

## Article

# Eco-Sustainable Wood Waste Panels for Building Applications: Influence of Different Species and Assembling Techniques on Thermal, Acoustic, and Environmental Performance

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**Abstract:** Multiple high quality wood waste from a window manufacturer is identified and collected. Eco-sustainable panels, with promising acoustic and thermal insulating performance, were then fabricated. The available wood is of different tree species (pine, oak, and mahogany) and size (pieces of wood, mixed coarse chips, and mixed fine chips). Moreover, scraps of olive tree pruning from local areas were collected for reuse. The aim of the research is to assembly panels ( $300 \times 300 \text{ mm}^2$ ) both with different techniques (hand-made and hot-pressed) and type of adhesive (vinyl and flour glues) and to evaluate their thermal, acoustic, and environmental performance. All the panels present thermal and acoustic performance comparable with the similar ones available in the literature or with commercial solutions. The thermal conductivity varies in the  $0.071$  to  $0.084 \text{ W/mK}$  range at an average temperature of  $10^\circ\text{C}$ , depending on the tree species, the assembly technique, and regardless of the type of adhesive used. Oak wood panels are characterized by both better sound absorption ( $\alpha$  peak value of  $0.9$ , similar to pine pressed sample with flour glue) and insulation (transmission loss up to  $11 \text{ dB}$  at  $1700 \text{ Hz}$ ) properties. However, their added value is the low environmental impact assessed through life cycle analysis in compliance with ISO 14040, especially for panels assembled with natural glue.

**Keywords:** recycled wood waste; eco-sustainable panels; thermal properties; acoustic characteristics; life cycle assessment



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## 1. Introduction

The thermal insulation properties of the opaque and glazing building envelope represent a fundamental requirement in the building strategy design: nearly zero energy buildings (NZEB) are the final objective able to limit heat losses and to reduce energy consumptions both for heating and cooling of buildings. In a circular economy perspective, the use of waste materials from industrial and agricultural processes is very promising.

### 1.1. Properties of Wood and Engineered Wood Products

Wood has a wide range of physical and mechanical properties among its many species. It is also a renewable resource with an exceptional strength-to-weight ratio [1]. Color and odor, specific gravity, moisture content, grain, shrinkage and swelling, and strength are the important characteristics which determine the properties of wood and timber, such as specific gravity. All types of wood have values below 1: hardwoods specific gravity ranges between  $0.7$  to  $0.9$ , whereas in most of the softwoods it lies below  $0.7$ . Hardness and strength of wood depend to a great extent on its density. Moreover, wood is a highly hygroscopic material, with an average moisture content generally in the  $30\%$  to  $50\%$  range after the harvesting phase. When fully saturated in cell walls and cavities, the moisture content of wood may be as high as  $200\%$ . Because of its hygroscopicity, wood always

contains moisture, which affects all its properties, but it should be noted that only moisture contained in cell walls is important, merely adding mass to the material itself.

The adoption of engineered wood products, such as particleboards, cross laminated timbers, and so on, represents a greener solution when compared with timber, keeping almost the same properties [2]. In some cases, engineered wood products (e.g., glued wood composites) are superior to natural wood in terms of structural and material properties. They can be used instead of precious natural species in the structural and wall construction systems of buildings, saving natural resources and building energy.

Wood-based scraps can be used for creating compounds, biofuels, and chipboard panels [3]. Wood is, in fact, one of the most resistant and long lasting natural organic materials. In particular wood fibers have good thermal and acoustic insulation properties, comparable to the ones of other natural insulation materials, and largely available as a waste in wood industry. The addition of binder or glue is able to give shape stability, but it can increase the airflow resistivity, despite it decreases the sound absorption.

### *1.2. Wood Waste in Building Construction Sector*

Wood generally requires low energy for producing a usable end-product with respect to other competitive materials, such as steel, concrete, or plastic [3]. This is the reason why it is so suitable as construction material. Wood-based materials can achieve both efficient environmental and economic benefits [4]. When comparing engineering wood (cross-laminated timber) with concrete and steel structures, the first show a lower environmental impact [5,6]. Timber buildings gained, therefore, popularity in the building industry, especially thanks to their environmental benefits with respect to concrete and steel structures [7].

Anyway, deforestation imposes to seek suitable replacement for wood, both in cellulose derivatives and in the buildings construction area [8]. The European building sector represents a significant material stock for wood-based construction materials. The average wood consumption per year increased from 5.2 million tonnes in the 1950s and 1960s (FAO, 1971) to 6.4 million tonnes (UNECE/FAO 2008; United Nations 2010) between 1990 and 2010. The increased use of solid wood began to expand at the end of 1980s in the western European countries (UK, Austria, Italy, and Germany), also facilitated by technical innovations and newly adopted building regulations. As a consequence, market demand of wood-based construction materials increased both for construction of new residential buildings and for energetic renovation and retrofitting of old buildings. Nowadays, it is also regarded as a way to meet the European climate targets of decreasing CO<sub>2</sub> emissions, creating added value due to the lower environmental impact and higher emissions efficiency than reference production systems. The central production of prefabricated products, which results in a cost-competitive construction time, is another important strength of wood products. Most of them are produced on an industrial scale, with a market share constantly increasing, despite it is still below 10% of total market demands for insulation materials and structural construction elements [9].

In a circular economy perspective an important role can play the agricultural and industrial wood waste, which can represent an important resource in terms of secondary raw material. It can be used for the production of wood insulation panels.

### *1.3. Wood-Waste Panels*

Many research works [10–12] demonstrated that the discarded products of industrial and cultivation processes can be used as base materials for insulating panels. Locally available by-products (rice husk, wheat husk, wood fiber, and textile waste fiber) were used to produce composites with a biodegradable poly(butylene adipate-co-terephthalate)/poly(lactic acid) (PBAT/PLA) blend binder by hot pressing [13]. The density and thermal conductivity of the produced composites were in the 378 to 488 kg/m<sup>3</sup> and 0.08 to 0.14 W/mK ranges, respectively. The lowest thermal conductivity (0.08 W/mK) was observed for the rice husk composite with a density of 378 kg/m<sup>3</sup>. Other works analyzed the

environmental, thermal, and acoustic properties of panels made with rice husk, cork scraps, end-life granulated tires, coffee chaff, waste paper pressed and glued with polyethylene fibers mat, waste paper pressed and glued, and waste paper pressed and glued with wool fibers assembled with similar techniques [14,15]. It was observed that the panels made with waste paper present the best thermal performance, whereas the lowest environmental impact is related to rice husk and coffee chaff solutions.

Wood-based panels are at most recyclable and they are characterized by good thermal inertia and vapor permeability, with a reduced environmental impact. Additionally, mechanical properties are in general compliant with requirements for building construction use, despite lower values were found when comparing agro-industrial waste particleboards with eucalypts wood [16]. In Zhang et al. [17] two kinds of structural wood wall integrated with wood plastic composite (WPC) were designed and their thermal insulation performance was studied. The systems with 50 mm thick WPC wall panel reached a thermal transmittance of about  $0.21 \text{ W/m}^2\text{K}$ , which can meet the standard of wall thermal level and it is suitable for severe cold areas [17]. Zoltán Pásztor et al. [18] studied insulating panels composed of shredded bark of *Robinia pseudoacacia*. They found a thermal conductivity of the panels of about  $0.06 \text{ W/mK}$ , similar to other natural insulation materials. Ferrandez Villena et al. [8] found similar thermal performance for panels made from Vine (*vitis vinifera* L.) prunings: a thermal conductivity value in the  $0.0642$  to  $0.0676 \text{ W/mK}$  range was obtained, together with a good fire resistance capacity. A thermal conductivity of  $0.041 \text{ W/mK}$  was obtained for a sample made of wood fibers characterized by a relatively low density ( $145 \text{ kg/m}^3$ ) [19]. Short-cut loose woodchips were also used as filling in an insulating sandwich panel; thermal conductivity values of  $0.042$  and  $0.065 \text{ W/mK}$  were found for densities of  $110$  and  $205 \text{ kg/m}^3$ , respectively [20]. The analysis of the thermal insulation performance of bamboo-based shear walls in light-frame buildings showed that the thermal conductivity is lower when compared with wood ones, both at the material and at shear wall levels [21]. In a round robin test process, a sample of birch wood fiber was also investigated. It showed an average thermal conductivity value of  $0.0427 \text{ W/mK}$ ; no data about density are available [22]. A significantly lower thermal conductivity value ( $0.0094 \text{ W/mK}$ ) was found when using wood fibers as core materials of vacuum insulation panels (VIPs), with a density in the  $180$  to  $200 \text{ kg/m}^3$  range [23].

Good sound absorption performance were also obtained when considering composing materials based on alfa and wood fibers: peak values of  $0.98$  were found in the  $2048$  to  $2288 \text{ Hz}$  frequency range for a thickness of about  $20 \text{ mm}$  [24]. Insulation panels of approximately the same thickness based on bark spruce (*picea abies* L.) and larch (*larix decidua*) showed peak values of the absorption coefficient in the  $0.4$  to  $0.6$  range [25].

A few studies are available in the literature about the environmental impact of wood-waste panels. A research study [26] deals with life cycle assessment (LCA) of an innovative insulation panel based on eucalyptus bark fibers, with densities in the  $25$  to  $50 \text{ kg/m}^3$  range. It showed embodied energy and carbon emissions lower than traditional insulation materials (expanded polyurethane, polystyrene, glass fibers, and glass wool).

In this context the first part of ReScaLe—FiAer (Produzione di pannelli isolanti eco—sostenibili mediante REcupero degli SCarti del LEgno derivanti dalla realizzazione di sistemi FInestrati innovativi a base di AERogel) project, funded by the Fondazione Cassa di Risparmio di Perugia, is focused on the reuse of several high quality wood scraps from a local window manufacturer. Three different types for tree species (pine, oak, and mahogany) and for size (pieces of wood, mixed coarse chips, and mixed fine chips) were selected; preliminary analyses were carried out, in order to evaluate the properties of the raw material. Afterwards, the different kinds of wood were assembled with vinyl glue, but also with flour-based glue. The use of natural glues is indeed able to reduce environmental impact, without significantly modify properties with respect to synthetic binders [27].

The thermal performance of the panels was evaluated by means of the experimental apparatus called Small Hot Box; the acoustic performance was tested by means of an impedance tube. A specific life cycle assessment analysis was performed, in order to

evaluate the environmental impact of the panels with respect to other traditional and innovative solutions.

Nowadays, this research is important for the scientific world, in a circular economy perspective. The recycling process of the industrial wastes is a primary decisive action that will allow the reduction in the wastes volume. At the same time it will make available secondary raw materials, avoiding the extraction of new resources, and reducing the environmental impact.

## 2. Materials and Methods

### 2.1. Raw Materials

Multiple high quality wood waste, deriving from the different processing phases, was collected in the FAIL Società Cooperativa (Marsciano, Italy) [28], partner of the project ReScaLe—FiAer (Figure 1). This Umbrian window manufacturer provided scraps from the manufacture of window frames, different both for tree species (pine, oak, and mahogany) and for size (pieces of wood, mixed coarse chips, and mixed fine chips). The three species of wood most used by the producer were selected and in particular: pine (*Pinus sylvestris* L.), oak (*Quercus petraea*), and *Swietenia macrophylla*, commonly known as mahogany. All the species mentioned above come from the forests of the Appenini mountains, that are not so far from the producer industry (about 90 km), and from Alpi mountains, quite distant (about 600 km). Both these extensive forest areas are very precious for the supply of wood in the center of Italy.



Figure 1. Wood waste samples.

The main properties of the raw materials were measured at University of Perugia Biomass Research Centre (CRB) [29] by means of thermogravimetric and thermal stability analyses (LECO TGA-701 apparatus, [30–32]), carbon, hydrogen, and nitrogen contents (LECO Truspec CHN elementary analyzer, [29,33]), and the higher heating value (calorimeter LECO AC 350 [29,34–36]).

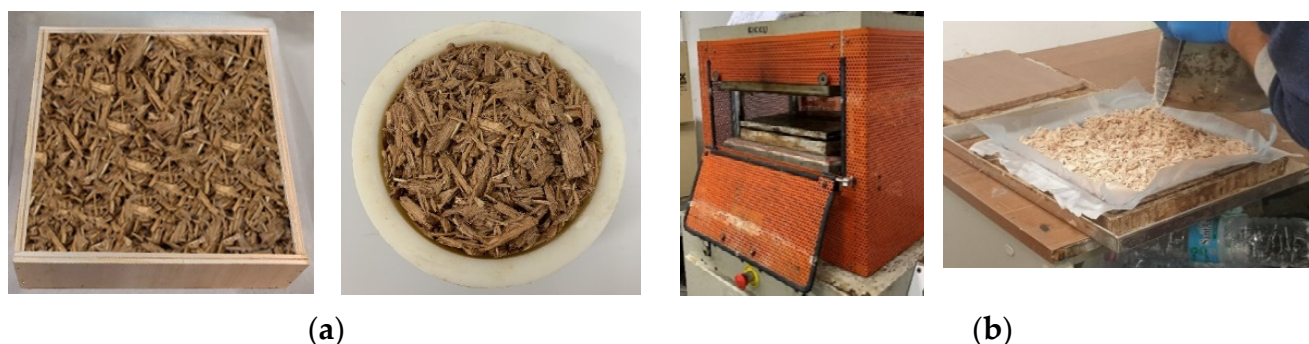
### 2.2. Fabrication of Eco-Sustainable Panels

Wood pieces were chipped by means of a hammer chipping machine (model TRITO 25/66, ISVE, Italy) available at the Biomass Research Centre—University of Perugia, with a 30-mm sieve, in order to obtain a homogeneous size of the shavings. In addition to the polyvinylacetate (PVA) glue, easily available and characterized by low cost and degree of toxicity, flour glue (mixture of flour and water) was prepared in laboratory, in order to fabricate the samples reducing the environmental impact.

Several preliminary tests were performed for identifying the optimal mixtures allowing to obtain panels with good mechanical and compactness properties, but with the minimum amount of glue [36]. The panels were assembled by hand at room temperature (Figure 2a) for each tree species (pine, oak, and mahogany—acronym abbreviation *P*, *O*, and *M*, respectively):



- With vinyl glue (acronym *Vin*), 50% wood, 25% vinyl glue, and 25% water;
- With flour glue (acronym *Flo*), 40% wood and 60% flour glue and water.



**Figure 2.** Assembling of the panels by hand (a) and hot press device (b).

Different shapes and sizes molds were used, in order to fabricate square ( $300 \times 300 \text{ mm}^2$  dimensions) and cylindrical (100-mm diameter) samples for thermal and acoustic characterization, respectively. Moreover, pine wood, which accounts for about 70% of the total production of the company, was mixed also with olive wood from the pruned branches, very present in the Umbrian territory, for fabricating samples with 10% of olive wood waste and 90% of pine, hand-assembled both with vinyl and natural glue. These samples were appointed *P+OL*, in order to highlight the presence of olives scraps.

Other two pine wood panels (with both vinyl and natural glues) were assembled by means of a hot press available at the Science and Materials Technology Laboratory—Department of Civil and Environmental Engineering—Terni (Figure 2b). The mixtures (50% pine, 25% vinyl glue, and 25% water for sample with vinyl glue, and 40% pine and 60% flour glue and water for panel with natural one) were stirred making helical movements, by means of an universal lab mixing device for about 60 s. A no-release peel play tissue was used in the walls of the hot press mold, in order to facilitate the removal of the samples after drying. The closed mold was inserted into the press and subjected to the following cycles:








- Sample with vinyl glue: pressure equal to 2 MPa for 25 min, then increased to 12 MPa for 55 min, and a temperature of  $130^\circ\text{C}$  (total time 80 min);
- Sample with flour glue: pressure equal to 2 MPa for 30 min, then increased to 12 MPa for 70 min, and a temperature of  $100^\circ\text{C}$  (total time 100 min). The lower temperature was set due to a faster mass loss of the flour glue when compared to the vinyl one.

In order to distinguish the pressed panels, they were appointed with the acronym *press* in the name. Two samples for each type were fabricated for thermal measurement. The main characteristics of the samples are resumed in Table 1.

The panels fabricated with the press were 0.9-cm thick; 5 samples for each glue type were assembled, with a very thin layer of glue (vinyl or natural), in order to obtain two final samples with a suitable thickness for the thermal tests of 4.5 cm.

For the acoustic characterization, samples with two different thicknesses (25-mm and 50-mm) were fabricated; in particular, three samples for every kind were prepared, as suggested by the standards. The thicknesses were incorporated in the acronym, in order to easily identify them. Failing to use a cylindrical mold by means of the hot press, two 10-cm diameter samples (45-mm thick) were cut out of the panels using a cylindrical hole saw, after performing the thermal tests. In this case, number 45 was inserted in the acronym for the thickness, as you can see in Table 1.

**Table 1.** Main features of the samples for thermal and acoustic measurements.

Fabrication	Wood	Adhesive	Acronym	Thickness [m]	Picture	
thermal characterization (300 × 300 mm <sup>2</sup> )						
hand-assembly	pine	vinyl	P_Vin	0.040	 	
		flour	P_Flo	0.035		
	oak	vinyl	O_Vin	0.034		
		flour	O_Flo	0.036		
	mahogany	vinyl	M_Vin	0.040		
		flour	M_Flo	0.045		
	pine + olive	vinyl	P+OL_Vin	0.038		
		flour	P+OL_Flo	0.042		
hot press	pine	vinyl	P_Vin-pres	0.045		
		flour	P_Flo-pres			
acoustic characterization (100-mm diameter)						
hand-assembly	pine	vinyl	P_Vin_25	0.025	 	
			P_Vin_50	0.050		
		flour	P_Flo_25	0.025		
			P_Flo_50	0.050		
	oak	vinyl	O_Vin_25	0.025		
			O_Vin_50	0.050		
		flour	O_Flo_25	0.025		
			O_Flo_50	0.050		
	mahogany	vinyl	M_Vin_25	0.025		
			M_Vin_50	0.050		
		flour	M_Flo_25	0.025		
			M_Flo_50	0.050		
hot press	pine	vinyl	P+OL_Vin_25	0.025	  	
			P+OL_Vin_50	0.050		
		flour	P+OL_Flo_25	0.025		
			P+OL_Flo_50	0.050		
		vinyl	P_Vin-pres_45	0.045		
			P_Flo-pres_45			

### 2.3. Thermal and Acoustic Characterization

The panels were characterized both in terms of thermal and acoustic performance. Thermal properties were evaluated with a Small Hot Box apparatus [37]. It is composed of one box (external dimensions  $0.94 \times 0.94 \times 0.50$  m) which represents the hot chamber. The envelopes are made of very thick insulation material (20 cm of foam polyurethane + 2 cm of wood), in order to minimize the thermal losses and the heat flux through the walls. The thermal conductivity  $\lambda$  of the expanded polyurethane is  $0.0245 \text{ W/m K}$  and the thermal transmittance of the walls is  $0.114 \text{ W/m}^2 \text{ K}$ . The second part of the experimental system is the closure side of the box (dimensions  $0.94 \times 0.94 \times 0.20$  m thick). It is a sandwich wall composed of two panels of wood (2 cm each one) with a central layer of expanded polyurethane (20 cm). The sample ( $0.3 \times 0.3 \text{ m}^2$ ) is installed in the central part of a sandwich insulated panel, which is tightened to the hot side. Each test was performed with the heat flow meter method for a duration of about 2 h. Stationary conditions of temperature (hot and cold sides) and of the thermal flux were maintained during the test. The measurements of thermal flux and surface temperatures of the two sides of the sample (by means of thermal flux meter model HP01—Hukseflux and 4 thermo-resistances on each side, respectively) allow to calculate thermal conductivity. The average values of the temperatures of the four probes installed in each side of the sample and the mean thermal heat flux are used for the calculation of the thermal resistance  $R$  of the samples.  $R$  is the ratio of the difference of the surface temperatures ( $T_{sh}$  and  $T_{sc}$ , respectively, for the hot and cold sides) by the mean heat flux through the sample  $q$ . The value of the thermal

conductivity can be calculated from the mean value of the thermal resistance during the selected period (about 2–3 h) and the thickness of the specimen  $s$  (Equation (1)):

$$\lambda = \left[ \frac{s \cdot (T_{sh} - T_{sc})}{q} \right] \quad [\text{W/mK}] \quad (1)$$

For each test the relative uncertainties (type B) were calculated, in compliance with UNI CEI ENV 13005: 2000 [38]. The experimental data were measured at an average temperature of the sample in the 32 °C to 38 °C range, due to the operation conditions allowed by the test facility. In order to compare the panels performance to those of other wood-based ones available on the market or in the literature, the measured data were reported at a standard temperature of 10 °C in compliance with ISO 10456 [39], considering a temperature conversion coefficient of 0.0046 1/K suggested by the standard for wood panels.

The acoustic characterization was carried out by measuring sound absorption (normal incidence absorption coefficient) and sound insulation (Transmission loss, TL) properties in an impedance tube (Kundt's tube, Brüel & Kjær, model 4206; 1/4 inch microphones Brüel & Kjær, model 4187). The absorption coefficient values were measured using the two microphones configuration, according to ISO 10534-2 standard [40], as the absorbed part of the acoustical energy of a wave incident on the tested sample in a specific configuration with respect to the total incident energy (the no-absorbed part is reflected back to the source side). The reflection factor ( $r$ ) is given in Equation (2) and it can be obtained by measuring the transfer function between the two fixed microphone positions ( $H_{12}$ ), the transfer function for the incidence ( $H_I$ ) and the reflected ( $H_R$ ) wave, the wavenumbers ( $K_0$ ), and the distance between the top of the sample surface and microphone position  $x_1$ . The normal incidence absorption coefficient ( $\alpha$ ) was obtained as shown in Equation (3):

$$r = \left[ \frac{H_{12} - H_I}{H_R - H_{12}} \right] e^{(2ik_0x_1)} \quad (2)$$

$$\alpha = 1 - |r|^2 \quad (3)$$

Transmission loss values were evaluated as noise abatement measured with the four microphones configuration: two microphones are installed between the samples and the sound generator source and the other two on the back of the sample. It is related to the sound transmission coefficient ( $\tau$ ) as:

$$TL = 10 \cdot \log \left( \frac{1}{\tau} \right) \quad [\text{dB}] \quad (4)$$

#### 2.4. LCA Analysis: Methodology and Input Data

The environmental impact of the insulating panels was analyzed by means of life cycle assessment. In the present study, the panels made by pressing technique were considered in view of a large-scale production. The software used is SimaPro [41], developed on the basis of ISO 14040 and ISO 14044 standards [42,43]. In life cycle analysis it is important to follow the international standard ISO 14040-series [42], very useful for the goal and scope definition and for the inventory step. The program, according to ISO 14040, is structured in four steps, in which the aims and objectives are analyzed thanks to an inventory analysis, an impact analysis and an interpretation and improvement phase. In the first phase the system boundaries, study objectives, and functional unit are required to be defined. As concerning the life cycle inventory phase, data were directly collected at individual process level (primary data) from the manufacturing company, such as the consumption of the production process (energy, water, etc.) and the distances from the suppliers of the raw materials. Secondary data were derived from international databases (Ecoinvent) or calculated with suitable models (IPCC).

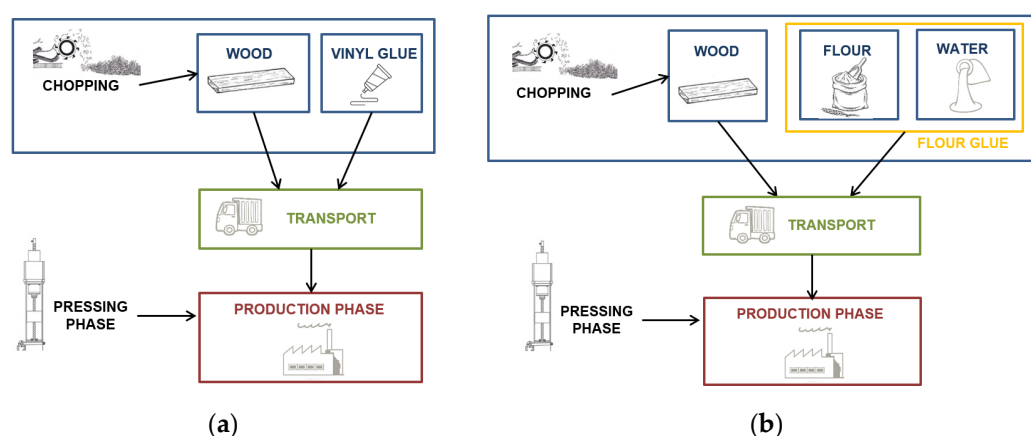
In this environmental study, only the pine wood panels assembled by hot press were considered because pine is the wood species most used in the company and because the hot press method is more similar when thinking at an industrial production process. Furthermore, including hot pressing, results in favor of security will be obtained. For the studied systems with wood, vinyl, and flour glue, the data related to the wood scraps were supplied by the manufacturers, whereas for the data of the glues they were assumed from the literature [41]. Once the inventory analysis is completed, the method of evaluating the impact of all is chosen and the calculation returns the unit of the process taken into consideration. The aim of the evaluation is the definition of the global warming potential (GWP 100 years) as environmental impact index associated with the panel production. GWP quantifies the carbon footprint, basing on a relative scale which compares the specific green house gas (GHG) emissions with an equivalent mass of CO<sub>2</sub>, whose GWP is defined equal to 1.

In order to evaluate the environmental behavior of the wood-based panel chain, 1 m<sup>2</sup> of manufactured panel was considered. An additional functional unit was also introduced, in order to assess the life cycle of the panel from a thermal point of view and to perform the comparison with other waste recycled panels. The mass (kg) of insulating panel that involves a thermal resistance  $R$  equal to 1 m<sup>2</sup>K/W, according to a proposal of the Council for European Producers of Materials for Construction [44], is defined as:

$$f.u. = R \times \lambda \times \rho \times A \quad [\text{kg}] \quad (5)$$

$R$  is the thermal resistance, equal to 1 (m<sup>2</sup> K/W);  $\lambda$  is the thermal conductivity of the panel in (W/m K);  $\rho$  is the density of the panel in kg/m<sup>3</sup>;  $A$  is the area, equal to 1 m<sup>2</sup>.

In defining the system boundaries, a “cradle to gate” approach was considered and energy, mass flows, and environmental impacts were assessed, from the wood-based residual to the manufactured end-product at company gate. In the specific case, the environmental impact assessment of the pressed pine wood panels with vinyl glue (P\_Vin-pres) and flour glue (P\_Flo-pres) is reported, following the flow diagrams in Figure 3.



**Figure 3.** LCA analysis: flow charts of the panels fabrication: wood-based panel with vinyl glue (a); wood-based panel with flour glue (b).

For wood, the impact is zero as it is completely recycled. The only impact is linked to the mill which is used to shred the pieces of wood up to the size considered suitable for the construction of the panel. The hammer shredder has a 3 cm screen, a power of 5.5 kW and an average production of 100 kg/h. The impact on the transport of raw materials is relevant only for vinyl glue (northern Italy); it is relatively lower for flour. For the panel fabrication a hot press was used, with consequent consumption of electricity but also of water. It has a consumption of about 13 kWh per 1 m<sup>2</sup> of panel. Finally, a euro 5 heavy vehicle (12–15 m/ton) was hypothesized for the transport of the materials and a distance



of 0 km for the wood (the raw materials are in the fabrication company) and about 20 km was hypnotized for the flour glue, considering the closeness to the fabrication company.

### 3. Results and Discussion

#### 3.1. Thermal Performance

From the preliminary thermogravimetric and thermal stability analyses, it was observed that no-relevant differences were found between the tree samples species and the obtained values are in compliance with different wood types literature data [35,36]. However, thermal stability curves allowed to set a limit temperature of 230 °C for hot pressing of the samples, a value beyond which the mass loss is up to about 30%.

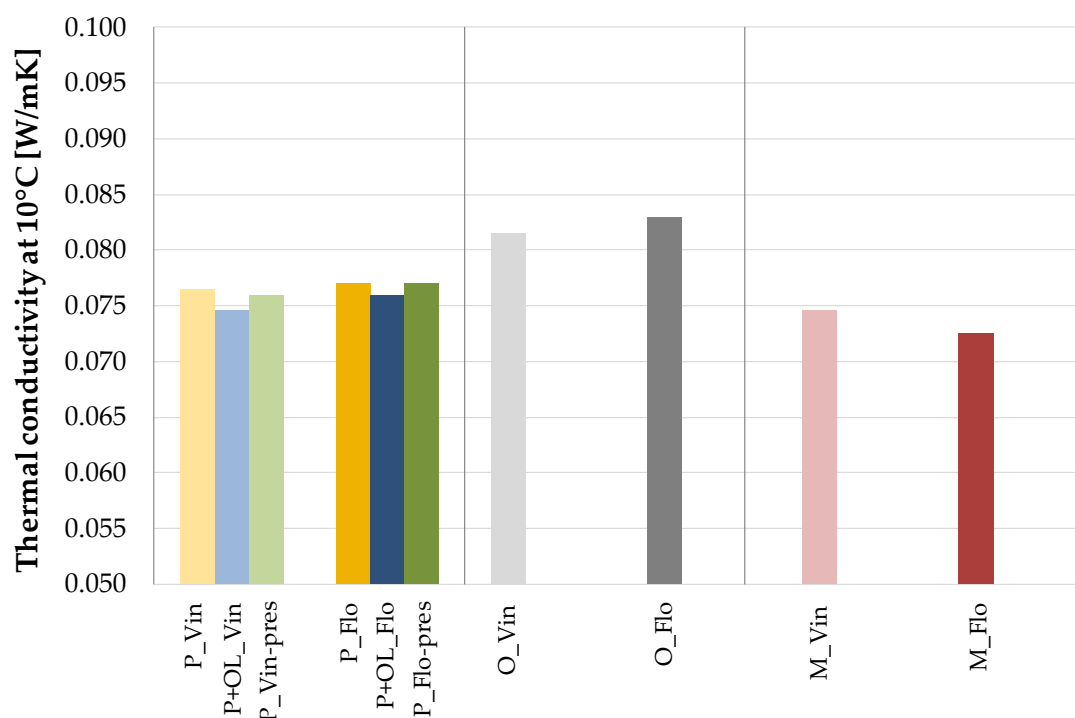
Hand-assembled square samples for thermal tests are characterized by not very constant thickness (0.034–0.045 m). Among the samples with vinyl glue, the oak one is characterized by the highest density (345.5 kg/m<sup>3</sup>), in compliance with the raw material value. This difference disappears when using natural glue, probably due to different boiling times and, therefore, thickening during the preparation of the flour glue. Adding olive wood to pine, the density increases with both adhesives.

Thermal performance of the panels is shown in Table 2. For each sample, two tests were carried out, by setting temperature values at 45 °C and 50 °C and keeping the air temperature difference between the hot (in the box) and cold (in the laboratory room) side of the sample at least equal to 20 °C. As expected, thermal conductivity value increases with set temperature. Thermal resistance values vary between 0.50 m<sup>2</sup>K/W (thermal conductivity  $\lambda$  equal to 0.080 W/mK) for the mahogany panel with vinyl glue and 0.39 m<sup>2</sup>K/W ( $\lambda = 0.920$  W/mK) for the oak one with flour glue, under the same test conditions (hot side temperature at 45 °C). In general, the densities of the samples with flour glue are higher than the ones of panels with vinyl glue. It can be observed that for higher densities, the thermal properties worsen; in fact, oak samples that have the highest densities seem to be the worst in terms of insulation. In addition, natural glue seems to slightly worsen thermal properties (+ 3.4% is the maximum thermal conductivity increase measured for the oak sample), despite the difference is not very significant, within the measurement error. No significant differences were found between thermal performance of samples assembled with adhesives of synthetic and natural origin, also in [27].

**Table 2.** Thermal properties of eco-sustainable panels (Small Hot Box—thermal flux meter method).

Sample	Density [kg/m <sup>3</sup> ]	Test [°C]	ΔT <sub>s</sub> [°C]	ΔT <sub>air</sub> [°C]	Φ <sub>med</sub> [W/m <sup>2</sup> ]	λ [W/mK]	<i>u</i> (λ) [%]	Standard Deviation [W/mK]
hand-assembly								
P_Vin (t = 40 mm)	282	45	19.87	23.19	35.71	0.085	13	±0.000
	282	50	20.55	28.48	43.87	0.085	14	
P_Flo (t = 35 mm)	325	45	15.80	23.43	38.60	0.086	4	±0.001
	325	50	18.89	27.57	47.04	0.087	4	
O_Vin (t = 34 mm)	345	45	18.66	25.29	48.98	0.089	18	±0.003
	345	50	22.38	30.02	61.09	0.093	19	
O_Flo (t = 36 mm)	333	45	12.93	23.57	32.95	0.092	21	±0.002
	333	50	15.52	24.38	41.10	0.095	23	
M_Vin (t = 40 mm)	282	45	18.94	24.64	30.06	0.080	10	±0.006
	282	50	18.43	25.16	40.34	0.088	12	
M_Flo (t = 45 mm)	345	45	12.83	23.03	23.41	0.082	8	±0.000
	345	50	16.92	22.73	30.87	0.082	9	
P+OL_Vin (t = 38 mm)	293	45	18.14	24.72	39.62	0.083	9	±0.001
	293	50	19.25	25.12	42.55	0.084	7	
P+OL_Flo (t = 42 mm)	340	45	20.03	23.15	40.54	0.085	8	±0.000
	340	50	19.85	25.08	40.17	0.085	7	
hot press assembly								
P_Vin-pres (t = 45 mm)	398	45	17.39	24.20	32.52	0.084	4	±0.001
	398	50	20.68	28.3	39.43	0.086	6	
P_Flo-pres (t = 45 mm)	405	45	16.21	23.9	30.62	0.085	3	±0.001
	405	50	20.12	27.8	38.90	0.087	5	

The addition of olive scraps leads to a slight improvement in thermal performance, with a reduction in thermal conductivity of about 2% with both adhesives (0.075–0.076 W/mK, Figure 4). This improvement is in line with data found in [8], where samples made of pure vine pruning were characterized by  $\lambda$  values in the 0.0642–0.0676 W/mK [8], lower than the ones found for the mixture investigated in the present paper, where pruning is only 10% by weight.



**Figure 4.** Thermal conductivity of the panels reported at 10 °C, according to ISO 10456 [39]: influence of different species and assembling techniques.

When reported at the standard temperature of 10 °C [40], the mahogany panel is characterized by the best thermal properties ( $\lambda$  equal to 0.075 and 0.073 W/mK for vinyl and flour glue, respectively), similar to the pine ones (around 0.076 W/mK regardless glue type and assembling mode). The thermal conductivity of the oak panel is slightly higher (0.082 and 0.084 W/mK), as shown in Figure 4. The results are in agreement with the performance of black locust, poplar, larch, spruce, Scots pine, and hot pressed black bark of *Robinia pseudoacacia* with formaldehyde panels ( $\lambda$ -values in the 0.061–0.077 W/mK range) studied by Pásztor et al. in [18,45] and measured by means of a hot plate method. The properties of eco-sustainable panels are also in line with the ones of some commercial products, such as the mineralized wood wool panels with cement ( $\lambda$  = 0.065 W/mK) [46].

Furthermore, the thermal properties are strongly affected by the density; glued chip-board panels (density of about 700 kg/m<sup>3</sup>) have a thermal conductivity of 0.16 W/mK, whereas much lower values (0.04–0.05 W/mK) are achieved with very light wood fiber panels (50 kg/m<sup>3</sup>) [47–49]. Loose material, consisting in short-cut woodchips from coniferous trees without bark and with low bulk density (110 and 205 kg/m<sup>3</sup>) showed lower values of the thermal conductivity (0.042 and 0.065 W/mK, respectively) when compared to the panels investigated in the present paper. The last have an average density of about 320 and 400 kg/m<sup>3</sup> for hand and hot pressing assembled samples, respectively. Similar results are obtained for wood fiber-based panels in [27] ( $\lambda$  in the 0.037 to 0.038 W/mK range with a density of about 150–200 kg/m<sup>3</sup>) and in [19] ( $\lambda$  equal to 0.041 W/mK with a density of 145 kg/m<sup>3</sup>).

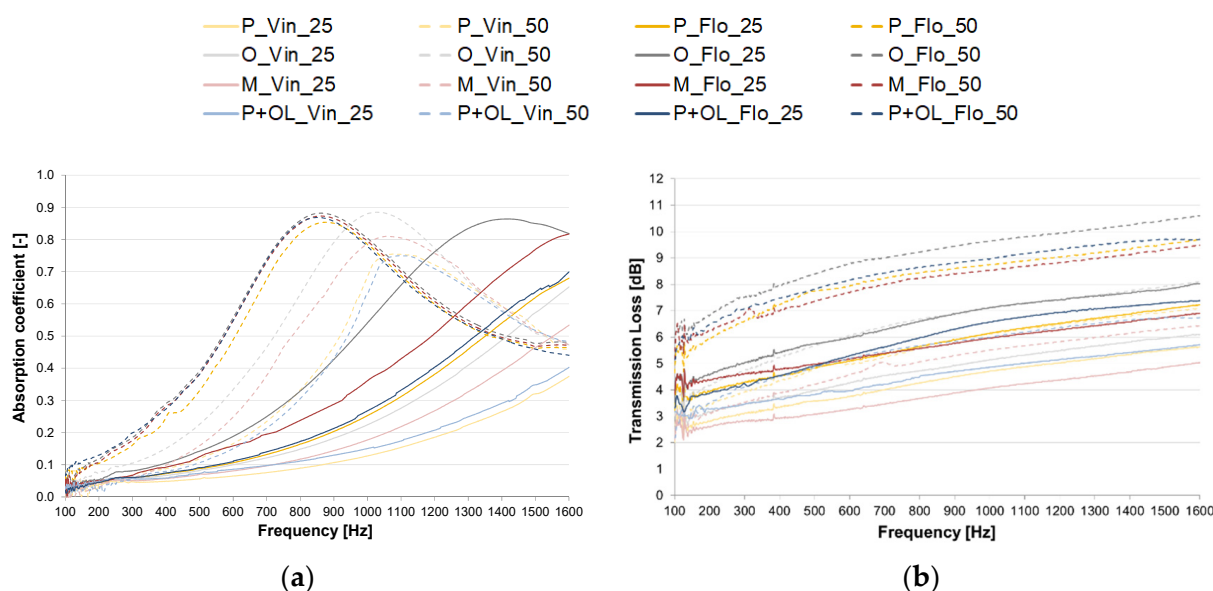
Despite their not excellent thermal performance, eco-sustainable wooden panels are anyway comparable to some standard thermal insulation materials available on the market, such as expanded vermiculite (0.077–0.082 W/mK).

Finally, for some tests, surface temperatures and heat flux through the samples were very steady, involving a relative uncertainty value in compliance with the measurement error of the apparatus (5–6%). However, very high values were obtained for some measurements; for oak samples the uncertainty of the test was up to 23%, probably due to a no-homogeneity of the material, by involving a difference of about 8–10 °C between top and bottom surface temperatures. The thermal properties of the hot pressed pine samples are comparable to manually assembled ones; thermal flux and surface temperatures are much more stable, resulting in lower relative uncertainty values (3–6% with respect to 4–14%).

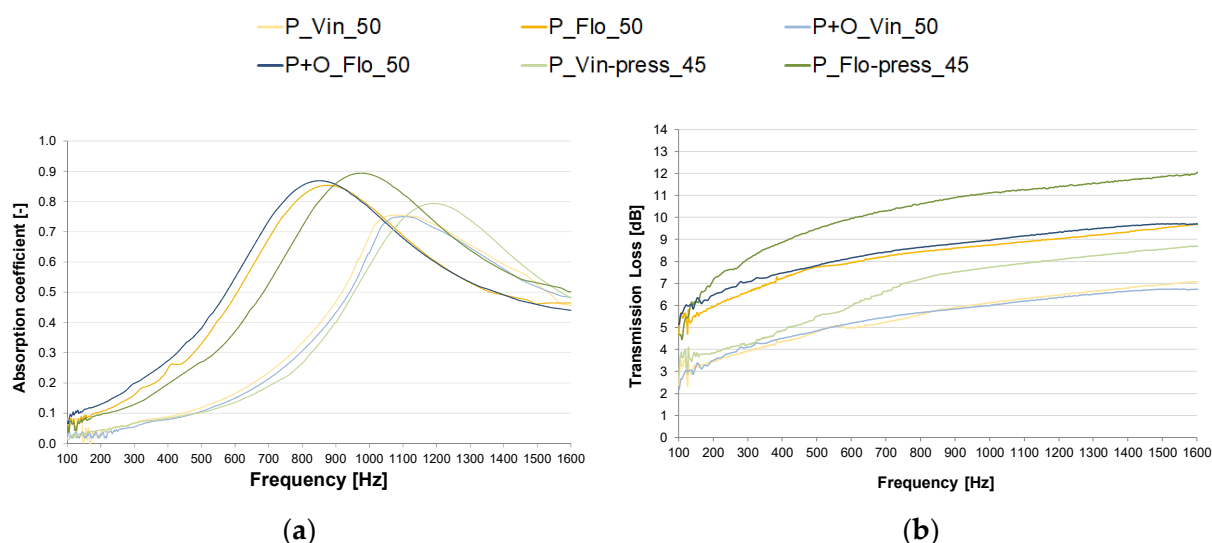
### 3.2. Acoustic Performance

The absorption coefficient  $\alpha$  and TL trends at normal incidence in the 100 to 1600 Hz frequency range of each hand-assembled sample are reported in Figure 5. In Figure 6, the influence of different assembly techniques on acoustic properties of pine panels are shown, with the same thickness. The first peak of the absorption curve increases with the thickness and it is moved to lower frequencies, due to the higher tortuosity of the more thick sample, in compliance with [49]. When considering the same thickness and glue, oak is characterized by the best absorption performance, with a peak value of about 0.90 (O\_Vin\_50) at about 1000 Hz and of about 0.85 (O\_Vin\_25) at about 1400 Hz (Figure 5a). A very high peak value of 0.98 at about 1600 Hz was found for an oak panel 19-mm thick also in [24]. Lower peak values were instead found in [25], for panels 19–21 mm thick, made of bark chips (larger size than the samples in the present paper, in the 8 to 30 mm range); the peak values vary between 0.40 and 0.60 in the 1000 to 2000 frequency range, depending on the chips species.

The absorption peaks are slightly higher and shift towards higher frequencies for pressed samples (Figure 6) and for samples assembled with flour glue.



**Figure 5.** Acoustic properties of hand-assembled panels: (a) sound absorption coefficient and (b) Transmission loss at normal incidence.



**Figure 6.** Influence of pressing technique on the acoustic performance of pine panels: (a) sound absorption coefficient and (b) Transmission loss at normal incidence.

In order to easily compare the acoustic properties of the panels, the sound absorption average (SAA) index (number rating of sound absorption properties at the twelve 1/3 octave bands from 200 Hz to 1600 Hz) 49 is calculated, according to [50] (Figure 7). At the same thickness, the flour glue improves the sound absorption performance, with a maximum increase for 25-mm oak panel (SAA equal to 0.26 with flour glue with respect to 0.13 with vinyl glue). No detail is specified about the sound absorption data in [27] and the influence of the glue (natural or synthetic) is not available; so a direct comparison is not possible for acoustic performance. The differences between wood species are less marked for the 50-mm thick samples, with both glue types (31% maximum difference instead of 38% for the 25-mm samples made of the same wood types). The lower density differences of 50-mm flour glue samples involve the same acoustic absorption properties, with a maximum difference of oak and mahogany of 8% with respect to pine. Adding waste from olive tree pruning results in a slight sound absorption improvement with both adhesives. Even the pressing does not involve great variations: SAA is reduced by a maximum of 5% compared to manually assembled pine panels (thickness 5 cm), despite the density of the samples is slightly higher and the thickness is smaller (4.5 cm). The absorption properties of the panels are better than the ones of a 30-mm mineralized wood fiber panel studied in [51] (maximum  $\alpha$ -value of 0.42 at 1600 Hz). In general, lower differences in terms of acoustic absorption behavior are observed for different wood types when considering the flour glued samples. Slightly higher differences are recorded in the vinyl-glued systems.

The oak samples (more dense) have the best transmission loss performance (Figures 5b and 6b). In general, the flour glue improves TL-values: the increase is limited in the 25-mm samples (about 1.5 dB), whereas it is about 2–3 dB in the 50-mm thick panels. The sound insulation properties of pine and mahogany with natural glue are similar (TL = 2.5–5.5 dB and TL = 4–7 dB for the 25-mm and 50-mm thick samples, respectively). Oak TL values are about 1.5–2.5 dB (25-mm) and 2–4 dB (50-mm) higher than pine and mahogany. Adding olive trees to the mixture results in a maximum increase of 0.5 dB in the 25-mm flour glue sample. On the contrary, pressing involves an increase in density and consequently in acoustic insulation performance; TL increases up to 2.5 dB in the panel with natural glue. It is also specified that the panels assembled by hot pressing have a lower thickness (4.5 cm) than the one of the samples manually assembled (5 cm).

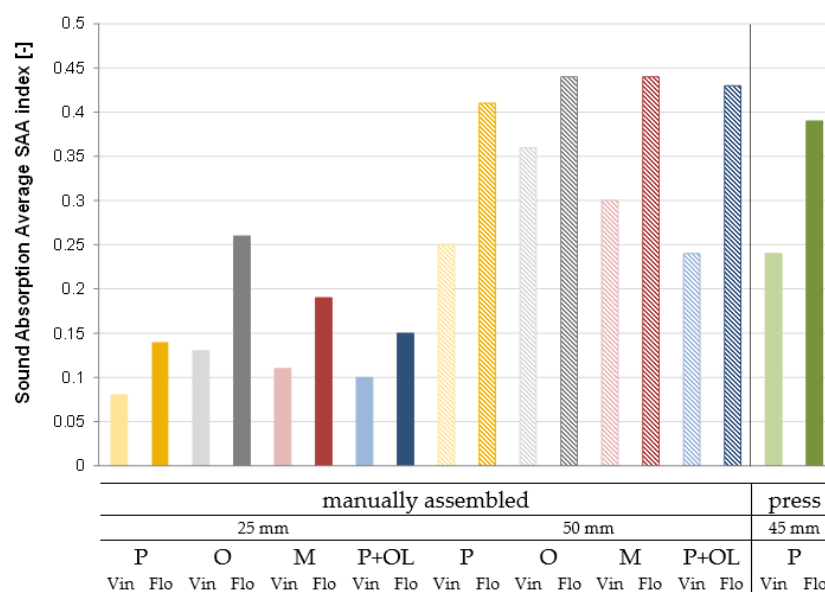


Figure 7. Sound absorption average (SAA) index of the investigated panels.

### 3.3. Life Cycle Analysis

The main results obtained for the examined panels are analyzed below, as specified in the previous paragraph: a functional unit equal to  $1 \text{ m}^2$  of panel surface and equal to a unit of thermal resistance ( $1 \text{ m}^2\text{K/W}$ ) were considered. In the first case, a standard thickness of 4.5 cm was assumed whereas in the second case, considering a unit of thermal resistance, the equivalent thickness able to guarantee this insulation is equal to 7.6 cm. The impact, evaluated in kg of equivalent  $\text{CO}_2$ , can be assessed for the different phases involved in the fabrication of the final panel. In particular, the contribution of glue, water, shredding phase of the wood that makes up the panel, hot press contribution, and impact of transport were considered. In Figure 8a,b, the comparison between the two solutions is represented. From the results in Figure 8a, it is possible to observe that the higher impact for the standard panel is represented by the vinyl glue and from the pressing phase (P\_Vin-pres). For the panel with flour glue (P\_Flo-pres), on the other hand, the main impact is given by the pressing step: a longer time is required in order to press the panel with the natural glue. Additionally, considering the second functional unit, the impact of the glue is not negligible, whereas the impact related to pressing is similar for the two types of panels, with a slightly higher value for the natural one.

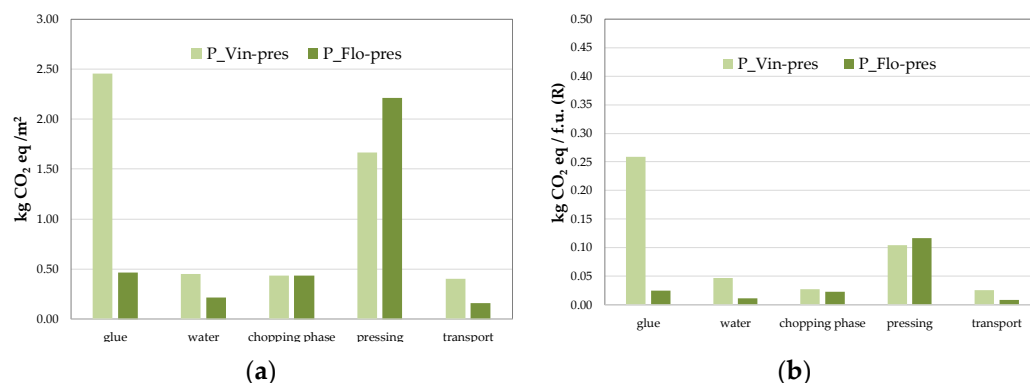


Figure 8. Global warming potential calculated for the different phases for both the panels (P\_Vin-pres and P\_Flo-pres): f.u. equal to  $1 \text{ m}^2$  (a); f.u. equal to  $R = 1 \text{ m}^2\text{K/W}$  (b).



For the panel with traditional glue, the overall GWP considering a time horizon of 100 years is equal to 5.4 kg of equivalent CO<sub>2</sub>, whereas 3.5 kg of equivalent CO<sub>2</sub> is obtained for the panel with flour glue. Considering the analysis based on the equivalent thermal performance of the panel, 0.46 and 0.185 kg of CO<sub>2</sub> are obtained, respectively. In order to compare the panels with other natural or synthetic solutions, it is possible to note an environmental impact quite low for the wooden panel, both with standard and flour glues (Table 3) [2,52]. Lower values are obtained for other similar panels with agricultural waste but the final environmental impact index is deeply influenced by the distances between the raw materials and the fabrication place (these distances are very low for coffee chaff and hempy-based panel, characterized by the lowest values of GWP). The highest values are that of panels composed of glass and wool fibers and expanded polystyrene (about 8–10 kg of CO<sub>2</sub> per m<sup>2</sup>).

**Table 3.** Comparison between the global warming potential of different insulating materials (in bold data from the present paper).

Materials	GWP (kg CO <sub>2eq</sub> Per m <sup>2</sup> )
Cellulose-based panel	0.73
Cork-based panel	5.72
Expanded Polystyrene	8.25
Panel with glass fibers	7.70
Panel with wool fibers	9.89
Hempy-based panel	0.17–0.26
Kenaf-based panel	1.13
Sheep wool	1.46
Rock wool	2.77
Wood wool	1.56
Rice Husk	1.10
Granulated rubber panel	3.60
Coffee chaff	0.58
Panel with glued waste paper	8.0–3.1
<b>Wood-based panel with vinyl glue (P_Vin-pres)</b>	<b>5.41</b>
<b>Wood-based panel with flour glue (P_Flo-pres)</b>	<b>3.49</b>

#### 4. Conclusions

This work, part of the ReScaLe—FiAer project, is focused on the reuse of pine, oak, and mahogany wood waste deriving from the production process of an Umbrian windows company, in order to fabricate insulating panels with vinyl and flour glues and manually and hot press assembling techniques. For the pressing of the samples, a temperature lower than 230 °C was fixed, in order to avoid a considerable weight loss of the material, according to the thermal stability curves. Square samples of 300 × 300 mm<sup>2</sup> (thickness in the 34 to 45 mm range) and cylindrical ones of 100-mm diameter (25-mm and 50-mm thicknesses for hand-made samples and 45-mm for press ones) were assembled for evaluating the thermal and acoustic properties, respectively. Further samples were manually assembled with the scraps of the olive tree pruning with both adhesives. The thermal characterization was carried out by means of Small Hot Box apparatus. Thermal conductivity values in the 0.071 to 0.084 W/mK range at an average surface temperature of 10 °C were obtained. The best performance is related to the mahogany samples, similar to pine ones, both with vinyl and flour glue. Pressing does not influence the thermal properties of the panels, whereas the thermal conductivity is reduced of about 2% when adding olive waste. Results are in agreement with the properties of similar commercial panels, with literature values, and are quite similar to the ones of other standard insulation materials, such as expanded vermiculite.

Furthermore, the samples are characterized by good sound absorption and insulation properties tested in the impedance tube. Oak panels, with lower densities, have the best performance, which improves with increasing thickness. An increasing in  $\alpha$ - and TL-values

is observed with flour glue (SAA equal to 0.44 for oak and mahogany 50-mm panels and  $TL = 11$  dB at 1600 Hz for oak 50-mm sample) when increasing the thickness of the samples, the differences due to the wood type are smaller in terms of sound absorption and insulation performance. The hot press allows to increase sound insulation performance up to 2.5 dB with natural glue.

In order to focus the attention on the future possibility of starting a production chain of wooden panels through the recovery of production waste, their environmental impact was studied by means of life cycle assessment. Higher impact is related to glue in the sample with vinyl adhesive, whereas the pressing phase has an almost equivalent effect in the two panels. The obtained global warming potential values are of the same magnitude of several insulating materials. Finally, the use of natural glue will be preferred in order to reduce the environmental impact of the panels, without affecting the thermal performance, and improving the acoustic one.

A possible development of the production process at industrial scale is the subject of future studies, together with companies interested in giving an added value to their wastes; we are also proposing new research projects in order to improve the studies in this sector. A good idea for strongly reduce the thermal conductivity could be to use them as core of vacuum insulation panels (VIPs), as proposed in [23].

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