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Sustainable Wood-Waste-Based Thermal Insulation Foam for Building Energy Efficiency

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Abstract: Wood is one of the most abundant biomaterials on Earth, which has been used for centuries in construction applications including furniture, roofing, flooring, and cabinetry. However, wood chips—which are a low-quality and plentiful waste byproduct of lumber milling, woodworking, and shipping operations—have low economic value and complicated disposal methods. In this paper, we propose a strategy for wood chip reuse through the fabrication of bio-based building insulation foam. Through a high-temperature chemical treatment delignification process, we introduced additional small pores within the wood chips, effectively lowering their thermal conductivity, and used them in combination with a binding agent to produce a porous insulation foam. The porous insulation foam achieved a low thermal conductivity of 0.038 W/(m·K) and a high compressive strength of 1.1 MPa (70% strain). These characteristics demonstrate that wood waste can be repurposed into an effective building material, addressing challenges in both waste management and sustainable construction.

Keywords: buildings; thermal comfort; thermal insulation; wood waste

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1. Introduction

Around the world, building operations account for approximately 40%, or 10 gigatonnes, of total carbon dioxide (CO_2) emissions because of the energy-intensive process of producing building materials and maintaining construction operations [1]. Heating, ventilation, and air conditioning (HVAC) systems, which are the dominant source of energy use in buildings, are a key component for curtailing CO_2 emissions [2]. In particular, a building's thermal insulation plays a critical role in its overall energy efficiency, where a product with low thermal conductivity is desired to maintain a more consistent and comfortable indoor temperature with lower energy consumption. Some examples of common commercially available building insulation products include mineral wool, expanded polystyrene, extruded polystyrene, and polyurethane [3]. While these insulation materials are readily available and offer relatively low thermal conductivities (~0.030–0.040 W/(m·K) for mineral wool, expanded polystyrene, and extruded polystyrene [3]; 0.025–0.046 W/(m·K), depending on moisture content, for polyurethane [3]), many products rely on petroleum-based materials, posing challenges for the solid waste industry because of the complicated disposal process for plastics [3]. Instead, using low-carbon products can decrease CO_2 emissions from the building materials' fabrication process by over 80% [1]. Thus, the fabrication of environmentally friendly building insulation materials can offset the production of petroleum-based materials, repurpose waste, and enhance building energy efficiency.

The global market for bio-based insulation is expected to reach USD 229 million by 2027, with a compound annual growth rate of 23.1% from 2022 to 2027 [4]. Wood specifically is a promising biomass building material due to its CO_2 sequestration during growth, natural availability, favorable mechanical strength, durability, and ability to be processed into high-performance engineered materials [5–7]. As an abundant waste byproduct from various milling, woodworking, and shipping operations, wood chips (e.g., sawdust) have low economic value and complicated disposal methods [8]. Depending on the source, some wood can be recycled (i.e., wood from shipping pallets), while other wood is instead sent to landfills (i.e., wood from construction and demolition debris) [9]. Wood chip repurposing strategies include use in products such as mulch, particle board, oriented strand board, and building insulation [10]. Researchers have discovered that it is possible to use biomass-based materials (e.g., wood waste) to fabricate environmentally friendly and thermally efficient insulation products [11,12]. For example, Merli et al. prepared environmentally friendly panels from wood waste through hot-pressing and hand-assembling techniques with vinyl and flour glue binder [11]. Similarly, Cetiner et al. prepared thermal insulation from wood waste through the wet-spray and loose-fill methods without binder [12]. A typical application for these environmentally friendly building insulation materials is the use in wall construction systems such as timber framing [12]. Unfortunately, many wood-based insulation materials have only been shown to achieve a thermal conductivity in the range of 0.048–0.084 W/(m·K) [11,12]. One explanation for this high thermal conductivity range may be the large percentage of binding agents (e.g., 25% vinyl glue and 60% flour glue) used in the insulation fabrication process, which is necessary to form a cohesive bond with the natural wood waste [11]. Another explanation may relate to the structure and size of the pores in the wood, as the lower porosity of natural wood could enable heat transfer via conduction throughout the voids of the cell lumina [13]. Because of the crucial function of pores in the overall thermal transfer, the creation of additional small voids through chemical treatment can serve as an effective method for increasing the tortuosity of the heat transfer pathway, thus decreasing the overall thermal conductivity [14,15].

We propose the fabrication of an environmentally friendly building insulation material using delignified waste poplar wood chips in combination with a bio-based binding agent. In the wood chips, the additional micropores introduced from the reduction in lignin and hemicellulose contents during the delignification process improve the thermal insulation performance by creating extra voids and extending the length of the heat transfer pathway (Figure 1a). Our bio-based insulation is made by foaming natural or delignified wood chips with a high viscosity carboxymethylcellulose sodium salt (CMC) adhesive binder. Foaming with binder maintains the foam's structure in comparison with that of a foam without binder. The porous insulation foam can be easily fabricated in two steps: (1) delignifying the wood chips through high-temperature chemical treatment and (2) foaming the wood chips with CMC binder by mixing in ambient conditions (Figure 1a,b). This novel and sustainable porous insulation foam with low thermal conductivity and sequestered CO_2 can both replace typical landfill-consuming petroleum-based products and outperform the thermal conductivity of natural insulation materials such as cork [16], cotton [17], flax [17–21], hemp [17–21], sea grass [22], straw bale [23], coconut [24], cellulose fibers [25], reeds [26], sheep's wool [27], and wood waste [11,12] (Figure 1c). The size of our newly fabricated porous insulation foam is ~100 mm × 100 mm × 20 mm, but this method can be scaled-up to any desired size (Figure 1d). With a low thermal conductivity of 0.038 W/(m·K) and a high compressive strength of 1.1 MPa (70% strain), the porous insulation foam demonstrates that wood waste can be repurposed into an effective construction material suitable for building envelope applications such as wall assemblies.

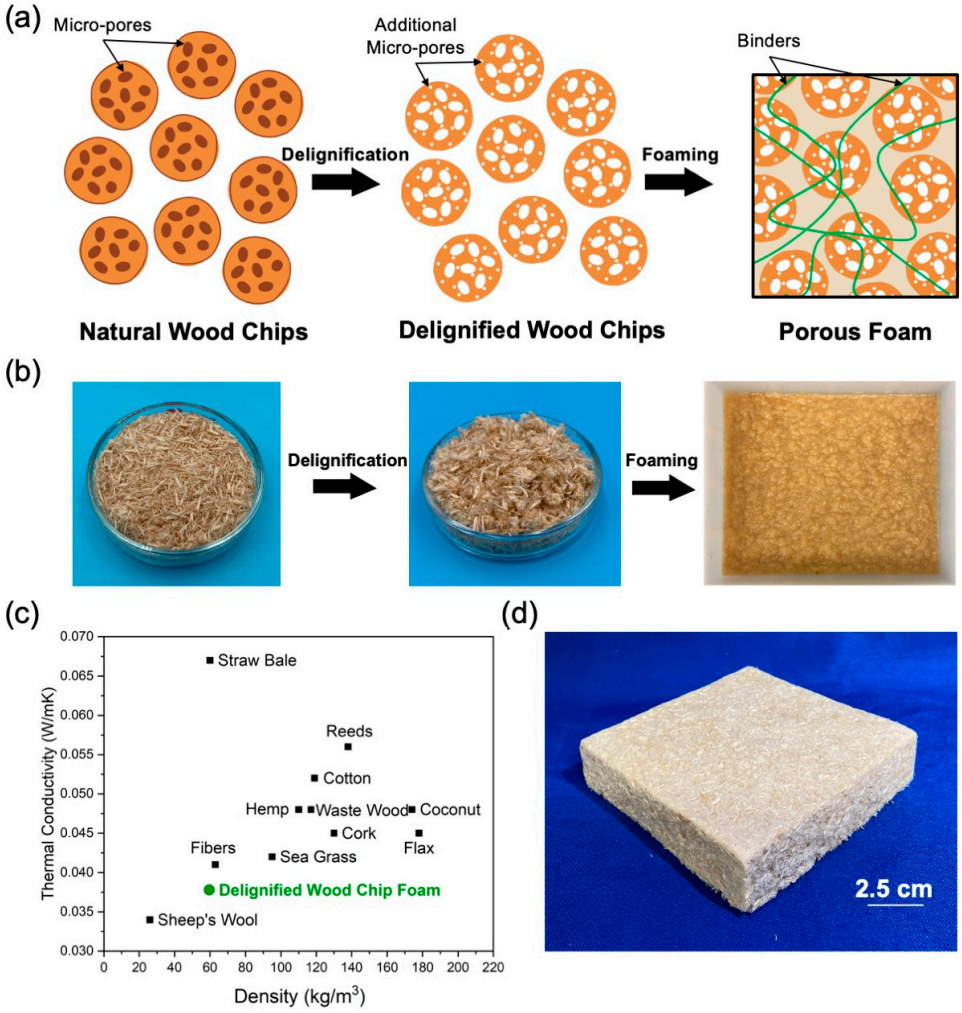


Figure 1. Fabrication process. (**a**) Detailed schematic and (**b**) photographs of the foaming fabrication process. (**c**) Thermal conductivity comparison of various bio-based thermal insulation materials. (**d**) Newly fabricated porous foam from delignified poplar wood chips.

2. Materials and Methods

2.1. Materials

2.1.1. Materials and Chemicals

We selected poplar wood (Populus deltoides Bartr. ex Marsh × P. nigra L.; density 0.3–0.39 g/cm^3, ~30% hemicellulose, and ~20% lignin) because of its appealing properties, including low cost, ubiquitous abundance, and quick growth [28]. Poplar was harvested from the Hugo Sauer Nursery (Rhinelander, WI, USA), debarked and chipped at the USDA Forest Service Forest Products Laboratory (Madison, WI, USA), and frozen before shipping. The hammermilled poplar wood chips (passing through a 1/4" screen) were used as a starting material for the insulation foam. Sodium hydroxide (NaOH, >97%) was purchased from Sigma-Aldrich (St. Louis, MO, USA) and used in combination with deionized (DI) water.

2.1.2. Preparation of Delignified Wood Chips

To prepare for chemical treatment, the wood chips were dried to constant weight at 103 °C overnight (according to ASTM D4442) and moisture-conditioned at ambient conditions (relative humidity ~50% and temperature ~20 °C) for 24 h (according to ASTM D4933) [29,30]. The wood chips were then soaked overnight in a 5 wt.% NaOH solution, boiled, and washed with DI water until reaching a neutral pH. Next, the delignified wood chips were dried to constant weight at 103 °C overnight (according to ASTM D4442) and

moisture-conditioned at ambient conditions (relative humidity ~50% and temperature ~20 °C) for 24 h (according to ASTM D4933) [29,30].

2.1.3. Preparation of Bio-Based Binder

The incorporation of binders allows the delignified wood chips to form a lightweight yet strong porous network. Though typical binders used in wood-based insulation foams include epoxy resin [31], flour glue [11], and sucrose [32], CMC was selected because of its widespread use in composite materials, sustainable composition, high viscosity (1500–3000 centipoise for a 1% solution), and ability to be activated into a gel-like solution [33]. The CMC powder, purchased from Sigma-Aldrich, was measured and combined with DI water in a beaker with a stir bar and mixed at room temperature on a hot plate stirrer. After the majority of the CMC was dissolved into the beaker containing DI water, the mixture was heated and stirred overnight to allow for complete solubility of the CMC. Finally, the mixture was removed from the hot plate stirrer and cooled to ambient conditions (relative humidity ~50%, temperature ~20 °C) before use.

2.1.4. Fabrication of Thermal Insulation Foams

A square silicone mold was used to fabricate the thermal insulation foam samples. The CMC binder, already combined with DI water into a gel, was added to a dish with the prepared wood chips. The CMC–DI water–wood chips mixture was stirred by hand with a glass stirring rod for 2 min before being poured directly into the silicone mold. The silicone mold was then gently tapped to remove air bubbles from the CMC–DI water–wood chips mixture. The silicone mold was transferred to a chest freezer (−20 °C) and left to freeze for ~12 h. The frozen silicone mold containing the CMC-DI water-wood chips mixture was then transferred to a freeze dryer (−83 °C) until all of the water was removed (>48 h, depending on the silicone mold and foam size).

2.2. Methods

2.2.1. Characterization of Natural and Delignified Wood Chips

Density measurements were taken to understand the effect of the delignification process on the wood chips. Each measurement was independently taken three times. A scanning electron microscope (TESCAN, Brno, Czechia, XEIA SEM) was used to characterize the morphology of the natural and delignified wood chips. A Fourier transform infrared instrument (Thermo Nicolet, Waltham, MA, USA, NEXUS 670 FTIR) was used to characterize the FTIR spectrum of the natural and delignified wood chips. The attenuated total reflectance (ATR) method was used over the range of 4000 to 400 cm^{-1}, with less than a 0.1 cm^{-1} resolution and 32 scans per sample. Each sample was observed at least five times, and the baseline was subtracted.

2.2.2. Characterization of Thermal Insulation Foams

A heat flow meter (Thermtest, Hanwell, NB, Canada, HFM-25) was used to characterize the thermal conductivity of the natural and delignified wood chip foam samples. Each measurement was independently taken three times. An optical microscope (ShenZhen Andonstar Technology, Shenzhen, China, AD207S) was used to characterize the morphology of the natural and delignified wood chip foam samples. An infrared camera (FLIR Merlin MID E8) was used to visualize the temperature distribution response of the natural and delignified wood chip foam samples. A universal testing machine (Instron 3367) was used to characterize the compressive strength of the natural and delignified wood chip foam samples. The testing system had a load capacity of 30 kN, and the compressive strength was evaluated with a crosshead speed of 5 mm/min.

3. Results and Discussion

3.1. Fabrication and Characterization of Natural and Delignified Wood Chips

The main heat transfer mechanism in wood is thermal conduction via the solid materials of the cell walls and the air voids present between the pores of adjacent channels. By removing the lignin between the neighboring channels of the wood and introducing additional pores, it is possible to effectively suppress thermal transport [34]. As a result, the delignified wood chips are better suited for use in thermal insulation materials due to their reduced thermal transport. In addition, the delignification process exposes more surface area of the cellulose, thus enhancing the ability to form a stable foam [35]. The wood chips before and after delignification are shown in Figure 2a,b. Unlike the natural wood chips, the delignified wood chips had a lower density due to the removal of lignin and hemicellulose after chemical treatment (Figure 2c), from 0.087 g/ cm^3 (before delignification) to 0.053 g/cm^3 (after delignification). Note that these density measurements were performed three times for oven-dried wood chips. SEM images confirmed the removal of lignin and hemicellulose after treatment (Figure 2d,e,g,h). Note the presence of solid material (i.e., lignin and hemicellulose) in the middle lamella region between neighboring fibers of the natural wood before treatment (Figure 2d,g). Due to the reduction in solid materials (i.e., lignin and hemicellulose) from chemical treatment, the delignified wood chips have additional pores and separation between adjacent fibers, thus resulting in an altered geometric structure of the delignified wood (Figure 2e,h) [36]. Additionally, as shown in Figure 2f, the removal of lignin and hemicellulose from the wood chips was confirmed by the differences (as shown along the black dashed lines) between the FTIR spectra of the natural (red) and delignified (blue) wood chips. Peaks at 1030 cm^{-1} were seen in both samples and were attributed to the cellulose backbone. The removal of the peak at 1737 cm^{-1}, which arises from the C=O (double bond) stretching, and the reduction in the peak's intensity at 1236 cm^{-1}, which arises from C-O (single bond) stretching, indicate the removal of hemicellulose from the natural wood after the delignification process [37–39]. The decreases in the intensity of the peaks at 1648 and 1591 cm^{-1} and the absence of peaks at 1504 and 1460 cm^{-1}, which correspond to the lignin designation of the aromatic skeleton stretching vibrations, indicate the successful removal of lignin after the delignification process [40,41]. The differences between the FTIR spectra demonstrate the reduction in the hemicellulose and lignin contents of the treated delignified wood chips.

3.2. Fabrication and Characterization of Wood-Chip-Derived Thermal Insulation Foams

In a typical process, we mixed the source material (wood chips) with the binder (CMC) and DI water using a glass stirring rod. The wood chips were mixed with CMC binder concentrations of 0, 5, 10, and 15 wt.% until a wet mixture was formed. Both dried wood chip foam samples shown in Figure 3a (natural) and Figure 3b (delignified) contained 15 wt.% CMC binder. To evaluate the thermal performance of the wood chip insulation, the HFM-25 was used. During measurement, the HFM-25 uses a steady state one-dimensional heat flux to evaluate the response of a sample when placed between two parallel plates, where the upper (hot) plate and the lower (cold) plate have a set temperature difference of 20 °C. This machine works by performing a calibration test and using the results to evaluate the thermal conductivity performance of an unknown sample. In a typical experiment, we first conducted the calibration test and then put the sample into the chamber between the two plates for testing, where a heat flux sensor calculated the sample's thermal conductivity after achieving a steady state (usually ~0.5–1 h). Each measurement was performed three times, independent of one another. Figure 3c demonstrates a comparison of the thermal conductivities of the natural and delignified 15 wt.% CMC binder wood chip foams, where the delignified wood chip foam has a lower thermal conductivity (0.038 W/(m·K)) compared with that of the natural wood chip foam (0.039 W/(m·K)). The natural wood chip foam shows rigid "bundles" of fibers via optical microscope (Figure 3d) and SEM (Figure 3g) images. On the other hand, the delignified wood chip foam shows an interlocking "network" of fibers via optical microscope (Figure 3e) and SEM (Figure 3h) images. To further illustrate

the thermal insulation performance of the wood chip foams, an infrared thermal camera was used to map the temperature distribution. Pieces of foam (2.5 cm × 2.5 cm × 2.5 cm) were cut and placed on top of a hot plate. After being heated for 30 min at 100 °C on the hot plate, both the natural and delignified 15 wt.% CMC binder wood chip foams demonstrated similar thermal behavior, as shown by the distribution map measured with the infrared camera in Figure 3f. This temperature mapping verified the thermal conductivity findings of the HFM-25 (0.038 W/(m·K) for the delignified wood chip foam and 0.039 W/(m·K) for the natural wood chip foam) and demonstrates the delignified wood chip foam's suitability for use as a thermal insulation material. Measuring compressive strength can provide information about the foam's mechanical properties. Figure 3i demonstrates the compressive stress–strain curves for both the natural and delignified 15 wt.% CMC binder wood chip foams. The inserted image shows a 2.5 cm × 2.5 cm × 2.5 cm piece of 15 wt.% CMC binder delignified wood chip foam loaded into an Instron 3367 testing apparatus. As the strain increased for both samples, the compressive strength of only the delignified wood chip foam significantly increased. When the compressive strain was 70%, the compressive strength of the 15 wt.% CMC binder delignified wood chip foam achieved 1.06 MPa, demonstrating a more than six times higher performance than the 15 wt.% CMC binder natural wood chip foam of only 0.17 MPa. To understand the effect of moisture on the mass, thermal conductivity, and strength of the 15 wt.% CMC binder delignified wood chip foam, the sample was conditioned in a high-humidity environment (relative humidity > 95%) for 65 h. Figure 3j compares the mass of the sample before and after moisture conditioning, with the mass increasing from 13.93 g (relative humidity ~50%) to 18.27 g (relative humidity > 95%). Figure 3k demonstrates the change in thermal conductivity before and after moisture conditioning, which drastically increased from 0.038 W/(m·K) (relative humidity ~50%) to 0.072 W/(m·K) (relative humidity > 95%). These results agree with the expected trend set forth by Cetiner et al., where wood-waste-based insulation foam conditioned in a higher-moisture-content environment showed higher thermal conductivity than wood-waste-based insulation foam conditioned in a lower-moisture-content environment [12]. Compression testing revealed that the high-humidity-conditioned sample (relative humidity > 95%) demonstrated a lower compressive strength than the air-conditioned sample (relative humidity ~50%), with the high-humidity-conditioned sample achieving a compressive strength of 0.01 MPa at 10% compressive strain and the air-conditioned sample achieving a compressive strength of 0.03 MPa at 10% compressive strain (Figure 3l).

To understand the relationship between binder content and thermal conductivity, different delignified wood chip foam samples were prepared by varying the CMC binder content, including 0 wt.% (Figure 4a), 5 wt.% (Figure 4b), 10 wt.% (Figure 4c), and 15 wt.% (Figure 4d). The HFM-25 used to evaluate the thermal conductivity performance of the delignified wood chip foam samples is shown in Figure 4e. An example of the calibration sample (NIST 1450, fibrous glass board) can be seen between the upper and lower plates in Figure 4e. The thermal conductivity test results for the delignified wood chip foam samples with varied CMC binder content are shown in Figure 4f. Out of all of the CMC binder content values tested, the 15 wt.% CMC binder delignified wood chip foam featured the best (lowest) thermal conductivity of 0.03785 W/(m·K). These results agree with the trend set forth by Ismail et al., where a wood-waste-based insulation foam with higher binder content (e.g., 15 wt.%) showed lower thermal conductivity than a foam with a lower binder content (e.g., 0 or 10 wt.%) [31]. To evaluate the resistance of the 15 wt.% CMC binder delignified wood chip foam, different temperature ranges were tested, including 10–30 °C, 15–35 °C, 20–40 °C, and 25–45 °C. The thermal conductivity test results for the 15 wt.% CMC binder delignified wood chip foam were evaluated at the mean temperatures (T_{mean}) of the aforementioned temperature ranges. As shown in Figure 4g, the 15 wt.% CMC binder delignified wood chip foam sample experienced a slight increase in thermal conductivity as the mean temperature between the upper and lower plates of the HFM-25 increased (from 0.03785 W/(m·K) at T_{mean} = 20 °C to 0.03982 W/(m·K) at T_{mean} = 35 °C). These results agree with those of Cetiner et al., where

a wood-waste-based insulation foam sample tested using an HFM experienced a lower thermal conductivity at a lower mean temperature (e.g., T_{mean} = 20 °C or 30 °C) than a wood-waste-based insulation foam sample tested at a higher mean temperature (e.g., T_{mean} = 40 °C) [12]. The wood chip foam can be suitable for various applications because it can be prepared in different shapes and sizes depending on the mold used during the fabrication process (Figure 4h). To determine the 15 wt.% CMC binder delignified wood chip foam's potential for use in the construction industry, a preliminary cost analysis was conducted. Using the aforementioned procedure and current prices for chemicals (e.g., NaOH, 0.45 USD/kg [42]), waste wood (e.g., poplar wood chips, 0.125 USD/kg [43]), and binders (e.g., CMC, 1.6 USD/kg [44]), the estimated manufacturing cost for the 15 wt.% CMC binder delignified wood chip foam was calculated to be ~29.06 USD/m^3. This price is in a similar range to that of many commercially available building insulation materials (18–23 USD/m^3 for extruded polystyrene, 25.60–44.70 USD/m^3 for cork, 27–38 USD/m^3 for wood fiber, and 46–62 USD/m^3 for foamed glass) [45]. With process optimization and materials purchased at an industrial scale, as opposed to a laboratory scale, it is thought that the manufacturing cost for the 15 wt.% CMC binder delignified wood chip foam could be reduced even further.

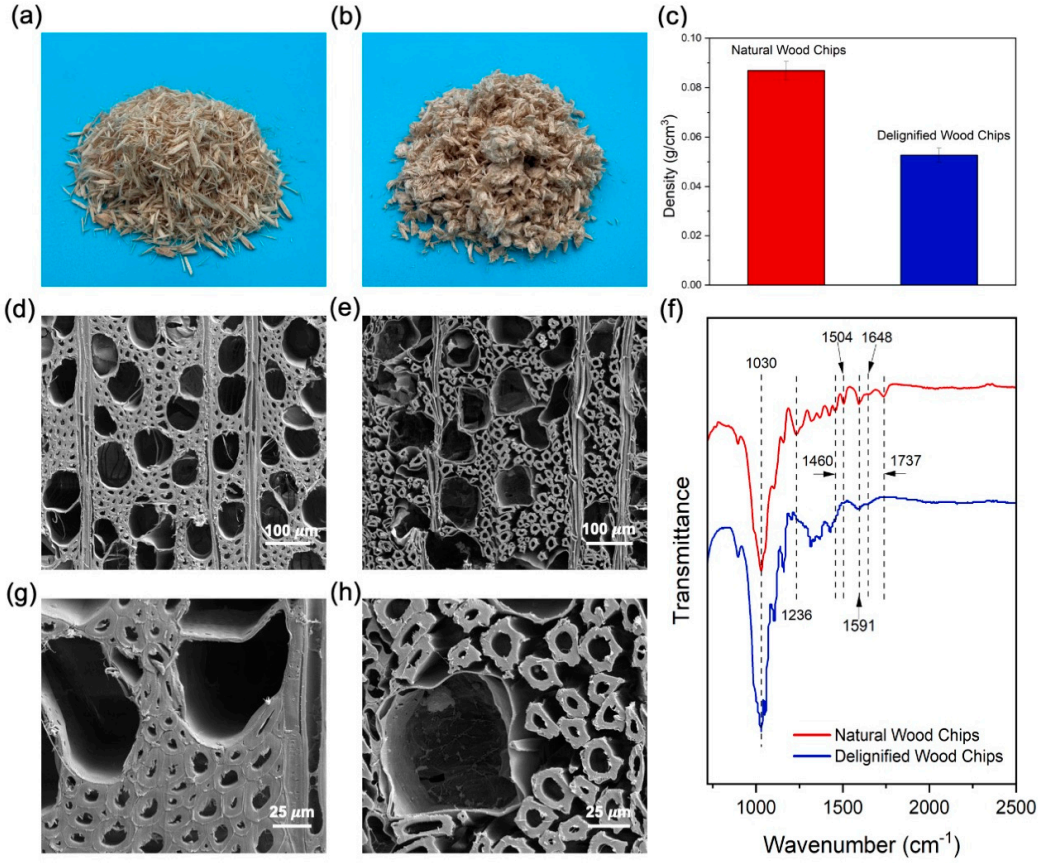


Figure 2. Structural and compositional characterization. (**a**) Natural and (**b**) delignified wood chips. (**c**) Density comparison of natural and delignified wood chips. SEM images of (**d**) natural and (**e**) delignified wood chips. (**f**) FTIR spectra. Magnified SEM images of (**g**) natural and (**h**) delignified wood chips.

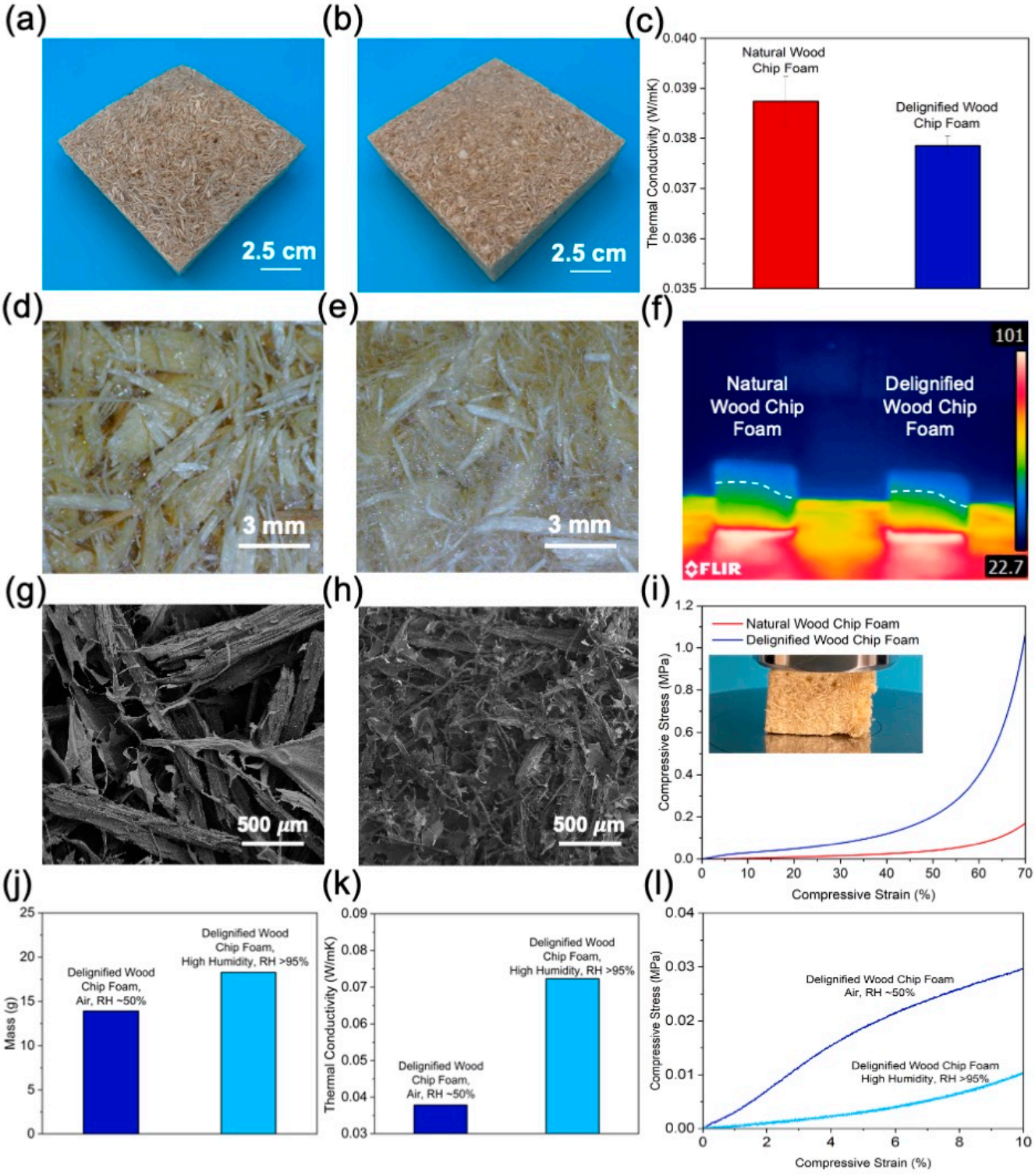


Figure 3. Performance properties of 15 wt.% CMC binder wood chip foams. (**a**) Natural and (**b**) delignified foams. (**c**) Thermal conductivities of the natural and delignified foams. Optical microscope images of the (**d**) natural and (**e**) delignified foams. (**f**) Infrared camera image. SEM images of the (**g**) natural and (**h**) delignified foams. (**i**) Compressive strength graph. Influence of moisture of the 15 wt.% CMC binder delignified wood chip foam on (**j**) mass, (**k**) thermal conductivity, and (**l**) compressive strength.

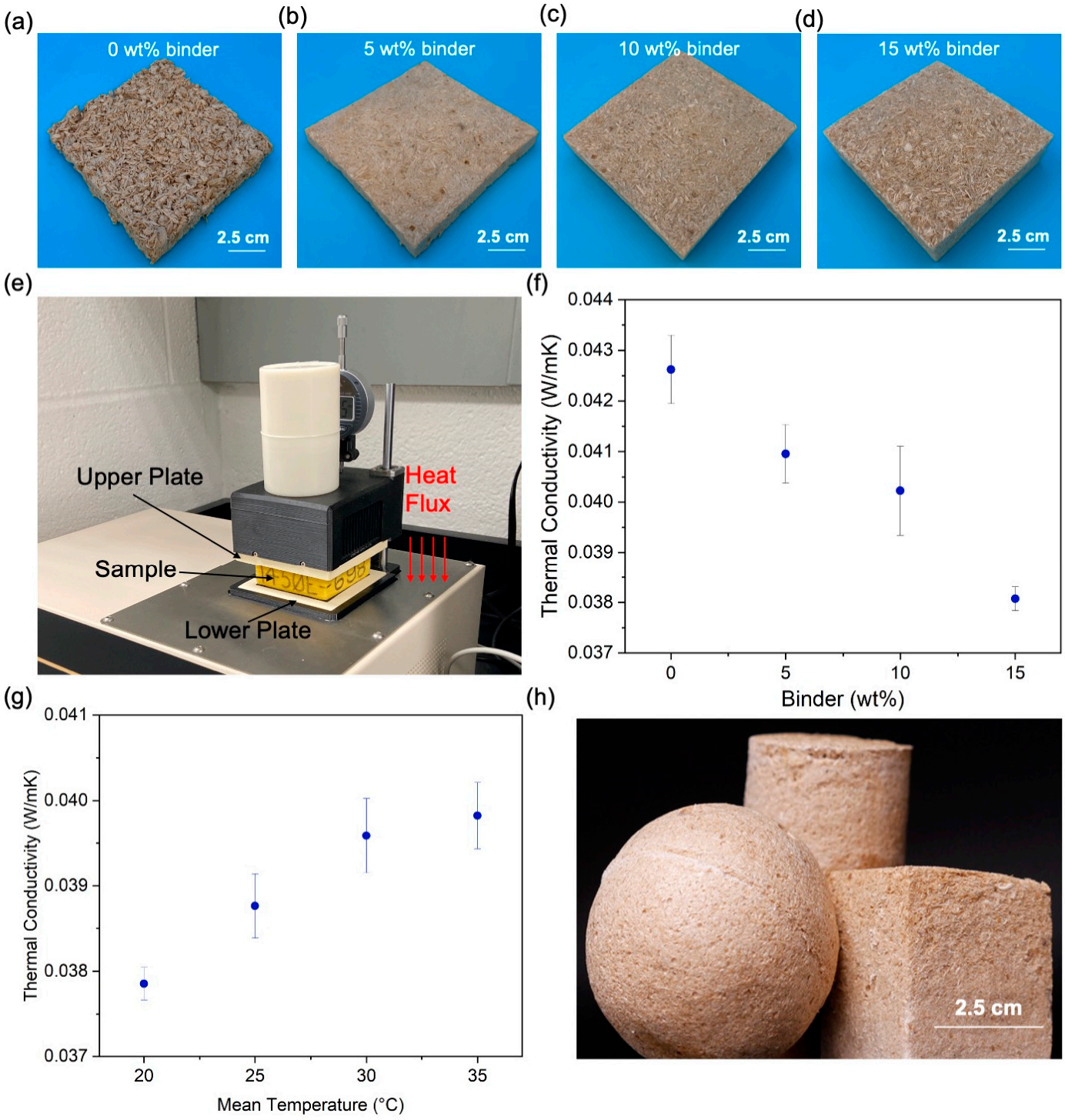


Figure 4. Thermal insulation performance. Delignified wood chip foam samples with varied CMC binder content, including (**a**) 0 wt.% binder, (**b**) 5 wt.% binder, (**c**) 10 wt.% binder, and (**d**) 15 wt.% binder. (**e**) HFM-25 apparatus. (**f**) Thermal conductivity of delignified wood chip foam versus CMC binder content. (**g**) Thermal conductivity of 15 wt.% CMC binder delignified wood chip foam versus mean temperature. (**h**) Wood chip foams with different shapes.

4. Conclusions

In summary, we have demonstrated the fabrication of an environmentally friendly porous insulation foam made of waste wood chips and a bio-based binding agent. Through a chemical treatment delignification process that removes lignin and hemicellulose, it is possible to introduce additional pores within the wood chips, thus altering the overall geometric structure of the wood chips and creating a stable thermal insulation foam. When foamed with 15 wt.% CMC binder, the delignified wood chip insulation foam suppresses thermal transport (0.038 W/(m·K)) and demonstrates high mechanical performance (1.1 MPa at 70% compressive strain). The achievement of our study is attributable to the thermal and mechanical properties of the delignified wood chip thermal insulation foam, with a potential application in building envelope systems such as timber wall framing. The reported delignified wood chip foam demonstrates that wood waste can be repurposed into an effective building material, addressing challenges in both waste management and sustainable construction. Future work could include an industry-scale investigation of the fabrication process or experimentation with alternative bio-based binders.

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Conflicts of Interest: Liangbing Hu cofounded a company, InventWood, to commercialize cellulose-based material innovations. However, all results reported within this manuscript were performed under federal sponsorship. The remaining authors declare no competing interest.

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