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Production of Typha domingensis thermal insulation boards for refrigeration

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Abstract

The present study proposes formulations of ecomaterial insulation based on Typha domingensis for the design of insulation boards for refrigerators. The biosourced chips are obtained by thermopressing a Typha + cassava starch composite, with 80% Typha particles (particle size 1.7 mm) and 20% starch. The values obtained for the samples with binder show a thermal conductivity varying between 0.094 W/m. K and 0.5345 W/m. K. After demoulding and drying, briquettes measuring 10 cm × 10 cm or 15 cm × 10 cm are obtained, with thicknesses of between 3 and 5 cm. A case study shows that, in addition to their environmental benefits, these briquettes significantly reduce thermal loads compared with polyurethane, attesting to their excellent insulating properties.

Keywords: Typha Domingensis; Biosourced Chips; Cassava Starch; Polyurethane; Refrigeration; Environment

1. Introduction

The Typha domingensis area in Benin is characterised by its highly invasive nature: it is now massively colonising freshwater or slightly brackish herbaceous marshes, to the detriment of much of the native herbaceous flora. This uncontrolled expansion threatens local biodiversity and has major socio-economic repercussions, particularly in the agricultural, fish farming and pastoral sectors [1]. However, in some countries, similar species are used in an environmentally-friendly way, which suggests that sustainable use of Typha domingensis could be a lever for local development in Benin. Diouf et al. [2] studied the fermentability of Typha domingensis in mesophilic anaerobic digestion, alone or in co-digestion with faecal sludge and cow dung. They used batch digesters at 37°C, comparing the biogas produced by different proportions of typha and animal substrates. The experiments showed that co-digestion significantly increased methane production compared with typha digestion alone, highlighting the energy potential of this invasive macrophyte for organic waste recovery in Senegal. Lo et al. [3] and Sonko et al. [4] conducted a study on the improvement of the agronomic value of faecal sludge by co-composting with Typha domingensis leaves. They have found that composting of sewage sludge with Typha biomass is a good option to valorise faecal sludge in agriculture. The National Program for the Reduction of Greenhouse Gas Emissions in Senegal launched the "Typha" project, aimed at transforming Typha australis (a related species to Typha domingensis) into thermal insulation materials [5]. They have explored several formulations: typha alone, typha-earth, and typha-magnesite. Bricks, panels and hoardings were manufactured and tested (porosity, thermal conductivity, mechanical strength). The materials showed reduced thermal conductivity (~0.5 W/ (m.K)) and a good strength/weight compromise, validating their use in tropical climates. In his PhD thesis, Hounkpatin [6] evaluated the use of Typha domingensis to improve the energy performance of buildings in humid tropical climates. After characterising several typha-starch composites, he showed that the L91 composite (fraction 1.70 mm, 20% starch) has the lowest thermal conductivity (≈ 0.058 W/ (m.K)), making it ideal for

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refrigeration and passive insulation applications. Alassole [7] studied the impact of thermal insulation using Typha domingensis panels on the thermal behaviour of a building in southern Benin. His study, based on energy simulations, revealed that insulating the roof with these panels reduces the average indoor temperature by 2.05°C, while being economically competitive with synthetic insulation.

These studies show that Typha domingensis is a multifunctional resource. It was with this in mind that the "Eco-froid" project was launched, the main aim of which is to design a refrigerator incorporating a biobased thermal insulator extracted from Typha domingensis and using an alternative refrigerant, in order to preserve heat-sensitive foodstuffs and health products [8]. In this way, the project aims to transform an ecological constraint into a technological opportunity, while reducing dependence on fossil resources and improving the energy efficiency of the refrigeration system. The first phase of the project involves developing thermal insulation panels from Typha domingensis, then comparing their economic feasibility and insulating performance with those of conventional materials such as polyurethane or polystyrene. The aim is to develop a process for recovering energy from Typha domingensis by developing a thermal insulator suitable for refrigeration applications.

Insulation materials in the construction industry play a crucial role in improving the thermal performance of buildings, reducing energy demands, and reducing carbon emissions [9]. Commercialization of bio-based insulation materials for minimizing operational energy consumption in the building sector has already been implemented in France, and it is estimated that energy recovery in 2050 would save 4.1 million m^3 of land, 75,000 tons of fossil fuel and 89 million euros [10].

The ultimate aim is to offer cold rooms using a biobased insulator, thereby promoting a more sustainable industrial approach that respects the environment.

2. Materials and methods

This section presents the equipment and/or materials and techniques used in the manufacture of Typha domingensis-based sheets.

2.1. Equipment

The materials used to manufacture the insulation boards are described below

Typha domingensis, commonly known as southern reed or southern cattail, is a perennial aquatic macrophyte with a trailing rhizome, forming dense stands that can reach over 2.5 m in height. At high densities, it reduces plant diversity, modifies hydrological flows and can alter the ecological functions of wetlands, justifying its status as an invasive species in many regions, particularly in Benin's Atlantic, Oueme-Plateau and Mono-Couffo departments.

Starch is a complex reserve carbohydrate, or polysaccharide, synthesised by most higher plants and formed from repeated units of D-glucose $(C_6H_{10}O_5)_n$. It comes in the form of semi-crystalline granules made up of two homopolymers: amylose, which is linear and helical, and amylopectin, which is highly branched. Insoluble in cold water, it gelatinises under the effect of heat to form a viscous starch, a property used as a thickening agent in the food industry. Cassava starch is the binder used in our case.

The drying oven is used to dry typha granules at high temperature. Comprising a stainless-steel drying chamber insulated with high-performance caulking to minimise heat loss, the oven incorporates a temperature controller using a PID (Proportional-Integral-Derivative) regulator with a PT100 thermocouple probe, guaranteeing accuracy of around ±1°C.

The 0.75 kW VICKING knife mill is a mechanical fragmentation device designed to reduce Typha domingensis stems to fine particles by crushing them between rotating notched elements. It consists essentially of a rotor with high-strength steel teeth driven by an internal combustion engine, guaranteeing a high peripheral speed for a clean cut of the plant fibers.

The multi-mesh sieve is a set of stacked sieves with openings ranging from coarse (8 mm) to extremely fine (0.315 µm), enabling very fine particle size classification.

The TED electronic scale provides fast, accurate weighing of raw materials and panel samples over a range of 1g to 3,000 g, enabling the proportions of reinforcement and binder to be accurately determined for sample formulation.

The Hobart variable speed mixer is an industrial planetary mixer designed to provide fine homogenisation of Typha domingensis and starch particles. It features a Variable Frequency Drive (VFD) that precisely modulates the voltage and frequency applied to the motor, providing smooth, continuous control of rotation speed without jerking or gear jerking. Its capacity and robustness enable it to handle volumes ranging from 5 to 30 liters (depending on the model), with typical motor outputs of 0.25 HP to 1.5 HP and an all-gear drive system guaranteeing reliable transmission and limited maintenance.

The traditional mechanical screw press is a simple, robust device based on an endless screw mechanism housed in a perforated cylinder. By manually activating the screw, increasing pressure is generated, pushing the biomass towards the outlet and expelling the liquids through the perforations in the cylinder. The machine is generally designed by hand, using a steel or cast-iron frame, a feed hopper, a screw with a suitable diameter (between 30 and 80 mm) and a sieve or cylinder with meshes calibrated according to the fineness of extraction required.

AutoCAD is a computer-aided design (CAD) software package for creating 2D technical drawings (and 3D models). Widely used in architecture, civil engineering, mechanical engineering and electrical engineering, it can be used to produce sections, elevations and diagrams with a high degree of precision and fine management of layers, dimension styles and hatching.

Microsoft Excel is the benchmark spreadsheet program for organising, processing and analysing numerical data using a grid of cells equipped with automated functions and complex formulas. It includes more than 480 functions covering statistical, financial, logical and text manipulation fields, as well as visualisation tools (graphs, histograms, pivot tables) for translating data into clear, usable indicators. Thanks to its real-time co-editing capabilities, its add-ins (Solver, Analysis ToolPak, Power Query) and its language support (VBA, Python), Excel is a pillar of companies accounting, financial and analytical activities, facilitating budget modelling, performance monitoring and decision-making.

3. Research Methodology

This section examines the various stages in the manufacturing process for Typha domingensis-based thermal insulation panels. A case study is also presented to assess the thermal performance of the sheets obtained.

3.1. Preparation of Typha particles

Typha domingensis particles were prepared according to a rigorous protocol designed to ensure particle size homogeneity suitable for the intended applications. The mature stems were harvested by hand, then sun-dried for a fortnight on a flat, dry, well-ventilated surface. Once dried, the stems were cut into granules measuring approximately 1 cm×2 cm. The pellets were then conditioned in an oven to remove any residual moisture, a crucial step in preventing agglomeration during grinding. Grinding was carried out using a toothed mill, reducing the aggregates to fine and medium particles. Finally, mechanical sieving was carried out using a series of nested sieves with decreasing apertures, ranging from 8 mm to 0.315 µm. This process separated the particles according to size, with the largest retained in the upper sieves (rejects) while the finest passed through the lower sieves (sievesate). Sieving was considered complete when the weight of the rejects on each sieve remained constant, ensuring a stable and reproducible particle size distribution: this is how Typha particles are obtained.

3.2. Mixing Typha + Starch + Water

The starch, used as a binding agent, was purchased on the local market. Among the various compositions studied, the L91 composite, made up of Typha domingensis particles with a particle size of 1.7 mm and containing 20% starch, demonstrated the best thermal conductivity based on the work of Hounkpatin [6]. The mixture used to produce the pulp is made up of 20% starch and 80% typha particles with a particle size of 1.7 mm.

To prepare the paste, 80% of the total desired mass of typha particles with a particle size of 1.7 mm is weighed using an electronic balance. Next, measure 20% of the total mass in starch. Dissolve the starch in cold water to obtain a homogeneous suspension, taking care to mix well to avoid lumps. The typha particles and starch suspension are then added to a suitable container and mixed thoroughly using a blender. If the resulting paste is considered too thick, a moderate amount of water can be added to achieve the desired consistency

3.3. Obtaining the insulation boards

Before pressing, the mould must be thoroughly cleaned and dried. If necessary, the inside can be coated with an environmentally-friendly adhesive to strengthen the adhesion of the typha fibers. The prepared paste is then poured into the mould in homogeneous layers, taking care to pack it well to eliminate air bubbles, thus optimising thermal insulation.

The pressing operation is carried out using a mechanical screw press, applying even pressure to effectively compact the dough. This step is maintained for a suitable length of time to promote the adhesion and cohesion of the fibers. Finally, the resulting insulation board is removed from the mould and left to dry to ensure its stability and mechanical strength.

3.4. Refrigerator sizing

This case study concerns the preservation of serum. The serum, which has a heat capacity of 4.18 kJ/ (kg °C) and a density of 1050 kg/m^3 is introduced at a temperature of +8 °C. For this study, the refrigerator was installed in a room where the ambient temperature was 27 °C, while the temperature inside the refrigerator was maintained at +2 °C. The relative humidity inside is 80%, compared with 75% outside. Daily traffic in the refrigerator is estimated at 10%. Lighting is provided by three LED lamps of 9 W each, operating for8hours a day. The external dimensions of the appliance are as follows: length 3 m, width 2.5 m and height 2 m. The surface heat exchange coefficients are taken as follows: $1/h_i = 0{,}06\ m^2.°C/W$ and $1/h_e = 0{,}03\ m^2.°C/W$.

The sizing of the refrigerator is based on the establishment of a refrigeration balance, making it possible to quantify the sum of the heat inputs that need to be compensated for in order to maintain the refrigerated enclosure and its contents at a stable, predefined temperature. Drawing up this balance requires great precision, as it has a direct influence on the installation and running costs of the refrigeration system.

3.4.1. Inputs through the walls

Due to heat exchanges between the inside and outside of the enclosure, the walls will lose a certain amount of heat, which can be evaluated by

$$Q_p = \frac{K \times S \times \Delta T}{1000} \qquad (1)$$

- Q_p : amount of heat lost through the walls (kW).
- K: thermal transmittance of the walls (W/m^2.K).
- S: surface area of all the walls (m^2).
- ΔT: temperature difference between the outside and inside of the cold room (K).

It should be noted that the outside temperature corresponds to the temperature where the cold store is installed. This temperature may vary according to environmental conditions; however, as a precautionary measure, the most unfavourable value is generally used. For example, calculations are often based on a minimum outdoor temperature of 25 °C and a maximum of 35 °C.

3.4.2. Inputs through the introduction of products

When new products are introduced into the refrigerator, a significant amount of heat is added due to the difference in temperature between the products introduced and the temperature inside the refrigerator. This heat input must be taken into account in the refrigeration balance in order to maintain optimum preservation conditions. The following formula can be used to estimate it.

$$Q_m = Cp \times M \times \Delta T \qquad (2)$$

- Q_m: total heat to be removed from the products introduced (kW).
- Cp: specific heat of the products introduced (kJ/ (kg. K)).
- M: quantity of foodstuffs introduced (kg).
- ΔT: temperature difference between the products at the time they are introduced and the storage temperature (K).

3.4.3. Air exchange

It is planned to renew the ambient air in the cold room. This process consists of partially replacing the indoor air with air from outside. This intake of new air means that it has to be cooled from the outside temperature to the temperature at which the products are kept, generating an additional thermal load. The thermal load induced by air renewal is calculated using the following expression

$$Q_{re} = \dot{m}_e \times \Delta h \qquad (3)$$

- Q_{re} : heat input by air exchange in (kW)
- $\dot{m}_e$: mass flow rate of outside air admitted in (kg/s)
- Δh : enthalpy difference between the outside air and the air in the refrigeration system (kJ/kg).

3.4.4. Input from lighting

To evaluate the heat power dissipated by lighting, the following formula can be used:

$$Q_e = \frac{P \times N \times t}{24000} \qquad (4)$$

- Q_e : heat released by lighting (kW).
- P: power of each lamp (W).
- N: number of lamps in the cold room.
- t: lamp operating time (h).

3.4.5. Cooling capacity

The cooling load Q_{int} (in kW) is the sum of the thermal loads

$$Q_{int} = Q_p + Q_m + Q_{re} + Q_e \qquad (5)$$

t_int is the daily running time of the refrigeration plant in hours. Let's take t_{int}=16 hours/day.

The intermediate cooling capacity of the evaporator P_{int} (in kW) is written as

$$P_{int} = \frac{Q_{int} \times 24}{t_{int}} \qquad (6)$$

The provisional determination of the number and type of evaporators to be provided is based on the provisional calculation of the provisional cooling capacity Q_{prev} which is obtained by adding 20% to the intermediate cooling capacity Q_{int} [11, 12].

$$Q_{prev} = 1.2 \times P_{int} \qquad (7)$$

3.4.6. Wall heat transfer coefficient

The wall heat transfer coefficient is defined as follows

$$K = \frac{1}{\frac{1}{h_i} + \sum_n^1 \frac{e_n}{\lambda_n} + \frac{1}{h_e}} \qquad (8)$$

- K : Thermal transmittance of the wall in question (W/$m^2.°C$).
- $1/h_i$: Internal surface thermal resistance ($m^2.°C/W$).
- $1/h_e$: External surface thermal resistance ($m^2.°C/W$).
- $\sum_n^1 \frac{e_n}{\lambda_n}$: Sum of the thermal resistances of the different layers of material making up the wall ($m^2.°C/W$).

4. Results and discussion

4.1. This section presents and discusses the results obtained.

4.1.1. Thermal insulation panels obtained

Refrigerators usually incorporate insulating materials such as polyurethane foam, rock wool or polyethylene foam. The thickness of these insulating layers varies according to the manufacturer's specifications and the type of appliance, in order to optimise the compromise between energy performance and size. The curve shown in Figure 1 illustrates the thermal resistance of typha and polyurethane as a function of thickness.

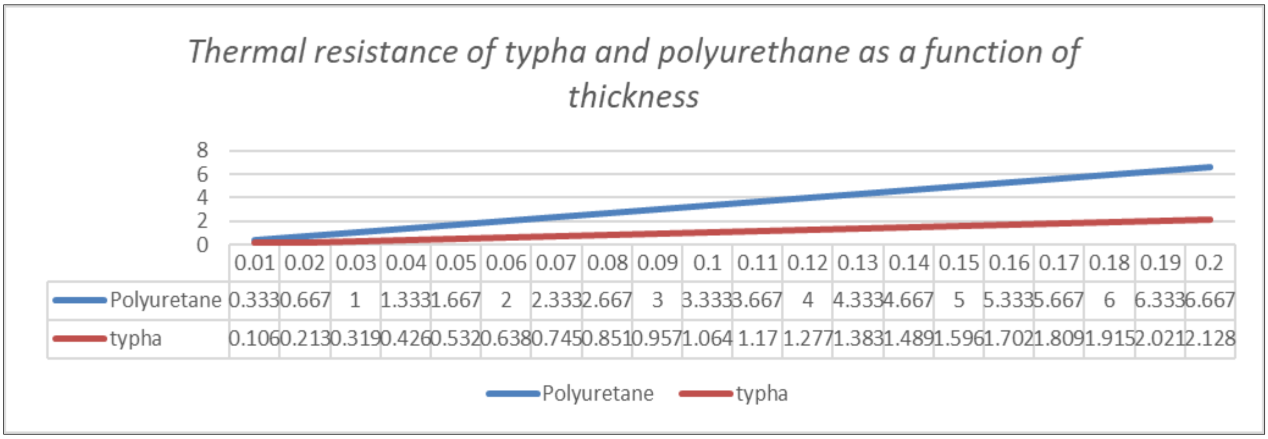

Figure 1 Curve showing the evolution of the thermal resistance of typha and polyurethane as a function of thickness

This curve shows a strictly linear relationship between the thermal resistance and the thickness of the insulating material, with a slope of 0.034 K.mm/W. This value means that for each additional millimeter of thickness, the thermal resistance increases by 0.034 K.mm/W. In addition, the association of a positive correlation highlights that increasing thickness directly enhances the material's ability to resist heat transfer, which is expected since lengthening the conduction path increases the energy loss required to pass through the material. This is in line with work carried out by Dieye et al. [13]. According to their work, a prototype panel made from defibrated typha has a better thermal insulation performance (0.085 W/ (m.K) for 66.66%), which is comparable with many of natural insulating materials. They said that the panels also have low thermal effusivities which show that they have low thermal inertia. Furthermore, a similar result has obtained for the newly developed magnesite-bound typha board which exhibits high strength and dynamic stability despite a low thermal conductivity of about 0.055 W/ (m.K) and can solve energetic as well as static problems [14]. Another study carried out by the Fraunhofer Institute [15] allowed to design a thermal insulation panel made of Typha (Latin for "cattail") characterized by a thermal conductivity of 0.052 W/(m.K) and also illustrating the linear relationship between thickness and thermal resistance. The work of Hounkpatin et al. [1] confirms this linearity between thickness and thermal resistance. This relationship is of vital importance in the design of thermal insulation, as it enables the influence of thickness on overall thermal resistance performance to be quantified precisely, and wall dimensions to be optimised according to energy requirements.

Figure 2 shows some of the thermal insulation boards obtained after the various stages described above.

Figure 2 Photograph of sun-dried chips

5. Case study

5.1. Refrigerator architecture

Figure 3 is a sketch showing the dimensions of the refrigerator.

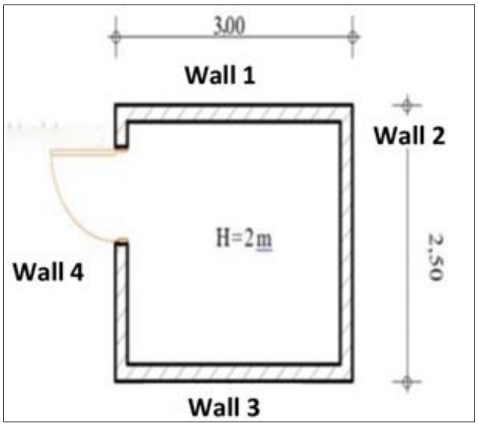

Figure 3 Refrigerator architecture

5.2. Technical specifications for insulation

The walls of the refrigerator can be insulated with polyurethane, Typha or plastic, the technical specifications of which are given in Table 1.

Table 1 Characteristics of some insulating materials

Insulation	Thickness (m)	Thermal conductivity (W/(m. K))
Polyurethane	0.05	0.03
Typha	0.15	0.094
Plastic	0.01	0.023

5.3. Fridge dimensions

The dimensions of the refrigerator are summarised in the table below

Table 2 Fridge dimensions

	Thickness (m)	External dimension (m)			Inside dimension (m)		
		L_e	l_e	H_e	L_i	l_i	H_i
Polyurethane	0.07	3	2.5	2	2.86	2.36	1.86
Typha	0.17	3	2.5	2	2.66	2.16	1.66

With

- L_e/ L_i : external/internal length of walls (m)
- l_e / l_i : external / internal width of walls (m)
- H_e/ H_i : external/internal height of walls (m)

5.4. Thermal transmittance coefficients of some combined insulating materials

The thermal transmittance coefficients of some combined insulating materials are calculated in the table above:

Table 3 Heat transfer coefficients

Thermal transmittance $(W/(m^2.°C))$	
Polyurethane + plastic	0.38
Typha + plastic	0.361

5.5. Assessment of thermal loads

5.5.1. Thermal loads due to wall transmission

The contributions from the walls include the thermal loads by transmission from the side walls, the ceiling and the floor. They are estimated in Table 4.

Table 4 Wall transmission heat loads

Wall transmission heat loads (kW)		
	Polyurethane	Typha
Internal wall (1)	$Q_{p1} = 0.0505$	$Q_{p1} = 0.0398$
Internal wall (2)	$Q_{p2} = 0.0417$	$Q_{p2} = 0.0323$
Internal wall (3)	$Q_{p3} = 0.0505$	$Q_{p3} = 0.0398$
Interior walls (4)	$Q_{p4} = 0.0417$	$Q_{p4} = 0.0323$
Ceiling	$Q_{pp} = 0.0641$	$Q_{pp} = 0.0518$
Floor	$Q_{ps} = 0.0641$	$Q_{ps} = 0.0518$
Total	$Q_p = 0.3126$	$Q_p = 0.2478$

5.5.2. Summary of thermal loads

In addition to these thermal loads, there are other thermal loads such as those due to air renewal, lighting and the introduction of serum. Table 5 provides a summary.

Table 5 Heat balance

	Thermal loads (kW)			
	Q_p	Q_{re}	Q_e	Q_m
Polyurethane	0.3126	0.211	0.009	0.304
Typha	0.2478	0.211	0.009	0.304

5.5.3. Load distribution

The load distribution for each insulation is as shown in Figures 4 and 5 respectively.

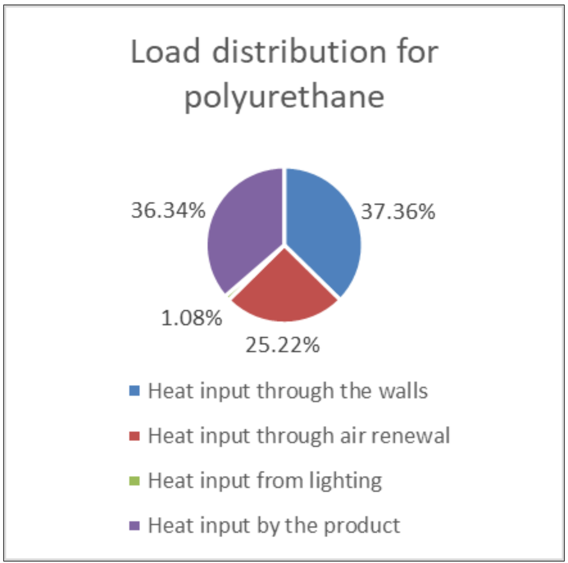

Figure 4 Load distribution: case of polyurethane

This diagram clearly illustrates the main heat sources involved in maintaining the temperature within the refrigerated enclosure and its contents. Heat input through the walls appears to be the most significant, accounting for around 38% of all thermal loads. This is closely followed by heat input from the products, which accounts for 36.34%. Air renewal is also a significant source, accounting for 25.22% of the total. On the other hand, heat generated by lighting is marginal, accounting for just 1.08%.

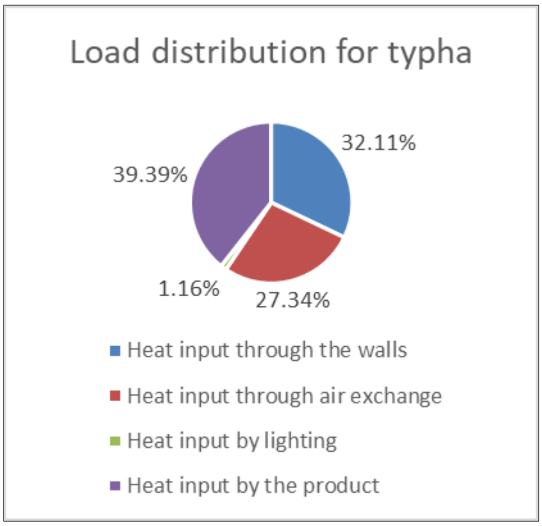

Figure 5 Load distribution: case of Typha

Heat input from products is the main source of heat load, accounting for almost 40% of the total. This is followed by air changes, which account for 32.11%, then transfers through the walls, which account for 27.34%. Lighting, on the other hand, contributes only a small amount of heat, just 1.16%.

Lafond and Blanchet [16] report that natural fibre wools (wood, hemp, etc.) can achieve conductivities close to those of expanded polystyrene (EPS) (~0.036 W/ (m.K)) while offering 2 to 3 times greater vapour permeability, and therefore better hygro-thermal behaviour without the addition of a vapour barrier. However, the insulating effect of ecological insulating materials is lower than that of conventional insulating materials and more unsuitable [17].

6. Conclusion

This article discussed the production of typha domingensis thermal insulation boards for refrigeration.

Biobased boards produced by thermopressing a composite of *Typha domingensis* (80%) and cassava starch (20%) demonstrate excellent insulating properties, with a thermal conductivity of between 0.094 and 0.5345 W/(m. K), and reduce thermal loads by more than 20% compared with polyurethane foams. Their low cost and low carbon footprint make them a promising candidate for green refrigeration.

On the other hand, future work could focus on improving the performance of *Typha-starch* composites by optimising the grinding and granulometry parameters to maximise the surface/volume ratio and the compactness of the panels; industrialising the panels by defining standardised harvesting, pre-treatment (drying, hulling, disinfection) and manufacturing protocols that guarantee consistent panel quality, while complying with European certifications [18].

These improvements could make the sheets even more effective in terms of thermal insulation and make them viable on a wider scale.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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