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Research Article

Improving the energy efficiency of a refrigerated warehouse through the use of palm tree pruning waste as thermal insulator

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ABSTRACT

This work investigates the effect of palm tree pruning waste (PTPW) on thermal insulation and energy consumption of a refrigerated warehouse (RW). The thermal properties of PTPW depend strongly on its compactness, i.e. how much it weighs divided by how much space it takes up. The thermal conductivity of PTPW measured using the box method is about 0.069 W/m °C for a mass/occupied volume ratio of 0.064 g/cm^3. It is comparable or lower than that of other natural materials discussed in the literature. The dynamic thermal simulation tool "TRNSYS" was applied to predict the thermal behavior of RW. The thickness of PTPW material was considered as variant to choose the better condition allowing achieving results very close to those of polyurethane. Obtained results highlight that 30 cm thick PTPW can reduce temperature by 1 to 2°C compared to 10 cm thick polyurethane. An improvement in the energy efficiency of the refrigerated warehouse was also highlighted. So, because of its performance, low cost, and eco-friendly nature, PTPW can compete with conventional insulating materials.

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INTRODUCTION

Thermal insulation is an important technology for reducing energy consumption in buildings by preventing heat gain/loss through the building envelope. There are many different insulation materials such as, polystyrene, polyurethane, fiberglass, mineral wool, foam, expanded pure agglomerated cork, wood-wool, cellulose, etc. [1–5]. Table 1 summarizes some advantages and disadvantages of the common types of thermal insulators. Because of

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their advantages such as low cost, abundance, recyclability, availability, no toxicity, renewable and eco-friendly features, natural fibers can replace the synthetic materials and its related products for the less mass and energy conservation applications [2–9]. Several research works have been developed to highlight the thermal insulation capacity of various materials: La Gennusa et al. [10] have studied the insulating properties of some materials composited from waste or vegetal products. Gounni et al. [11] have developed new thermal insulation material made from textile waste based on acrylic and wool using needle punching method. Philip and Rakendu [12] have investigated the use of water hyacinth-based panels as a raw material for the production of thermal insulation materials. Lertsutthiwong et al. [13] have developed new composite panels, with low thermal conductivity, produced from a mixture of solid waste from tissue paper manufacturing and corn peel. Manohar [14] has investigated the potential of biodegradable coconut and sugarcane fiber for use as thermal insulators in building. The thermodynamic properties of tropical wood were studied by Ngohe-Ekam et al. [15] and correlated with the basic density of material. In another works, the thermal properties of leather and carpentry wastes were investigated and the applicability of these materials as insulators was highlighted [16–18]. Other studies were conducted using straw [19], matter material derived from recycled bottle [20], textile sub waste [21], rubber waste particles [22], recycled cellulose fibers [23], duvet waste notably polyester and duck feathers [24], composite material based on date palm leaflets and expanded polystyrene wastes [25], etc.

With the increasing concerns with the quality and the safety of foods, several standards and guidelines have been developed to improve the design, construction, and operation of storage warehouses [26]. Historically, the use of cold through freezing or refrigeration has been one of the most common methods for food preservation over long periods. In this context, refrigerated warehouses are used to store fruit, vegetables, and food because they keep their freshness and flavor. They help in eliminating sprouting, rotting and insect damage. Cold storage also helps stabilize market prices and evenly distribute goods both on demand basis and time basis. Cold storage facilities have one of the highest electrical energy consumption rates in the commercial building sector. One of the factors causing variation in the temperature of foods and other products is the heat transmitted in or out through the walls of the refrigerated warehouse by the process of conduction and radiation. This problem can be avoided using thermal insulation which creates a barrier that prevents the transmission of energy and maintains the interior at a suitable temperature. The most insulating materials used in cold storage installations are cork, expanded polystyrene sheeting, sandwich panels with a polyurethane or polyisocyanurate insulation core, etc.

The main objective of this research work is to analyze the potential of using a natural agro-waste material, namely palm tree pruning waste (PTPW) as alternative thermal insulation material for refrigerated warehouses. Thermal properties of PTPW were first highlighted and a dynamic thermal simulation (DTS) tool was then used to predict the thermal behavior of a model cold installation.

MATERIALS AND METHODS

Materials

The agro-waste material used in this study is palm tree pruning waste (PTPW) which is a renewable resource. The abundance of this material presents an opportunity to develop green building materials at low cost. Palm trees become heavier as they grow, this can cause them to break or crack. This is why it is essential to prune cut them periodically. This operation generates a large amount of fibrous wastes. PTPW tested in this work are from gardening wastes of the city of El Jadida (Morocco). The material was first dried in an oven at 60°C for 24 h and then grounded to obtain particle size less than 5 mm. The density of palm bark fibers is around 0.064 g/cm3. Their chemical composition is as follow: Carbon 38.79%, Hydrogen 5.12%, Nitrogen 0.28%, and Sulphur 0.22%. The contents of cellulose, hemicellulose, and lignin in PTPW are 47.62%, 18.00% and 16.38%, respectively (Table 2) [27]. Scanning electron microscopy (SEM) micrograph (Fig. 1) of crushed PTPW shows a porous structure with an irregular shape.

Thermal Conductivity Measurement

Thermal conductivity is a property of the material. It expresses the extent to which a material conducts heat in stable conditions. In this work, thermal conductivity measurements were conducted by the box method (Fig. 2) [17,18] based on the use of an isothermal enclose with a heat exchanger at its base, which contains water-glycol fluids maintained at low temperature by a cryostat. The device has two boxes provided with a heater and there are two environments above and below the sample. Each box has an open face and contains on the interior of its superior face an electrical resistance heating R. The interior of boxes plays the role of the hot atmosphere. The material (Length 27 cm × Width 27 cm × Height 4 cm) to be tested is placed (Fig. 2) in such a way that side flows are negligible. When the permanent regime is established, the expression of thermal conductivity is deduced as follows:

$$\lambda = \frac{e}{S \times (T_h - T_c)}[q - C(T_b - T_a)] \qquad (1)$$

$$q = \frac{U^2}{R} \qquad (2)$$

Table 1. Some advantages and disadvantages of thermal insulating materials [2–5]

Material	Advantages	Disadvantages
Fiberglass	– Non-flammable, resistant to moisture damage, easy to install, and effectively blocks heat flow. – Resistance to microbiological attack and to chemicals.	– It can be highly irritating to skin and lungs. – Tendency to settle after installation if not properly installed. – Permeability to moisture.
1.1 Cellulose	– Environmentally friendly as it is made from organic, recycled paper and cardboard. – The thermal conductivity of loose-fill cellulose (0.04 W/m.K) is about the same as or slightly better than glass wool or rock wool. – Offers good thermal properties and has a low embodied energy.	– Cellulose fibers are naturally hygroscopic: their insulating ability decreases significantly when they absorbs moisture. – Cellulose contains small particles which can be blown into the building through inadequate seals around fixtures or small holes. – If improperly installed, loose fill cellulose could settle after application. – The high flammability of cellulosic fibers requires them to be treated before installation.
1.2 Rock wool (Mineral wool)	– Low density and high porosity. – It is able to withstand extremely high temperatures. – Non-combustible. – High compressive strength.	– It is more expensive. – Loses effectiveness if the insulation becomes wet. – Uneven surface.
1.3 Spray foam	– Excellent for enclosing and insulating existing walls, abnormally shaped areas, or working around obstructions. 1.4 – Reduces the likelihood of mold development. – Very durable. – Energy efficient.	– Liquid polyurethane foam isn't very thick and contracts with age. 1.5 – Requires protection from the sunlight and some solvents. 1.6 – High application cost. 1.7 – It can only be applied by a professional contractor.
1.8 Foam boards	– Can insulate almost any area of home. 1.9	– Can be costly when installed on finished/existing walls.
1.10 Natural fibers and agricultural by-products	– Renewable materials. – Low thermal conductivity. – Energy efficient. – Abundant and cost effective. – Non toxic and no skin irritation. – Lower environmental impacts.	– Chemical treatment before being used. – Flammability, high wettability and absorbability. – Nonhomogeneous.

Table 2. Chemical composition of PTPW fibers [27]

C (%)	H (%)	N (%)	S (%)	Cellulose (%)	Hemicellulose (%)	Lignin (%)
38.79	5.12	0.28	0.22	47.62	18.00	16.38

where, λ is the thermal conductivity (W/m °C), e is the thickness of the sample (m), S is the sample area (27×27 cm^2), q is the heat flux emitted by joule effect (W), C is the coefficient of thermal loss from the box (0.16 W/°C), Th is the temperature of hot surface of sample (°C), Tc is the temperature of cold surface of sample (°C), Tb is the inside temperature of box (°C), Ta is the room temperature experiments (°C), U is the voltage (70 V) and R is the resistance of the heater element (2631 Ω).

Multilayer specimens (plasterboard/material/plasterboard) were used to measure thermal conductivity of PTPW fibers. Dimensions of plasterboard are as follow: surface 27×27 cm^2, thickness 1.2 cm, distance between boards 1.6 cm. Therefore, the overall height of the composited specimens

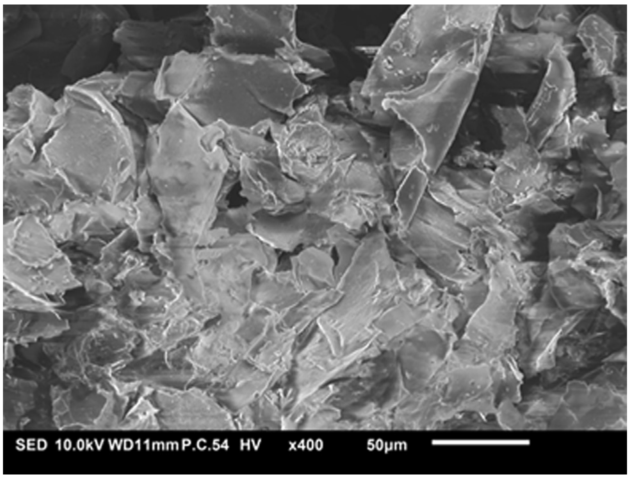

Figure 1. SEM micrograph of crushed *palm tree pruning waste (PTPW)*.

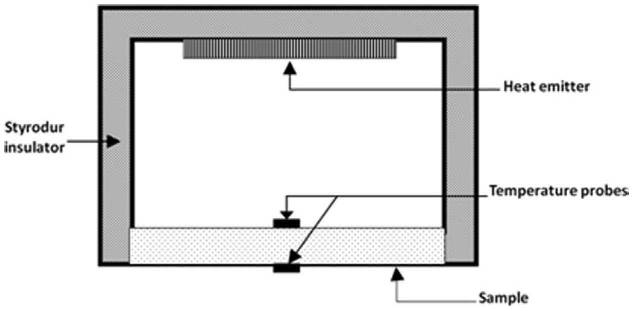

Figure 2. Schematic view of box for thermal conductivity measurement.

is 4 cm. Each layer is defined either by its thermal resistance R (m^2 °C/W) or by its thermal conductivity ? (W/m °C), and its thickness e (m).

$$R_t = \frac{e}{\lambda} \tag{3}$$

The heat flux penetrating through the composite specimen, knowing the surface temperatures of each side in steady-state regime is given as:

$$\varphi = \frac{T_{int} - T_{ext}}{\frac{1}{h_1 S} + \sum \frac{e_i}{\lambda_i S} + \frac{1}{h_2 S}} \tag{4}$$

where h1 and h2 are the individual heat transfer coefficients for the hot and cold fluids, respectively (W/m^2 °C), and Tint and Text are the surface temperatures of air in contact with internal and external surface of the multilayer composite material, respectively, and S is the surface of the sample (27 × 27 cm^2).

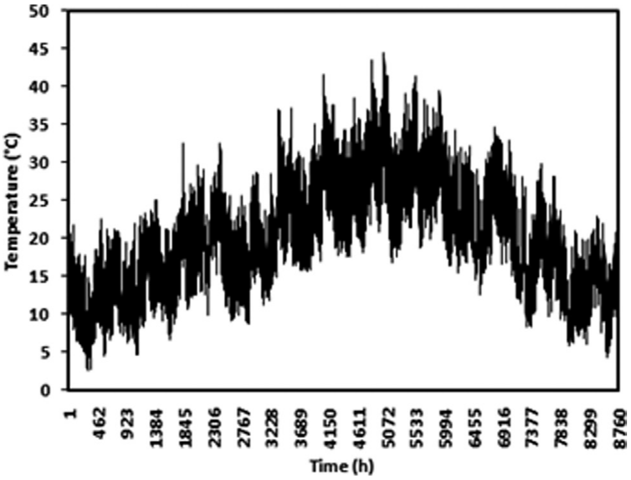

Figure 3. Annual variation in the average air temperature of Marrakech city.

Weather Conditions

The average meteorological data of Marrakech city (Morocco) were used in this study. Marrakech is west of the foothills of the Atlas Mountains. It has a dry climate; it's very hot in summer and cold in winter with low and irregular rainfall. Fig. 3 shows the annual variation in the average air temperature in the city of Marrakech. The minimum temperature reached is 2.5°C, while the maximum temperature is 44.6°C. July is the hottest month of the year, while January is the coldest month. The annual average temperature is 20.3°C.

Simulation Software

In this work, the software TRNSYS "Transient System Simulation Program" was used. The refrigerated warehouse considered in this work is defined by introducing its characteristics in the visual TRNBuild interface of TRNSYS multi-zone building (type 56). It is divided into eight thermal zones. The internal temperature of each zone was calculated for a time step of 1 hour.

The effect of applied material on the temperature of each area, considered in the refrigerated warehouse, was studied using thicknesses ranging from 10 to 75 cm. The refrigerated warehouse behavior was studied passively, without energy supply. The different thermally homogeneous zones are highlighted in Fig. 3, and the characteristics of the main elements of the building are given in Table 3.

RESULTS AND DISCUSSION

Thermal Conductivity of PTPW

Because of its divided form, palm tree pruning waste was placed between two plaster panels (Length 27 cm × Width 27 cm × Height 1.2 cm) to give a multilayer material P/PTPW/P (Length 27 cm × Width 27 cm × Height 4 cm).

Zones 1→6: Cold rooms (Area of each room: 180 m^2; Height: 7.8 m); Zone 7: Corridor (Area: 540 m^2; Height: 5 m);
Zone 8: Loading dock for trucks (Area: 36 m^2; Height: 5 m)

Figure 4. Different areas of the refrigerated warehouse and their dimensions.

Table 3. Refrigerated warehouse envelope characteristics.

Component	Layer	Thickness (cm)	U (W/m².K)
Exterior wall	Mortar	1.2	0.239
and Roofing	Hollow brick masonry	7	
	Mortar	1.2	
	Intermediate layer of air	10	
	Inox- steel	1	
	Polyurethane	10	
	Inox- steel	1	
Interior wall	Inox- steel	1	0.267
	Polyurethane	10	
	Inox- steel	1	
Flooring	Aerated concrete	30	0.285
Doors	Inox- steel	1	0.33
	Polyurethane	8	
	Inox- steel	1	

Separate panels were used so that heat cannot be transferred easily because there is no connection between their parallel surfaces. In order to obtain layers of different densities, the available volume between plaster panels (1166.4 cm^3) was filled by various amounts of PTPW ranging from 0 to 0.064 g/cm^3. It should be noted that if the mass of PTPW between the two plasterboards is less than 0.04 g/cm^3, the interior volume which is (27 × 27 × 1.6 cm^3) will not be completely occupied by PTPW. This can cause heat transfer in a heterogeneous medium.

The thermal conductivity and the thermal resistance of the composite specimens P/PTPW/P were first measured using the box method and then the values of the parameters corresponding to PTPW were theoretically deduced.

The effect of PTPW material is well revealed from the results shown in Fig. 5 and Fig. 6. The first thing we can see (Fig. 5) is that, in absence of PTPW (ratio: 0 g/cm^3), the thermal conductivity of specimen is relatively higher than that of plaster panels separated by PTPW because the mobile air when it is used alone and subjected to convection, it is not a good thermal insulator. For this reason, insulator materials are used to stabilize air and improve consequently the effect of insulation. Obtained results highlight that heat transfer decreases considerably when PTPW are used to separate plaster panels. As can be seen (Fig. 5), the thermal conductivity of the composite specimen P/PTPW/P decreases from 0.127 W/m.°C to 0.084 W/m.°C when increasing the ratio “PTPW mass/available volume between plasterboards” from 0 to 0.064 g/cm^3. However, the thermal resistance which is inversely proportional to the thermal conductivity increases from 0.315 to 0.476 m^2.°C/W.

The thermal properties of the system “plasterboard/PTPW/plasterboard”, considered as multilayer composite material, were used to deduce those of PTPW material. The thermal conductivity of plasterboard was first measured, it is about 0.320 W/m.°C. Obtained results (Fig. 6) highlight

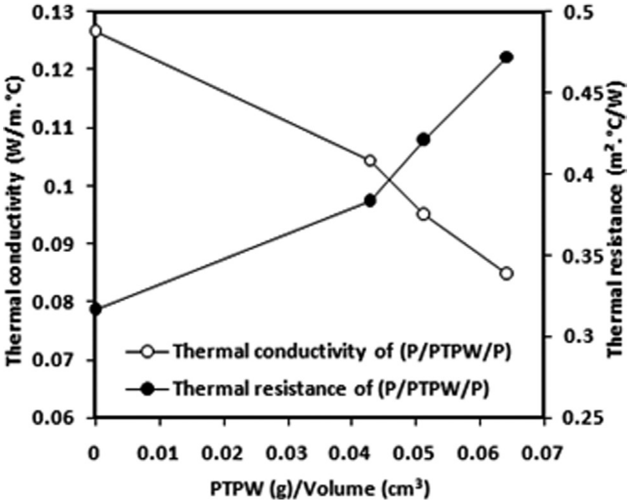

Figure 5. Thermal conductivity and thermal resistance of multilayer composite material as a function of "PTPW mass / volume" ratio.

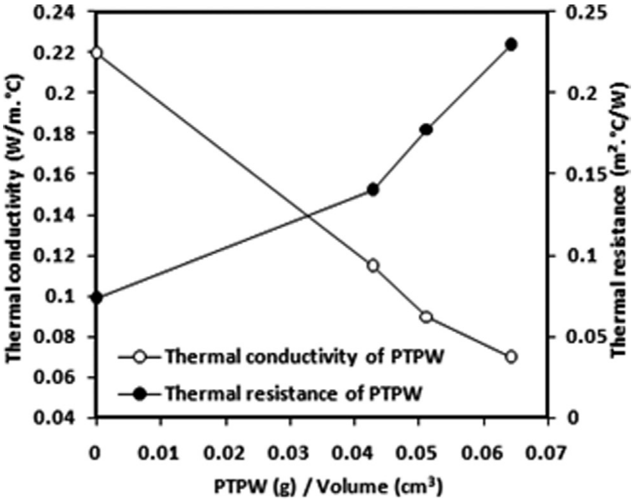

Figure 6. Thermal conductivity and thermal resistance of PTPW placed between panels.

Table 4. Comparison of the thermal conductivity of PTPW with that of some unconventional and conventional insulation materials.

Materials	Density (kg/m³)	λ (W/m.K)	References
PTPW	64	0.069	This study
Bagasse	70–350	0.046–0.055	[28]
Corn cob	177–334	0.101	[28]
Cotton (stalks)	150–450	0.0585–0.0815	[28]
Date palm	187–389	0.072–0.085	[28]
Durian	357–907	0.064–0.185	[28]
Reeds	130–190	0.045–0.056	[28]
Sansevieria fiber	1410	0.132	[28]
Wheat straw board	150–250	0.0481–0.0521	[29]
Rock wool	40–200	0.033–0.040	[28]
Expanded polystyrene	15–35	0.031–0.038	[28]
Extruded polystyrene	32–40	0.032–0.037	[28]
Polyurethane foams	–	0.020–0.030	[30]

that the thermal properties of PTPW depend strongly of its compactness, i.e. how much it weighs divided by how much space it takes up. For example, λ of the volume limited by plasterboards decreases from 0.220 to 0.069 W/m.°C when increasing the mass of PTPW from 0 to 0.064 per cm³. However, the thermal resistance increases from 0.073 to 0.232 m².°C/W.

A comparison of the thermal conductivity of PTPW with that of some materials discussed in the literature [28?30] is shown in Table 4. As it can be seen, λ_{PTPW} is comparable or lower than that of other natural materials. Generally, we notice that PTPW can compete with several insulation materials.

Thermal Simulation Study

In the refrigerated warehouse, the insulation of the cold rooms, the corridor and the loading dock for trucks is ensured by means of polyurethane foam sandwich panels which are composed of two sheets of metal and a rigid core in between. The rigid core has a polyurethane material known for its thermal insulation properties. Polyurethane foam sandwich panels are widely used in industrial

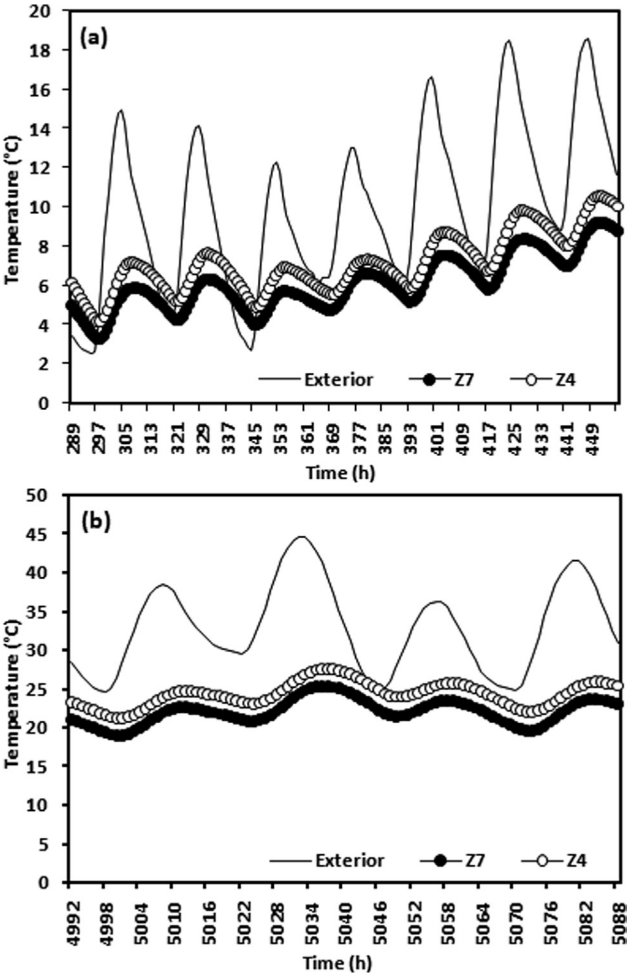

Figure 7. Variation of outside temperature and that of the zones 4 and 7 during the (a) coldest week and the (b) hottest week.

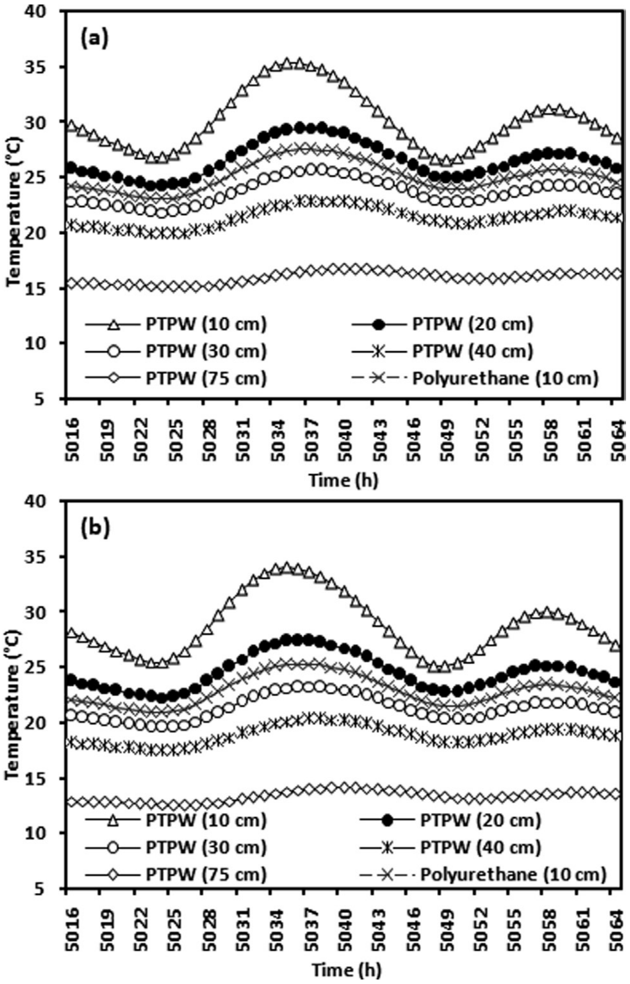

Figure 8. Variation of temperatures of zones 4 (a) and 7 (b), during the very hottest days of summer, considering polyurethane and different thicknesses of PTPW as insulators.

buildings, cold storages, warehouses, office buildings and other commercial units.

The objective of this part is the simulation of the thermal behavior of the building in the case where polyurethane or PTPW is employed. The energy efficiency of the considered refrigerated warehouse will be evaluated in both cases.

A preliminary test was performed by studying, at first, the effect of an insulation layer of polyurethane (λ = 0.028 W/m.°C, ρ = 40 kg/m^3, e = 10 cm). It was found that variations in temperature are generally dependent of the defined area. This trend is especially more pronounced in cold rooms and corridor during the cold and hottest periods. Fig. 7 shows the measured air temperatures in these areas (zone 4 as example and zone 7) compared with the external air temperatures recorded from January 12 to 19 (the coldest week of winter season) and from July 24 to 31 (the hottest week of summer season). During the coldest (2.5–18.5°C) and hottest (24.5–44.6°C) weeks, all internal temperature values recorded in zone 7 are lower than those in zone 4. The difference is attributed to the orientation of the two zones.

Fig. 8 shows the variations in temperature of zones 4 and 7 of the refrigerated warehouse during the typical 48 h of summer (29 and 30 July) when considering various thicknesses of PTPW (10, 30, 40 and 75 cm) instead of polyurethane. Results show that there is an obvious effect on the temperature which is strongly dependent on the thickness of the PTPW applied layer. For example, by increasing the thickness of PTPW from 10 to 75 cm the highest temperatures recorded in zones 4 and 7 decrease from 35.3°C to 16.3°C (Fig. 8a) and from 33.9°C to 13.6°C (Fig. 8b), respectively.

In order to highlight the optimal thickness of PTPW layer recommended to minimize heat transfer as much as possible, the effect of this biomaterial was compared with that of a 10 cm thick polyurethane layer with which the

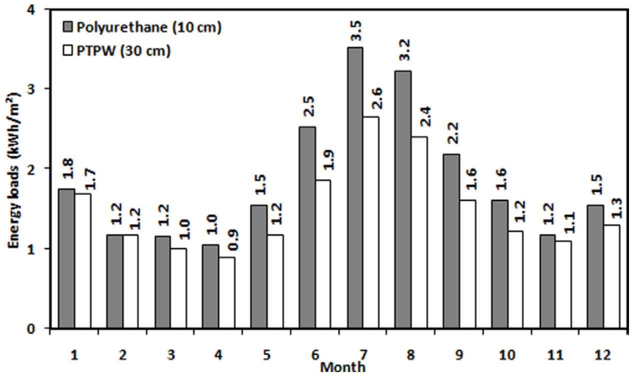

Figure 9. The monthly energy loads of the refrigerated warehouse when PTPW (30 cm) or polyurethane (10 cm) is considered.

thermal insulation of the refrigerated warehouse is normally ensured. The comparison between simulation results (in zones 4 and 7) during the very hottest days of summer is presented in Fig. 8. Compared to the control state (insulation with 10 cm of polyurethane), a considerable improvement in the temperature of zones 4 and 7 was revealed essentially with the thickness 30 cm. The temperature values recorded in this case are 1 to 2°C lower than those reached with the use of polyurethane.

Energy Consumption

Reducing energy consumption is one of the main challenges in most countries. It is one of the economic necessities and of the main sustainability trends among many sectors.

Because of its location in a hot semi-arid climate, the refrigerated warehouse studied must be kept at a temperature suitable for storing food. The thermal conditions which must be imposed are as follows: 0 to 15°C for cold rooms and 15 to 25°C for corridor and loading dock. Fig. 9 shows the monthly energy loads of the refrigerated warehouse for PTPW (30 cm) and polyurethane (10 cm). From the results obtained, it turned out that PTPW (30 cm) compared to polyurethane (10 cm) can reduce energy requirements whether during all seasons of the year mainly in the hottest period. For example, the energy loads in July can decrease by 25.7% when PTPW (30 cm) is used. The annual unit energy loads are 22.5 kWh/m² and 18.1 kWh/m² when polyurethane (10 cm) and PTPW (30 cm) were considered, respectively. This corresponds to a reduction of 19.6% in the annual unit energy consumption.

CONCLUSION

Palm tree pruning waste (PTPW), which is a natural material known by its abundance (low price), has good thermophysical properties. It has a low thermal conductivity of about 0.069 W/m.°C when it is compacted with a density of 0.064 g/cm³. The simulation results, obtained by the use of TRNSYS program, show that PTPW material can acts as a thermal barrier for refrigerated warehouse (RW) envelopes. It can reduce energy consumption and therefore the expenditures associated with it. The effect on the temperature of RW areas is strongly dependent on the thickness of the PTPW applied layer. Compared to 10 cm thick polyurethane, a decrease in temperature during the very hottest days was highlighted essentially by the use of 30 cm thick PTPW. Likewise, a significant reduction in the annual unit energy consumption has been achieved when considering this thickness. So, PTPW material can compete with conventional insulating materials and can provide multiple applications in particular to decrease energy consumption and costs in space cooling.

NOMECLATURE

λ	thermal conductivity (W/m.°C),
R_t	thermal resistance (m².°C/W),
C	coefficient of thermal loss from the box (0.16 W/°C),
φ	heat flux penetrating through the composite specimen (W),
e	thickness of the sample (m),
h_1	individual heat transfer coefficient for the hot fluid (W/m².°C),
h_2	individual heat transfer coefficient for the cold fluid (W/m².°C),
q	heat flux emitted by joule effect (W),
U	voltage (V)
R	Resistance of the heater element (Ω),
S	sample area (cm²),
T_a	room temperature experiments (°C),
T_b	inside temperature of box (°C),
T_c	temperature of cold surface of sample (°C),
T_{ext}	surface temperature of air in contact with external surface of the material (°C),
T_h	temperature of hot surface of sample (°C),
T_{int}	surface temperature of air in contact with internal surface of the material (°C),
ρ	density (kg/m³),
DTS	dynamic thermal simulation,
P	plaster panels,
PTPW	palm tree pruning waste,
RW	refrigerated warehouse,
SEM	Scanning electron microscopy.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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