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Bio-Based Composite from Sunflower Stalks for Building Wall Panels

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ABSTRACT

Burning sunflower stalks after harvesting could pose a significant environmental risk due to particulate matter 2.5 pollution. The use of low-cost recycled materials in building products is on trend. The objective of this study was to investigate a bio-composite made from sunflower stalks and sunflower bark using various ratios of natural latex as a binder and to compare the effects of hot ovens and hot compression. Three bio-composite-to-binder ratios of 1:4, 1:5, and 1:6 were compared. The physical, mechanical, thermal, and acoustic properties of the bio-composite were determined. The test box was used to evaluate the thermal performance of bio-composites. The bio-composites had a density similar to flat-pressed particleboards. The moisture content varied from 6.01 to 14.20%, with only the 1:5 and 1:6 sunflower stalk bio-composites by hot compression having a moisture content higher than 13%. Thickness swelling ranged from 5.63% to 12.03%. All composites had a fire resistance that passed the UL94HB standard, classified as at least flame retardant. As natural latex increases, the water absorption of sunflower stalks decreases while at the same time increasing fire resistance. The thermal conductivity coefficient ranged between 0.117 and 0.161 W/mK. The hot-compressed 1:6 sunflower bark bio-composite exhibited a room temperature profile that was similar to that of the MDF board. The hot compression method revealed better results in density, water absorption, flexural strength, and flexural modulus than the hot oven method.

1. Introduction

Due to climate change, decreases in rainfall, and soil deterioration that harm agricultural production and lower prices, farmers in Thailand grow sunflowers as complementary plants after harvesting the main crops like corn, peanuts, or soybeans. Furthermore, sunflower fields will become a tourist attraction, increasing farmers' income during the flowering period. The farmer will plant sunflowers in September and harvest them at the end of December or January. Farmers also grow sunflowers to raise bees. According to the Lopburi Provincial Development Plan 2022, sunflowers are considered an economic crop for the province. It has a planting area of 6.757 km^2, yielding 149 Mg/km^2, equivalent to 1,004.99 Ton/year. Farmers will earn 13.75 baht/kg from growing sunflowers. However, after harvesting the seeds, farmers must either plow and cover them, resulting in increased expenses and lower profits, or burn them, leading to environmental pollution (particulate matter, PM 2.5).

The waste-to-resources approach is currently gaining popularity in waste management. Sunflower stalks are agricultural residues that have attracted interest due to their large amounts [1]. Sunflower stems can provide thermal insulation when combined with other materials [2-3]. In addition, the sunflower stalks have favorable mechanical and thermal insulation properties, which supported the present research on the use of the stalk in the production of a composite for sound absorption [4]. The inner part of the sunflower stem contains the sponge, which is characterized by large, irregular cavities that contain air [5]. The higher the porosity, the lower the thermal conductivity coefficient [6].

The fact that agricultural residues can be cheaper and more environmentally friendly justifies the research as an alternative to synthetic materials. For example, Binici et al. [6] demonstrate that combining sunflower (30-50 g of sunflower stalk fiber and 15-25 g of sunflower stalk sponge) and wheat stalks (30-50 g) with vermiculite (150 g) can yield an environmentally friendly and cost-effective insulation material with good insulation properties. According to TS EN and ASTM C 51, the thermal insulating material, obtained by hot pressing to a thickness of 20 mm, exhibited sufficient physical, mechanical, and thermal properties. da Rosa et al. [7] constructed a thermal insulating board using rice husks (4-52% w/w), sunflower stalks (40-45% w/w), gypsum (20-30% w/w), and jute fabric (7-10% w/w/) and tested its performance against a solar collector with glass wool thermal insulation. Mati-Baouche et al. [8] developed a method of manufacturing eco-insulating materials using 100% natural sunflower stalk particles glued with chitosan solution as a binder. Chitosan at 4.3% (w/w) and a size greater than 3 mm yielded a thermal conductivity of 0.056 W/mK, a maximum stress of 2 MPa, and an acoustic coefficient of absorption of 0.2, making these properties competitive with insulating bio-based materials on the market.

Due to the excellent elasticity, tensile strength, resilience, and dynamic mechanical properties of natural latex, it is widely used in the medical [9], automotive [10], and construction industries. The vulcanization process is necessary in the production of bio-composites using natural rubber latex, but it is also the most time-consuming step. The microwave radiation for latex vulcanization significantly reduced production time [11]. However, microwave radiation tends to heat cellulose fibers of sunflower stems, which could potentially catch fire. Therefore, in this study, a bio-composite of sunflower stem and natural latex was heated in hot air ovens and hot compression for vulcanization.

This study investigated the bio-composite using (i) sunflower stalks and sunflower bark, (ii) varying the ratio of natural latex as a binder, and (iii) using a hot oven and hot compression. The physical, mechanical, and thermal properties were evaluated. The best results in thermal conductivity for each molding method were later tested in further acoustic absorption coefficient and thermal insulation performance.

2. Materials and methods

2.1 Materials

Dried sunflower stems, a by-product of sunflower cultivation, were obtained from the Jumpee sunflower field in Lop Buri Province. The sunflower stem consists of a rigid external part called bark, which has a pore size of less than 10 mm, and a lightweight inner part with a honeycomb structure called pith, which has a pore size of more than 100 mm [12]. In this study, the properties of a bio-based sunflower composite made from sunflower stalks (a mix of bark and pitch) and sunflower bark were compared. The dried sunflower stalk (Fig. 1a) and sunflower bark (Fig. 1b) were shredded using a shredder (182U, Bosco, Thailand) into a diameter range of 0.3–1.0 cm (Fig. 1c-d) and oven dried at 105°C for 15 min. Natural latex (Prevulcanized latex high modulus, HM, THAITEX) was used as a binder for a sunflower bio- composite.

2.2 Sunflower bio-composite preparation

In this study, the ratios of shredded sunflower to natural latex were 1:4, 1:5, and 1:6 (w/w). The mixture was filled into a stainless mold measuring 20 x 20 x 1.5 cm according to TIS 876-2547 [13], where the density should be more than 200 kg/m^3. Two molding methods were used to investigate. That is, the bio-composite made from shredded sunflower bonded together with a natural latex was molded at 100 °C for 1 h by hot compression (LP-S-20, LAB TECH Engineering, Thailand) compared with a hot air oven (101-3B Shaoxing, Jingmai Instrument Equipment, China).

After drying, twelve sunflower bio-composites were cut into a specimen size of 5 x 5 x 1.5 cm to evaluate their physical, mechanical, and thermal properties. A good thermal resistance for each molding type was chosen for further absorption coefficient testing and a hot box for thermal characterization.

2.3 Physical characterization

The density, moisture, and thickness swelling of the specimen composite were examined according to Thai Industrial Standard (TIS) 178-2549 [14] and 876-2547 [13], respectively. The water absorption of the specimen composite was tested according to ASTM D1037 [15]. The specimen sample's flammability was evaluated according to UL94 horizontal burning (HB) test [16]. Each test used five specimens.

2.4 Mechanical and thermal characterizations

The flexural strength (σ_f) and flexural elasticity modulus (E_f) of the specimen composite were evaluated in accordance with ASTM D790 [17]. A universal testing machine (UTM, Instron 5569) conducted a three-point bending moment test on the specimen composite, measuring 0.15 x 0.70 x 0.03 cm. The conditions for testing were as follows: load cell of 1 kN, speed of 1.28 mm/min, and support span of 48 mm. Five specimens were used this test.

The thermal conductivity of the specimen composite was measured according to the thermal constant analysis method [18] using a hot disk thermal constant analyzer (hot disk AB). Triplicates were performed.

2.5 Absorption coefficient testing

The ratios presenting the lowest thermal conductivity were further tested for absorption coefficient. The sunflower bio-composite was cut in a cylindrical shape of 9.8 and 2.8 cm in diameter and a thickness of 1.5 cm for testing the acoustic properties in an impedance tube. The cylindrical composite was tested in an impedance tube according to ISO 10534-2 [19], where frequencies ranged from 250 Hz to 6400 Hz. The sound absorption coefficients (SACs) and the noise reduction coefficient (NRC) of the specimen composite at different frequencies were evaluated based on ISO 10534-2 [19]. Triplicates were performed.

2.6 Statistic analysis

Data analysis of the physical, mechanical, and thermal properties was performed using SPSS 28.0 software (IBM, Chicago, IL, USA). One-way analysis of variance (ANOVA) and the Least Significant Difference (LSD) test (95% confidence interval) were applied to detect significant differences between means.

2.7 Simulated use of the composite as wall panel and its thermal insulation performance

All materials used in this test were the same as those used for construction on the market. The testing box was made of polystyrene foam (EPS), which has fire-retardant properties. It has good insulation and low thermal conductivity (0.032–0.036 W/mK at 10 °C). The density of this material is 15 kg/m^3, making it suitable for use in construction. The cubic testing box measuring 0.60 x 0.60 x 0.60 m with a thickness of 0.10 m was conducted for heat transfer testing (Fig. 2a). The front was set for installing a testing panel measuring 45 x 45 x 9.1 cm (Fig. 2b). The test panel consisted of four layers (Fig. 2c), in which the external wall was fiber cement of 12 mm in thickness, followed by a wooden frame of 35 mm, a specimen sample of 15 mm (Fig. 2d), and gypsum of 9 mm in thickness.

To measure the heat transfer in different testing materials of test box, the thermocouple type K with a range 0-1,250 °C and ± 5 °C accuracy connected with data logger (GRAPHTEC midi LOGGER model GL840) were fixed at a central of external surface wall, internal surface wall, and inside test box (Fig. 3a-c). The pyranometer (Kipp & Zonen: Model CMP 11) with a range 310-2,800 μm connected with data logger (Fig. 3d). All of the test boxes were facing south [20]. The distance between each box was 2 meters to prevent the shadows from crossing each other (Fig. 3e). Temperatures inside and outside the experimental box were recorded for three days in a row at the courtyard of Rajamangala University of Technology Rattanakosin (RMUTR), Salaya, Nakhon Pathom, Thailand.

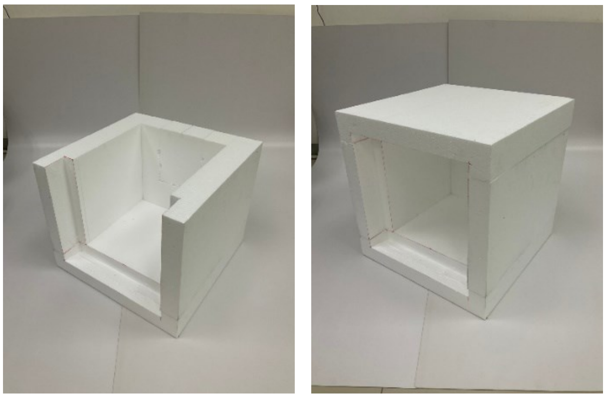
(a) 

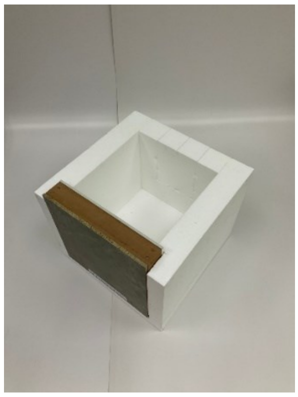
(b) 

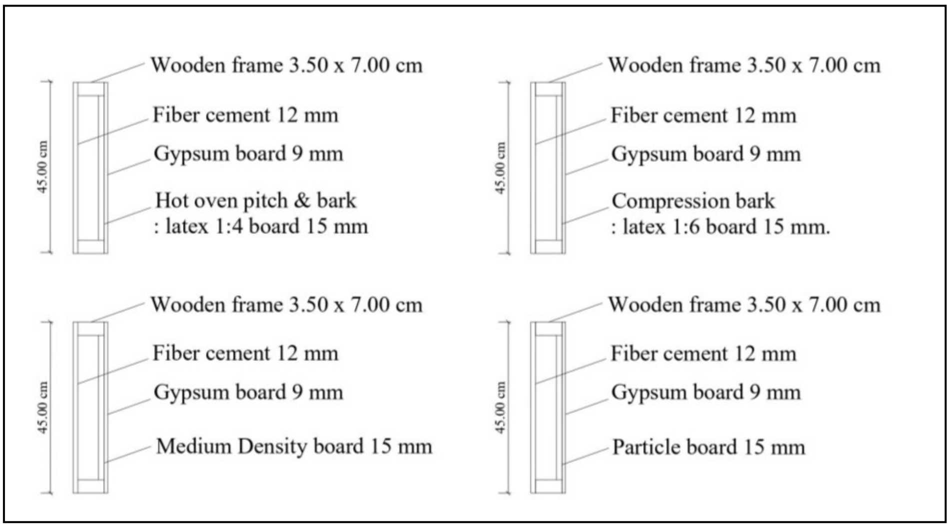
(c) 

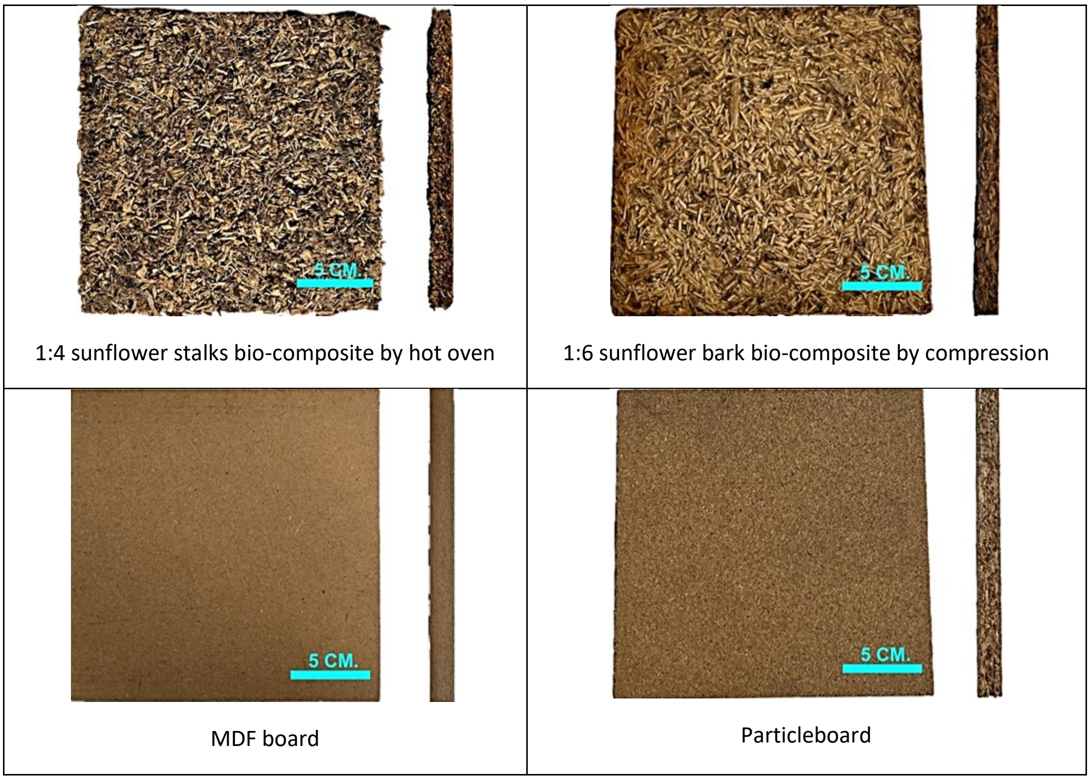
(d) 

Fig. 1 Dried sunflower stem: (a) sunflower stalk; (b) sunflower bark; (c) shredded sunflower stalk; and (d) shredded sunflower bark.

(a) 

(b) 

(c) 



(d)

Fig. 2 Testing box design apparatus. (a) The polystyrene foam testing box; (b) The front box design for panel testing; (c) The details of panel layer testing; and (d) the testing materials.

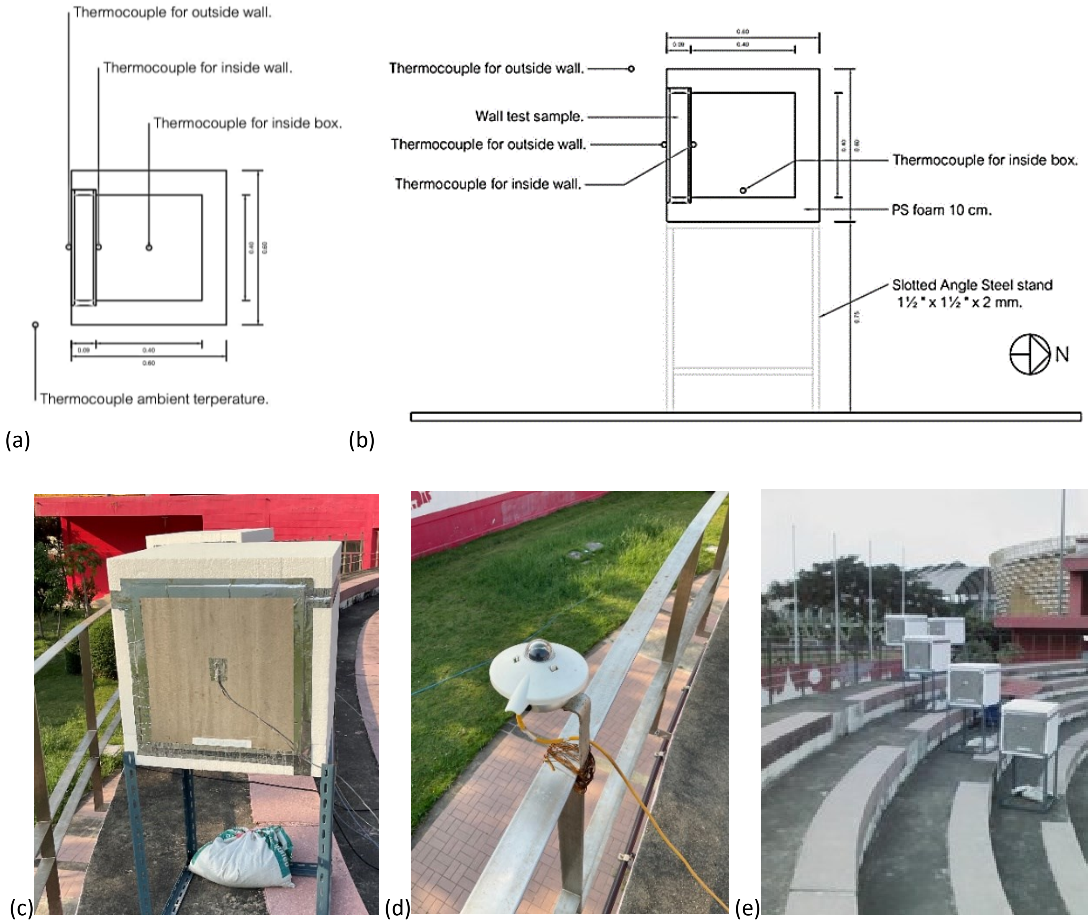


Fig. 3 The thermocouples in the testing box are measured from (a) top view and (b) side view; (c) the thermocouple and data logger connected to the testing box; (d) a pyranometer; and (e) the testing box exposed to heat radiation.

3. Result and discussion

3.1 Physical property of sunflower bio-composite

The physical property of sunflower bio-composite presents in Table 1. Compression-molded composite sheets have a smoother appearance with fewer pores, and the fibers are closer together than with hot oven molding. When bent, both methods gave the bio-based composite sheet a flexible shape. In all ratios, bio-composites formed by compression molding have a higher density than oven molding. In every ratio, the density of the sunflower stalk composite exceeded that of the sunflower bark composite. As natural latex increases, the density of sunflower stalk bio-composites increases, but the density of sunflower bark bio-composites tends to decrease. It could be that latex has a higher density than natural fibers [21]. All composite ratios had the same density as flat-pressed particleboards, which is 400–900 kg/m^3, as demonstrated by Thai Industrial Standard [13].

The moisture content of the bio-composite by hot compression was higher than that of the hot oven for all ratios of both sunflower stalk and bark. The moisture content of bio-composites by hot oven and sunflower stalk bio-composites by compression tended to increase as the proportion of natural latex increased, but the moisture content of sunflower bark bio-composites by compression tended to decrease due to a lack of sponge. All ratios had moisture levels that were within the range suggested in TIS 876-2547 [13] (4–13%). The only ones that didn't fall within this range were the 1:5 and 1:6 sunflower stalk bio-composites by compression, which had moisture levels that were 13.74–14.20 %.

Water absorption of the sunflower stalk bio-composites with both hot compression and hot oven was inversely proportional with the density. That is, the water absorption decreases with the density increases due to the shrinking pore space [21]. Therefore, lower in the density, higher its water absorption with more pore space of the bio-composite [22]. As the natural latex increases, the water absorption of the sunflower stalk bio-composites with both hot compression and a hot oven decrease. That is in line with Jaktorn and Jiajitsawat [23] finding that water absorption decreased as the latex ratio increased. Furthermore, it was observed that higher water absorption with more sunflower stalks. Chikhi et al. [24] discovered an increase in water absorption upon the addition of more fibers.

The sunflower bark bio-composite caused less swelling than the sunflower stalk bio-composite. Only the 1:4 sunflower stalks bio-composite produced by a hot oven and compression had a higher swelling value than TIS 876-2547 [13], which should be less than 12%. As the proportion of natural latex increased, the thickness swelling of the bio-composite produced by a hot oven for all ratios decreased, as did the composite created by compressing sunflower stalks. However, Usubharatana and Phungrassami [21] discovered a correlation between the thickness swelling and the proportionality of latex. In addition, Khedari et al. [22] observed that high density had a high swelling thickness.

When the proportion of natural latex increased, the fire resistance of all ratios for bio-composites by compression and sunflower stalks by hot oven increased, while sunflower bark by hot oven had a lower fire resistance. The slowest burning rate ranged from 20.97 to 21.29 mm/min received from the 1:6 sunflower stalks bio-composites by compression and hot oven, respectively. According to the UL94HB standard, all bio-composite samples are classified as at least flame retardant.

Table 1 Physical property of bio-based sunflower composites by hot oven and hot compression (mean ± sd).

Properties of sunflower bio-composites	Hot oven molding						Hot compression molding					
	Sunflower bark: Natural latex			Sunflower stalks: Natural latex			Sunflower bark: Natural latex			Sunflower stalks: Natural latex		
	1:4	1:5	1:6	1:4	1:5	1:6	1:4	1:5	1:6	1:4	1:5	1:6
Density (kg/m^3)	616.35^{a} ± 10.75	620.53^{a} ± 17.47	578.08^{b} ± 7.95	515.67^{a} ± 30.34	567.81^{b} ± 15.30	665.29^{c} ± 9.94	653.67^{a} ± 16.20	681.65^{b} ± 13.66	588.61^{c} ± 14.11	716.78^{a} ± 30.10	864.24^{b} ± 4.56	851.89^{b} ± 6.86
Moisture (%)	6.78^{a} ± 0.17	7.44^{b} ± 0.11	7.33^{b} ± 0.13	6.01^{a} ± 0.35	6.52^{a} ± 0.73	10.75^{b} ± 0.30	10.07^{a} ± 0.33	10.30^{a} ± 0.20	8.97^{b} ± 0.58	9.45^{a} ± 1.18	14.20^{b} ± 0.26	13.74^{b} ± 0.23
Water absorption (%)	43.91^{a} ± 3.31	39.72^{b} ± 3.00	43.25$^{a, b}$ ± 2.19	79.80^{a} ± 4.94	65.21^{b} ± 7.04	34.06^{c} ± 1.26	27.38^{a} ± 2.06	24.83^{b} ± 1.60	40.75^{c} ± 1.63	38.33^{a} ± 3.02	14.37^{b} ± 1.07	10.41^{c} ± 0.97
Thickness swelling (%)	7.42^{a} ± 0.79	5.75^{a} ± 1.96	5.63^{a} ± 0.73	12.03^{a} ± 2.02	11.68^{a} ± 2.39	7.79^{b} ± 0.77	6.27$^{a, b}$ ± 1.60	5.81^{a} ± 0.97	7.35^{b} ± 0.46	12.43^{a} ± 2.94	8.75^{b} ± 1.49	5.67^{c} ± 0.88
Flammability (mm/min)	27.28^{a} ± 2.85	25.01^{a} ± 3.40	32.41^{b} ± 2.86	30.03^{a} ± 5.58	28.21$^{a, b}$ ± 5.70	21.29^{b} ± 4.89	30.73^{a} ± 1.55	28.70^{a} ± 3.76	28.96^{a} ± 7.76	26.04^{a} ± 1.31	29.02^{a} ± 5.62	20.97^{b} ± 1.46

Table 2 Mechanical property of bio-based sunflower composites by hot oven and hot compression.

Properties of sunflower bio-composites	Hot oven molding						Hot compression molding					
	Sunflower bark: Natural latex			Sunflower stalks: Natural latex			Sunflower bark: Natural latex			Sunflower stalks: Natural latex		
	1:4	1:5	1:6	1:4	1:5	1:6	1:4	1:5	1:6	1:4	1:5	1:6
Flexural strength (MPa)	0.194^{a} ± 0.042	0.369^{b} ± 0.067	0.281$^{a, b}$ ± 0.076	0.131^{a} ± 0.034	0.420^{b} ± 0.064	0.399^{b} ± 0.124	0.632^{a} ± 0.080	0.593^{a} ± 0.089	0.526^{a} ± 0.107	0.632^{a} ± 0.060	0.519^{a} ± 0.165	0.570^{a} ± 0.108
Flexural modulus (MPa)	13.59 ± 2.99	30.16 ± 7.55	24.52 ± 6.39	9.06 ± 2.98	33.33 ± 6.10	27.50 ± 7.45	73.41 ± 7.67	66.35 ± 10.78	57.97 ± 12.73	73.62 ± 8.09	59.18 ± 14.86	63.46 ± 13.14

Table 3 Thermal property of bio-based sunflower composites by hot oven and hot compression.

Properties of sunflower bio-composites	Hot oven molding						Hot compression molding					
	Sunflower bark: Natural latex			Sunflower stalks: Natural latex			Sunflower bark: Natural latex			Sunflower stalks: Natural latex		
	1:4	1:5	1:6	1:4	1:5	1:6	1:4	1:5	1:6	1:4	1:5	1:6
Thermal conductivity (W/mK)	0.148[a] ± 0.001	0.126[b] ± 0.001	0.142[c] ± 0.001	0.117[a] ± 0.003	0.160[b] ± 0.000	0.135[c] ± 0.001	0.137[a] ± 0.001	0.143[b] ± 0.001	0.128[c] ± 0.001	0.161[a] ± 0.000	0.156[b] ± 0.000	0.152[c] ± 0.001
Thermal diffusivity (mm^2/s)	0.176 ± 0.007	0.197 ± 0.006	0.135 ± 0.002	0.174 ± 0.008	0.182 ± 0.006	0.135 ± 0.006	0.222 ± 0.007	0.122 ± 0.003	0.204 ± 0.003	0.170 ± 0.002	0.171 ± 0.005	0.179 ± 0.002
Specific heat (MJ/m^3K)	0.841 ± 0.039	0.642 ± 0.025	1.049 ± 0.015	0.674 ± 0.030	0.880 ± 0.030	1.004 ± 0.044	0.619 ± 0.019	1.172 ± 0.026	0.628 ± 0.015	0.950 ± 0.015	0.912 ± 0.027	0.852 ± 0.011
Thermal resistance (m^2K/W)	38.35 ± 3.87	47.60 ± 0.40	42.27 ± 0.34	51.22 ± 0.11	37.47 ± 0.04	44.31 ± 0.17	43.72 ± 0.32	41.86 ± 0.14	46.85 ± 0.37	37.27 ± 0.10	38.50 ± 0.04	39.40 ± 0.13

Note: The average and standard deviation values were derived from five specimens, except for the thermal conductivity test from triplicates. The values with different superscript letters in a row between ratio and molding method are significantly different ($p<0.05$).

3.2 Mechanical and thermal properties of sunflower bio-composite

Table 2 presents the flexural stress and thermal conductivity coefficients of the bio-composite samples. By hot compression, the flexural stress of sunflower bark and stalk bio-composites was not significantly different ($p<0.05$), ranging from 0.519 to 0.632 MPa. As the proportion of sunflowers decreased, flexural stress decreased. However, in the hot oven, the flexural stress of 1:4 sunflower bark and stalk bio-composites was significantly different from that of 1:5 bio-composites ($p<0.05$). That is, the flexural stress increased with natural latex. The flexural strength exceeds 0.098 MPa that is sufficient for use in heat insulation materials. The flexural modulus ranged from 13.59 to 73.62 MPa.

As shown in Table 3, thermal conductivity values ranged between 0.117 and 0.161 W/mK. The bio-composites made from 1:4 sunflower stalks (515.67 kg/m^3 density) and 1:6 sunflower bark (588.61 kg/m^3 density) had the lowest thermal conductivity for the hot oven (0.117 W/mK) and hot compression methods (0.128 W/mK). The thermal conductivity coefficient of a material should be less than 0.1 W/mK [6]. Previous studies found a direct correlation between thermal conductivity and density. That is, the best thermal properties are associated with low density [6, 25-26]. With clay as a binder, sunflower bark had a thermal conductivity of 0.158 W/mK and a density of 714 kg/m^3 [12].

3.3 Acoustic property of sunflower bio-composite

Figure 4 presents the sound absorption coefficient (SAC) of the sunflower bio-composite after measurement on the impedance tube. The sound absorption coefficient (SAC) is a measure of a material's ability to absorb sound. The sound absorption coefficient is between 0 and 1. It should ideally be close to 1, indicating that the material can absorb more sound, whereas the lower the value, the less sound absorption it has or the more sound it reflects. However, typically it is around 0.40. The SAC of the 1:4 sunflower stalks and natural latex bio-composite obtained using a hot oven was 0.62 at 1,500 Hz, while the SAC of the 1:6 sunflower bark and natural latex bio-composite obtained by hot compression was 0.49 at 2,000 Hz. It meant that the 1:4 bio-composite aborted the noise by 62% at 1,500 Hz and had a greater sound absorption coefficient than that of the 1:6 bio-composite.

This may be due to bio-composites' porosity and particle gaps (Fig. 5). The 1:4 sunflower stalks and natural latex bio-composite, produced in a hot oven, have greater porosity and particle gaps, which lead to higher sound absorption in some frequency ranges compared to the 1:6 sunflower bark and natural latex bio-composite made using hot compressing (Fig. 4).

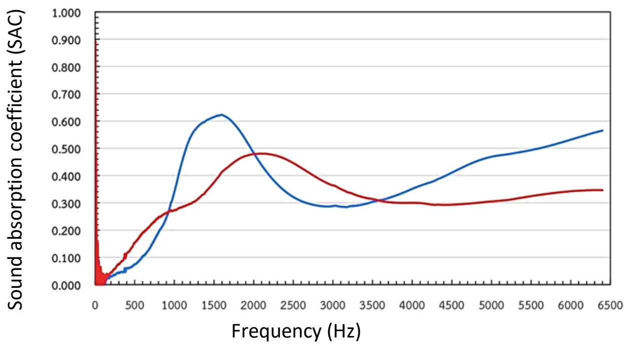


Fig. 4 Sound absorption coefficient spectra for the 1:4 sunflower stalks and natural latex bio- composite obtained using a hot oven (blue line) and the 1:6 sunflower bark and natural latex bio-composite obtained by hot compression (red line).

Fig. 5 Light microscopic observation at a magnification of 3x of the 1:4 sunflower stalks and natural latex bio-composite obtained using a hot oven (left) and the 1:6 sunflower bark and natural latex bio-composite obtained by hot compression (right). The scale refers to 10 mm.

The noise reduction coefficient (NRC) represents the amount of sound energy reduced when that material is used to absorb sound. The NRC is calculated as the average sound absorption coefficient of a material across different frequencies (250-2000 Hz). The NRC of both bio-composites was relatively the same. That is, the NRC of 1:4 and 1:6 bio-composites was 0.233 and 0.241, respectively (Table 4). The absorption classes are designated A-E, where absorption class A has the highest sound absorption (0.7-1.0). These bio-composites may be classified as class E between 0.15-0.25 [27]. Class E is suitable for moderate soundproofing, such as an infrastructure.

3.4 Thermal performance in testing box

Figure 6 presents the solar radiation and ambient temperature. The highest amounts of solar radiation on days 1–3 was 1,028.99, 1,008.28, and 1,025.88 W/m^2, respectively, that were detected at the times of 12.27, 12.13, and 12.16, respectively. The highest amount of solar radiation causes the highest ambient temperature. It was due to the fact that when the Earth receives the most solar radiation at noon, it releases an amount of absorbed heat into the surrounding area and sky, leading to an increase in the ambient temperature [28]. However, the highest ambient temperature occurred on days 2 and 3, following a reduction in solar radiation. That is, the highest ambient temperature of 29.80 and 32.80 °C was detected after the solar radiation decreased at times of 15.14 and 14.46, respectively. This attributes to the emission of absorbed heat from the earth and surrounding atmosphere.

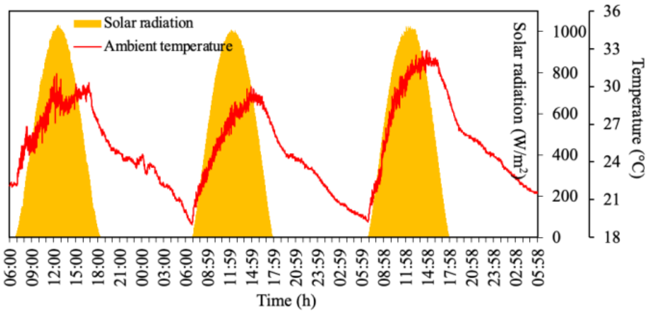


Fig. 6 Solar radiation and ambient temperature for 3 testing day.

Figure 7a shows the particleboard's temperature profiles in the testing box. During the experiment for 3 days, the temperature of the test box's external wall was higher than that of the internal wall during the daytime, i.e., from 9:00 a.m. to 4:48 p.m. on Day 1, 7:11 a.m. to 4:38 p.m. on Day 2, and 7:03 a.m. to 4:41 p.m. on Day 3. That is, the external wall's temperatures during the 8.00 a.m.–3.30 p.m. period were higher than the internal wall's, which were 3-6.6°C, 3.2–8.1°C, and 3.3–8.9°C for Days 1–3, respectively. After that, the external wall's temperatures emit heat during the evening and night, leading to the external wall's conditions being lower than those of the internal wall. In addition, this caused the room temperature to be higher than the internal wall after 20.30, but the room temperature was lower than that of the internal wall when heat from the external wall transferred to the internal wall during the daytime.

Figure 7b shows the temperature profile of the MDF board in the testing box. The temperature of the external wall during 7.04 a.m.–4.24 p.m., 7.12 a.m.–4.12 p.m., and 7.03 a.m.–4.22 p.m. was higher than that of the internal wall and room in the test box. Especially from 9.00 a.m. to noon, the temperature of the external wall was different from the internal wall up to 6.00–9.50°C. Heat emissions caused the external wall's temperature to drop. The temperatures of the internal wall and room gradually decreased, but their temperatures were still higher than those of the external wall. Throughout the experiment, the room temperature remained lower than that of the internal wall.

Figure 7c shows the temperature profile of a 1:4 sunflower stalks and natural latex bio-composite by hot oven. The external wall consistently had a lower temperature than the internal wall and room, with the exceptions of 7.30–12.07, 7.17-9.47, and 7.11–11.01 a.m. The average temperature of the external wall was higher than that of the internal wall and room, 0.5–1.43 °C. During 8.16–8.40 a.m.–1.54–2.45 p.m., the internal wall's temperature was higher than that of room 1.00–2.30 °C. After 5.09–5.20 p.m. onwards, the internal wall's temperature was higher than that of the room, approximately 0.20 °C. It can imply that heat from the external wall transfers to the internal wall very quickly and accumulates at the internal wall and room. The pores in the bio-based composite facilitated the rapid heat transfer from outside to inside the room.

Figure 7d shows the temperature profile of the 1:6 sunflower bark and natural latex bio-composite obtained by hot compression in the testing box. Before 2.50 p.m., the internal wall and room had lower temperatures than the external wall. After 5 p.m., the external wall's temperature decreased faster than that of the internal wall and room. Furthermore, the temperature of the room consistently remained lower than that of the internal wall, with the exception of the range from 7.37–7.54 to 8.14–8.50 a.m., while the temperature of the room exceeded that of the internal wall by 0.10-0.20 °C. It was noticed that the temperature of the room was lower than the external and internal walls during the day, which was similar to the particle and MDF boards.

Table 4 Noise reduction coefficient (NRC) of bio-composites.

Bio-based composite	250 Hz	500 Hz	1,000 Hz	2,000 Hz	Average	NRC
1:4 sunflower stalks and natural latex by hot oven	3.60%	7.38%	33.97%	48.34%	23.32%	0.233
1:6 sunflower bark and natural latex by hot compression	5.85%	15.34%	27.26%	47.85%	24.10%	0.241

The 1:4 sunflower stalk bio-composite from a hot oven had the lowest external wall temperature compared to other test panels. It was followed by the 1:6 sunflower bark bio-composite obtained by hot compression, the MDF board, and the particleboard. The MDF's internal wall temperature increased the same as that of the 1:6 sunflower bark bio-composite, but it emitted heat slower. The particleboard's internal wall temperature was the slowest increase, but it decreased the same as the 1:6 bio-composite.

The temperature inside the particleboard was lowest during sunrise but highest during sunset. The temperature inside the testing box of the 1:4 sunflower stalk bio-composite quickly absorbed heat but emitted heat the same as that of the MDF and the 1:6 sunflower bark bio-composite. Interestingly, the temperature inside the MDF board's testing box was equal to that of the 1:6 bio-composite.

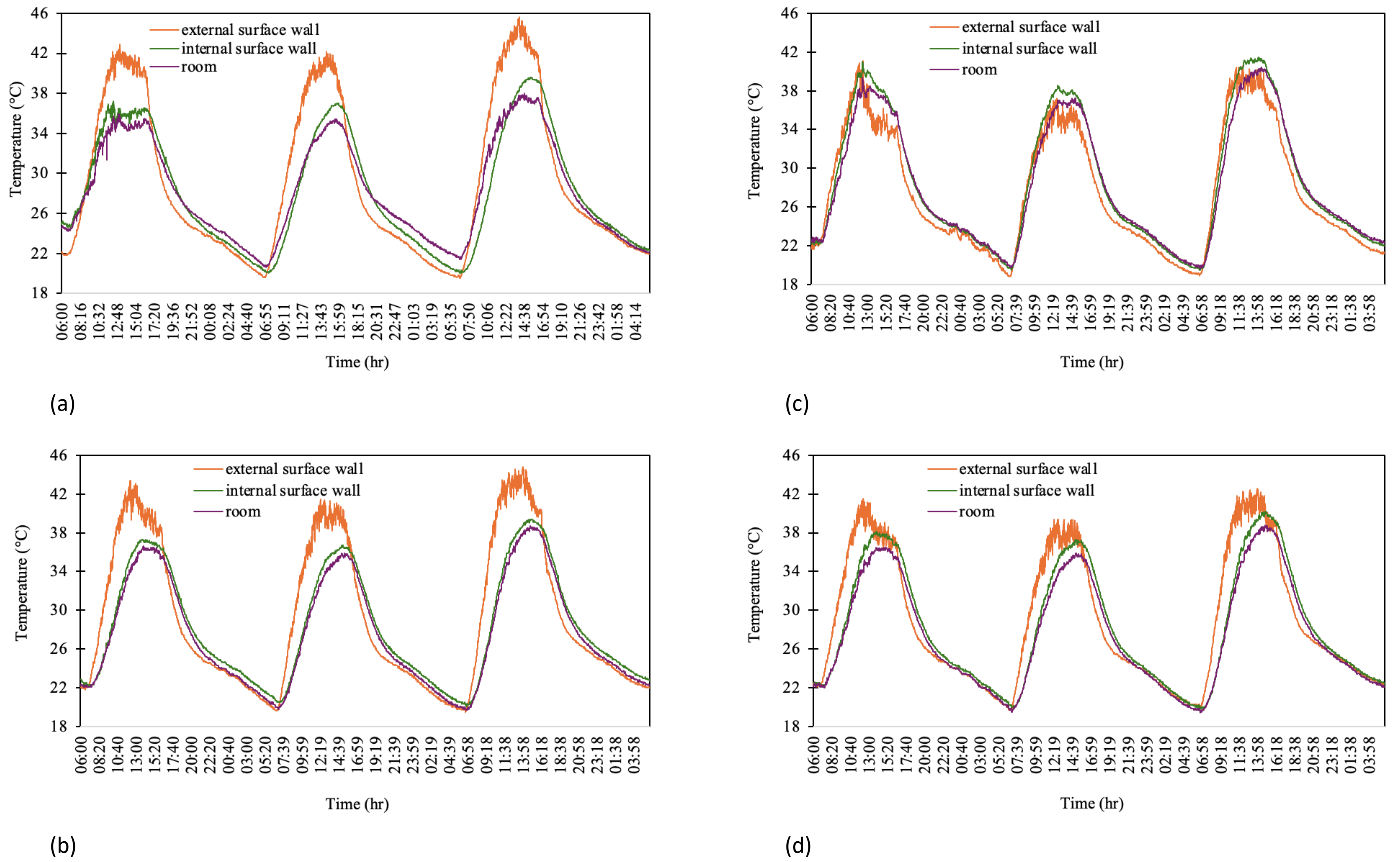


Fig. 7 Temperature profile of the testing box of (a) particleboard, (b) MDF board, (c) 1:4 sunflower stalks, and (d) 1:6 sunflower bark bio-composites.

4. Conclusion

The following results were obtained from this study:

Bio-composites have a density of 515.67–864.24 kg/m^3, which is comparable to that of flat-pressed particleboards. Only the 1:5 and 1:6 sunflower stalk bio-composites formed by hot compression had a moisture content greater than 13%. Thickness swelling ranged from 5.63% to 12.03%. All composites had a fire resistance of less than 33 mm/min. The thermal conductivity coefficient ranged between 0.117 and 0.161 W/mK.

The NRC values for 1:4 sunflower stalks in a hot oven and 1:6 sunflower bark in a hot compression were 0.233 and 0.241, respectively. The 1:4 sunflower stalks and 1:6 sunflower bark bio-composites show a good acoustic characteristic at a low-frequency range of 1,200–2,000 and 1,600–2,300 Hz, respectively.

The hot compression method provided lower density, lower water absorption, better flexural strength, and better flexural modulus than the hot oven method. As natural latex increases with increasing fire resistance, the water absorption of sunflower stalks decreases. This method is suitable for bio-composite production. The hot-compressed 1:6 sunflower bark bio-composite exhibited a room temperature profile that was similar to that of the MDF board.

Sunflower stem and natural latex can form a bio-composite that serves as an alternative to non-renewable composites. For building products, however, some improvements were required in their thermal conductivities and acoustic absorption coefficients. In addition, this bio-composite can be developed by using other biological materials, such as water hyacinth, in terms of appearance, beauty, and usability, or as a surface insulation sheet, etc.

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