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COMPARATIVE ANALYSIS OF OPTIMIZED SUSTAINABLE LEAF INSULATION TILES AND POLYSTYRENE FOR ENHANCED THERMAL PERFORMANCE

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ABSTRACT

Polystyrene insulation materials like styrofoam are major contributors to microplastic emissions, posing significant environmental and health risks. Their popular use in construction raises concerns regarding their sustainability. This research investigates a sustainable alternative to polystyrene insulation using fallen leaves from oak trees (OT), maple trees (MT), and birch trees (BT). Leaf insulation tiles were produced through hydro-immersion, boiling, grinding, and chemical treatments with varying hydrochloric acid, glycerin, and sodium hydroxide concentrations. The resulting paste was molded into tiles, baked, and dried. These tiles' thermal insulation properties and toxic gas emission levels were contrasted with conventional styrofoam using unique Arduino systems. Temperature difference measurements from 2 cm thick OT, MT, and BT tiles were 43 degrees Celsius, 40 degrees Celsius, and 38 degrees Celsius, respectively, indicating favorable results compared to 1 cm thick styrofoam at 10 degrees Celsius and closely matching 2 cm thick styrofoam at 37 degrees Celsius. Toxic gas emissions measured at 300 seconds for OT, MT, and BT were 140 ppm, 55 ppm, and 161 ppm compared to styrofoam's 90 ppm. Notably, increased glycerin concentrations in OT tiles of a subsequent trial had a temperature difference of 36 degrees Celsius and reduced gas emissions to 91 ppm, suggesting the probability of further optimization. As proof of concept research, these findings indicate that leaf insulation tiles have comparable insulation properties to styrofoam while likely offering significant environmental benefits. Ongoing optimization and data collection aims to validate these findings of a viable, sustainable alternative to traditional insulation.

INTRODUCTION

Microplastic pollution is an escalating environmental issue, with particles that have been found to contaminate the human body through its transfer from organism to organism [1]. Of the contributors to microplastic emissions, are styrene insulation materials, such as Styrofoam, which are commonly used for insulation in buildings [2]. Used globally for insulation, styrene is notorious for producing persistent microplastic particles while moving around the environment [3]. Thus, addressing the source of such emissions is crucial for global sustainability in the coming years [4]. This research proposes an innovative insulation material made from fallen leaves as an alternative to regular styrene, reducing microplastic contamination globally and addressing the biodegradability of common insulation materials. Leaves, primarily composed of cellulose, hemicellulose, and lignin, provide the material with a sound, stable structure capable of comparable insulation properties to styrene [5, 6]. The cellular structure of leaves forms a matrix that should trap air, a poor conductor of heat, within its empty spaces, creating a barrier that promotes insulation and lowers the heat transfer coefficient of the insulation material [7]. By using recycled leaves with insulative properties, the alternative insulation material should produce fewer microplastic particle emissions as compared to

the styrene insulation materials, emit less flammable gases, such as CO and CH4, and will be more biodegradable while still retaining similar insulative properties [8]. The proposed method starts with the collection of various fallen leaves and grinding them into a paste. This leaf paste was then combined with an acid, plasticizer, and base to form a composite tile for further processing and baking. The insulation-creating method in this study was derived from other methods of creating biodegradable plastics using various organic materials such as potato peels [9, 10, 11]. The insulation tile manufacturing process was refined and optimized by varying the quantities and concentrations of the respective additives. By varying the concentration levels of hydrochloric acid, sodium hydroxide, and glycerin in the leaf composite, the leaf insulation tiles produced different results regarding their insulation properties and toxic gas emissions when heated. The hydrochloric acid was intended to break down the leaf particles [12], the sodium hydroxide was to neutralize the acidity of the paste, and the glycerin was to plasticize the composite [13]. The effectiveness of these tiles as insulating materials was evaluated by their comparable heat transfer coefficient, determined by using a thermal monitoring system utilizing temperature sensors and an Arduino microcontroller system. Their gas toxicity levels were evaluated by a gas detection Arduino system. In addition, various other tests, such as breaking force and burning rate were performed to compare the characteristics of this alternative

insulation material with those of conventional styrene. Mimicking the natural role of leaves in providing insulation for bird nests and regulating temperature fluctuations in the environment [14], this research aimed to develop a sustainable and effective new insulation material suitable for industrial applications. Based on the feasibility of creating a beneficial insulation material using fallen leaves, the scarcity of actual development of insulation products surprised us, inspiring us to examine more closely. The study should motivate other scientists who emphasize the sustainability of insulation materials to invest more resources in the development of fallen leaf insulation materials.

EXPERIMENTAL METHODS

Materials and Reagents: Fallen leaves were collected from Bergen County, NJ, for the study. Chemicals including 2.0 N HCl and 1.0 N NaOH were purchased from Sigma-Aldrich, with natural glycerin from the same supplier. Glassware ranged from 50 to 1000 mL beakers obtained from Harvard Apparatus, Inc. Additional equipment such as a stainless steel container, blender, laboratory heater, dehydrator, electric burner, paper towels, and ceramic plates were sourced from various manufacturers. Sheetrock was bought locally from Home Depot in Paramus, NJ, and Arduino parts from the Arduino Online Store.

Collections of Fallen Leaves: Fallen leaves were collected from the three tree species. The trees were in an Englewood Cliffs, NJ, USA residential area, at Google Maps coordinates (40.87415, -73.95474). They were collected from October to early December, packed into recyclable brown bags, and left indoors until used.

Insulation Tile Manufacturing Processes: The dimensions of the insulation tiles were 100 cm squared and 2.0 cm thick, manufactured using a plastic mold under the same approximate conditions. Diagram 1 below illustrates the processes of insulation tile manufacturing. Each step is described below.

Physical Treatment: Fallen leaves were collected under trees and stored in biodegradable brown bags from Home Depot, Paramus, NJ, labeled by the common names of the trees: oak, maple, and birch (Step a). The leaves were then rinsed and de-stemmed under running water (Step b), followed by boiling in a 3-gallon pot for one hour to soften (Step c). Afterward, the leaves were blended in a Meade blender with 200 ml of water for three 30-second sessions at the finest grinding setting, achieving speeds of 3000 rpm, resulting in nearly liquid, finely ground leaves with mean particle sizes between $10 \sim 30$ um (Step d). Finally, the ground leaves were strained through a strainer lined with two layers of paper towels, pressed to remove excess water, and prepared for chemical processing (Step e).

Chemical Treatment: The leaf dough from Step (e) was weighed at approximately 400g and placed into a 2-gallon plastic container for mixing. Hydrochloric acid was then added as the acidic hydrolysis agent in Step (f), and stirred with a plastic spatula to ensure a homogeneous mixture. The HCl solution was proportioned to 25 grams of leaf dough. Five minutes after thorough mixing, glycerin was measured with a 50 ml syringe and incorporated into the dough during Step (g) for plasticization, using the same mixing technique as with the HCl. For neutralization, NaOH was added per 25g of dough and mixed until homogeneous. The study varied the concentration of each chemical, denoted by ratios such as a/b/c/d for HCl concentration, HCl volume, glycerin volume, and NaOH volume per 25g of leaf dough, respectively.

Completing our Tile Manufacturing Processes: After several chemical treatments, the product was shaped using a custom-made plastic mold (10 cm x 10 cm base, 6 cm height, 1 mm thick walls), featuring a 2 cm-high red line. The mold was filled with leaf dough up to this mark, placed on a ceramic tile, and then carefully removed, leaving the shaped dough on the tile. This was subsequently baked in an electric oven at 120°C for 2 hours.
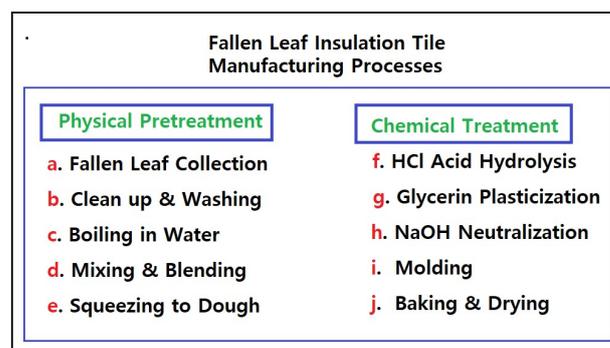

Diagram 1 presents the process taken for manufacturing insulation tiles from fallen leaves.

Insulation Tile Characterization Methods: The insulation tiles created for the study were tested for their physical and chemical characteristics as described below.
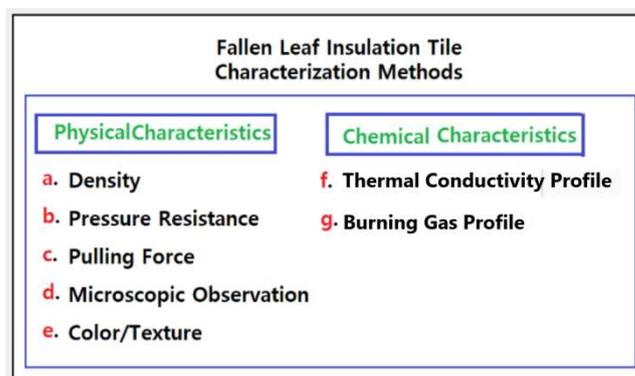

Diagram 2 presents the various characteristics that were observed and assessed following the manufacturing process.

Physical Characteristics

Density Measurement: To measure the density of an insulation tile sample, two 200 ml beakers and one 100 ml beaker were utilized. Initially, a 200 ml beaker was zeroed on an electronic balance. An insulation tile sample was then placed in the beaker, and its mass was recorded. The beaker was filled to a known volume with water from the 100 ml beaker, and the sample's density was calculated by dividing its mass by the volume of the water.

Pressure Resistance: A G500 pressure gaugewith a measurement unit of Newton (N) was used to measure the pressure resistance of the leaf tiles. A leaf tile sample measuring 5 cm x 5 cm was placed in the middle of a ceramic tile, and the gauge was held upright with its tip at the center of the sample. Pushing down on the pressure gauge, the digital output was observed when the tile had been dented about 2-3 mm.

Pulling Force: A binder clip of length 5 cm was clamped to one end of the leaf insulation tile. The pulling force meter was hooked onto the ring of the binder clip and pulled up. The digital values were recorded at the point of breakage.

Microscopic Observations: The Takmly digital microscope was employed to observe a leaf insulation tile sample, magnifying up to 1000 times and allowing images to be saved to a PC. For the observation, a piece of the tile was torn, crushed into a thin layer on a ceramic surface, and examined under the microscope. A transparent plastic ruler with millimeter markings was placed on the sample to estimate the particle sizes. The resultant images and size measurements were recorded and stored on a computer for further analysis.

Thermal Conductivity Measurements: The thermal conductivity measurement system consisted of two sheetrock layers measuring 28.5 cm x 15.0 cm and 1.5 cm in thickness, with an insulation tile sandwiched between them. The sheetrock closer to the heat source had a 3 in x 3 in opening to allow direct heat exposure to the insulation tile. Temperature data were collected using an Arduino Uno paired with two DS18B20 temperature sensors, which measure temperatures from -55°C to 155°C. The setup also included a 2004 LCD and a Samsung 64 GB Evo memory card for data storage. Measurements were recorded every 3 minutes and, when requested, at 30-second intervals, directly to a microSD card. This arrangement facilitated continuous monitoring of heat transfer through the insulation using an electric oven and PC setup. The system's configuration ensured accurate and consistent thermal readings, critical for evaluating the insulation material's properties.

Fourier's Law of Thermal Conductivity: Fourier's Law of thermal conduction was used to estimate the temperature difference as shown in Equation 1. In this study, heat flux (Q), window area (A), and insulation material thickness were constant. As the heat source temperature was maintained throughout the experiment, heat flux remained steady, implying that thermal conductivity (K) and temperature difference have a linear relationship. Thus, comparing temperature differences effectively reflects variations in thermal conductivity. We calculate the leaf insulation K_{li} with Eq. 4 in which K_{sf} was the thermal conductivity of styrofoam insulation sheet with known as $K_{li}*deltaT_{li}/deltaX_{li} = K_{sf}*deltaT_{sf}/deltaX_{sf}$. (Q = heat flux [Joule/second], A = Area [m squared], K= thermal conductivity [W/m-k], T = temperature [Celsius degrees])

on an Arduino Uno with a 32GB microSD immediately upon activation. This setup facilitated real-time monitoring of toxic gases typically emitted in combustion processes.

Statistical Analysis

All the raw data was summarized as mean and standard deviation. Student's t-test was performed when needed (P<0.05).

RESULTS AND DISCUSSIONS

Typical Building Materials: The thermal conductivity and toxic gas emissions of Styrofoam and ceramic materials were assessed to establish benchmarks for comparison with leaf insulation tiles. Styrofoam tiles of 1 cm and 2 cm thicknesses were very firm and reached thermal equilibrium plateau at different times of 50 minutes and 90 minutes with delta Ts of 9.96°C and 37°C respectively. The burning indicator of toxic gas levels indicated a gas output of 90 ppm at 300 seconds of burning with a heating rod. The burning indicator profile was isolated to fit a linear function closely. Using the slope from the linear function, the beaker-filling rate of the gas was 1.1501 ppm/s.

Comparative Analysis of Tree Species: The following studies assessed how different tree species affect the insulation tiles' performance regarding thermal insulation and toxic gas emission levels. All three of the subsequent studies were observed to be very soft and sticky.
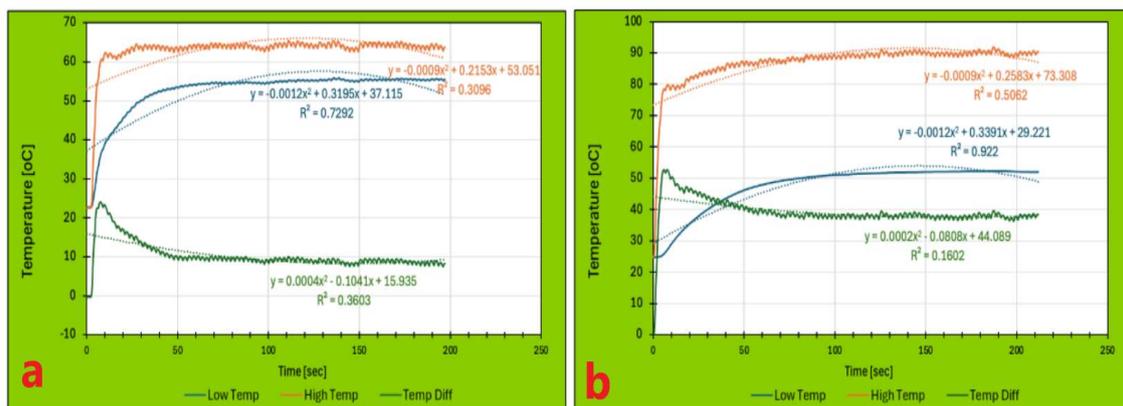

Fig. 1. Presents the thermal conductivity profile of the Styrofoam Studies 1 (a), and 2(b)
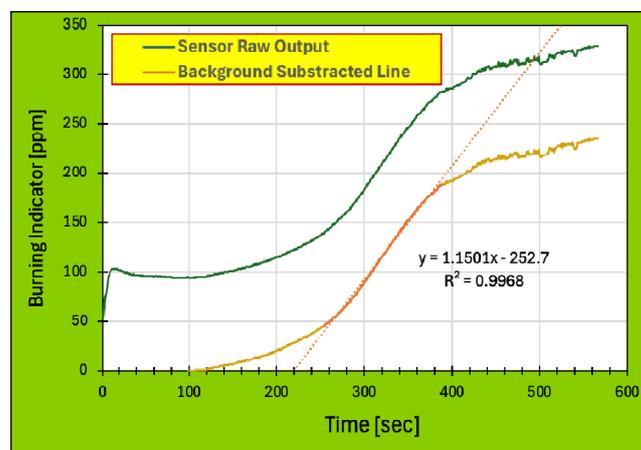

Fig. 2. Presents the burning indicator profile of the Styrofoam study

Burning Gas Measuring Arduino System: The MQ-5 semiconductor gas sensor, known for its sensitivity to flammable gases such as LPG, methane, and carbon monoxide, was utilized to measure burning gas quality. The sensor required a 5-minute preheat using a 60-joule/sec soldering iron connected to a 100 V supply. Data logging commenced

Oak Tree, Chemical Ratio 1.0/6/10/300, Increased HCl Volume: Increasing the HCl volume to 6 mL (from 2 mL in Study 2), this study aimed to explore the effects of a higher acid content on insulation properties and emissions. It resulted in a 100-minute plateau time and a 43-degree Celsius delta T. Emissions increased to

140 ppm at 300 s, with a beaker-filling gas rate of 0.55 ppm/s, indicating that while increasing HCl volume can enhance certain material properties, it also raises environmental concerns due to increased emissions. The presence of additional water from the increased HCl volume increased porosity and air pockets which are beneficial for insulative properties. However, at a certain extent, too much water, such as in this case, compromised the material structure, resulting in a slight decrease in delta T. The additional HCl resulted in reactions with the leaf dough's natural material makeup, promoting more structural stability for better insulation, but also creating more toxic gas byproducts. There was only a slight decrease in thermal conductivity as the HCl and water's effects balanced out.

Maple Tree, Chemical Ratio 1.0/6/10/300: Maple tree tiles, tested under the same increased HCl volume as Study 3, showed an improved environmental performance with the lowest emissions at 55 ppm and similar insulation efficiency, characterized by an 80-minute plateau time and a 40-degree Celsius temperature difference. The beaker-filling gas rate was 0.2952 ppm/s with toxic gas emissions of 55 ppm at 300 s, highlighting its effectiveness and lower environmental impact.

Birch Tree, Chemical Ratio 1.0/6/10/300: Birch tiles displayed the least efficiency in both insulation, with a 70-minute plateau time and a 38 degrees Celsius temperature difference, and emissions, with 161
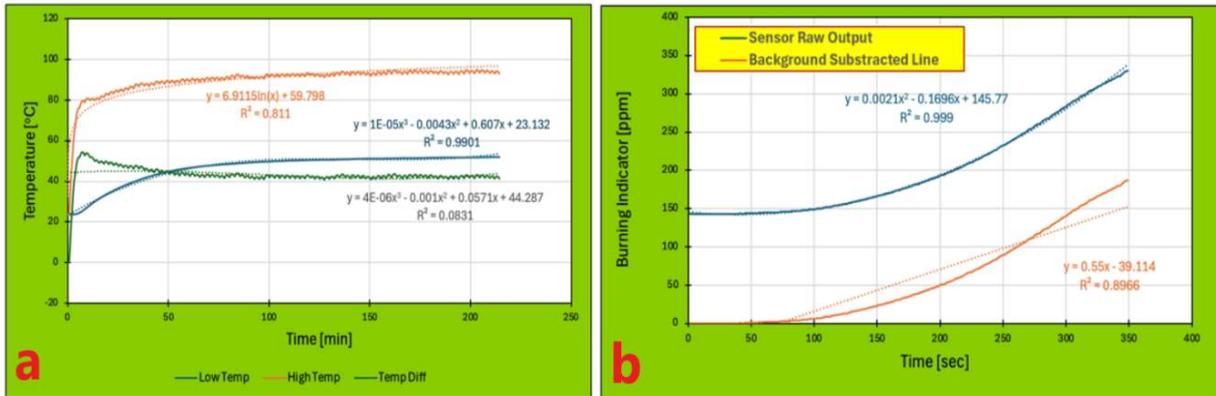

Fig. 3. Presents the thermal conductivity profile (a), and the burning indicator profile of Study 3 (b).
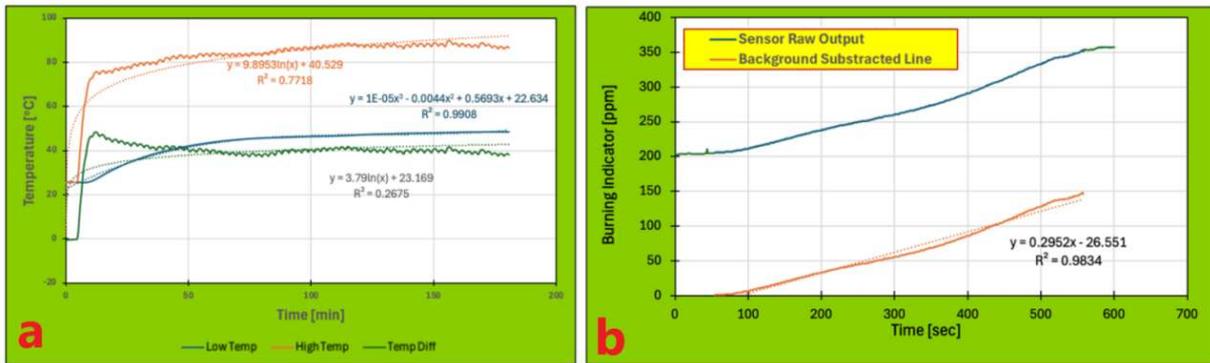
Fig. 4. presents the thermal conductivity profile (a) and the burning indicator profile (b) of Study 4
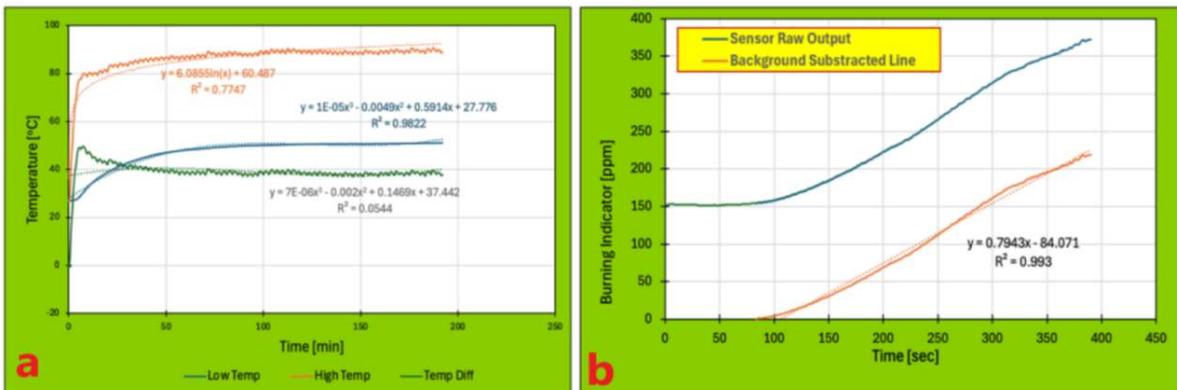
Fig. 5. presents the thermal conductivity profile (a) and the burning indicator profile (b) of Study 5

Comparative Tables with K value

Table 1. Presents the HCl volume change data with K

HCl VOLUME				
Study #	Chemical Ratio	Equilibrium Reaching Time	ΔT, K (W/m·K)	PPM
2	1.0/2/10/300	100 minutes	46°C, 0.029	117
3	1.0/6/10/300	100 minutes	43°C, 0.031	140

ppm. The beaker-filling gas rate was 0.79 ppm/s, the highest among the studies, indicating significant environmental challenges.

Table 2. Presents the glycerin volume change data with K

GLYCERIN VOLUME				
Study #	Chemical Ratio	Equilibrium Reaching Time	ΔT, K (W/m·K)	PPM
2	1.0/2/10/300	100 minutes	46°C, 0.029	117
6	1.0/2/15/300	90 minutes	36°C, 0.037	91

Table 3. presents the HCl concentration change data with K

HCl CONCENTRATION				
Study #	Chemical Ratio	Equilibrium Reaching Time	ΔT, K (W/m·K)	PPM
6	1.0/2/15/300	90 minutes	36°C, 0.037	91
7	2.0/2/15/300	100 minutes	40°C, 0.033	209

Table 4. presents the NaOH volume change data with K

NaOH VOLUME				
Study #	Chemical Ratio	Equilibrium Reaching Time	ΔT, K (W/m·K)	PPM
7	2.0/2/15/300	100 minutes	40°C, 0.033	209
8	2.0/2/15/500	80 minutes	33°C, 0.04	94

Table 5. presents the tree species (oak/maple/birch) change data with K

OAK / MAPLE /BIRCH COMPARISON				
Study #	Chemical Ratio	Equilibrium Reaching Time	ΔT, K (W/m·K)	PPM
3 OAK	1.0/6/10/300	100 minutes	43°C, 0.031	140
4 MAPLE	1.0/6/10/300	80 minutes	40°C, 0.033	55
5 BIRCH	1.0/6/10/300	70 minutes	38°C, 0.035	161

Other characteristics of leaf insulation tiles

Density: Our insulation tiles' mean density was 0.666±0.399 [g/ml] (n=7). The average density of our insulation tiles was relatively greater than that of typical Styrofoam insulation tiles, which is 0.32 [g/ml]. It was measured to examine their physical properties and further see how they can be utilized for practical applications.

Crushing Force: The crushing force of our leaf insulation tile was measured as described in the Methods section. It was calculated to be 14.51±5.26 [N] (n=7). In contrast, when we measured the crushing force of Styrofoam, it was measured as 5.35±2.33 [N]. Our insulation tile was notably stronger than the Styrofoam regarding our crushing force.

Pulling Force: The pulling force was evaluated as described above in the Method section. It was found to be 0.086+/0.065 [kg], while that of Styrofoam was 0.825+/-0.321 [kg]. The data suggests that the pulling force was significantly less than that of Styrofoam. Though it is deemed fragile, the pulling force may not be a major weakness as an insulation tile, since most insulation materials are sandwiched between other structural materials, such as sheetrock, plywood, and concrete, during installation.

Microscopic Observations: We could tell that most of our insulation tiles were created in a homogeneous state, since the spread of fiber rods and grains looked identical. When measuring particle sizes relative to the thickness of the standard black line, approximately 30-50 μm particles were observed across the photos, with some embedded fiber fragments.

CONCLUSION

The study tiles were compared with Styrofoam insulation tiles to determine if these new leaf insulation tiles were comparable with Styrofoam while being biodegradable and more eco-friendly without

emitting microplastics into the environment. They were additionally compared with each other to determine the exact effects of changing the concentrations and volumes of the respective chemical treatments. We found that increasing HCl volume could result in a decrease in delta T when overly excessive due to a compromisation of structure from excessive amounts of water and higher toxic gas emissions due to toxic gas byproducts released when HCl reacted with natural leaf material. However, if an optimal amount is used, the water should increase thermal insulation along with HCl by promoting structural stability and insulative air pockets. Increasing glycerin volume could result in an increase in thermal insulation by plasticizing the structure to a certain extent until it becomes too sticky and compromises the structure of the tiles. It decreases the toxic gas emissions. Increasing HCl concentration resulted in increased thermal insulation as it promoted structural stability and its insulative air pockets by breaking down large particles, but it increased toxic gas emissions significantly by producing toxic gas byproducts. Increasing NaOH volume should decrease toxic gas emissions while not changing the thermal insulation. However, since only 5 minutes were allowed for the HCl to react, the NaOH neutralized the HCl before it had a chance to react, thus decreasing thermal insulation along with toxic gas emissions. The study with the most optimal results for the oak tree studies was Study 6 with a delta T of 36 degrees Celsius and toxic gas emissions of 91 PPM, closely matching that of the 2 cm thick Styrofoam insulation tile which had a delta T of 37 degrees Celsius and toxic gas emissions of 90 PPM. Thus, our leaf insulation tiles are a viable alternative to polystyrene insulation as they maintain nearly identical insulative properties and gas toxicity as styrofoam insulation while still being more eco-friendly by not emitting microplastic particles and being biodegradable.

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