

Thermal insulation based on agroforestry waste

Ortiz-Rodríguez, Lilia. PhD

Cuevas-Suarez, Carlos. PhD

Ruiz-Colorado, Nora Isela. PhD

Arcila-Lozano, Cynthia Cristina. PhD

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Thermal insulation based on agroforestry waste

The Book will offer selected contributions from researchers of the Tecnológico Nacional de México/Instituto Tecnológico Superior de Perote in its areas of Engineering. In addition to having a complete evaluation, by the coordinators of the Tecnológico Nacional de México/Instituto Tecnológico Superior de Perote, of the quality and punctuality in its chapters, each individual contribution was refereed with international standards [V|LEX, RESEARCH GATE, MENDELEY, GOOGLE SCHOLAR y REDIB]. The Book thus proposes to the academic community recent reports on new progress in the most interesting and promising areas of Engineering.

Thermal insulation based on agroforestry waste

Books

Autores

Ortiz-Rodríguez, Lilia. PhD

Cuevas-Suarez, Carlos. PhD

Ruiz-Colorado, Nora Isela. PhD

Arcila-Lozano, Cynthia Cristina. PhD

Tecnológico Nacional de Mexico/Instituto Tecnológico Superior de Perote

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Prologue

The growing generation of agroforestry and plastic waste is one of the main environmental and economic challenges of our time. In response to this reality, the present research proposes an innovative and sustainable alternative: the development of a thermal insulating material made from agroforestry and PET waste, through a pressing process. This aims to both reduce the pollution caused by the burning of such waste and to provide a useful resource for the construction of panels with optimal thermal properties.

The study focuses on the characterization of sawdust generated in Mexico, analyzing the environmental, economic, and social implications of its accumulation, and highlighting its potential for valorization as a raw material. To this end, a prototype for measuring thermal conductivity was developed — a key parameter that determines a material's ability to function as an insulator — thereby providing experimental evidence supporting the feasibility of this technological proposal.

The research falls within the strategic areas of the Secretariat of Science, Humanities, Technology and Innovation [SECIHTI], particularly in the field of the dissemination and universal access to science, by generating applicable and open-access knowledge in the field of sustainable materials. It also integrates contributions from previous studies on natural fibers and agro-industrial waste, which have proven effective in the development of insulators with performance superior to conventional materials.

This work aims not only to address the urgent need to responsibly manage agroforestry and polymer waste but also to open up economic and technological opportunities for transforming such waste into high value-added products. It aspires to contribute to the advancement of sustainable construction, energy efficiency, and scientific innovation, while fostering a culture of comprehensive resource utilization and environmental commitment.

*Landa-Morales, Cristina. PhD
August, 2025*

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Thermal insulation based on agroforestry waste


Aislante térmico a base de residuos agroforestales

Ortiz-Rodríguez, Lilia ^a *, Cuevas-Suarez, Carlos ^b, Ruiz-Colorado, Nora Isela ^c and Arcila-Lozano, Cynthia Cristina ^d

^a  Tecnológico Nacional de Mexico/Instituto Tecnológico Superior de Perote •  LEN-4905-2024 •  0000-0002-5548-0078 •  291742

^b  Tecnológico Nacional de Mexico/Instituto Tecnológico Superior de Perote •  LEN-6489-2024 •  0000-0001-8556-9885 •  538584

^c  Tecnológico Nacional de Mexico/Instituto Tecnológico Superior de Perote •  LEL-7181-2024 •  0000-0001-8994-7943 •  204018

^d  Tecnológico Nacional de Mexico/Instituto Tecnológico Superior de Perote •  LIC-9098-2024 •  0000-0001-6365-6578 •  101416

Classification:

Area: Engineering

Field: Engineering

Discipline: Industrial Engineering

Sub-discipline: Solid waste management and treatment

Key Books

The main contributions of this research are based on the use of agroforestry and PET waste to produce thermal insulation through a pressing process, which will serve to include this type of material in the manufacture of panels, as well as reducing the pollution generated by the burning of this type of waste. Show the characterization of sawdust in Mexico, the problems caused by its generation in environmental, economic, and social terms, but also the economic opportunity that its transformation represents. In addition, a prototype was built during this project to measure thermal conductivity, a property that allows us to establish whether a material is insulating. The areas of contribution within the SECIHTI [Secretariat of Science, Humanities, Technology, and Innovation] in which the presented project is framed include "Dissemination and universal access to science," given that it is an initiative aimed at scientific dissemination, education, and the promotion of equitable access to knowledge. The key aspects are knowledge of sawdust, its generation processes, current trends, and the opportunity to maintain forest resources by optimizing their use. One author has an SNII scholarship, three of the authors have an updated PRODEP Desirable Profile. One author has a scholarship. COVEICYDET [Veracruz Council for Scientific Research and Technological Development] funded the project presented in the book. The authors of the article generated four citations in the last year. They come from state public institutions and belong to the public education system, in particular the decentralized technological system. National Technological Institute of Mexico/Higher Technological Institute of Perote. The most frequently used keywords are recycling, waste, thermal insulation, and thermal conductivity.

Area: Promotion of frontier research and basic science in all fields of knowledge.

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* ✉ [\[lilia.ortiz@perote.tecnm.mx\]](mailto:lilia.ortiz@perote.tecnm.mx)

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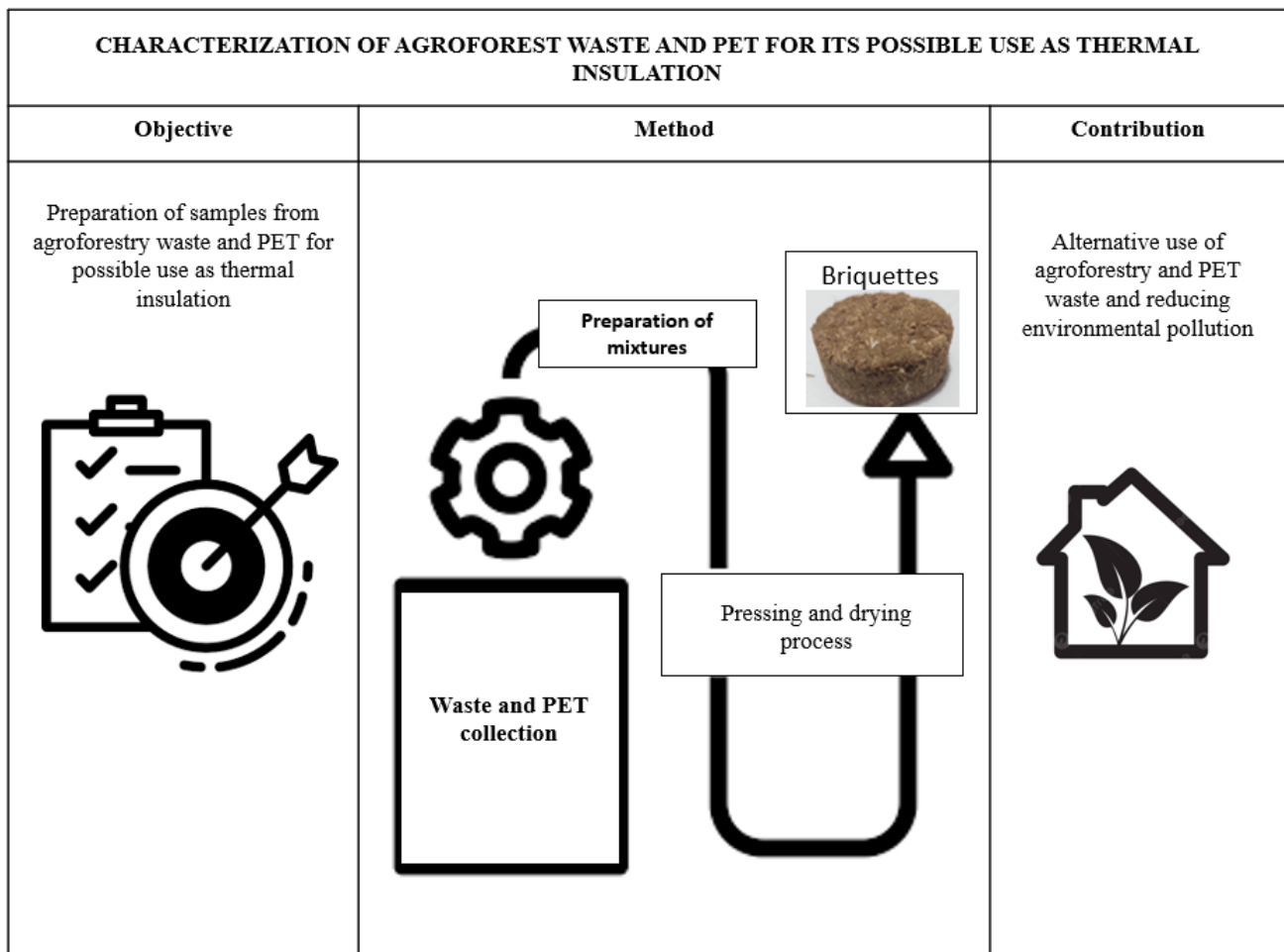
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Abstract

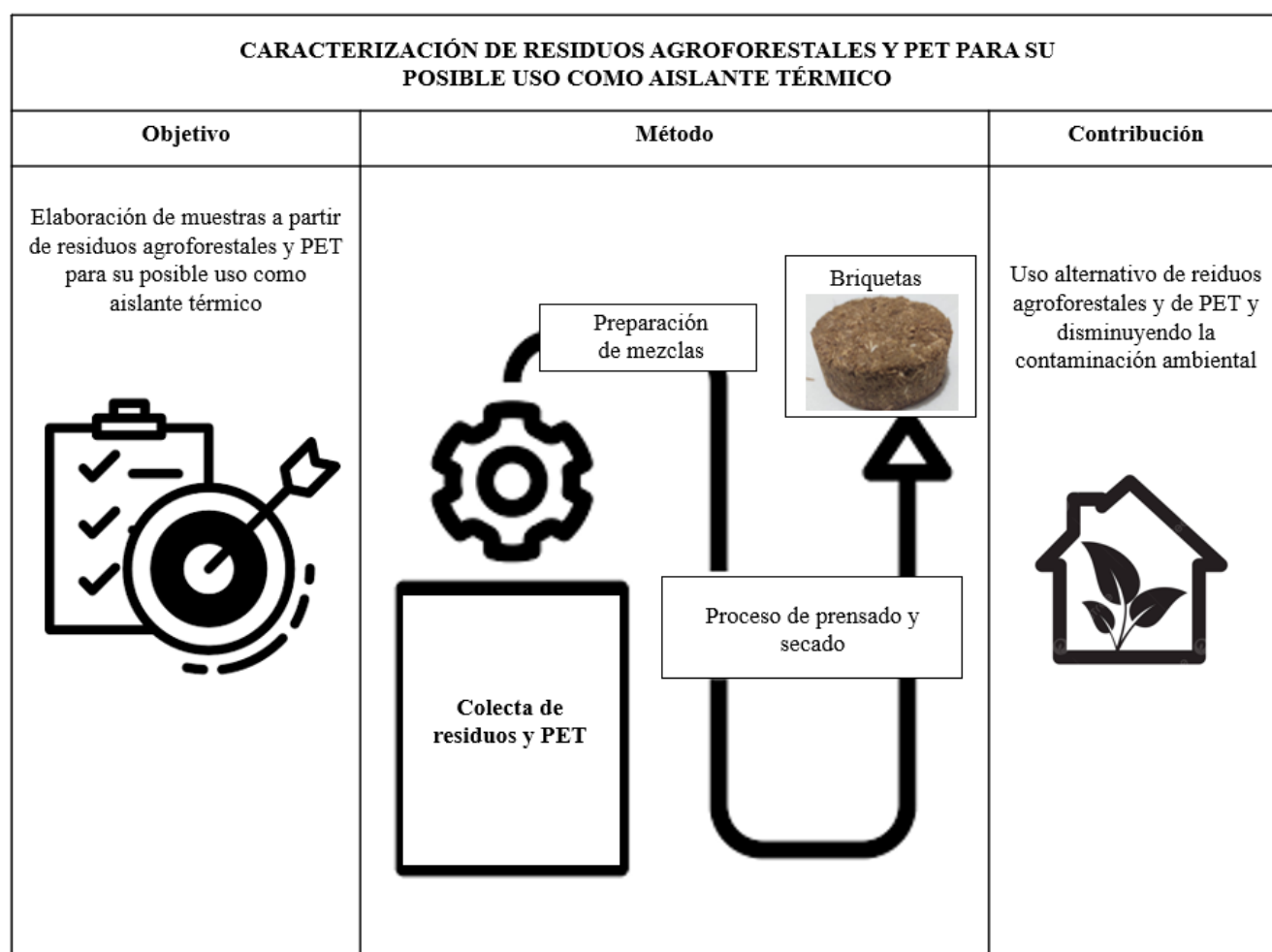
Thermal insulators are materials of natural or synthetic origin that, due to their low thermal conductivity, significantly reduce heat loss. The constant increase in the global population has led to a growing demand for housing, which in turn has driven the development of more efficient and sustainable buildings. To meet these requirements, materials used as thermal insulators must not only offer high resistance to heat transfer but also possess other essential characteristics: they must be impact-resistant, durable, fire-resistant, and capable of maintaining their structural integrity over time. In recent years, various eco-friendly alternatives have been explored, particularly organic materials of natural origin, such as plant fibers derived from cereal and coffee husks, straw, cane, coconut shells, and sawdust. These locally available and low-cost resources offer a sustainable option to replace conventional materials that have a greater environmental impact. Furthermore, the possibility of combining these organic components with inorganic compounds to enhance their physical and thermal properties opens up a wide range of adaptable options, depending on the environmental conditions where the insulator will be used. In the present study, an experimental prototype was developed to measure thermal conductivity using the hot plate method. Additionally, a new insulating material was formulated using agroforestry residues, aiming to repurpose waste that is commonly underutilized. This approach not only helps reduce the environmental footprint of construction but also promotes the circular economy. The incorporation of renewable materials fosters innovation within the green building industry.



Waste, Recycling, Thermal Insulation, Sustainable

Resumen

Los aislantes térmicos son materiales de origen natural o sintético que, debido a su baja conductividad térmica, reducen significativamente la pérdida de calor. El incremento constante de la población mundial ha generado una mayor demanda de viviendas, lo que a su vez ha impulsado el desarrollo de edificaciones más eficientes y sostenibles. Para cumplir con estos requerimientos, los materiales utilizados como aislantes térmicos deben poseer no solo una alta resistencia al paso del calor, sino también otras características importantes: deben ser estables ante impactos, duraderos, resistentes al fuego y mantener su integridad estructural a lo largo del tiempo. En los últimos años, se han explorado diversas alternativas ecológicas, particularmente materiales orgánicos de origen natural, como fibras vegetales provenientes de cascarillas de cereales y café, paja, caña, cáscara de coco y aserrín. Estos recursos, disponibles localmente y de bajo costo, ofrecen una opción sostenible para reemplazar materiales convencionales con mayor impacto ambiental. Además, la posibilidad de combinarlos con compuestos inorgánicos para mejorar sus propiedades físicas y térmicas abre un abanico de opciones adaptables según las condiciones del entorno donde se utilizará el aislante. En el presente trabajo, se desarrolló un prototipo experimental para medir la conductividad térmica mediante el método de placa caliente. Asimismo, se formuló un nuevo material aislante a partir de residuos agroforestales, buscando aprovechar desechos que comúnmente no tienen un uso valorizado. Este enfoque no solo permite reducir la huella ambiental de la construcción, sino que también promueve la economía circular. La incorporación de materiales renovables impulsa la innovación en la industria de la construcción ecológica.



Residuos, Reciclaje, Aislante Térmico Sustentable

Introduction

The use of waste after it is generated depends on its physical and chemical characteristics and how useful it is. In some studies, the components present in agro-industrial waste generated in the processing of the country's main crops were identified for use, depending on their compatibility, as raw materials for the production of bioplastics [Prado-Martínez et al., 2013; Temesgen, 2018].

Various studies have also been conducted to develop thermal insulation based on natural fibres such as sheep's wool, cotton and materials derived from plant fibres. One such material is agro-fibre panels, which are manufactured from agricultural waste and have structural properties that exceed those of wood-based panels [Peña et al., 2015]. The availability of agroforestry and polymeric waste, together with the need to minimise the environmental damage caused by their disposal, has led to research aimed at developing technologies that use them as raw materials in the production of biofuels, pulp, paper and new-generation, high value-added chemical products. Among the promising materials for these purposes are agro-industrial residues, which are widely available around the world, as they are generated from the harvest and processing of various agricultural products in high social demand [Sarkar et al., 2012].

Although these materials are usually grouped together to differentiate them from other plant residues, the quantities of the main structural components [lignin, cellulose and hemicellulose], which are natural polymers that represent about one-third of plant tissues and confer insulating capacity, vary greatly.

A material behaves as a thermal insulator when it hinders the passage of heat through it or when heat losses in the system in which it is applied are minimal. Therefore, the thermodynamic property that determines this characteristic in a material is that its thermal conductivity is lower. For this reason, various laboratory-scale experiments have been carried out to characterise the artificial drying of radiata pine wood at conventional and accelerated temperatures. with the aim of obtaining data to determine the thermal conductivity of wood using reverse methodology.

It was reported that thermal conductivities increase with increasing humidity and temperature, with values ranging from 0.34 to 0.56 [W/m °K] for humidity variations between 22% and 64%; and temperatures between 70°C and 90°C, respectively [Acuña, 2018]. One of the efficient methods for determining the thermophysical parameter [k] thermal conductivity is the steady-state hot plate method, which consists of knowing the mass and density of the specimen and measuring the temperature in the thermal insulation chamber. This method has been tested on solid blocks of jalcreta blocks [González et al, 2023] and in thermo-clay blocks with three mixtures: 75% clay - 25% polystyrene, 80% clay - 20% polystyrene and 85% clay - 15% polystyrene [Rodríguez et al., 2008]. Thermal conductivity can be determined using the Fourier's Law heat transfer equation [Peña et al., 2015]. Studies such as those by Sekino, 2016, have been conducted to determine the insulating capacity by measuring the thermal conductivities [k] of cellulose fibre [CF] and wood chip [WS] mats, and the dependence of the conductivity values on density. The results revealed that the dependence of the k values of CF mats on density was solely due to an increase in the number of thermal bridges, composed of fibres and their contact points.

This study evaluates the capacity of agglomerates made from PET and agroforestry residues [sawdust, pine bark] as a possible thermal insulation material.

Chapter I. Overview of heat transfer

Heat refers to the form of energy that is transferred from one system to another due to the difference in temperatures between the two systems. The science that studies the causes of this transfer is called heat transfer [Cengel & Ghajar, 2015].

Heat transfer is an important process in many aspects of everyday life and in various industrial applications. Heat transfer involves the exchange of heat between two objects or systems that have a temperature difference. This exchange always occurs from the object with the higher temperature to the object with the lower temperature and ends when both objects reach thermal equilibrium [Zhanxiao et al., 2025]. Mechanisms such as conduction, convection and radiation are involved in this process and can work alone or together.

In industry, heat transfer is critical for the design of equipment such as heat exchangers, cooling systems, drying processes and thermal insulation. It is also key to optimising energy consumption and improving the efficiency of production processes, reducing costs and minimising environmental impact [Cengel & Ghajar, 2015].

In industry, heat transfer plays an important role in the design of equipment such as refrigeration systems, heat exchangers, drying processes and insulation. It also plays an important role in optimising energy consumption, improving the efficiency of production processes, reducing costs and minimising environmental impact.

Box 1

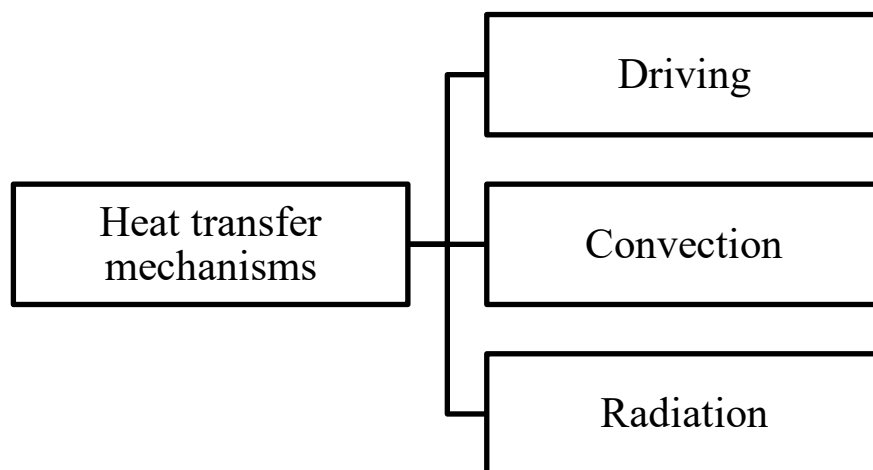


Figure 1
Heat transfer mechanisms

Source of reference: Cengel & Ghajar, 2015

Driving

Conduction is a process that occurs mainly in solids and is based on the exchange of energy between neighbouring particles due to molecular vibrations or, in metallic materials, the movement of free electrons. A material's ability to conduct heat is defined by its thermal conductivity. For example, metallic materials such as copper and aluminium are excellent heat conductors due to their high thermal conductivity, while materials such as wood and plastic act as insulators due to their poor ability to transmit thermal energy.

In practical applications, conduction is used in the design of heating systems and in the calculation of heat loss in buildings. A study by Peña et al. [2015] highlights that the thermal conductivity of materials such as clay blocks depends on factors such as density and porosity.

Convection

Convection refers to the transfer of heat between a solid surface and a moving fluid. This mechanism can be:

- Natural: When the movement of the fluid is caused by density differences caused by temperature changes. A clear example occurs in the Earth's atmosphere, where hot air rises while cold air sinks.
- Forced: This occurs when the movement of the fluid is caused by mechanical devices such as fans or pumps.

This mechanism is crucial in industrial production, such as in heat exchangers used to cool equipment or in HVAC systems to control the temperature of indoor spaces [Cengel & Ghajar, 2015; Tang et al., 2018].

Radiation

Thermal radiation is a process that does not require a material medium to transfer heat, as energy is propagated through electromagnetic waves. All objects with a temperature above absolute zero generate radiant energy. This mechanism is essential in applications such as solar energy systems and industrial furnace design.

The effectiveness of radiation depends on the emissivity and surface temperature of the material. Black or rough surfaces have high emissivity, making them efficient at emitting and absorbing thermal radiation [Holman, 2010].

Fourier's law

Fourier's law, formulated by French physicist Jean-Baptiste Joseph Fourier, is the fundamental principle of calorimetry and is used to describe heat transport through a material. From a mathematical perspective, where k represents the thermal conductivity of the material and dT/dx denotes the temperature gradient, it represents the change in temperature across the material. The negative sign indicates that heat moves from the higher temperature zone to the lower temperature zone. Fourier's law addresses the phenomenon of heat flow in a medium as a result of a temperature difference, stating that the rate of heat transfer is directly proportional to the temperature gradient $[\Delta T]$ and the thermal conductivity of the material. It establishes that heat flow $[Q]$ is related to the cross-sectional area $[A]$ and the temperature difference between the two ends of the material, but inversely proportional to the length $[L]$ of the conductor. The equation that describes this relationship is:

$$Q = -kA[dT/dx] \quad [1]$$

Fundamental principles

- Cross-sectional area: As the area allocated to heat transfer increases, the heat flow also increases.
- Temperature difference: The higher the temperature variation between the two bodies, the more intense the heat exchange.
- Conductor Length: As the length of the conductor increases, the passage of heat is reduced because the resistance to heat transfer increases.

A crucial law in the field of thermal engineering and thermal conduction process simulation. Fourier's Law provides a basis for analysing conduction in continuous media applicable to a variety of materials and conditions. However, in contexts where rapid temperature variations occur or, conversely, behaviour at microscopic scales is considered, it may be necessary to implement adjustments or more sophisticated models. As Cengel and Ghajar [2015] mention, 'although Fourier's Law operates as a phenomenological approximation, its accuracy has been confirmed experimentally in most solids and liquids under steady-state conditions.'

Thermal conductivity

Thermal conductivity is an essential physical property of materials that reflects their ability to transmit heat. This phenomenon is based on the transfer of thermal energy through the vibrations of particles in solids, mainly free electrons in metals and lattice vibrations in non-metallic materials.

The higher the thermal conductivity, the more efficiently a material can transfer heat from a higher temperature zone to a lower temperature zone.

This property is crucial in various industrial and technological applications, from the manufacture of heat exchangers to the design of electronic devices.

Metals such as copper and aluminium exhibit high thermal conductivities due to the mobility of their electrons, making them ideal choices for cooling systems or heat sinks. In contrast, materials such as wood or plastic have low thermal conductivity and are used as insulators. According to Callister and Rethwisch [2012], ‘the thermal conductivity of materials depends both on the crystal structure and the type of atomic bonds present,’ which explains the large variations between different types of materials.

In addition, thermal conductivity is also affected by external factors such as temperature, material purity, and the presence of impurities or defects. For example, in semiconductors, the incorporation of foreign atoms [doping] can significantly modify the material's ability to conduct heat. As Ashby and Jones [2012] point out, ‘optimising thermal conductivity is fundamental in the design of functional materials, especially in electronic and energy applications’. Understanding this property allows for improved thermal efficiency in multiple sectors, including construction, automotive, and aerospace. It is the ability of a substance to transmit kinetic energy from its molecules to other nearby molecules or to elements with which it interacts [Incropera, 1999].

Thermal conductivity [k] is an inherent characteristic of a material that defines its ability to transmit heat. Materials such as metal have high thermal conductivity and are excellent heat conductors, whereas materials such as wood are considered insulators due to their low thermal conductivity. Thermal conductivity, represented by the letter k, is an inherent property of materials that determines their ability to conduct heat.

Thermal conductivity values vary widely depending on the material:

- High values: Metals such as copper and aluminium.
- Low values: Insulating materials such as glass or air.

In the context of construction, Peña et al. [2015] highlight that the effective thermal conductivity of clay partitions depends on their composition and internal structure. This knowledge is essential for designing building materials that optimize the energy efficiency of buildings.

Thermal conductivity in gases, liquids and solids:

- Gases

Compared to liquids and solids, gases tend to have lower thermal conductivity. This is because the molecules in a gas are further apart from each other and therefore conduct heat less efficiently. Heat conduction in gases occurs mainly through molecular collisions, in which the more energetic molecules transfer heat to the less energetic ones.

Factors that determine the thermal conductivity of a gas include its temperature, pressure and chemical composition. For example, light gases have high thermal conductivity, while denser gases have low conductivity. In addition, thermal conductivity tends to increase with increasing temperature.

- Liquids

In fluids, thermal conductivity exceeds that of gases, although it is lower than that of many solids. In this condition, heat transfer occurs through atomic or molecular diffusion, in which molecules are closer together and have the ability to transmit energy more efficiently than in gases.

The mechanism that causes thermal conductivity in liquids is not fully understood, but it is known that elements such as molecular structure and interactions between molecules play a fundamental role. Liquids are often used in cooling systems because of their ability to transfer heat efficiently.

- Solids

Of the three states of matter, solids have the highest thermal conductivity, as their molecules or atoms are organized in a dense network structure that facilitates the efficient movement of vibrations through the material.

Metals are particularly efficient at transferring heat thanks to the existence of free electrons, which promote the transmission of thermal energy. On the other hand, non-metallic materials can have considerably lower thermal conductivity. This phenomenon is described mathematically by Fourier's law, which states that heat flow is proportional to the temperature gradient and the space through which the heat propagates [Connor, 2019].

Applications

Thermal conductivity has different uses in different areas of science and technology. For example, in the electronics industry, heat management is essential for the operation of components such as processors and integrated circuits, where materials with high thermal conductivity such as copper or aluminum are used to distribute heat during operation. This property is important in the design of electronic devices, as it allows the temperature rise to be controlled and damage to components to be prevented. Also in construction, in the design of materials for heat insulation, such as fibreglass or polystyrene, their main application as heat insulators is to improve energy efficiency and reduce heating or cooling consumption.

This property also applies to the production of heat transfer equipment, such as exchangers and cooling systems, the basic chemical industry and air conditioning [Lin et al., 2018; Eivari et al., 2021]. Fourier's Law has multiple applications in various areas, as mentioned below:

- Civil engineering

It is used to design energy-efficient buildings, optimizing heat transfer to maintain comfortable internal conditions.

- Electronic engineering

It is crucial in the thermal management of electronic devices, helping to prevent overheating and extending the durability of components.

- Heating and cooling systems

It allows the performance of thermal systems in buildings and machinery to be calculated and optimized [Teachy].

Thermal properties

The thermal properties of a material are essential for understanding how it responds to changes in temperature. These properties include heat output, which is the amount of heat that the material can store, and thermal conductivity, which measures the speed at which the material can transfer heat.

In addition, thermal expansion describes how the volume of the material changes with increasing temperature. Materials with high thermal conductivity, such as metals, are ideal for applications that require rapid heat transfer, while materials with low thermal conductivity, such as insulators, are used to reduce heat transfer. 'The evaluation of thermal properties is essential for designing new materials in high-energy applications, especially in electronic components and energy storage systems' [Zhang et al., 2020]. The thermal properties of a material determine its ability to transfer and store thermal energy. Among the most relevant are:

- Heat capacity

This refers to the amount of energy required to increase the temperature of a unit of mass by one degree. Materials with high heat capacity, such as water, are ideal for conserving heat energy.

- Thermal diffusivity

This is an assessment of how quickly a material can react to temperature changes. It is determined as the ratio between thermal conductivity and volumetric heat capacity.

- Thermal expansion

This indicates the change in the dimensions of a material when subjected to temperature variations. This effect is critical in applications involving significant thermal fluctuations [Cengel, 2015].

Prediction models

Currently, advanced models have been developed to predict the thermal properties of materials. Among them are:

- Traditional mathematical models

Based on physical principles and fundamental laws, such as Fourier's law for heat conduction.

- Artificial neural networks [ANNs]

These machine learning tools are capable of processing large amounts of experimental data to predict thermal properties. According to Rosa et al. [2024], this approach is particularly useful for materials such as concrete, whose thermal conductivity varies depending on its composition and environmental conditions.

Measurement methods

Describing the thermal characteristics of materials requires precise experimental procedures. Some of the most common include:

- Protected hot plate method

This method measures thermal conductivity by placing the sample between a hot and a cold plate, ensuring thermal equilibrium conditions. It is ideal for homogeneous materials and is governed by ASTM C177.

- Hot wire method

This consists of heating a wire inside the material and recording the temperature increase. This method is fast and suitable for materials with high thermal conductivity.

- Peltier cell-based methods

Used for compact and portable systems. The Peltier cell facilitates precise temperature control, allowing for fast and reliable measurements.

Chapter II. Materials used in thermal insulation

Energy demand has increased in recent years as a result of population growth and improved living standards. This has made greenhouse gas emissions one of the main environmental concerns and, therefore, energy conservation a crucial issue in today's sustainable development. The demand for environmentally friendly and energy-efficient buildings has led to efforts to develop technologies that contribute to conserving energy and resources, especially in the construction sector, through the use and exploitation of recycled materials, as well as organic and inorganic fibres [Asim et al., 2020]. This is why one of the most important challenges in the construction sector around the world is the reduction of energy consumption.

Thermal insulators are natural or synthetic materials that are highly resistant to the passage of heat, thereby reducing its transfer through the material [Velázquez -Rodríguez, 2015].

This situation has led to the search for new options with sustainable characteristics that provide a material that achieves thermal insulation in buildings while reducing waste produced in the agricultural and industrial sectors.

This chapter describes the characteristics that materials must have in order to be used as thermal insulators, as well as the various materials used for this purpose and the environmentally friendly and sustainable alternatives that seek to reduce the waste generated by various human activities.

Properties of insulating materials

Materials considered to be insulators must have air in their internal cavities or some dry gas encapsulated in an inert and still state; this is a common characteristic, together with low thermal conductivity, which gives them the title of insulating materials.

Thermal insulation materials must perform under certain specifications, so their design must take into account more than just the thermal conductivity of the material. They undergo various tests to verify their durability and ability to maintain their thermal insulation properties. In addition to technical aspects such as durability and the manufacturing process, these tests also consider physical aspects such as thermal performance and fire retardancy [Okokpujie et al., 2022].

The most commonly used insulating materials in buildings have a thermal conductivity between 0.03 and 0.05 W/mK. Materials with lower thermal conductivity values are increasingly being used, including gases other than air, such as polyisocyanurate, which has a conductivity between 0.02 and 0.03 W/mK, as well as aerogels with values between 0.01 and 0.015 W/mK [Berardi, 2017].

Box 2

Table 1

Thermal conductivity values of different materials

Material	Thermal conductivity [W/mK]
Sawdust	0.092
Oat straw	0.091
shredded paper	0.091
Coffee husks	0.076
Rice husks	0.070
Hemp	0.067
Corrugated cardboard	0.065
Flax	0.055
Sheep wool	0.051
Cellulose	0.045
EPS foam slab	0.0375
Rigid polyurethane	0.032

Source: Modified from González-Serrud 2023.

Other qualities to consider in insulating materials [Velázquez-Rodríguez, 2015]:

- Thermal transmittance [U]: measures the amount of energy that flows per unit of time and surface area.
- Water vapour diffusion resistance factor [m]: in insulation intended to preserve a cold surface; if the insulation allows moisture in the air to come into contact with the cold surface, it will condense and wet the entire insulation, creating problems of insulation capacity loss.
- Density [r]: mass of material per unit volume.
- Specific heat [cp]: capacity of a material to accumulate energy in its unit of mass.
- Thermal resistance [Rt]: ratio between the thickness and thermal conductivity of the material; the higher the value, the greater the insulating capacity.

Materials used as thermal insulators

An insulating material is defined as one that has high resistance to the passage of heat, preventing transfer from a system to the environment and therefore protecting against cold and heat, contributing to energy efficiency. For a thermal insulator to be effective, it must have low thermal conductivity [less than 0.05 W/mK] and a resistance greater than 0.25 m²K/W [Palomo Cano, 2017; Canto et al., 2018].

Many insulating materials are made from polymers to which additives are added to increase their mechanical strength. According to Okokpujie et al. [2022], insulating materials are grouped into four main categories: organic materials, inorganic materials, composite materials and basic materials. On the other hand, Durakovic [2020] classifies insulating materials with applications in construction into three groups: inorganic, organic and new technology materials. Inorganic materials include rocks, fibreglass, calcium silicate, perlite and vermiculite; organic materials are subdivided into petrochemicals [polystyrene, polyurethane, polyisocyanurate] and renewable materials [cellulose, wool, shells] considered environmentally friendly.

Table 2 shows different types of thermal insulation materials used in buildings.

Box 3

Table 2

Materials used in the manufacture of thermal insulators.

Insulating materials	Subtypes and examples
1. Organic materials	a) Fibrous: cellulose, cotton, wool, pulp, nanocellulose, wicker, synthetic fibres. b) Cellular: polystyrene, polyurethane, polyisocyanurate, polyethylene, cork, rubber.
2. Inorganic materials	a) Fibrous: glass, waste wool, rock. [b] Cellular: perlite, vermiculite, calcium silicate, ceramic products.
3. Metallic thermal insulators or metallised reflective membranes	They must have gas-filled or air-filled panels to have an effect.
4. Aerogels	Used in thermal and acoustic insulation; also used in chemical processes [absorbents, substance extraction, catalysis], electronics [insulators and sensors], pharmaceuticals, fillers [varnishes, paints] and as kinetic energy absorbers.
5. Waste materials	They represent a solution in waste management. The materials are reused avoiding their combustion or disposal. Examples: coconut shells and bagasse, leather, cotton, textiles, rubber, and plastic waste.
6. Cementitious composite materials	-----
7. Polymeric materials	-----

Source: Okokpujie y col., 2022

In recent years, there has been an increase in the use of natural materials to manufacture structures that insulate heat and, at the same time, reduce environmental impact as they are considered waste.

In addition to having characteristics such as low thermal conductivity, they are effective as vibration insulators.

Plant fibres have physical advantages such as low density, insulation and structural strength; from a productivity point of view, they are also readily available, low cost and easy to process. Furthermore, they can be considered harmless and biodegradable materials, which makes them environmentally friendly. These characteristics are an advantage of natural fibres that promote their rational use and the preservation of the environment.

Cellulose is the ideal insulation material for all seasons, insulating against heat and cold; its properties also make it a good acoustic insulator. There are various products on the market made from cellulose extracted from different sources, mixed with other materials such as cement, borax, or polyolefin fibres; panels with thermal insulation properties and low density made from a mixture of peanut shells, polyester and cement [Saldaña-Acosta et al., 2016].

The use of cellulose as an insulator has been common practice in some countries since the early 20th century. This polysaccharide can be obtained from various materials such as newspaper, coconut husks, rice husks and cane fibres; however, due to the natural decomposition of cellulose, additives such as borax are necessary to slow down the process. González-Serrud et al. [2023] proposed the development of a new material from cellulose for use as a thermal insulator. They obtained cellulose from agricultural waste [rice husks] and industrial waste [newspaper], using white glue as a binder and borax as an antiseptic and fire retardant. The new material was subjected to physical and mechanical tests to compare its performance with other organic fibres. It was found that the material has low thermal conductivity [0.0410 [W/mK] [Table 1], making it useful as a thermal insulator; however, due to the short length of its fibres, its tensile strength is very low, while its compressive strength is moderate, only slightly lower than that of wood and sugar cane fibres.

To improve the characteristics of natural fibres, experiments have been carried out with the addition of different organic compounds to help maintain thermal conductivity and reduce volatility. Cassava starch and pita palm fibre [*Agave Americana Marginata*] have been proposed as modifying or enhancing compounds. Yucca starch has adhesive properties similar to paste or glue due to the presence of amylose and amylopectin [Canto et al., 2018].

A material of great interest due to its 100% recyclability and its application in the creation of materials is polyethylene terephthalate [PET]. The cost of recycling polyethylene terephthalate [R-PET] is 20 to 60% lower than the cost of producing it [V-PET], and it also reduces energy consumption by 50 to 70%. Around the world, PET recycling is concentrated in the production of fibres. At the same time, the textile industry generates millions of tonnes of waste, of which only a small percentage is recycled and reused. This presents an opportunity for reusing fibres in the construction industry through the creation of insulating materials, as recycled textiles have good thermal conductivity and diffusion properties and can replace commercial insulating materials such as extruded polystyrene or mineral wool [Hegyí et al., 2021].

On the other hand, gypsum is the most widely used material for covering interior walls in buildings due to its high production, accessibility and low cost. However, it produces a delicate covering with low resistance to fragmentation. Many studies have shown that adding fibres to gypsum forms a matrix that inhibits fragmentation when subjected to external tensile forces, increasing its flexural strength and resistance. The natural organic fibres that have been incorporated are wood, straw and coconut fibres; synthetic organic fibres such as polyvinyl alcohol and inorganic fibres [glass and carbon fibres] [Iqbala et al., 2025].

The generation of industrial waste represents a serious ecological problem that can be mitigated by the application of recycling and reuse strategies aimed at clearly and efficiently exploiting the treated materials. On the other hand, agricultural waste, which in many cases is reduced through combustion, also causes problems for the environment. In recent years, therefore, ways have been sought to use it as a source of organic compounds or in combination with others to create new properties with potential in the area of sustainable building construction. This trend is enabling the use of waste in combinations and proportions that will allow for reduction and sustainable use at low cost.

Chapter III. Thermal conductivity

Thermal conductivity is a characteristic that determines the ability of a material to transmit heat when there is a temperature difference. It plays a fundamental role in heat transfer in solids, liquids and gases. Materials with high thermal conductivity, such as copper and aluminum, are ideal for applications where efficient heat dissipation is essential.

In contrast, those with low thermal conductivity, such as rock wool or polystyrene, are used as thermal insulators.

This property, expressed in $W/[m \cdot K]$, represents the amount of heat that passes through a material as a function of its area, thickness and the temperature gradient to which it is exposed [Tritt et al., 2004]. Factors affecting thermal conductivity

- Material composition: The atomic and molecular structure influences how thermal energy is transmitted.
- Temperature: In metals, thermal conductivity decreases with increasing temperature due to electron dispersion, while in non-metallic solids it tends to increase.
- Humidity: Porous materials, such as bricks, lose their insulating capacity when they absorb water, as this promotes heat transfer.
- Purity and structural defects: The presence of impurities and flaws in the crystal structure hinders the movement of phonons or electrons, reducing thermal conductivity [Cengel et al., 2015].

Heat transfer mechanisms in solids

In solids, heat transfer is mainly thermal wire, where energy is propagated through molecular interactions or free electrons controlled by Fourier's laws. In addition, convection phenomena between the solid and adjacent fluid in solids associated with connected systems are included in Newtonian cooling. According to Stephen, Boltzman and Plank's laws, especially in the relevant vacuum or at high temperatures, can also give rise to thermal radiation [Barrera et al., 2021].

- Electronic conduction: Characteristic of metals, where free electrons facilitate the efficient transport of heat.
- Phonon conduction: Characteristic of non-metallic materials, where thermal energy is transmitted through vibrations of the crystal lattice.
- Anisotropic conductivity: Present in materials such as graphite and some carbon crystals, where thermal conductivity depends on the direction in which heat flows. [Holman et al., 2010]

Fourier's law

Fourier's law describes heat transfer in a material, establishing that the heat flow per unit area is proportional to the temperature gradient. Its mathematical expression is:

$$q^n = -k \frac{dT}{dx} \quad [2]$$

Where:

q^n is the heat flowing per unit area or also known as the heat density in the x-direction, the variable k is the thermal conductivity of the material where it is transferred.

In the International System of Units [SI], thermal conductivity is expressed in $W/[m \cdot K]$ [watts per metre per kelvin]. $W/[m \cdot ^\circ C]$ can also be used, since one kelvin and one degree Celsius represent the same temperature rise.

The negative sign in the equation indicates that heat is always transferred from a higher temperature zone to a lower temperature zone, according to the second law of thermodynamics.

Although thermal conductivity can change with temperature in some materials, in many applications it is considered constant. Typical thermal conductivity values for different materials are given below. [Valadez et al., 2002]

Box 4**Table 3**

Thermal conductivity values

Material	kW/m°C
Rigid polystyrene	0.027
Fibreglass	0.036
Air	0.0262
Water	0.613
Common brick	0.72
Refractory	1.0
AISI 302 steel	15.1
AISI 302 steel	63.9
Pure aluminium	237
Pure copper	401

*Source: Valadez et al., 2002***Power Flow**

Power flow, also known as load flow analysis, is an essential tool in electrical engineering to examine the behaviour of electrical power systems under stable operating conditions. Its main objective is to determine the voltage values and angles at each system node, as well as the active and reactive power flows on transmission lines. This analysis is crucial to ensure efficient, safe and stable operation of power grids, especially when energy demand continues to increase.

An electrical power system consists of generators, transformers, transmission lines, loads and control equipment. The nodes or busbars of the system are divided into three types according to the variables known and those to be calculated:

1. Specific power bus [PV type bus]: the generated active power and voltage are known, but the reactive power is unknown.
2. Load busbar [PQ type busbar]: The active and reactive powers consumed are known, but the voltage and its angle are unknown.
3. Reference busbar or slack bus: The voltage and its angle [usually zero] are fixed, and the active and reactive powers needed to balance the system are calculated.

Power flow analysis aims to solve a set of non-linear equations that connect the voltage, current and power variables through Kirchhoff's laws and power line parameters. These equations determine how these elements are interrelated at each node of the system.

Methods of power flow analysis:

- Gauss-Seidel method: this is one of the simplest and easiest iterative methods to implement. However, it has a slow convergence rate, especially when dealing with large or ill-conditioned systems.
- Newton-Raphson method: It is the most common due to its high accuracy and fast convergence. This method linearises non-linear equations using a Taylor series expansion and solves them iteratively. The calculation of the Jacobian, which contains the partial derivatives of the equations with respect to the variables, is fundamental in this process.
- Fast decoupled method: This method facilitates the calculation by assuming that the active and reactive powers are mainly influenced by the angles and magnitudes of the voltages, respectively. Although less accurate than the Newton-Raphson method, it offers a faster calculation [wer et al., 1994].

OHM's Law

Ohm's Law, formulated by the German physicist Georg Simon Ohm in 1827, is one of the fundamental principles of electricity. Its importance lies in the fact that it establishes a linear relationship between electric current, voltage and resistance in an electric circuit.

The law states that the electric current [I] flowing through a conductor is directly proportional to the applied voltage [V] and inversely proportional to the resistance [R] of the conductor. Mathematically, it is expressed as:

Where:

$$I = V/R$$

- I is the current in amperes [A],
- V is the voltage in volts [V],
- R is the resistance in ohms [Ω].
- This equation implies that, when the voltage in a circuit increases, the current will also increase if the resistance remains constant. Conversely, if the resistance increases and the voltage remains the same, the current will decrease.
- According to Dorf and Svoboda [2014], Ohm's Law is only valid in certain materials and conditions. For example, in ohmic conductors such as copper and aluminium, the relationship between voltage, current and resistance is linear. However, in non-linear materials, such as diodes or semiconductors, this relationship does not hold true due to the particular characteristics of these materials.
- Resistance and Factors that Affect It
- The resistance of a material depends on several factors, among which the following stand out:
 - The nature of the material: Good conductors, such as metals, have low resistance due to their high density of free electrons.
 - Temperature: In metals, resistance increases with temperature because the vibration of atoms hinders the flow of electrons. However, in materials such as semiconductors, the opposite behaviour is observed.
 - The dimensions of the conductor: Resistance is directly proportional to the length of the conductor and inversely proportional to its cross-sectional area.
- Although Ohm's Law is essential in electricity, it has some limitations:
 - It does not apply to non-linear materials: In devices such as semiconductors and integrated circuits, the relationship between voltage, current and resistance is not linear.
 - Temperature dependence: In systems where the temperature varies considerably, resistance can change drastically, invalidating calculations based on constant values. [Dorf et al., 2014]

Methods for measuring thermal conductivity

Thermal conductivity is an essential property of materials that describes their ability to transfer heat. The main experimental methods used to measure this property are detailed below, along with their characteristics and limitations.

Stationary methods

Stationary methods are widely used to measure thermal conductivity, based on creating a constant temperature gradient in a material and measuring the heat flow through it. The most common techniques include:

- Longitudinal heat flow method: In this approach, a material is placed between two plates whose temperature difference is controlled and measured. It is based on Fourier's Law, which states that heat flow is proportional to the temperature gradient. The accuracy of the method depends on the control of the gradient and the minimisation of lateral heat losses.
- Protected hot plate: This method uses a heating plate between two identical samples of the material to be measured. The plate is kept at a constant temperature while the heat flow to the samples is monitored. Although it offers high accuracy, it requires complex experimental setups.
- Single hot plate: A variant of the previous method, in which a single sample of the material is used. Its simplicity makes it suitable for practical applications, but it can be less accurate due to heat losses.
- Advantages and limitations of stationary methods: They are ideal for measuring the thermal conductivity of homogeneous solids with low anisotropy. However, their main limitation lies in the time required to reach a steady state and their susceptibility to experimental errors.

Transient methods

Transient methods are widely used due to their short measurement time and the fact that they do not require a stable condition to be determined.

The hot-wiring [hot-current] method involves inserting a thin wire into the material and increasing the temperature after constant application of an electric current, allowing the thermal conductivity to be calculated using linear source models in an infinite medium [Wang et al., 2020]. TPS or Hot-Disc, on the other hand, uses a circular probe as a heat source and sensor. This probe is placed between two fixed samples and, using thermal heartbeat, has achieved the thermal conductivity and diffusivity of the transient reaction [Sunqvist et al., 2019].

Methods in the frequency domain and steady state. In the frequency domain, the method stands out for its ability to minimise the effects of radiation. This method uses a metal element deposited on the sample that acts as a heater and thermometer, measuring the response in the third harmonic when alternating current is applied, which allows the thermal conductivity to be estimated with great accuracy, especially in thin films [Cahill & Pohl, 2019]. On the other hand, steady-state methods, such as the Searle bar or the guarded hot plate, are based on establishing constant thermal gradients and measuring the resulting heat flow, directly applying Fourier's law [Yu et al., 2016].

Transient methods measure thermal conductivity by observing how a material responds to a temperature change over a limited period of time. These techniques are useful for materials with low thermal conductivity or complex structures.

- Hot wire method: In this method, a thin conductive wire acts as both a heat source and a sensor. It is placed inside the material to be analysed, a current pulse is applied, and the change in temperature is measured over time. This method is simple and suitable for liquids, solids, and gases. There are two variants:
- Linear hot wire: Used for homogeneous materials, it assumes that heat is transferred radially from the wire.
- Transverse hot wire: Suitable for anisotropic materials, it allows the thermal conductivity to be studied in different directions.
- Hot needle method: Similar to the hot wire method, but uses a needle with a temperature sensor and a heater. This method is commonly used to measure the thermal conductivity of soils and granular materials, as it can penetrate loose samples.
- Flash laser method: This method applies a laser pulse to one side of the material and measures the temperature on the opposite side. It allows the thermal conductivity to be obtained indirectly by combining the density and heat capacity of the material. It is ideal for small samples and provides fast and accurate results, although it requires specialised equipment and is expensive.

- Advantages and limitations of transient methods: They are useful for materials with low thermal conductivity or complex structures, but often require specialised equipment and are more expensive.
- Selecting the method according to the type of material
- Homogeneous solids: Stationary methods, such as the protected hot plate, are more suitable for isotropic materials due to their accuracy and simplicity.
- Anisotropic materials: Transient methods, such as the transverse hot wire or flash laser, are more effective for studying thermal conductivity in different directions.
- Liquids and gases: The linear hot wire method is highly adaptable for these types of materials.
- Porous or granular materials: The hot needle method is efficient for penetrating complex structures and is ideal for these types of materials. [Tritt et al., 2004]

Thermal efficiency

- Thermal efficiency describes the ability of a system to convert thermal energy into useful work. This concept is crucial in heat engines, power plants, cooling systems, among others. According to Adrian Bejan in his book *Advanced Engineering Thermodynamics*, thermal efficiency is not only key to the design of energy systems, but also to sustainability and the minimisation of energy losses.
- Thermal efficiency is defined as the ratio between the useful work produced and the heat supplied to the system:

$$\eta = W/Q_{in} = 1 - [Q_{out}/Q_{in}] \quad [3]$$

Where:

Q_{in} = is the heat absorbed by the system.

Q_{out} = is the heat rejected to the environment.

Factors Affecting Thermal Efficiency

1. Temperature difference: According to Carnot efficiency, increasing the temperature difference between thermal reservoirs increases the efficiency potential. However, in real systems, achieving these extreme differences may be costly or unfeasible due to technological and economic constraints.
2. Energy losses: In real systems, friction, heat losses to the environment and irreversibility of processes limit thermal efficiency. These losses are related to the second principle of thermodynamics, which states that there will always be energy dissipation in natural processes.
3. Materials and Design: Bejan emphasises the importance of design in reducing losses and maximising heat transfer. Advances in thermally conductive and insulating materials, such as new composites or advanced insulation techniques, make it possible to optimise the performance of thermal systems.
4. Controlling Irreversibility: Irreversible processes, such as rapid expansion or compression, generate entropy and reduce efficiency. Designing systems that minimise these irreversibilities, such as by optimising process rates or controlling enthalpy, is key to improving thermal efficiency [Bejan et al., 2016].

Chapter IV. Development of a possible thermal insulating material

In the region of Perote, Veracruz, the genus *Pinus* occupies a very relevant place from an ecological, industrial and ecotourism point of view, in the region there is an important variety and abundance of this genus, which places it as one of the key components within the temperate climate vegetation and for the communities of the region [Cuevas et al., 2024].

Given the lack of alternatives to halt the changes in the temperate climate vegetation in the Perote region [Cuevas et al., 2023] and to be able to apply some kind of use to the temperate vegetation in the region [Cuevas et al., 2023], 2023] and to be able to apply some use for organic and inorganic waste and stop it from being an everyday problem that has affected the entire planet, causing an increase in greenhouse gases and the destruction of ecosystems, it is essential to use this waste to obtain raw materials with low environmental impact, which are usually good sources of biomass, which gives them ideal properties to be used as energy sources, as well as their capacity to act as thermal insulators [Espinoza et al., 2022].

One of the alternatives is that by recycling PET and agroforestry waste in particular, environmental pollution can be reduced to a certain extent by creating a thermal insulator from this waste, which has the advantage of being able to decompose through the action of microorganisms within the biological cycles of the natural environment [Pablo-Calderón, 2019]. Thermal insulation aims to reduce heat flow, preventing heat transfer from the system to the environment. There are insulation manufacturing processes in which the mixture of different compounds can produce a lower thermal conductivity, resulting in an improved system, as each insulating material presents different conditions [Espinoza et al., 2022]. For an insulator to be effective, it must have a low thermal conductivity, which generates better heat retention and better performance [López Villanueva et al., 2021; Palomo, 2017]. Therefore, insulating materials can be considered as those that have high properties of resistance to the passage of heat, reducing the transfer of this heat to its opposite side, therefore, we can say that they protect from cold and heat.

In Mexico, CENAM has the National Thermal Conductivity Standard for insulating materials, which allows measuring both insulating materials and some others used in the construction of buildings. To date, studies have been carried out on different materials, with the intention of obtaining real thermal conductivity data and applying them with confidence in the calculation of thermal loads [Lira-Cortés et al., 2008].

Therefore, developing a prototype thermal insulator, made from PET and recycled agroforestry waste, will be used in homes in the region of Perote, Veracruz, Mexico, where the lowest average temperature is between 0°C and 10°C for 6 months. This will make it possible to tackle the climate environment in the locality by creating a pleasant atmosphere inside the home, as well as providing an alternative for recycling the aforementioned waste, as well as an economic alternative in the manufacture of this thermal insulator.

Methodology

Collection of agroforestry and PET waste:

The materials used are of vegetable origin and polyethylene Terephthalate [PET], these were obtained from waste from the forestry industry, from timber forest exploitations and areas located within the region of Perote, Veracruz.

Sample preparation:

Once collected, a drying process was followed at room temperature for the agroforestry waste, the PET was cut to tiny sizes so that it could be mixed with the vegetable waste, and to ensure that the materials were completely compacted, the resins of the vegetable waste were used, adding grease, serving as a binding medium, and through a manual pressing process, the final products were obtained in the form of briquettes, table 4.

Box 5**Table 4**

Material used for the elaboration of the mixtures

Sample	Material used	Binder
A	Sawdust	Paste
B	Sawdust and pine bark	Paste
C	Sawdust and PET	Paste

Source: Own elaboration

To make the briquettes possible, the mixtures were placed in moulds of 2 inches in diameter and half an inch in height, and by manual pressure for 2 minutes the briquettes were moulded, then left to dry at room temperature for 12 hours, fig. 2.

Box 6**Figure 2**

Processing of the samples [briquettes]

*Source: Own elaboration***Density estimation:**

The volume was obtained by immersing the 1 cm³ sample covered with a small layer of liquid paraffin, in a 100 ml test tube, with water up to 90 ml, where the volume of water rose as the wood sample was immersed. The amount of water that rose was recorded, thus obtaining the direct volume by displacement of the water in millilitres, figure 3. Once the mass and volume had been obtained, the following expressions can be used to determine density:

$$D = M / V$$

[4]

Where:

D= Density [gr/ml]

M= Masa [gr]

V= Volume [ml]

Box 7**Figure 3**

Density estimation of samples

Source: Own elaboration

Moisture content

The moisture content of the sample was determined by taking 10 samples of 5 cm³ of each selected species.

The samples were weighed as soon as the trees were felled so as not to lose moisture over time. Once weighed, the samples were completely chipped to facilitate the water contained in the wood fibres to escape and accelerate the drying process.

The samples were placed on aluminium trays. They were placed in a drying kiln at a constant temperature of 95 to 105°C for 24 hours, where the moisture content was reduced to zero, figure 4.

Once the wet weight and dry weight data were obtained, the moisture content was determined using the following expression.

$$H = PI - PF \quad [5]$$

Where:

H= Moisture

PI= Initial weight expressed in grams

PF= Final weight expressed in grams

Box 8



Figure 4

Estimation of moisture content of samples

Source: Own elaboration

From the above operation, the net weight of the sample was obtained by weight difference, but to present the moisture data, which international coal quality standards require. It needs to be presented in percentage, so it was necessary to determine it in the following way:

$$Ch = (Pha - Psa) / Pha \times 100 \quad [6]$$

Where:

Ch= Moisture content of the sample expressed in %.

Pha= Wet weight of the sample expressed in grams

Psa= Dry weight of the sample expressed in grams

Results

As a result of the production of the briquettes, a base percentage of sawdust, PET and grease was fixed, according to the different mixtures used depending on the percentages of the different elements used, leaving a mixture that was considered to be the most suitable, table 5.

Box 9**Table 5**

Final formulations for sample preparation [briquettes, briquettes, briquettes, briquettes, briquettes, briquettes, briquettes].

Mix	% Material used	Binding agent
A	95% Sawdust	5% paste
B	80% Sawdust and 15% Pine Bark	5% paste
C	75% sawdust and 20 % PET	5% paste

Source: Own elaboration

As for the analysis of the physical properties, according to table 6, the mean obtained in the analysis of the representativeness. This makes the data to have a highly representative mean and due to these variability results are totally acceptable and allow to use the averages to make comparisons of the properties of the mixtures with some other materials.

Box 10**Table 6**

Analysis of the physical tests carried out on the samples

Property	Sample A	Sample B	Sample C
Humidity	27.41 %	30.71 %	39.92 %
Density [gr/ml]	1.47	1.17	1.13

Source: Own elaboration

Conclusions

The results obtained and observations made have been fundamental in determining the appropriate proportions and ensuring that the samples [briquettes] meet the desired requirements in terms of moisture content and density. The project focuses on providing an alternative use for agroforestry and PET waste, adding a percentage of innovation to the thermal insulation manufacturing process and, in turn, finding the appropriate and optimal proportion of material and additives to obtain efficient and sustainable samples [briquettes]. It is recommended that compression tests be carried out in the next stage to ensure that this alternative is viable for use as thermal insulation.

Chapter V. Sawdust in Mexico: Problem or opportunity?

Introduction

Sawdust is a plant-based material, a by-product of wood sawing. It is one of the main wastes generated by forestry activities and is generally a material that, without a purpose, causes industrial and environmental health problems. With advances in the development of new technologies, larger volumes of natural resources are being processed, thereby increasing the amount of sawdust generated. It is produced by the processes of cutting, grinding or crushing wood using saws or more sophisticated equipment [Serret-Guasch, *et al.*, 2016].

It is estimated that in 2018, the annual production of boards, tabloids, polines, coasters and cuttings generated more than 1 million m³ of sawdust from the genera *Pinus*, *Abies* and other conifers, although other estimates calculate a production of almost 3 million m³, which shows a need to improve utilisation rates. Currently, due to its high volumes worldwide, sawdust has become a raw material for the production of different products. Its physical and chemical composition determines its possible uses, such as substrates, insulation, local or industrial cleaning, agglomerates, fuels, among others [SEMARNAT, 2020; Zavala and Hernández, 2000].

This review of sawdust in Mexico aims to provide a comprehensive overview of the current situation of sawdust generation in the sawmill industry, showing its current value, environmental, social and forestry issues, and trends in its use according to new technologies and advances in the science of sawdust transformation.

Economic values

Mexico trades sawdust and similar products [waste, agglomerates such as briquettes, firewood, and similar products] with countries such as the United States, El Salvador, Aruba, and South Korea, which in 2024 amounted to 206,780 dollars. Figure 1 shows that the states with the highest international sales were Baja California, Tamaulipas and Nuevo León, while the states with the highest international purchases in 2024 were Chihuahua, Mexico City and Nuevo León [Ministry of Economy 2025].

Box 11

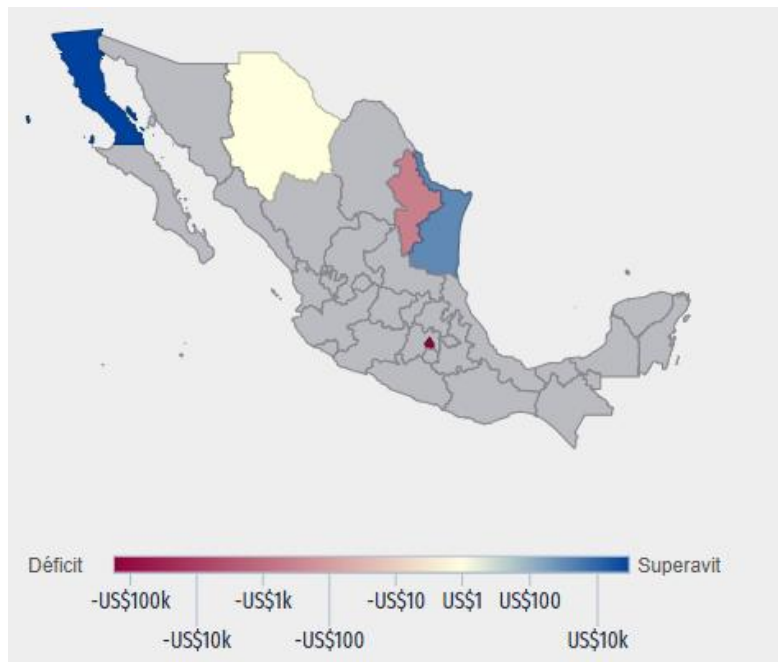


Figure 5

Trade balance in the states with the highest activity in the purchase and sale of sawdust, waste and sawdust agglomerates in Mexico, colours towards blue indicate international sales, towards red indicate international purchases.

Source: Secretaría de Economía 2025

Sawdust was considered a waste product, but in economic processes, this can be reconsidered depending on the value assigned to it, according to the possibilities of use in accordance with the scientific and technical knowledge applied to the processes of its use. When transformed into raw material, it acquires greater value in the markets. Accordingly, the use of forest residues in industrial processes is beginning to provide a solution to the health and environmental problems caused by their disposal in the sawmill industry, becoming a by-product of wood in the forestry industry [López *et al.*, 2014].

The cost of sawdust in sawmilling areas is very low or sometimes zero compared to other materials that are often used for the same purposes. It is incomprehensible why its sale price is so low. For example, 1 m³ of sawdust can cost up to \$100, while 1 m³ of composted pine bark costs \$1,000, or 1 m³ of moss peat costs \$2,500 [Rodríguez *et al.*, 2021].

Environmental issues

The forestry industry at the sawmill level generates sawdust as its main waste product, which is generally disposed of in the environment, thus generating a source of pollution mainly for the soil and surface water bodies. It also becomes a phytosanitary problem when stored in sawmill yards, where it decomposes and becomes a source of fungi and bacteria that affect the wood and wood chips from the sawmill itself. Sometimes, when the available storage space for sawdust and other waste such as coasters and trimmings is exceeded, they choose to burn it in unfiltered boilers, mainly affecting the air and surrounding communities [Concepción *et al.*, 2016].

To prevent the incineration of sawdust in sawmills and thus control air quality, there is federal regulation that prohibits the burning of sawdust, so it is given away or sold at a very low cost to avoid accumulation. The regulations are strict because the particles generated are easily dispersed into the atmosphere, causing respiratory problems, and are deposited in rivers and water reservoirs, requiring costly treatment to separate them and make the contaminated water suitable for consumption again [Mateo-Sánchez *et al.*, 2002; Medrano-Rodríguez & Pallasco-Catota, 2015].

Social issues

Sawmills are generally located in rural areas, which leads to less enforcement of regulations, coupled with a low environmental culture and low investment in recycling technology and techniques. Sawdust is usually dumped in areas close to communities or given away to be burned in homes, producing high emissions of carbon dioxide and soil, air and water pollutants, which cause respiratory and skin diseases among workers in the industry and people in the communities [Sucoshañay, 2009].

In urban areas where sawdust and wood shavings are dumped, there is a serious problem with drainage, gutters and drains, which is mainly observed during the rainy season, when flooding occurs, affecting citizens with various economic consequences, as well as cultural expressions, such as the use of sawdust to make ‘tapetes’ [rugs] for various religious celebrations, during which not all the material used is placed in containers or rubbish bins, sending large quantities into the drainage system [Fig. 2] [Medrano-Rodríguez & Pallasco-Catota, 2015].

Box 12



Figure 6

- A. Cultural expressions using sawdust as raw material. B. flooding of city streets due to clogged drains.
 B. Source EFE/Hilda Ríos y Miguel García/ Quadratín Edomex

Issues in forestry

During the different levels of the timber harvesting cycle, waste is generated, the quantities depending mainly on the efficiency of the technologies used, the more obsolete, the greater the amount of waste generated, and this erroneous disposal has contributed to the contamination of forests and subsequently to the degradation of forest ecosystems [Concepción et al., 2016; Sucoshañay, 2009].

At the same time, the use of obsolete machinery can generate impacts on remaining vegetation, emissions, soil, water bodies, higher operating costs, deterioration of gaps and roads, as well as safety risks [Figure 3], A relatively common practice has been observed, is the accumulation of sawdust in forests, which causes fungi to proliferate, leading to tree rot, pathogens and even fires as a source of fuel [Nájera Luna et al., 2012; Vargas-Abasolo, 2012].

Box 13



Figure 7

The use of machinery in forest harvesting can cause various problems in ecosystems if it is obsolete

Source: Vargas-Abasolo, 2012

Uses and Innovations in the use of sawdust

Dendroenergetics

The use of biomaterials for wood energy production has been gaining momentum in recent years, with coniferous sawdust being the most widely used in pellet production. To determine the quality of the raw material, the main parameters to be considered are: place of origin, moisture content, storage characteristics of the sawdust, the latter affecting the mechanical durability and moisture affecting the density of the pellets [Moreno-López et al., 2011].

Building Materials and Insulation

The combination of sawdust with other materials offers the possibility of generating new products, such as the case of sawdust with recyclable plastics, generating insulating materials or construction materials such as plastic wood of high quality, high social and economic benefit and low carbon footprint, also innovating in the board industry and production of wall elements [Concepción et al., 2016; López et al., 2014].

Livestock

Resources for the production of food, whether human or animal, are constantly competing with other industries, for the production of livestock, tests are constantly being carried out to solve the high volumes of raw material required, an example is the use of sawdust from Quercus, Pinus, using up to 10% sawdust in the preparation of feed for livestock. Tests are currently being carried out to inoculate the sawdust added to the feed with bacteria, so that the bacteria help to degrade the sawdust used, thereby increasing the percentage added to the feed.

Another use of sawdust that is being taken up again is to use it in pig and poultry farms, among others, as a floor covering, in order to mix it with animal faeces and urine, and its subsequent composting, thus increasing its commercial value, it is also used to regulate the temperature for animals in very cold regions [Medrano-Rodríguez et al., 2015].

Agriculture

The loss of fertile soils makes it necessary to look for alternative substrates and techniques for food production, without making the process more expensive, which is why low-cost by-products or industrial waste are the most viable option, both economically and environmentally. The forestry industry generates high volumes of potential substrates, which present stable characteristics, which is very necessary for a substrate, which must remain that way throughout the entire crop cycle [Pineda-Pineda et al., 2012].

Another use in the agricultural area is to place it on soils as a cover to conserve soil moisture in different plantations, and it has even been used as a material to recover degraded soils [Medrano-Rodríguez et al., 2015].

Use in forestry

Several tests have been carried out to use sawdust as a substrate, as long as nutritional requirements are added according to the seedling species. Studies have been carried out on *Cedrela odorata* in trays in greenhouses, with substrates in a 60:20 ratio:20, in which sawdust, peat moss and agrolite are used respectively, in this case the evaluations were carried out at the level of root development [weight] as well as height and diameter of the stem, calculating the Dickson quality index and the slenderness index, the results showed that with these percentages of the substrate, to produce a high quality plant, 9 kg/m³ of slow release fertiliser should be added [Mateo-Sánchez et al., 2011].

At the level of forest nurseries producing seedlings, work has been done against unfavourable characteristics of sawdust: chemical compounds with phytotoxic activity, such as terpenes, phenols and others; and high carbon-nitrogen ratio. This has been solved with the application of slow-release fertilisers and irrigation to generate leachates that carry away the cytotoxic substances. For *Pinus patula* production, mixtures are made with a ratio of 60:20:10:10:10 % sawdust, pine bark, vermiculite and perlite. Better results have been found with broadleaved sawdust than with coniferous sawdust, Figure 4 [Rodríguez et al., 2021].

Box 14



Figure 8

Seven-month-old *Pinus patula* plant with average diameters and heights by treatment, from left to right: T1 *A. religiosa*, T2 *H. brasiliensis*, T3 *G. arborea*, T4 *M. indica*, T5 *P. ayacahuite*, T6 *P. montezumae*, T7 *P. patula*, T8 *P. teocote*, T9 *Q. laurina*, T10 *Q. rugosa* and T11 *T. grandis*.

Source: Taken from Rodríguez 2021

The experimental evaluations using 11 different substrates made with sawdust from coppice and broadleaved trees, table 1 shows the values achieved by *Pinus patula* seedlings evaluating parameters such as diameter, height, aerial and root dry weight. [Rodríguez et al., 2021]

Box 15**Table 7**

Average values of morphological variables of seven-month-old *Pinus patula* plants grown in substrates with sawdust of 11 timber forest species

Tratamiento	D (mm)	A (cm)	PSA (g)	PSR (g)	PSA /PSR	IR	ICD
1. <i>A. religiosa</i>	4.53ab	25.03bc	3.61abc	1.15a	3.27bc	5.58bcd	0.55a
2. <i>H. brasiliensis</i>	4.54ab	23.53c	3.40bc	1.08ab	3.14c	5.23de	0.55a
3. <i>G. arborea</i>	4.68a	24.25bc	3.62abc	1.05abc	3.44abc	5.23de	0.54a
4. <i>M. indica</i>	3.89c	18.73d	2.67d	1.08ab	2.52d	4.89e	0.52ab
5. <i>P. ayacahuite</i>	4.59ab	28.28a	3.80a	1.08ab	3.65a	6.23a	0.50ab
6. <i>P. montezumae</i>	4.57ab	26.75ab	3.65abc	1.03abc	3.59ab	5.90abc	0.50ab
7. <i>P. patula</i>	4.57ab	24.90bc	3.76ab	1.05abc	3.60ab	5.48cd	0.53ab
8. <i>P. teocote</i>	4.67a	26.15abc	3.84a	1.05abc	3.73a	5.65bcd	0.53ab
9. <i>Q. laurina</i>	4.39b	26.10abc	3.53abc	0.95bc	3.71a	6.01ab	0.47b
10. <i>Q. rugosa</i>	4.43ab	27.13ab	3.63abc	0.98bc	3.74a	6.20a	0.48b
11. <i>T. grandis</i>	4.59ab	24.45bc	3.37c	0.90c	3.72a	5.37d	0.48b
<i>p</i>	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
VRC	≥4	20-30			1.5-2.0	≤7.5	≥0.5

D: diameter; **A:** height; **AW:** aerial dry weight; **RW:** root dry weight; **RQI:** hardness index; **DQI:** Dickson quality index; **RQI:** recommended values for fast growing conifers produced in trays; **RQV:** recommended values for fast growing conifers produced in trays; **RQI:** recommended values for fast growing conifers produced in trays.

Source taken from Rodríguez 2021

Chapter VI. Evaluation of the thermal conductivity of agroforestry waste based material

The study of materials with good thermal properties is important in industry and science, especially for creating sustainable thermal insulation. Agricultural waste is considered a viable option for making materials with low thermal conductivity, which helps reduce environmental impact and make use of organic waste. Perote, a municipality in Veracruz, has an economy based on agriculture and livestock and faces economic challenges that can be improved by using agroforestry waste and recycled plastics, such as PET, to manufacture insulation. To identify whether a material has insulating properties, thermal conductivity is used, as this property is essential for measuring its ability to prevent heat transfer. The lower the thermal conductivity value of a material, the more effective it is as a thermal insulator, as it reduces the circulation of heat through it. This property is crucial when choosing materials for applications that require effective temperature control, such as construction, refrigeration systems, or the production of technical clothing for adverse climates. Recent research indicates that materials with low thermal conductivity, such as foams, polymers, and certain compounds derived from agro-industrial waste, have proven useful in these types of applications [Riley et al., 2020].

Among the methods used to measure the thermal conductivity of materials is the hot plate method, which stands out for its accuracy and ease of adaptation. This method provides an effective way to determine how a material transfers heat through plates, allowing for the evaluation of its ability to conduct heat under specific conditions. In addition, the simplicity of the experimental setup and the relatively low complexity of the procedure make this approach accessible to various laboratories and industrial studies. Direct measurement of the temperature at both ends of the sample and the heat flow provide reliable data, allowing a precise value for the thermal conductivity coefficient to be obtained. It is especially useful in situations where rapid, low-cost measurement is required without compromising accuracy. The versatility of this method also makes it suitable for a wide variety of materials, from those with low conductivity, such as thermal insulators, to materials with high conductivity, allowing its use in various industrial and scientific applications [Velasco et al., 2016].

This work begins the exploration of the use of agricultural waste as thermal insulation, paving the way for future research seeking to improve its mixtures and evaluate its performance. Thermal insulation is key to energy efficiency in buildings, as it reduces heat transfer and, therefore, energy consumption in heating and cooling. Conventional insulating materials, although effective, are often synthetic and have a high ecological footprint. Using agroforestry waste and recycled PET offers a more sustainable alternative. Although agro-residues have limitations such as low density and high moisture absorption, combining them with PET can improve their thermal and mechanical properties. As stated by Serin et al. [2022], "a detailed review of past and recent research documents that agricultural waste can be suitable candidates as reinforcing or filler materials in composites for thermal insulation purposes

Materials and methods

To measure thermal conductivity, a prototype hot plate measurement machine was built in accordance with ASTM C-177-13, which details the requirements for measuring thermal conductivity. Materials were carefully selected to ensure proper operation of the equipment. The design was created in SolidWorks and the necessary materials were then purchased. The metal structure was built according to the design. Subsequently, the electronic components were installed, including temperature controllers and K-type thermocouples. A system was also programmed to control and record temperatures, displaying the data on OLED screens using Arduino boards, in accordance with ASTM C-177 [Ortiz et al., 2024].

Agricultural waste samples were collected in Perote, Veracruz, and used for mixtures that included sawdust, pine bark, and recycled PET. They were ground and sieved to obtain particles of the same size, mixing them with wheat flour paste. They were then moulded into cylindrical test tubes 2 inches in diameter and exposed to room temperature for 48 hours. Two formulations were used: Mixture A [80:20 sawdust-pine bark] and Mixture B [80:20 sawdust-recycled PET].

The thermal conductivity coefficient was measured in $W/m^{\circ}K$ using the hot plate method, recording the temperature at both ends of the sample and the heat flow through the material. The Fourier equation was used to calculate the heat transfer rate in these materials. Similar samples were sent to a specialised laboratory for thermal conductivity testing.

The results were reported as the average of three measurements and analysed using ANOVA with Statistica version 5 software. This methodology ensured the repeatability and reliability of the data obtained, minimising experimental errors and allowing a statistically significant comparison between the different types of mixtures. In addition, the use of specialised software facilitated the interpretation of the results and the identification of significant differences in the insulating capacity of the materials evaluated, providing greater robustness to the conclusions of the study

Results and discussion

Through experimental tests, the thermal conductivity coefficients of the mixtures were determined as shown in Table 8.

Box 16

Table 8

Thermal conductivity results W/m[°]K

Mix	Prototype	Specialised laboratory
A	0.102	0.191
B	0.107	0.095

Source: own elaboration

The results show that both samples have comparable thermal properties that support their potential for use in systems requiring efficient and sustainable thermal insulation. This finding is in agreement with what Martinez [2022] reported, stating that the thermal conductivity of sawdust varies from 0.04 to 0.08w/m - k, in pine bark from 0.05 to 0.09W/m- K and recycled PET from 0.15 to 0.35w/m -K. These values confirm the viability of recycled waste elders and plastics as alternatives to conventional synthetic insulation materials.

On the other hand, comparing the thermal conductivity measurement method used in this study with evaluations carried out in a specialised laboratory, it is determined that the developed prototype reaches 90% efficiency compared to the reference equipment. This high level of compliance confirms both the credibility of the experimental approach and the quality of the samples obtained.

From the point of view of thermophysics, it is important to emphasise that the efficiency of thermal insulation is determined by the characteristic factors of the material, such as the chemical composition of the mixture, bulk density, porosity and moisture absorption capacity [Serin et al., 2022].

These parameters have a direct impact on the material's ability to reduce heat transfer and maintain stable performance against changing environmental conditions creating critical aspects of optimisation in future studies.

Box 17



mix A



mix B

Figure 9

Image of the processed forest residue samples

Source: own elaboration

Figure 9 shows the mixtures produced. The values obtained indicate that both samples have similar thermal conductivity, suggesting that they can be used as thermal insulation materials with comparable properties. Mixture B [sawdust + PET] showed a slightly higher thermal conductivity coefficient, indicating lower insulation capacity compared to Mixture A [sawdust + pine bark]. This result may be related to the structure of the material and its specific composition.

In the study detailed by the specialised laboratory, a differential scanning calorimetry [DSC] analysis was performed, reporting that no signs of PET melting were observed, indicating that the material did not undergo a phase transition under the conditions evaluated. To complement this analysis, a TGA-DSC study was carried out, which found a high similarity between both samples. Exothermic reactions [upward peaks] were identified, attributed to the combustion of the material, which provides information on its thermal stability and possible applications in processes where heat resistance is a relevant factor.

Conclusions

The choice and treatment of agricultural waste [sawdust, pine bark, and recycled pet food] made it possible to obtain mixtures with sufficient thermal properties to open up the use of alternative thermal insulators.

This study is recommended to evaluate the thermal stability of the mixtures at higher temperatures and under changing environmental conditions. Extend the characteristics of the material, including mechanical and moisture resistance testing, to determine its viability in a given application.

In addition, it would be useful to study the long-term behaviour of these materials under thermal and mechanical loading cycles, as well as their resistance to biological agents such as fungi and insects or attacks. The environmental impact assessment of its production and final placement is also important to determine its sustainability as an ecological alternative to conventional insulators. These complementary studies will consolidate the use of these compounds in the construction industry and other sectors interested in more sustainable and efficient solutions.

Chapter VII. Conclusions

This project evaluated the thermal insulation properties of a material made from agroforestry waste [RAF] [sawdust and pine bark] mixed with polyethylene terephthalate [PET] waste. The main contribution of this work is its environmental impact, as it reuses both organic and polymeric waste, considering the ecological contribution in terms of energy savings when used as a thermal insulator. The thermal conductivity was determined in relation to the effect of the composition of the PET-RAF mixture for the development of a thermal insulating material that can compete with conventional insulating materials.

It has been demonstrated that the sawdust-based substrate for plants is mainly determined by factors such as the wood species, storage and time. When using it as a substrate, the presence of tannins must be taken into account, as they can reduce root growth, cause acid fermentation and, if very fresh, retain excess moisture. Therefore, the following should always be considered when preparing the substrate: the particle size of the sawdust, which should not be too small to avoid reducing the level of O₂; the chemical characteristics according to the species of origin; the pH, which ranges from 4 to 6 depending on the time; and the appropriate mixture with fertilisers and other structural materials.

The use of sawdust as a raw material improves the quality of life of the people who handle it, and the more it is used, the lower the volumes burned or dumped into the environment will be, thus reducing soil, water and air pollution, as well as the environmental impact. The development and use of new technologies will make it possible to generate less sawdust and wood waste from the sawmill industry [Acosta-Duran et al., 2008].

The importance of valuing natural resource conservation has increased in recent years, driven by awareness of global warming issues and associated economic policies. Different methods have also been encouraged to develop new materials from natural waste without causing ecological damage and allowing new natural sustainability to be generated in comparison with conventional products. Creating new natural materials is an economical and environmentally friendly alternative that can help solve the problem of thermal deterioration of agro-industrial products in the production and distribution chain. The benefit for the productive sector is that these materials can be used for various purposes, such as an ecological thermal barrier for buildings.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest. They have no financial interests or personal relationships that could have influenced this book.

Contribution of the authors

Ortiz-Rodríguez, Lilia: Technical manager of the funded project and coordinator of the working team, responsible for sample analysis and writing three chapters of the book.

Cuevas-Suárez, Carlos: Project collaborator and responsible for collecting the material and preparing the samples [briquettes].

Ruiz-Colorado, Nora Isela: Conducted the information search, writing and structure of the chapter.

Arcila-Lozano, Cynthia Cristina: Research, review and writing of chapter.

Availability of data and materials

The data and materials obtained in this research will be available upon reasonable request and will be shared for dissemination and educational purposes, in compliance with current regulations. Currently, these are kept in the research laboratory of the Forestry Engineering program at the Instituto Tecnológico Superior de Perote.

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Abbreviations

1. COVEICYDET Veracruz Council of Science and Technology

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Background

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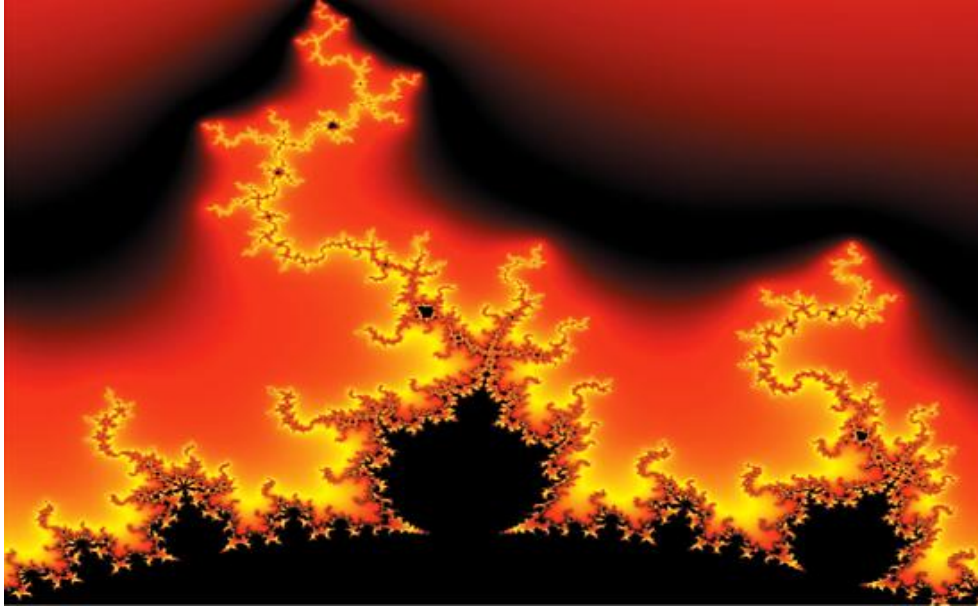


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