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Cochineal Wax (*Dactylopius coccus costa*) as an Eco-Friendly Alternative for Thermal Insulating Materials: A Physicochemical Approach

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Abstract. *Cochineal* (*Dactylopius coccus costa*) is an insect of remarkable historical and contemporary value, whose wax represents a local, renewable, and biodegradable resource. In this study, an innovative material was developed from cochineal wax collected in San Francisco Tepeyecac (San Martín Texmelucan, Puebla, Mexico), aiming to explore its potential as an eco-friendly alternative for thermal insulation.
The material was characterized using FTIR, UV-Visible, and GC-MS analyses, which revealed the presence of functional groups found in commercial insulating materials (CH_2, CH_3, C=O, C=C, COH) and identified nine compounds with insulating properties. Optical microscopy

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confirmed characteristic structures of both the wax and the fabricated material. In thermal conductivity tests, the material demonstrated stability under heat exposure, maintaining its structure after 10 seconds, and extinguishing the flame. At 50 °C, its performance in ice-melting experiments was comparable to that of wood and glass, while diamond detector measurements confirmed behavior similar to that of commercial insulators. These findings open a new line of research into the sustainable use of cochineal wax for thermal insulation materials, highlighting its potential industrial applications and its benefits to Mexican society.

Resumen. Cochineal (*Dactylopius coccus costa*) es un insecto de gran valor histórico y actual, cuya cera constituye un recurso local, renovable y biodegradable. En este trabajo se desarrolló un material innovador a partir de cera de grana cochinilla obtenida en San Francisco Tepeyecac (San Martín Texmelucan, Puebla, México), con el objetivo de explorar su potencial como alternativa eco-friendly para aislantes térmicos. El material fue caracterizado mediante FTIR, UV-Visible y GC-MS, identificándose enlaces funcionales relevantes (CH_2, CH_3, C=O, C=C, COH) y nueve compuestos con propiedades aislantes. La microscopía óptica reveló estructuras características de la cera y del material elaborado. En pruebas de conductividad térmica, el material mostró estabilidad frente a una fuente de calor, manteniendo su estructura después de 10 segundos de exposición. Además, a 50 °C, su desempeño en la fusión de hielo fue comparable al de la madera y el vidrio, y un detector de diamante confirmó un comportamiento similar al de los aislantes comerciales. Estos resultados abren una nueva línea de investigación sobre el aprovechamiento de la cera de cochinilla como insumo sustentable para materiales aislantes, con aplicaciones potenciales que podrían beneficiar tanto a la industria como a la sociedad mexicana.

Introduction

Cochineal (*Dactylopius coccus costa*), known in Nahuatl as *nocheztli* (blood of the prickly pear cactus) and in Mixtec as *nduku* (insect or blood), is a hemipteran insect found primarily on the leaves of the genera *Opuntia ficus-indica* and *Opuntia nopalea* [1]. In pre-Hispanic Mesoamerica, it was cultivated in what is now Puebla-Tlaxcala, Oaxaca, Michoacán, and Chiapas; where it was used for religious and tribute purposes, to dye textiles (blankets and leather garments), to color food (tamales and tortillas), and to paint houses and codices, among other uses.

Several industries worldwide and in Mexico, such as food, textiles, cosmetics, and phamaceuticals use cochineal to obtain various products, including breeding stock, extracts, dyes, carminic acid, calcium carminate, and lacquers [2]. When selecting and cleaning this insect, a large amount of wax (coccerin), small insects, spines, and other debris are released. The main compound present in cochineal wax is the triacotanol that acts as a powerful natural regulator of plant growth [3]. This wax has properties that make it an attractive and sustainable alternative for producing thermal insulation materials. Among these properties are its resistance to high temperatures due to its high melting point, and its low density, which makes it easy to handle without requiring significant force to be applied to the structure [4].

The widespread use of synthetic thermal insulators has had and environmental and health impact on the Mexican population [5]. This is due to the release of chemical compounds from these materials, which harms air quality, as well as the generation of solid waste, leading to soil and ground water contamination. This in turn affects the carbon footprint and the atmosphere, making a more sustainable alternative a necessity [6]. Cochineal wax could be a perfect solution, since there is not a wide range of literature related to the application of this material. It is obtained as an agricultural by-product, reduces waste and avoids petrochemical inputs, thereby lowering its environmental footprint compared to synthetic alternatives. Economically, this approach supports local farmers and rural economies, while synthetic insulators, although cheaper at an industrial scale, entail hidden costs for waste management and environmental remediation.

Khargotra et al (2024) described a method for fabricating a flat-plate solar collector from agroindustrial waste (rice husks, crop residue fiber, coconut coir, and nitrile rubber) [7]. Two materials were fabricated (50 and 70 mm thick), and the optimum temperature was determined to be 50-53 °C, with a thermal efficiency of 64.66%. The best collector was the one made from rice husks with a thickness of 70 mm. Alhabeed et al (2021) examined

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the thermal conductivity of five samples made from hari, grass, date seeds, and date palm fiber [8]. The heat flow method was used, and the results showed that all samples exhibited heat-transfer resistance in the range of 0.0530 to 0.1068 W/mK. The best thermal resistance was provided by the sample made from hair and fiber.

Arroyo-Figueroa et al (2023) conducted a physicochemical analysis of three samples of white wax obtained from the insect *Dactylopius coccus costa* to determine if it meets the characteristics for its use in natural products (pigments, dyes, and cosmectics) [9]. They determined the organoleptic characteristics: color, pH, melting point, and moisture content; concluding that it is possible to replace synthetic wax with natural cochineal wax, and therefore, this wax can be used in the production of natural products.

The performance of thermal insulating materials is primarily governed by their physicochemical parameters. Low thermal conductivity is the most critical property (0.015-0.10 W/(m•K)), as it minimizes heat transfer and ensures effective insulation [10]. Complementary factors such as density (10-200 kg/m^3) and porosity (70-95%) help trap air and reduce conduction, while high thermal stability (200-1000 °C) enables the material to withstand temperature variations without degradation [11]. In addition, low moisture absorption is essential, since water increases conductivity and diminishes efficiency [12]. Other parameters, including specific heat capacity (0.8-1.5 J/(g•K)), mechanical strength (0.02-0.5 MPa), and chemical resistance, further enhance durability and practical applicability [13]. Together, these characteristics provide a comprehensive framework for evaluating and optimizing materials intended for thermal insulation.

It is very important to mention that cochineal a renewable resource, as it can be obtained through sustainable production systems. It is biodegradable, resulting in a smaller carbon footprint. It is also worth noting that the farming of this organism can be associated with organic agricultural practices, which contribute to the maintenance of ecosystems and biodiversity [14]. Considering the above, this project proposes the physical and chemical characterization, using optical and microscopic techniques, of a potential thermal-insulating material developed from wax produced by cochineal. As well as its analysis by gas chromatography coupled to mass spectrometry; in the end, techniques related to the determination of the possible thermal insulating properties of the material were applied.

Experimental

The following reagent and equipment were used in this project: potassium alum ($KAl(SO_4)_2 \cdot 12H_2O$), a thermomixer (CGY IDT-228), a coffee grinder (Hamilton Beach 80410); in addition, a UV-Visible spectrophotometer (ThermoScientific Genesis 40), a FTIR spectrophotometer (Bruker Vertex 70), an optical microscope (VeLAB model VE-MSLCD), a gas chromatograph coupled to mass spectrometry (Agilent Technologies 7890A, MSD detector 5975C), and a diamond detector (Diamond Selector II-861) were used.

Cochineal wax collection

The cochineal wax was collected at the Nopalyecac group's greenhouse, located in the community of San Francisco Tepeyecac in the municipality of San Martín Texmelucan, Puebla (Mexico).

The cochineal insects were removed by hand from the prickly pear cactus, ground using a coffee grinder, and then sieved through a 2.5 mm mesh sieve to obtain the wax. Once the wax was obtained, it was placed in a plastic container to transport it to the laboratory.

Preparation of the thermal insulation material from cochineal wax

To prepare the material of interest, 1.25 g of potassium alum, 25 mL of distilled water, and 5 g of cochineal wax were mixed (20 min/120 °C), then the mixture was placed in a plastic Petri dish (15 days/20 ± 2 °C). After the drying period, the sample was removed from the Petri dish and characterized by the techniques mentioned below.

Material characterization using optical (UV-Vis/FTIR spectroscopy) and microscopic (optical microscope) analysis

Samples were analyzed by optical microscope using a 10x objective. Subsequently, they were analyzed by FTIR spectroscopy in ATR (Attenuated Total Reflectance) mode, with a resolution of 4 cm^{-1} and 120 scans,

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over the mid-infrared region (400-4000 cm^{-1}). Additionally, samples were analyzed using a UV-Vis spectrophotometer with a scan from 400 to 700 nm in absorbance mode. The obtained spectra were analyzed using Origin 8.0 software.

Material characterization using gas chromatography coupled to mass spectrometry

For this analysis, the material was redissolved in hexane and filtered using a filter (2 µm). A 30m•250mm•0.5 µm HP DB5-MS capillary column was used. The Carrier gas was helium with a Flow ratio f 1.0 mL/min. The initial temperature was 80 °C for 2 min, the heating ramp was 15 °C/min to 310 °C for 2 min, and the run time was 20 min. A 25:1 split injector was used, with a temperature of 300 °C and an injection volume of 3 µL. A 3-axis quadrupole mass spectrometer was used, in electron-impact ionization mode, with an electron energy of 1988.235 eV, a scan range of 15 to 700 M/z, an MS source at 230 °C, a quadrupole scan at 150 °C a 2 min solvent delay, and the NIST 2.0 library.

Thermal conductivity analysis of the manufactured material

In this stage, three experiments were performed. The first involved placing the material in direct contact with a heat source (a match flame) and measuring how long it retained the flame. In the second experiment, an ice cube of known volume was placed on the material of interest, as well as on wood and glass. The different materials, each with its respective ice cube, were heated to 50 °C (a representative intermediate temperature) on a heating plate. The time it took for the ice cube to melt on each material was recorded. This experiment was made in triplicate; ANOVA was made to determine statistical significant differences between materials. Finally, different insulator materials and the one made from cochineal wax were analyzed using a diamond detector to compare and determine whether or not the material of interest could be considered as an insulator material.

Results and discussion

The results obtained in this project are presented below:

In Fig. 1, micrographs obtained from the analysis of cochineal wax by optical microscopy are shown, where a material with interwined fibrils or filaments, which can be observed, may correspond to remnants of secretions or dermal structures of the insect [15]. Besides, compact granules, possibly associated with lipid or waxy compounds, are shown [16]. Additionally, amorphous and agglomerated structures with particles of varying sizes were identified. These characteristics are typical of insect-produced waxes [17], especially those secreted by female cochineal insects.

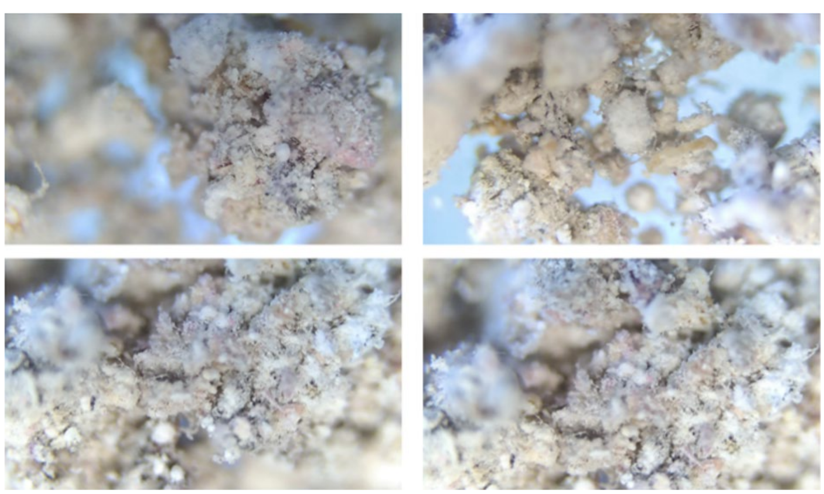

Fig. 1. Micrographs obtained from the analysis of cochineal wax by optical microscopy. 10x objective.

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Fig. 2 shows the material made from cochineal wax, and the micrographs were obtained through microscopic analysis of this material. The result is a solid, organic-based biomaterial with a granular, porous texture as revealed in the images. The observed color may be attributed to carmine, a compound present in cochineal residues [18]. Cochineal wax provides hydrophobic properties, cohesion, and structure, while potassium alum acts as a fixative coagulant [19]. The thermal process followed by prolonged cooling suggests slow gelation or crystallization, thereby allowing the formation of a solid matrix with well-defined morphological characteristics [20].

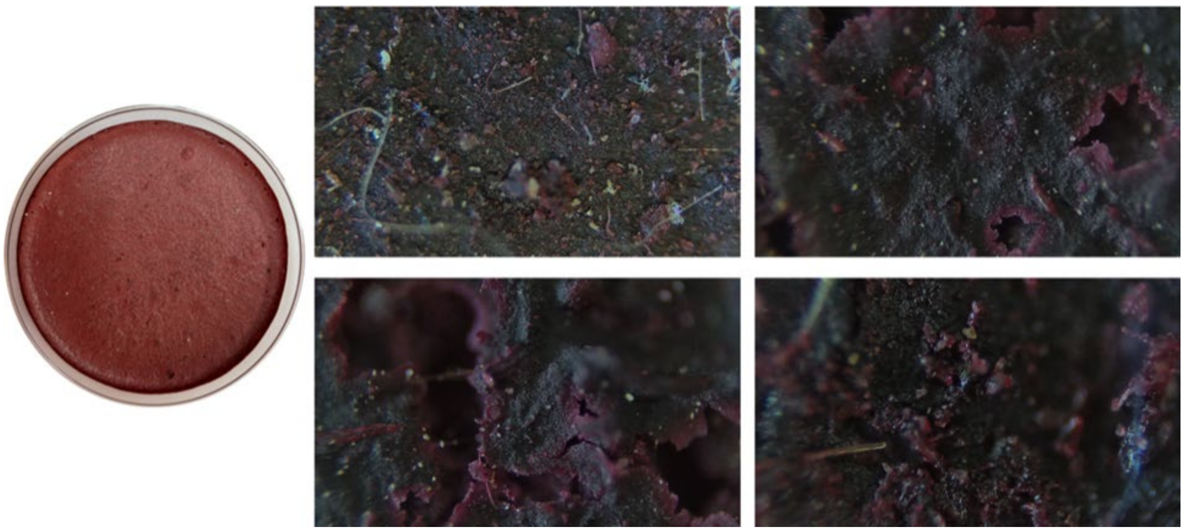

Fig. 2. Material made from cochineal wax (left side) and four micrographs of this material analyzed by optical microscopy 10x objective (right side).

Fig. 3 shows the FTIR spectrum obtained from the generated material. An absorption band is observed at 3350 cm^{-1} (-OH). The bands at 2855 and 2930 cm^{-1} are related to the stretching vibrations of the C-H bonds from methyl (CH_3) and methylene (CH_2) groups. The band at 1642 cm^{-1} corresponds to the C-O bond vibration, which is a stretching vibration of the anthraquinone in the central ring of carminic acid. At 1565 cm^{-1}, a band corresponding to the C=C stretching vibration of the aromatic ring was identified, as well as the scissoring vibration of the C-O-H bond and out-of-plane bending of the C-H bond [21]. The stretching vibrations of the C-C bond and the C-H bond were also determined at 1463 cm^{-1}; other bands (strain vibrations of the C-H and C-O-H bonds) present in carminic acid were identified at 1270 cm^{-1}. Band at 1080 cm^{-1} is related to the scissor vibrations of the C-O and C-O-H bonds, as well as the rocking vibration of the C-H bond [22]. Sanches et al. (2013) [23] reported the presence of the aforementioned bands upon analysis of nitrile rubber using attenuated total reflectance (ATR). Nitrile rubber is a material used in combustion systems for automobiles, ships, and aircraft. From a thermal insulation perspective, both materials act as poor conductors of heat due to their organic, carbon-rich composition, making them useful in contexts where low thermal conductivity and resistance to environmental exposure are desired, even though their mechanical behaviors differ significantly.

The bands related to the C-H bond (rocking) and the C-C-C bond (scissoring) were determined at 884 cm^{-1}. Finally, the bands at 532, 617, 675, and 758 cm^{-1} were attributed to interactions involving aromatic rings, C-H bonds, C-OH bonds, and C-H bonds, respectively [24]. The results obtained are similar to those from analyses of lignocellulosic fibers used in building construction, indicating that the material produced does not contain components that could be considered toxic [25].

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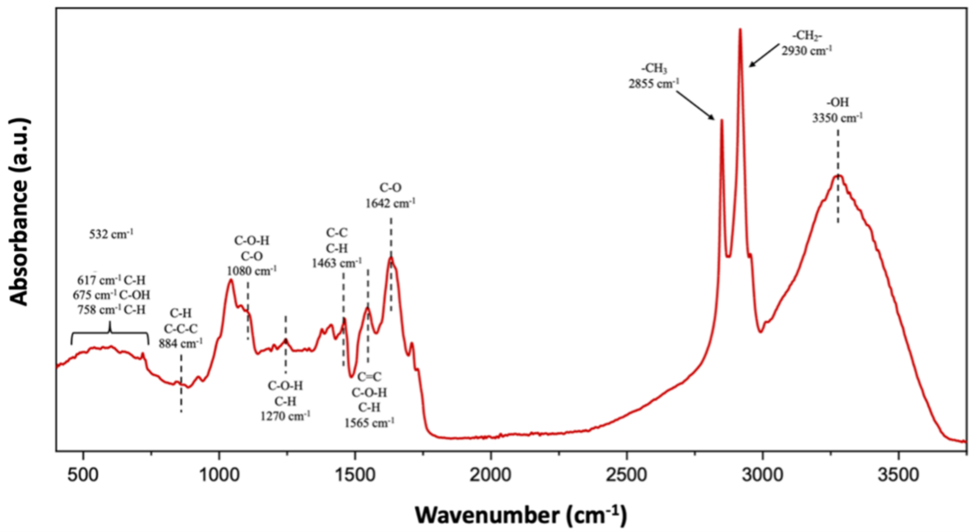

Fig. 3. FTIR spectrum corresponding to the material made from cochineal wax.

Fig. 4 shows the UV-Visible spectrum of the generated material. An absorption band at 540 nm is observed, which is related to the carbonyl bond (C=O) and attributed to an n-π* transition. It is reported that the presence of this bond facilitates the union of carminic acid with other organic molecules [26,27].

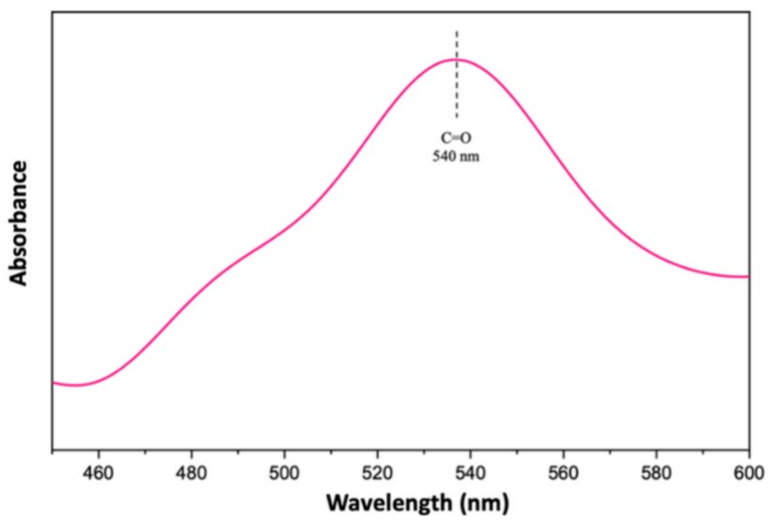

Fig. 4. UV-Vis spectrum corresponding to the material made from cochineal wax.

Table 1 shows the main components detected by GC-MS (Fig. 5) that are related to the possible thermal insulating activity of the material.

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Table 1. Main components determined by GC-MS in the material of interest.

Chemical compound	Retention time (min)	Main characteristics	Function in thermal insulation	References
2-cyclopenten-1-one	3.6336	Colorless liquid with a strong odor; a cyclic organic compound containing ketones.	A precursor to cyclopentane, used in foams.	[32]
Phenol	4.1338	Crystalline solid, characteristic odor; phenolic resin base.	In the form of phenolic resin for insulation.	[29]
Glycerin	4.6955	Viscous, colorless, plat-derived liquid; good heat retention.	Used in insulating bricks.	[31]
Cycloheptasiloxane	9.074	Cyclic siloxane, a volatile liquid, is used in cosmetics.	Cyclo siloxanes have useful thermal properties.	[34]
β-D-Glucopyranose	9.5126	Cyclic sugar; building block of cellulose.	Part of the cellulose was found in natural insulators.	[31]
Cyclooctasiloxane	10.5514	Larger cyclic siloxane; volatile liquid.	Useful in heat-dissipating coatings.	[34]
Phenol, 2-methyl- (o-Cresol)	11.9211	Crystalline solid; precursor to epoxy resins and disinfectants.	Phenolic resins for insulation.	[29]
n-Hexadecanol	12.7907	Solid fatty alcohol; used in cosmetics.	Phase-change material for termal storage.	[30]
n-Hexadecanoic acid	13.9526	Palmitic acid; White, stable, plant-derived solid.	Component in insulating and surfactant formulations.	[35]

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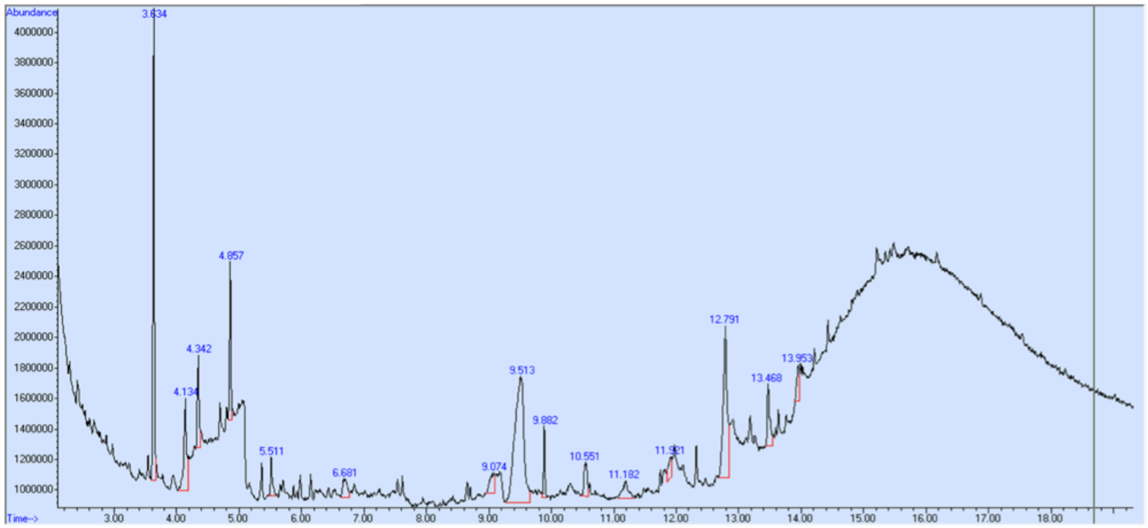

Fig. 5. Chromatogram obtained after analysis of the material.

The relationship between the spectroscopic results (FTIR and UV-Vis) and the compounds detected by GC-MS allows us to understand how the chemical structure of the material derived from cochineal wax translates into its potential thermal insulating properties, as well as the material's sustainability. In the FTIR, the absorption bands in the 3350 cm^{-1} (O-H), 1642 cm^{-1} (C=O), and 1565 cm^{-1} (aromatic C=C) regions confirm the presence of hydroxyl groups, carbonyls, and aromatic structures [28]. These functional groups correspond directly to the compounds identified by GC-MS: phenol and o-cresol contribute aromatic groups with O-H bonds [29], n-hexadecanoic acid and n-hexadecanol contain carbonyl (C=O) and alcohol (O-H) groups [30], glycerin and D-glucopyranose are molecules rich in hydroxyl groups, which reinforce the O-H and C-O-H bands [31].

UV-Vis spectroscopy revealed a band at 540 nm (C=O). This signal is associated with compounds such as carminic acid, 2-cyclopenten-1-one and fatty acids (n-hexadecanoic acids), which possess conjugated carbonyls capable of absorbing in this region [32]. The presence of these carbonyls also facilitates interaction with other organic molecules [33], which is consistent with the diversity of compounds detected by GC-MS. On the other hand, cyclic siloxanes (cycloheptasiloxane and cyclooctasiloxane), although they do not exhibit intense UV-Vis absorption, contribute to the FTIR signals in the low region (758-532 cm^{-1}), associated with Si-O and C-H bond vibrations [34]. Their chemical structure explains the material´s thermal stability and heat dissipation capacity.

To determine the material's potential thermal insulation capacity, a representative sample was selected. A lit match was used as a heat source and placed in direct contact with the sample. The material's behavior during exposure to the flame was observed and recorded, paying particular attention to the rate of heat propagation and any evident changes in the material's structure or appearance. The results are shown in Fig. 6. The experiment demonstrated that although the material ignited briefly, it extinguished after 10 s without losing structure. This suggests that the material has a possible thermal insulation capacity, since the heat did not spread rapidly or cause structural damage, indicating that the material's composition may be a polymer with flame retardants [35], a compound with mineral fibers [36] or a material with low thermal conductivity that prevents heat from spreading rapidly [37].

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Fig. 6. Interaction of the generated material with a lit match **(A)**, the fire interacts with the material **(B)**, and after 10 s, it goes out **(C)**.

To reinforce the potential application as a thermal insulating material, Table 2 presents the results obtained after placing ice cubes (4 cm length) on various materials. These materials were on a heating grid at 50 °C. Ice retention time was similar between the material made from cochineal wax (15 ± 1 min), glass (16 ± 1 min) and wood (16 ± 2 min). No significant statistical differences were determined between materials.

Materials like glass (1.4 W/m·K) and wood (0.2 W/m·K) have low thermal conductivity [38, 39] meaning they transmit heat slowly. The comparison with wood and glass was deliberately selected because these materials are readily available, widely used, and serve as well-established reference points for thermal insulation in everyday applications. Assessing the cochineal wax material against these conventional standards enabled a clear evaluation of its thermal performance relative to materials that are familiar to both industry and society. More advanced insulating materials, such as polymers or specialized composites, were not considered at this stage, as the objective was to establish a baseline comparison using accessible, non-specialized materials. This approach highlights the intrinsic insulating potential of cochineal wax before extending the analysis to more complex and engineered benchmarks. Based on the results obtained, it can be inferred that wax cochineal is also a poor heat conductor, so the ice absorbs heat at a similar rate, which explains why the melting times are very similar. This slight difference may be due to variations in texture, as well as surface contact [40,41].

Table 2. Time of ice cubes retention in solid state after placing them on different materials (50 °C). No significant statistical differences were determined between materials.

Material	**Time of ice retention in solid state (min)**
Cochineal wax	15 ± 1[a]
Glass	16 ± 1[a]
Wood	16 ± 2[a]

The thermal conductivity of diamond is approximately 2000-2200 W/m·K at room temperature (20 °C), making it the most thermally efficient material [42]. Using a thermal conductivity meter designed to detect diamonds, different insulating materials were compared. Table 3 shows the results obtained in this test. The LED scale (6) corresponds to the room temperature (25 °C) at which the sample was measured. For polystyrene, plastic, Pyrex glass, polyethylene, and the material (wax cochineal) samples, the numerical value is the same as in the control (6), indicating no heat transfer. However, in the case of distilled water, the device registers the highest numerical value (>8), indicating that water is a heat conductor.

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Table 3. Thermal conductivity obtained values from different materials after using on them a thermal conductivity meter designed to detect diamonds.

Control

Material	Device value
Control (No heat transfer)	6
Polystyrene	6
Pyrex glass	6
Plastic	6
Polyethylene	6
Material (wax cochineal)	6
Distilled water	>8

Conclusions

The development of material from cochineal wax represents a significant advance in the search for local, sustainable resources with technological potential. Spectroscopic (FTIR, UV-Vis), microscopic, and GC-MS analyses confirmed the presence of insulating structures and compounds, while thermal and fire tests demonstrated their stability and performance comparable to commercial insulators. This finding not only validates the scientific value of cochineal wax as a renewable alternative but also opens the possibility of transforming a traditional resource into an innovative solution for the Mexican industry. The potential applications of the cochineal wax-based thermal insulator extend to sectors such as construction, packaging, and food preservation. In construction, it can serve as a sustainable alternative for wall and roof insulation; in packaging, its biodegradability and non-toxic nature make it suitable for protective materials; and in food preservation, its low thermal conductivity helps maintain stable temperatures during storage and transport. This research marks the beginning of a promising line of investigation that can contribute to the development of environmentally friendly materials, strengthen the local economy, and position Mexico as a leader in the creation of sustainable insulators.

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