermal conductivity compared to the other materials being studied, the conventional WF manufactured via a dry process is ideal for renovations, as it will provide additional insulation when laid directly onto rafters without significantly increasing the dead load.

2.2. Water Vapor Permeability

Figure 2 shows the vapor permeability for each of the insulation materials being studied. There is a distinct gap between the vapor permeability of EPS and those of natural fiber composites. The vapor permeability for EPS is only 4 perm-inch, while it increases to 21 perm-inch for RWF, and ranges from 32 to 41 perm-inch for the other wood fiber materials. The hemp fibers, as mentioned earlier, are longer and interlock differently than wood fibers. This offers a pathway of air movement, allowing vapor to flow not only by diffusion, but also by convection. As observed, the vapor permeability of FHB is largely superior (83 perm-inch) to that of wood-based panels. As proposed in Supplement 7 of the International Building Code, materials can be divided in four class of water vapor permeability (Table 1) [16].
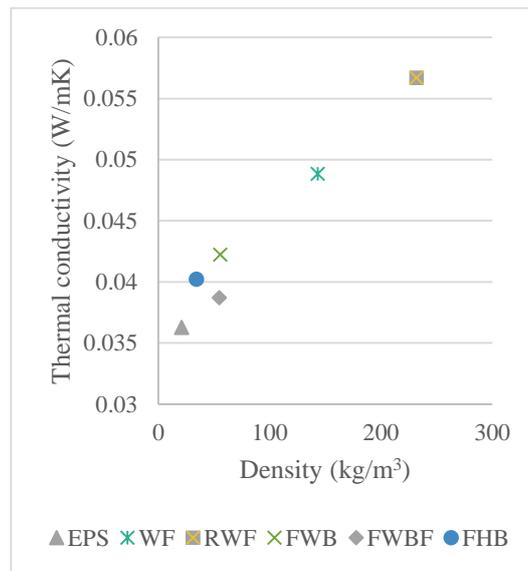
Figure 1. Relationship between the density and thermal conductivity of bio-based insulations and EPS.
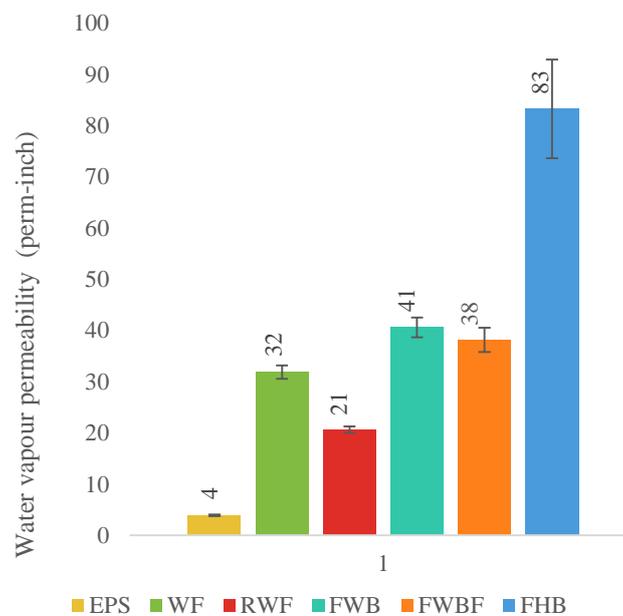
Figure 2. Water vapor permeability of bio-based insulations and EPS.

Table 1. Building materials permeance classification.

Vapor Impermeable	0.1 Perm or Less
Vapor semi-impermeable	1.0 perm or less and greater than 0.1 perm
Vapor semi-permeable	10 perms or less and greater than 1.0 perm
Vapor permeable	greater than 10 perms

Materials with a permeance inferior to 0.1 perm are classified as impermeable. The semi-impermeable category includes materials with a permeance between 0.1 and 1 perm. Below 10 perm and greater than 1 perm, EPS is in the category semi-permeable. With values greater than 10 perm, the wood and hemp-based panels are in the class of permeable materials. Because of the hygroscopic nature of wood and hemp fibers, these materials can react with the environment to reach an equilibrium moisture content.

Truly, even with a similar density and thermal conductivity, FWBF outperforms EPS due to its different core structure. While EPS is characterized by closed porosity with quasi-nonexistent diffusion between the cell walls, the combination of porosity and interlaying wood fibers in FWBF is ideal for good vapor permeance and thermal resistance. Made with only wood fibers interconnected with each other through heating and pressing with a wax emulsion, the great vapor permeance for RWF indicates its ability to transfer water vapor from a humid environment to a dryer one. Compared to the OSB vapor permeability of 30 perm [15], RWF, with a vapor permeability of 26, is not significantly different. Hence, as it was supposed, natural fiber insulation performs differently than EPS in cases of water leakage by allowing vapor transport to occur in the envelope. The presence of vapor can be critical when reaching the dew point, causing condensation to occur within the wall. Mold, decay and corrosion are signs of envelope failure [17].

2.3. Fire Behavior

2.3.1. Heat Release and Ignition

Fire behavior was studied using the cone calorimeter method. The curves for the heat release rate (HRR) of each sample are presented in Figure 3. Other fire behavior aspects, such as time to ignition, peak of heat release rate, carbon monoxide yield and smoke production are presented in Figure 4. The rapidity, intensity and length of burning may be observed through the shape of the HRR curve. EPS shows the longest time before ignition (28.0 s), represented by a high peak of heat release rate (338 kW/m^2), followed shortly by a second uptake before the heat release rate continually decreases until the material is completely burned. These values are representatives of Hidalgo's thesis. For a sample of EPS under an incident radiative heat flux of 45 kW/m^2, the ignition time was 27 s and the peak of HRR between 364 to 373 kW/m^2 [18]. As for the wood and hemp fiber products, the time to ignition and the peak of heat release rate were almost synchronous. Furthermore, for natural materials, the peak of heat release rate was not as high as EPS, but the tendency was that the denser the material, the higher the energy released. A lower density implies a faster propagation of heat inside the material. Emitting less energy while burning means that the fire load is reduced, and that it would be less likely to contribute to the early stage of a fire when compared to EPS. While the HRR of EPS rose to high levels, its contribution to time to fire was limited due to its fast consumption, as observed by an intense decrease after the second peak. For all natural fiber materials, the HRR reached its peak after ignition and dropped to almost a constant level until the entire combustion of the specimen had occurred. This behavior is associated with the thermal degradation of the material. When wood is burning, the dehydration of cellulose and the repolymerization of levoglucosan lead to the formation of aromatic structures and transform wood into graphitic carbon, commonly known as char. The three polymeric constituents of wood, i.e., cellulose, hemicellulose and lignin, are transformed into a mixture of volatile gases, tar (levoglucosan) and carbonaceous char with a distinct thermal decomposition level. With the lowest temperature of decomposition, hemicellulose starts to degrade at 180 °C to 350 °C. Cellulose follows when temperatures reach 275 °C to 350 °C, and then lignin at 250 °C to 500 °C [19]. With the aid of a pilot flame, like in the cone calorimeter test, the flaming combustion associated with pyrolysis is initiated at a temperature between 225 °C and 275 °C. While lower than with EPS, all samples presented a second HRR peak. Consistent with their respective order of decomposition, the HRR curve for natural fibers presents first the degradation of hemicellulose, with a shoulder before the highest peak of HRR due to cellulose, and then a lower tail related to the degradation of the lignin [20]. This quantity of released energy occurs when the entire sample consumes itself. The RWF demonstrates distinctive behavior by showing three major peaks after the initial peak of ignition. The aspect of the curve indicates that each of the three layers in the panel burns successively.

2.3.2. Smoke Obscuration

One of the most characteristic differences between samples is smoke production. As the units depended upon the burned area and not the mass of the sample, there was an important gap between wood-based fiberboards of different densities. Having more substance to burn, with longer combustion times, the two rigid wood fiberboards released more smoke than the low density batt insulation samples. On the other hand, despite having the same density, EPS (845 m^2/m^2) and the wood batt insulations demonstrated the biggest differences of smoke production, with a 32 times higher value for the expanded polystyrene. Ostman [21] noted that during combustion, wood releases smoke at a quantity of 25–100 m^2/kg, which is far less than synthetic polymers that can produce hundreds of thousands of m^2/kg. Regarding the safety of the occupants in a building, smoke release is a particularly important aspect. Indeed, the gases that are released during combustion are not only toxic and irritants, but they also considerably reduce the visibility needed to escape. On this fact, EPS is the poorest choice of insulation here, if only looking at smoke emissions.

2.3.3. Toxic Gases

The products of wood combustion are carbon monoxide, carbon dioxide and water. The use of a fire retardant can add toxic components to the smoke and increase the yield. However, it can lower the rate of burning and, therefore, decrease the smoke production rate, providing a longer evacuation time. Affecting the cognitive functions of occupants and influencing their ability to take effective actions to find safety, carbon monoxide is a toxic gas which needs to be taken into account when anticipating fires. The yield factor of CO (g/g) is the mass of gas generated divided by the mass of the specimen consumed. FWB (0.099 g/g) presents the highest carbon monoxide yield, followed by EPS, albeit the latter is far behind, with two times fewer emissions (0.051 g/g). The presence of polyolefin fibers in the FWB could explain this result. According to their difference of density, the air concentration of CO would be greater in the case of burning the same volume of material for RWF compared to EPS. While looking at bio-based materials, additives for binding or to protect from mold, insects or fire have an impact on the amount of toxic gases released. There is a common goal among scientists to develop complete bio-based solutions for building materials. The use of tannin-based glues makes up part of these efforts.
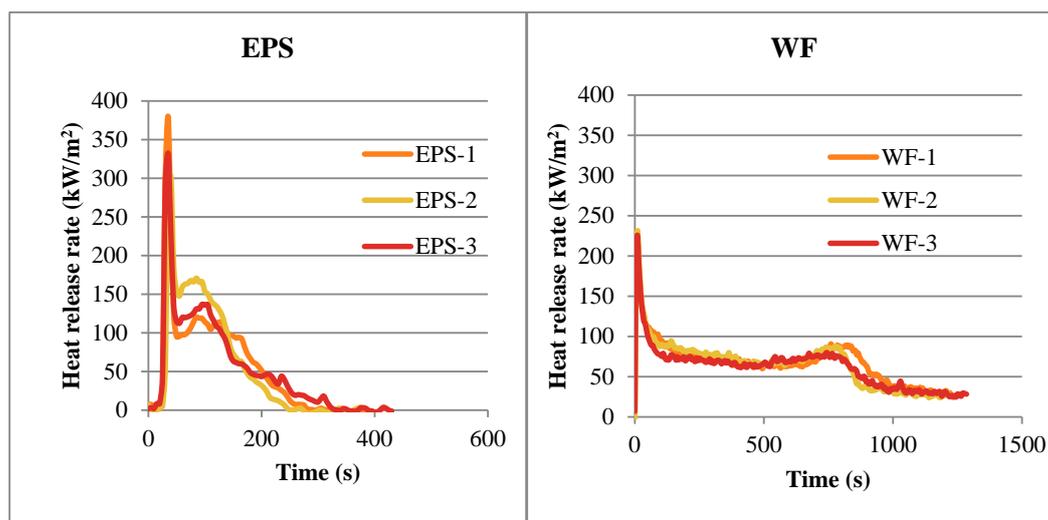
Figure 3. *Cont.*
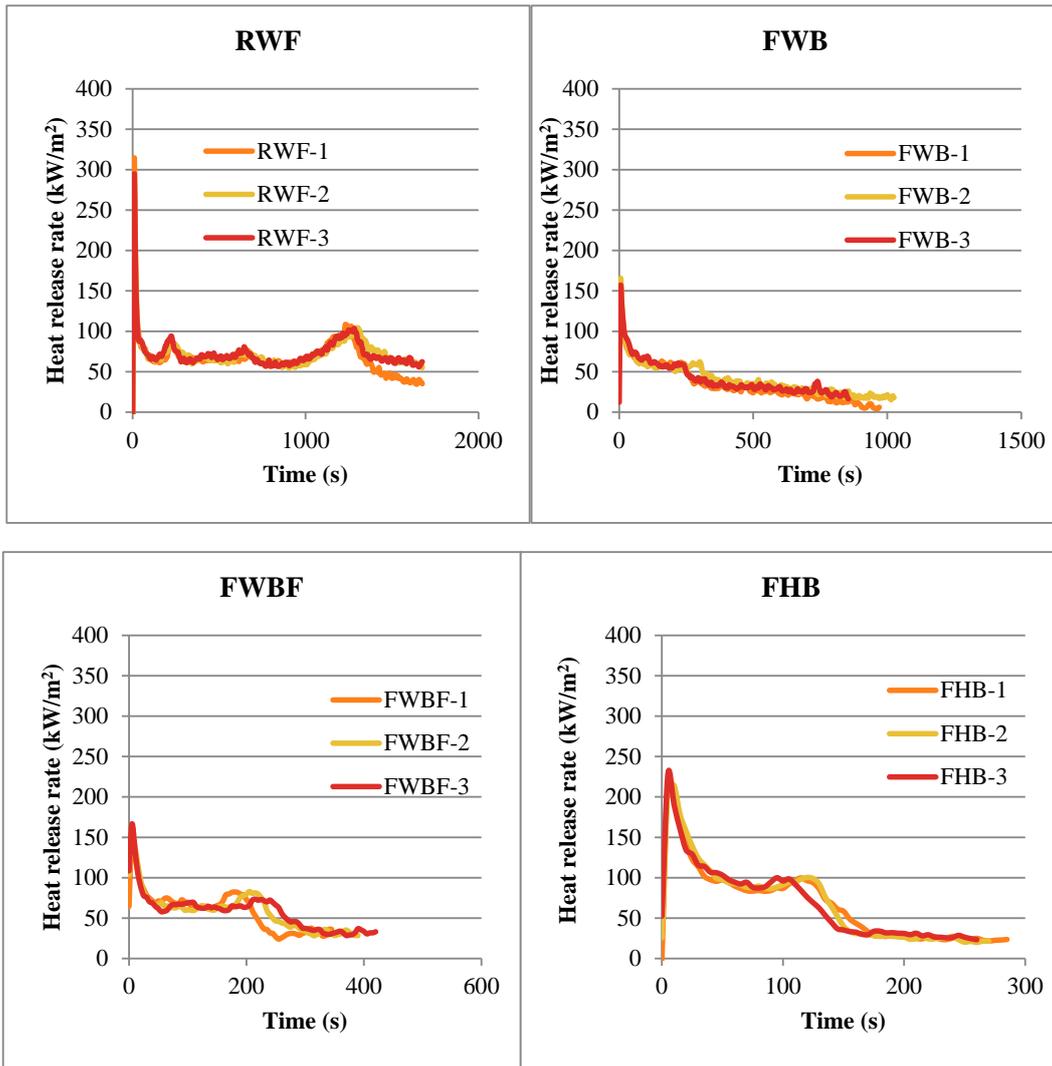
Figure 3. Heat release rate of EPS and five bio-based insulation materials.
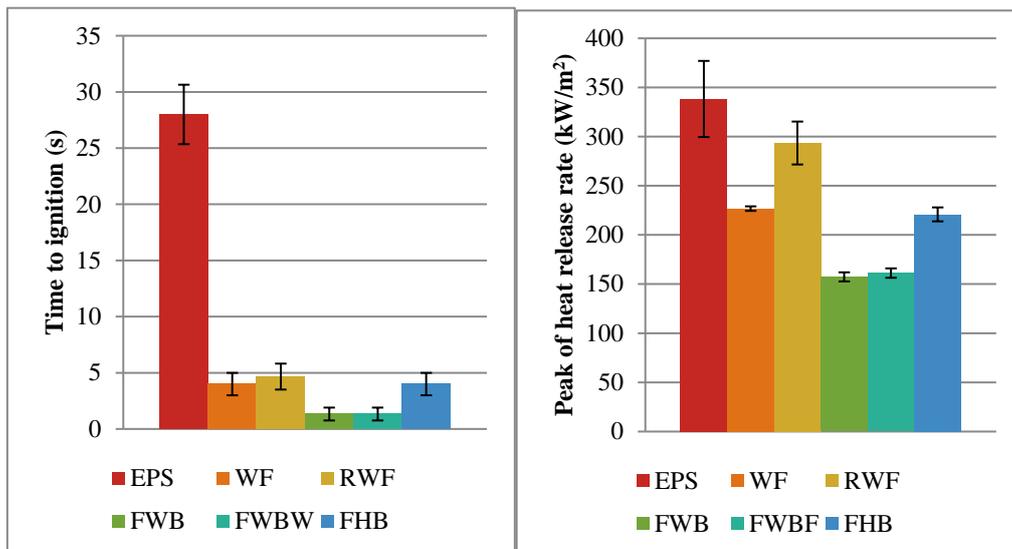
Figure 4. *Cont.*
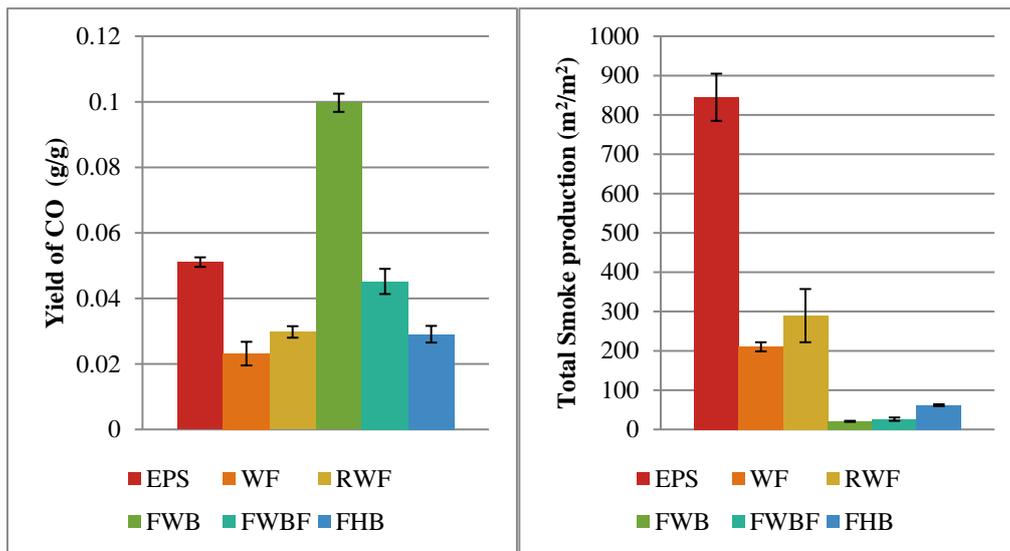
Figure 4. Time to ignition, peak of heat release rate, carbon monoxide yield and total smoke release for EPS and five bio-based insulation materials, determined via the cone calorimeter test.

2.4. Relative Assessment

To illustrate the relationships between the attributes of the insulation materials studied here, a relative assessment is presented in the form of a radar chart in Figure 5. The extremes of each category can easily be detected. Thermal conductivity was inversed to obtain thermal resistance in order to better represent the overall performance. The same process was applied to total smoke release, the peak of HRR and the carbon monoxide yield. With this modification, the largest surface is considered as the favorable case. The overall layout of EPS is distinct from the bio-based materials, with a maximal score for time to ignition and thermal resistance. Looking at the thermal performance, there is no significant gap between the studied samples; this was expected, given that these materials were chosen with the aim of fulfilling the function of limiting heat transfer in a building. However, their behavior of mass transfer differs more significantly. Water vapor can diffuse through materials, or can simply be transported by air in the case of deficient airtightness. The use of vapor-permeable materials in the envelope would ensure that the drying of the envelope would be achieved in case of humidity infiltration. Having a geometry of loosely-intertwined tapered fibers, the hemp fiber batt demonstrated twice the ability of other fiber-based materials to let water vapor flow. On the fire safety side, the principal point of interest is smoke release, due to its impact on the ability to breathe. The amount of smoke release for natural insulation is less than thrice that of the synthetic based one. Other than smoke, combustion leads to the release of toxic gases. This is a concern to consider when choosing adhesives to include in bio-based materials. Here, the polyolefins added to the wood batt insulation led to a significant amount of carbon monoxide being emitted. Globally, the technical behavior of insulation products made from different natural fibers present the same trend. They provide proper thermal resistance with advantageous water vapor permeability, and although they are combustible, demonstrate safer combustion behavior than polystyrene.
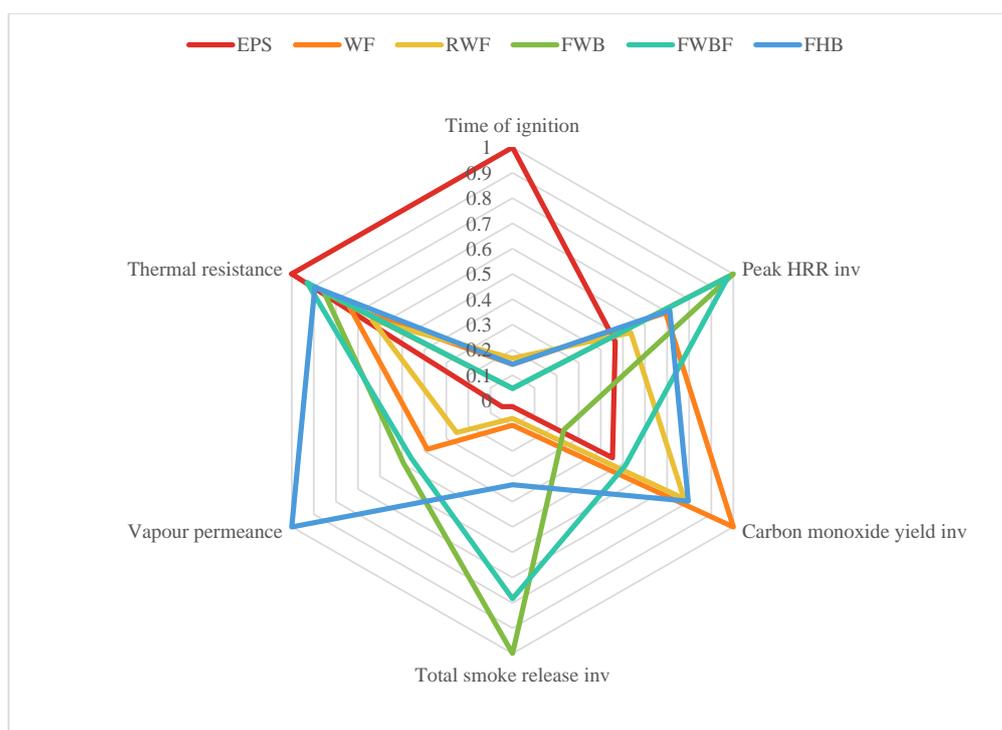
Figure 5. Relative assessment of the attributes of the studied insulation materials.

3. Materials and Methods

3.1. Materials

Five bio-based materials (Table 2) were compared with expanded graphite polystyrene (EPS), a common insulation material in SIP. EPS was manufactured by Isolofoam (Canada) [22]. Using a dry process, STEICO (Poland) manufactures wood fiberboards (WF) for external insulation with airtightness and weatherproofing properties. Polyurethane resin is the bonding agent in this process. Incorporating locally-sourced recycled wood fibers, the SONOclimat ECO4 (35 × 1220 × 2440 mm) is a recycled wood fiberboard (RWF) manufactured through a wet process and supplied by MSL in Louiseville (Canada) [23]. To represent low density flexible wood batt insulation (FWB), STEICO flex 036 was chosen. The ingredients entering the production were wood fibers, polyolefin fibers and paraffin wax. Still in the low density fiberboard product group, the ultra-low density composite was provided by FPInnovations (Canada). The boards received in dimension of (39 × 560 × 1270 mm) were produced according to the patent WO2015066806A1 Method of producing ultra-low density fiber composite materials [14]. The product was labelled in this study as flexible wood batt with foaming process (FWBF). Hemp was considered by adding a new product offered by NatureFibres, a company based in Asbestos (Canada). Their flexible hemp batt (FHB) insulation competes directly with wood batt insulation. Consistent with the different testing methods used in this study, the panels were cut to sample size and conditioned in an environmental chamber at 20 °C and 65% HR.

Table 2. Insulation products included for characterization.

Sample Abbreviation	Product	Commercial Name	Manufacturer
EPS	Expanded graphite polystyrene	Iso R plus Premium	Isolofoam (Canada)
WF	Wood fiberboard	STEICO internal	STEICO (Poland)
RWF	Recycled wood fiberboard	SONO climat ECO4	MSL (Canada)
FWB	Flexible wood batt	Steico flex036	STEICO (Poland)
FWBF	Flexible wood batt with foaming process	Ultra-low density composite (R&D state)	FPInnovations (Canada)
FHB	Flexible hemp batt	Naturechanvre	Naturefibres (Canada)

3.2. Thermal Conductivity

The thermal conductivity was determined by means of the heat flow meter method described in ASTM C518 [24]. The Lasercomp FOX 314 Heat Flow Meter (TA Instruments, New Castle, DE, USA) allowed us to test samples of thickness up to 102 mm with an area of 300 mm^2. The specimen ($35 \times 150 \times 150$ mm) was inserted between two plates of user-defined temperature. To achieve a temperature gap of 25 °C, the lower plate was set to 15 °C and the upper one to 40 °C. Four in-built encoders detected the actual sample thickness used in the data calculations. The heat flux from a steady state heat transfer through the specimen was determined by a heat flux transducer located in the center area of each plate. Using the thermal conductivity of a calibration standard, the thermal conductivity of the studied material could be evaluated.

3.3. Water Vapor Transmission

The water vapor transmission properties of the materials were determined using the water method described in ASTM E96 [25]. Glass jars were filled with water to a level of 38 mm from the mouth. The round samples of 60 mm diameter and 12.7 mm thickness were then sealed with silicone at the upper limit of a glass jar's aperture. The screw lid with an opening of 61 mm was attached. The dish assembly was weighed before being placed in a conditioned chamber at 50% HR and 21 °C. The weight and time of measurement were recorded periodically. The test finished when the change in mass was constant over six weighings. The slope of the straight line on the graph of weight change over time was used to calculate the water vapor transmission (WVT) properties as follows:

Water Vapor Transmission:

$$WVT = (G/t)/A \tag{1}$$

G = weight change (g)
t = time (h)
G/t = slope of straight line (g/h)
A = test area (m^2)
WVT = rate of water vapor transmission (g/hm^2)
Permeance:

$$Permeance = WVT/\Delta p = WVT/S(R_1 - R_2) \tag{2}$$

Δp = vapor pressure difference in mm Hg
S = saturation vapor
R_1 = relative humidity in the dish (100%HR)
R_2 = relative humidity in the controlled chamber (50%HR)

3.4. Fire Behaviour

The cone calorimeter (Figure 6) was chosen to evaluate the fire behavior of the insulation materials in the spirit of the ISO 5660 method, as suggested by Dagenais [26]. Some parameters pf fire behavior like ignitability, flammability, and smoke and gas release could be evaluated with this apparatus. A specimen was placed in a sample holder oriented horizontally with a spark-igniter just above it. A highly insulating material such as mineral fibers was lay down under the sample. The truncated cone was heated to produce a uniform and common testing radiant heat flux of 50 kW/m^2 across the surface of the 10 cm × 10 cm specimen. On top of the truncated cone, the exhaust hood collected the smoke and hot gases released after ignition. The concentration of various gases was analyzed in the exhaust system. To determine the heat release rate (HRR), the calculation was based on the general hypothesis developed by Huggett [27] that the amount of oxygen required for complete combustion is proportional to the net heat of combustion, or more precisely, that 13.1×10^3 kJ of heat is released per kilogram of oxygen consumed. With the addition of a calibration constant determined by burning methane of at least 99.5% purity, the combustibility parameters can be calculated [28]. These fire tests

were realized at FPInnovations' Materials Evaluation Laboratory in Quebec City (Quebec). The heat release rate curve over time can be traced. The time to ignition is an important variable as it indicates the flammability of the material. Other parameters such as the mass loss rate, smoke production and carbon monoxide release help to predict the hazard behavior of the product in case of a building fire.
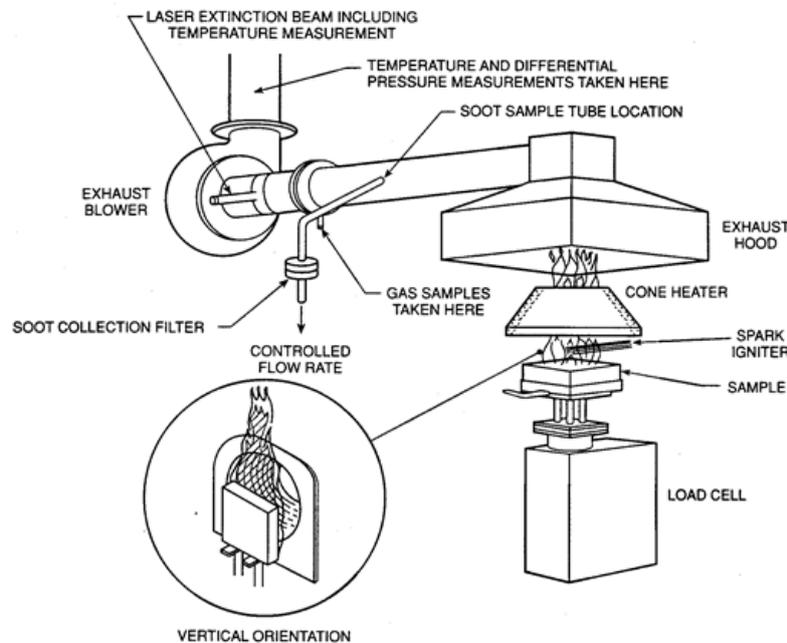
Figure 6. Small-scale cone calorimeter used in this study (Hurley).

4. Conclusions

The aim of this study was to evaluate and compare the technical performance of five bio-based insulation materials with a conventional, synthetic-based insulation, i.e., expanded polystyrene. The low density wood batts manufactured through a dry process (FWB) or a wet one with gas injection (FWBF) demonstrated densities and thermal conductivities in the same range as EPS. The wood fiberboard (WF) and recycled wood fiberboard (RWF) were designed as external rigid insulation boards with superior density. While comparing well to OSB in its vapor permeability ability, the thermal resistance was far greater than that of the traditional sheeting product. However, the best product in terms of the transport of water vapor was the flexible hemp batt (FHB) insulation, with a permeability almost twenty-five times higher than that of EPS. This attribute is significant for evacuating moisture in case of water leakage, and limiting the development of mold and decay. The intertwined pattern of longer hemp fibers allows the transport to occur of humidity, not only by vapor diffusion, but also by convection through the interstices.

Regarding fire behavior, low density batt insulations were consumed faster than EPS, but release a significantly lower amount of energy and would not be an enhancing component in the early stages of a fire. All wood and hemp-based insulations have the advantage of releasing smaller amounts of smoke than EPS. Smoke production is problematic in many respects, among which is the possibility that it will prevent occupants from safely finding an exit. The carbon monoxide yield was also lower for most of natural fibers materials compared to the EPS.

In the end, the properties of the bio-based insulations were not similar to the conventional expanded polystyrene on every studied aspect. Consequently, it is not possible to replace synthetic-based insulation with natural insulation without adjusting the end-use. As for the hemp and wood batt insulations, they could be used as the main core insulation in a box insulated panel bearing a heavy load, or simply in the cavities between wood frames, as mineral wool is used. Therefore, mastering the properties of bio-based insulation may allow architects and building designers to properly design

building envelopes in low environmental impact buildings. There is not an extensive range available of sustainable insulation products with densities and thermal resistances similar to those of EPS. Low density bio-based materials will provide an environmentally friendly solution to replace organic foams as building insulation. Eliminating synthetic-based materials with significant embodied energy will help to reduce the environmental impact of the construction industry, even more so in areas where energy is produced at a low environmental cost. There is a need to assess the overall hygrothermal behavior of bio-based material in building envelopes. Validation of the safety of these natural fiber materials regarding the risk of mold development will be performed in a future study. The finite element method will be used to simulate different levels of air leakages inside the envelope with numerical models.

Conflicts of Interest: The authors declare no conflict of interest.

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