Tilia sp.'s pruning residues wood panels for thermal insulation

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Highlights

- Thermal properties of panels made with *Tilia* sp.'s wood wool and polyvinyl acetate (PVA) glue were tested
- The first results show that these samples have thermal characteristics worthy of further study
- The valorization of pruning by-products could provide new resources to improve urban green care

7.1 Introduction

7.1.1 Street trees management issues: the case of exploiting pruning wastes

According to Butler and Spencer (2010), this is the Century of the City, and "The explosion in urban population looks set to continue through the twenty-first century, presenting challenges and opportunities for scientists." (Butler and Spencer, 2010, 901).

The World Health Organization (WHO) (2016, 149), while providing a scenario that backs up this concept, also states, "many cities lack sufficient trees and other types of vegetation that provide shade from the sun's rays and dissipate heat with evaporated water."

Therefore if this is the century of the city, it must also be the century of *nature* in the city, as well (Benedict and McMahon, 2006).

Urban nature is a crucial asset to allow for livable urban contexts (Gill et al., 2007; Newell et al., 2013; Demuzere et al., 2014; Norton et al., 2015). Among its various manifestations the arboreal component has a pivotal role (Rowntree and Nowak, 1991; Dwyer et al., 1992; Nowak et al., 1996a; Coder, 1996; Day and Dickinson, 2008; Lockhart, 2009; Gillner et al., 2015). Urban trees have a profound impact on various environmental compartments such as air, soil, and water and their respective cycles such as water cycling, thermal balances, and carbon sequestration

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(Lafortezza et al., 2009; Ennos, 2012; Fazio, 2012; Pataki et al., 2011; Zheng et al., 2016; Gage and Cooper, 2017).

Based on the research of Nowak et al. (1996b) an important tool, *I-Tree* (http://www.itreetools.org/streets/index.php, last access June 14, 2019), has been developed to understand and divulge the benefit of trees (Morani et al., 2014; Hilde and Paterson, 2014). Utilizing the tool named *Street* in I-Tree, Casey Trees and Davey Tree Expert Co. have developed the National Tree Benefit Calculation web tool (http://www.treebenefits.com/calculator/ last access June 14, 2019), to link to each tree, known as the specie, the location, and the diameter of the trunk, a monetary value in terms of benefits supplied by the tree itself.

Moreover, various research projects have demonstrated the positive impact of urban trees on PM10 removal, up to 92 g of PM10 per year/per tree (City Of Portland, 2010, 3−6, 3−7).

It is essential to underline that the trees can supply such great extent of benefit only if they are "vital and unaffected by pests and diseases" (Sjöman et al., 2012, p. 31).

Relatively recently, the relationships between trees' health and decay drivers have been subject to numerous studies (Dujesiefken et al., 2005; Dujesiefken and Liese, 2015) which led to a revised understanding of CODIT (Compartmentalization Of Decay In Trees; Shigo, 1984), that now emphasize more damage rather than decay (Dujesiefken et al., 2016).

A significant amount of the damage suffered by urban trees can be brought back to managing practices, in particular, pruning.

Since trees can have undesired interactions with urban assets, for example, power lines, and can sometimes present risks for public safety, pruning is an indispensable practice in urban contexts (Dujesiefken and Horst Stobbe, 2002; Smiley and Kane, 2006; Fini et al., 2015). Alex Shigo stated, "[pruning can either be] the best thing an arborist can do for a tree but at the same time, one of the worse things an arborist can do to a tree; much depends on how pruning is carried out" (Shigo, 1989). This statement has received support from newer research (Fini et al., 2015).

All this considered, it would be advisable for municipalities to take in serious consideration the need to qualify its personnel and to provide managing prescriptions for public and private contractors in charge of urban trees' management, such as the National tree safety Group guidance of 2011 [National Tree Safety Group (NTSG), 2011]. On the contrary, we are still witnessing the lack of this kind of attention in favor of short-term economic consideration by many Municipal authorities (Maurin and Desrochers, 2013; Fini et al., 2015), with a worrying trend leaning toward tree-removal programs (Rotherham and Flinders, 2019).

In this scenario, is not surprising that, despite the evidence of negative physiological outcome of such technique (Fini et al., 2015), topping trees is still considered a viable option and a lot of tree owners still consider it a fast and cheap way to obtain the wanted results (Campanella et al., 2009).

Campanella et al. (2009) have also demonstrated that such approach is not even economically sound in the medium term (30 years), since "topping is 1.4 fold more costly than selective thinning" (p. 49). So short-term gains should be compared accurately to medium/long-term considerations. To change this situation is far from being a simple task, and it will need the occurrence of a cultural transformation in the relationship between citizens, and therefore public administrations, and urban trees.

On the research side of the matter, it is pivotal to single out opportunities for obtaining economic benefit out of proper trees' maintenance in the short term.

An interesting opportunity regards the biomaterials of plant origin. They are becoming more appreciated by global markets longing for sustainability, and circular processes play an important role in this regard.

Industrial wastes or dedicated crops originate most of the biomaterials used in constructions. In the current scientific literature, there is a vast array of works devoted to the exploitation of organic waste (Six et al., 2016; Jimenez et al., 2017; Du et al., 2018) but still lacks thoughtful investigations for what concerns pruning residues originated by urban trees. In fact, pruning residues' valorization has been mainly considered for nonornamental plants such as vines (*Vitis* L.) and olive trees (*Olea europaea* L.) (Vecino et al., 2017; Jesus et al., 2017; Pérez et al., 2018). Just in the 48 neighboring states of the United States, the assessment carried out by the US Forest services (Dwyer et al., 1992) showed the magnitude of the usable urban pruning residues with 3.8 billion trees, covering 27.1% of the total urban areas (Konijnendijk, 2003).

7.1.2 *Why* Tilia *sp.?*

To have a healthy and sustainable urban tree population a high diversity of species and genera is needed (Sjöman et al., 2012). Despite this consideration, there is less biodiversity than expected in urban forestry (Blasi et al., 2005; Conti et al., 2005). Some genera are more represented in urban trees in particular *Acer* sp. and *Tilia* sp., as shown in a recent study on 328 cities (Moser et al., 2015; Yang et al., 2015). They are also the more common two genera in 10 Nordic cities (Fini et al., 2009; Terho, 2009; Sjöman et al., 2012).

In cities and parks of Western, Nordic, and Central Europe, out of 40 genera and 350 species of the Tiliaceae family, the linden trees are represented by a single genus (*Tilia*) with three species: *Tilia cordata* Mill., *T. tomentosa* Moench. (the most drought tolerant), and *T. platyphyllos* Scop. (the most water demanding) (Ţenche-Constantinescu et al., 2015). *T. cordata* Mill. is the most recurrent among urban deciduous trees (Radoglou et al., 2009; Stravinskiene et al., 2005). *Tilia* sp. are trees with a great traditional, historical, and cultural importance in many countries in Europe, where they are widely distributed (Pigott, 1991; Massetti et al., 2015; Ţenche-Constantinescu et al., 2015), despite their pollen being allergenic (Mur et al., 2001). The linden tree holds a particular importance in European culture being the sacred tree of Aphrodite in Greek mythology or the sacred tree of the fertility goddess Freia in German and Northern mythology, a sacred tree in Slavic mythology (Blench and Spriggs, 1999), a national symbol in Slovakia, Slovenia, and the Czech Republic (Snoj, 2009).

Generally, although linden trees are widespread in urban contexts, in many countries, reliable data on their actual presence and distribution on the national territories are not available.

Linden trees are commonly used for their robustness in term of resistance to biotic and abiotic stresses (Ţenche-Constantinescu et al., 2015), and their leaves have shown significant seasonal accumulation not only for Pb but also for Cr, Fe, Ni, Zn, and Mn (Bargagli, 1998; Piczak et al., 2003; Aničić et al., 2011). Recently, the COST Action E42, called valuable broad-leaved trees in Europe (Hemery et al., 2008), highlighted, between various aspects, the various traditional use of linden by-products (Pennati and Ferrini, 2008) ranging from gun powder to artist's charcoal and from animals feeding to preparation for calming infusions.

Between these uses, there is not the insulation of buildings envelope.

7.2 Composite materials—wood fibers and binders

Panels made out of wood fibers are a very heterogeneous cluster of materials depending on their characteristics, mainly linked to the tree species from which they originated, the process that generated the residues, and the production process of the panel themselves.

Nevertheless, they usually represent a viable solution to obtain low-cost insulation materials, that allow for an increasing of the energy efficiency of buildings, acting as a passive solution to the issues of heat losses and gains (Al-Ragom, 2003; Menconi and Grohmann, 2014; Menconi et al., 2017; Sevindir et al., 2017).

As thoroughly investigated in this book, and a vast scientific literature, bio-based insulation materials (e.g., sheep's wool, wood chips, seaweed, hemp fibers, reed, and wood wool) are very promising, and each of them present peculiar and interesting capabilities (Asdrubali et al., 2015; Kumar et al., 2016; Grubeša et al., 2018; Dénes et al., 2019).

Indeed, bio-based materials are gathering more and more interest also for reasons that go beyond their intrinsic characteristics as structural and nonstructural construction materials (Romano et al., 2019). Low primary energy consumption, lower disposal expenses, and efficient use of natural resources are some of the many themes addressed. Bio-based materials are usually produced from secondary raw materials, and they are generally more environmentally friendly than fossil fuel-based materials (Aditya et al., 2017; Cetiner and Shea, 2018; Gounni et al., 2019; Romano et al., 2019), especially considering potential negative effect on human health of some of the inorganic materials (Pacheco-Torgal et al., 2012).

Despite the benefits and the general interest in emissions reduction by National governments, there are still significant voids in European legislation surrounding embodied energy that prevents from exposing the full potential of bio-based materials in this regard (Scarlat et al., 2015).

Bio-based materials generally provide significant resistance to disrupting processes and factors such as moisture and fire. It must be noted, though, that even if bio-based materials have a lower embodied energy (Asdrubali et al., 2015; Menconi et al., 2017; Liu et al., 2017) and can have a potential negative carbon footprint (Cetiner and Shea, 2018), their inorganic counterpart are often more efficient from a thermal insulation standpoint (Menconi and Grohmann, 2014; Rocchi et al., 2018).

Even if it is not the most performant of the bio-based materials, wood continues to be a popular one, with a long history of usage in various forms, usually in sandwich panels (Kawasaki and Kawai, 2006), or in mixture with a binding material (Taoukil et al., 2012). The most common binders are PVA glue, Portland cement (mineralized wood panels), or polyurethane resins, to augment the structural resistance of the panels or to enhance their resistance to fire, moisture, and mold.

There is also experience of using wood wool without any binder (Cetiner and Shea, 2018). This choice, apart from the production cost reduction, may also have positive effects on the thermal performance of the materials since there has been evidence that the more fibrous materials have more potential air pockets, which would give an inherently lower thermal conductivity value (Romano et al., 2019). Indeed, the use of binders tend to lower the air content of the material, but composite materials (wood fibers + binders) have many advantages in terms of handling and usability.

7.3 Case study

7.3.1 Source material and preparation of the tiles

This case study entails the production of three different types of tiles using linden (*Tilia* sp.) tree's pruning waste as source material obtained in two different periods (late Summer and early Autumn) in a city of Central Italy (Perugia).

We produced the first sample using the swarfs obtained shredding linden's suckers cut at the end of August. We then produced the other two tiles shredding of the residues of a proper pruning process. The pruning was carried out in early October, after the fall of the leaves, to obtain more homogenous samples, with lower water content.

The density of the last two tiles differs depending on the pressure exerted during the production of the sample; this also affects their water content.

Fig. 7.1 Process' steps representation.

The shredding was carried out using a bioshredder with 18 blades, 70 cm max diameter, 2–4 mc/h (Fig. 7.2), Green Technik BC100 allowing to obtain wood wool.

The wood wool dried at ambient temperature for 3 weeks in a greenhouse

The shredded wood is a heterogeneous material (Fig. 7.3); therefore it can be difficult to characterize it. For the preparation of the samples, we sorted the material to select the more filiform elements, removing the more cumbersome parts (Fig. 7.4)

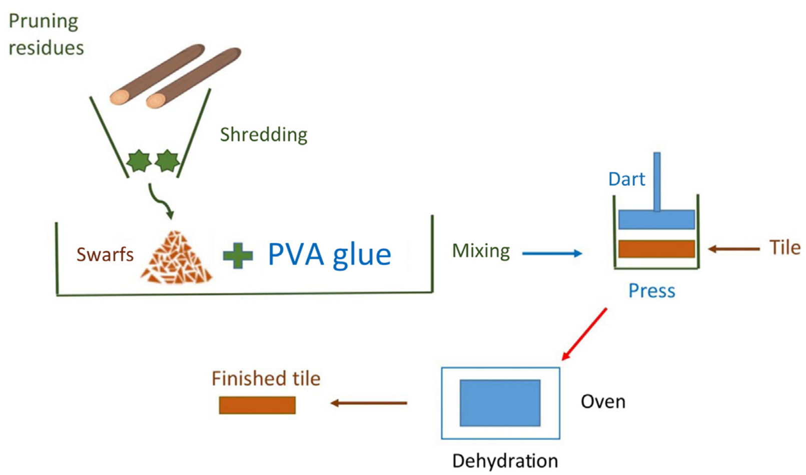

Figure 7.1 Process' steps representation.

Figure 7.2 Green Technik bioshredder.

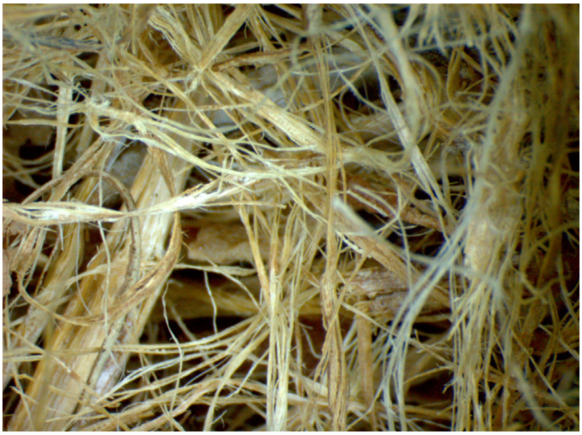

Figure 7.3 Linden tree's wood wool.

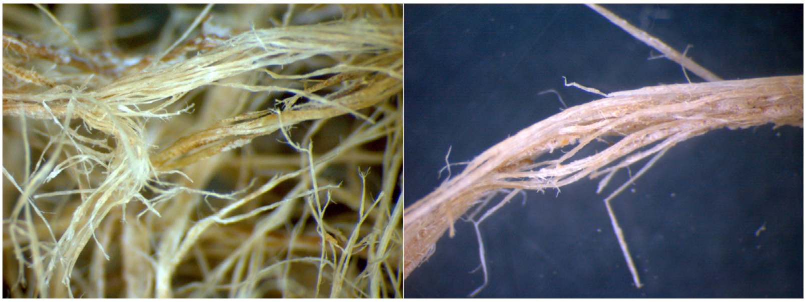

Figure 7.4 Wood wool fibers (optical microscope).

Table 7.1 Linden's wood wool characteristics.

Fibers dimensions	Length: 5–7 cm Width: 1 mm Thickness: 0.2 mm
Humidity	$(6.09 \pm 0.15)\%$

The measures of the shreds are the following: a length of between 5 and 7 cm, a width of around 1 mm, and a thickness of around 0.20 mm.

We calculated the humidity of the shreds, $(6.09 \pm 0.15)\%$, by drying the material in a natural ventilation oven at a temperature of 50°C for 24 hours.

The material characteristics are summarized in Table 7.1.

The idea was to obtain a composite material starting from this raw source, that could be used to produce self-sustainable panels, for easier usage and management, rather than the loose material.

Then we added PVA glue as a binder, for inexpensiveness and reliability, and also because it is a material vastly use in this regard.

A mixture of water and PVA glue was prepared in advance in both cases, with a glue percentage of 7.5 of the water's weight. The weight of the water was determined as equal to that of the wood wool.

The shreds were mixed manually with the combination of water and PVA glue and then pressed.

The tool used for pressing is composed of a PVC base with holes drilled on the base, through which pass 15 mm diameter rods. To shape the tiles and to confine the material, we used an aluminum mold. A cylindrical dart is then pushed by a threaded bar (clamp bar) to compress the material. This operation is carried out after the PVC cover is tightened on the aluminum profile using the nuts. The pressure on the dart and then on the material is produced by rotating the threaded bar (Fig. 7.5)

Regarding the composition of the different samples, the weight of water was equal to the wooden shreds, PVA glue represented about 7.5% by weight of the water.

The PVA glue was sufficient to provide a workable geometry to the tiles and adequate morphological stability of the samples. Nevertheless, it is unlikely that the binder was uniformly distributed in the mixture, and it was not possible to determine the amount of binder left in the final tiles since a small part of the liquid solution was squeezed out during tightening.

The samples were then dried in the laboratory at a temperature of 60°C for about 24 hours.

All three samples have a thickness of 30 mm and a density close to 300 kg/m^3. The pressure exerted by the dynamometric wrench was equal to 7 N m (c. 4.3 bar),

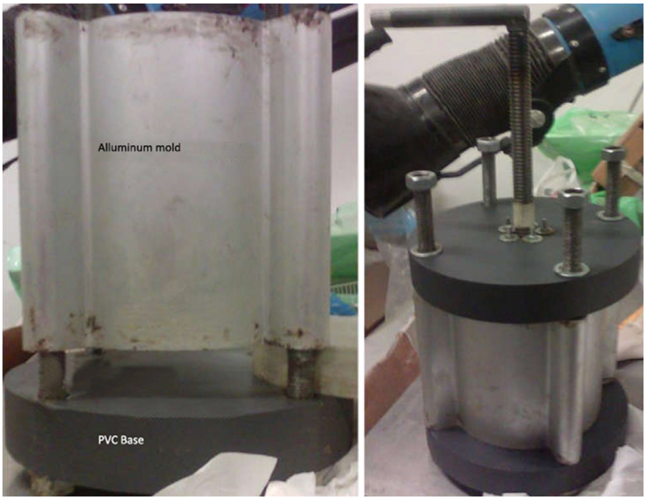

Figure 7.5 Pressing tool.

in order not to lose too much binder during the pressing phase. Still, the overall density of the three samples (333, 202, 260 kg/m^3) is decisively excessive for commercial use of the product. However, this consideration implies that the final results are to be considered an underestimation of the real capabilities of the materials, since, as it was recalled in the introduction, more potential air pockets would give an inherently lower thermal conductivity value (Romano et al., 2019), than the one presented by a denser material.

Each tile remained in the mold for 4 days, after the evacuation of all the excess water, and then transferred in the oven with the entire frame, for 48 hours at a temperature of 65°C.

The tiles were then cooled to room temperature, contained in a sealed transparent plastic bag, to check for the presence of residual moisture.

Afterward, the tiles were measured and weighed to calculate their density. The diameter of each sample is 160 mm.

A membrane probe was used to measure the thermal conductivity and specific heat of each tile. The probe was placed on the surface of each sample. The used instrument is a heat transfer analyzer by ISOMET, model 2104.

Measuring principle and accuracy are the following:

- Measuring principle: The device, through the probe, set up a temperature ramp, to produce a given ΔT. On the base of the energy spent to reach the mentioned ΔT, the instrument calculates the thermal conductivity of the material (k).
- Accuracy: ± 0.001 W/m/K, in terms of conductivity, and 1×10^3 J/m^3/K in terms of volumetric heat capacity.

Each sample was tested four times (two for each flat side).

7.3.2 EnergyPlus simulations

The composite materials obtained in the previous phase were tested using a thermal simulation carried out on a reference-building model that reproduces a typical rural house in Central Italy (Fig. 7.6).

This reference-building model was constructed, starting from an extensive literature search on the subject (Niccoli, 1902; Bonasera et al., 1955; Torregiani and Tassinari, 2003). The results of the analysis were validated through the analysis of the 860 CCs surveyed by the scattered rural building census of the Municipality of Perugia (Menconi et al., 2017).

Starting from the characterization of the typical rural house in Central Italy, we built a 3D model of the building with the following characteristics.

Exterior walls are made of traditional stonewalls of considerable thickness; the whole structure is held together by the mortar of lime and sand. The load-bearing walls have a thickness of 40 cm on the first floor and 55 cm on the ground floor. Solid bricks of 15 cm in length make the interior nonload bearing walls. Both external and internal walls are coated with a plaster layer of 2 cm, only on the inside face for the external walls and on both sides for internal walls. A concrete layer topped with ceramic tiles (Niccoli, 1902) forms the ground floor slab. The first

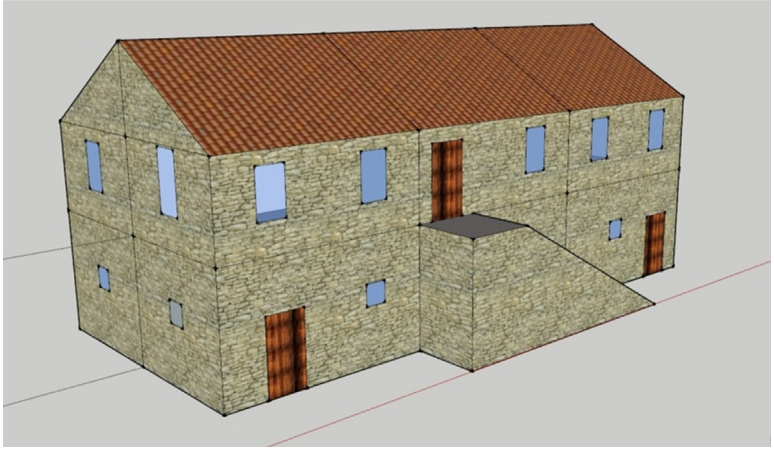

Figure 7.6 Reference-building reproducing a typical rural hose in Central Italy (*casa colonica*).

floor consists of a wooden truss on which rests a layer of bricks, one of loose material (sand and gravel) and another one of bricks. The roof is made of tiles, which are positioned on a wooden truss. Both external and internal doors are made of wood and have a thickness, respectively, of 5 and 2 cm. The windows are not colored single glazing.

We carried out the thermal simulation using the software EnergyPlus.

EnergyPlus is a staple tool in the industry, is freely downloadable, and is one of the complete tools available for dynamic simulation of thermal performances (Crawley et al., 2019).

We ran a yearly cycle to test the performances of the materials in both the warm and cold seasons. During autumn and winter, the house is heated when the internal temperature falls below 22°C, and during spring and summer, the house is cooled when the internal temperature rises above the 27°C using an ideal heating, ventilation and air conditioning (HVAC) system (Menconi et al., 2017). These simplistic HVAC operating rules were justified by the fact that our aim was comparing the thermal performances of different insulation materials and not to optimize the energy saving for the building.

This step goal is to compare the composite materials' thermal performances against two commercial materials made of wood residues, from the timber industry (plywood and hard fiberboards), and against two made using the fibers of two vegetable crops, widely used for insulation purposes (hemp and kenaf).

The method adds the proposed insulation materials, one by one, to the roof starting from the building model with no insulation, and then performs the annual dynamic simulation of the energy consumption for heating and air-conditioning the building. The thickness of all the insulating layers is fixed at 15 cm, and the panels are placed on the internal surface of the roof. The method foresee the positioning of the insulation layer only on the internal side of the roof, because it is the most

Figure 7.7 The three different tiles.

influential component of the envelope of residential building for thermal performance (Menconi et al., 2017) and again because the aim is to test the different behaviors of the various material starting from the same starting conditions.

The three tested tiles are produced, starting from two different types of shredded wooden waste. The first sample (a) is obtained by shredding linden's suckers, cut at the end of August. The other two samples (b, c) are produced by shredding proper pruning of the tree with a diameter smaller than 2 cm, in early October. These two samples differ in term of density (202 and 260 kg/m^3) varying the pressing (Fig. 7.7).

Performing the methodological steps described in the previous paragraph, it was possible to obtain the 12 values of thermal conductivity (λ), specific heat (ρ) of the three samples. Table 7.2 represents the obtained results.

7.3.3 Discussion

For the comparison of the studied material with commercial ones, we selected two of the more popular wood fiberboards products on the market [$\lambda = 4 \times 10^{-2}$ W/(m K); density 130 kg/m^3], two materials produced with dedicated plant fibers (hemp and kenaf), and literature references (Schiavoni et al., 2016: thermal conductivity from 0.038 to 0.050 W/m K, density from 50 to 270 kg/m^3, specific heat from 1.9 to 2.1 kJ/kg K) (Table 7.3).

The tiles showed similar thermal conductivities (λ) between each other despite the density's difference (8,37 $\pm$ 0,76; 8,30 $\pm$ 0,54; 8,60 $\pm$ 1,40 $\times 10^{-2}$ W/m K). These values are comparable with the ones found in literature regarding this class material (mainly produced with wood residues from the timber industry). But it must be noted that the values are still lower than the ones of the more engineered material (Schiavoni et al., 2016) but are already higher than plywood.

The measurement of these values presents some difficulties that are strongly related to the consistency and homogeneity of the samples. This issue ties to the typology of the probes used for the measurement, for a mass of unbonded fibers and in the absence of a well-defined geometry. This problem can affect the measure that is significantly influenced by the homogeneity of the sample chosen rather than by its actual properties (Domínguez-Muñoz et al., 2009).

Table 7.2 Thermal characteristics of the tested tiles.

	Thermal conductivity (W/m K)	Density (kg/m^3)	Specific heat (J/kg K)	Volumetric heat capacity (10^5 J/m^3 K)	Thickness (mm)
Linden wool tile (a)	0.0837 ± 0.0076	333	721	2.40 ± 0.44	15
Linden wool tile (b)	0.0830 ± 0.0054	202	1119	2.26 ± 0.51	15
Linden wool tile (c)	0.0860 ± 0.0140	260	1077	2.80 ± 0.65	15

Table 7.3 Characteristics of the materials used for the comparison.

	Conductivity (W/m K)	Density (kg/m^3)	Specific heat (J/kg K)	Volumetric heat capacity (J/m^3 K)	Thickness (cm)
Hard fiberboard	0.04	130	2100	273,000	15
Plywood	0.12	540	1210	653,400	15
Kenaf fiber	0.037	50	2050	102,500	15
Hemp fiber	0.044	50	1700	85,000	15

This is a common issue while measuring the intrinsic conductivity of the material. The geometry of the sample will always affect its air content, hence its density and, therefore, its thermal conductivity. The production of the tiles also presented several complications, since the wood wool does not present a completely fibrous configuration.

In this research, we used a binder to overcome such homogeneity and measurability issues. The ratio is trying not to affect too much wood wool properties, with the use of the binder.

The thermal simulation results are summarized in Table 7.4 and Fig. 7.8.

The energy simulation results show that the use of 15 cm layer of Linden-based panels applied on the internal side of the roof of a traditional Central Italy rural building could result in an energy saving up to 55%, particularly for the heating seasons. It must be noted that these results refer to ideal simulated conditions.

Again, the aim of this work is not to research for absolute values but to compare Linden-based materials with commercial ones having set the same environmental conditions.

At this stage of the research, the results are still incomplete. There are various other attempts that we need to be taken to optimize all the steps of the process.

Table 7.4 EnergyPlus simulation results.

	Heating (GJ)	Cooling (GJ)	Total HVAC (GJ)	Energy savings (GJ)	Energy savings (%)
No insulation	100.68	18.06	118.74		
Hard fiberboard	39.05	6.27	45.32	73.42	62
Plywood	50.73	7.75	58.48	60.26	51
Kenaf fiber	38.54	6.28	44.82	73.92	62
Hemp fiber	39.84	6.48	46.32	72.42	61
Tilia_a	46.18	7.26	53.44	65.3	55
Tilia_b	46.05	7.25	53.3	65.44	55
Tilia_c	46.45	7.27	53.72	65.02	55

HVAC, Heating, ventilation and air conditioning system.

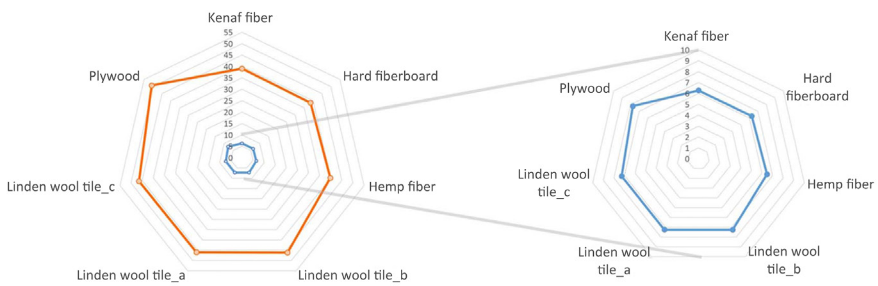

Figure 7.8 Heating and cooling consumptions.

Nevertheless, the first results look very promising, and the source material is worthy of further investigation.

Taking into account the density differences, the characterization of these first three materials is sufficiently close to the values of the commercial products to foresee a potential utilization of Linden-based products in the insulation materials' market.

The next step would be to test other bioshredders, with different specifics of power and blades configurations to produce a more refined material right from the shredding of the pruning residues. Other tests that would be required to carry out the optimization process would entail the combination of the wood wool with other binders, or even test its characteristics with no binders at all. This process could allow optimizing the physical attributes and, therefore, its thermal performances.

Noticing the presence of mold in sample (b) (Fig. 7.7), another optimization of the process should regard the definition of a more efficient dehydration protocol.

Then there are also some concerns regarding the general sustainability of PVA glue, as this is a material with significant embodied energy. The most intriguing action in this regard would be the use of linden wood own lignin as a binder.

This lignin could be obtained through the hydrolysis of the woody material itself (Schütt et al., 2011). We are willing to start experimenting using biological catalysts of microbiological origin.

7.4 Conclusion and future developments

This chapter showed the first contribution in testing the suitability of one particular material obtainable by the management of the urban forestry as a starting point to produce insulation panel for passive energy retrofitting of buildings. At the moment, only the thermal performance of such material has been evaluated. The results show that annual energy consumption for the conditioning of a residential building could be halved using panels obtained using this material. Benchmark values of commercial insulating material have significantly lower thermal conductivity values than the investigated one. This fact, apart from intrinsic differences between the various materials, is strongly dependent on the lack of an optimization step at this stage of the research. Therefore we can foresee compelling margins of improvement. From a sustainability standpoint, the wood wool obtaining from linden tree's pruning seems to be very promising, since it would represent the exploitation of waste material, while several commercial products use dedicated crops. Another area for future analysis is linked to the search for a more sustainable binder than PVA glue. Regarding this particular issue, an interesting strategy could be to obtain lignin dissolving non-lignin components of the source material (Glennie and McCarthy, 1962). Another interesting opportunity to investigate would entail using the wood wool as it is, without any binder.

Generally, the resulting characterization of the linden wool is close enough to the benchmark values to justify further analysis and experimentation for potential use in the insulation materials' market.

As a crucial positive trade-off, considering the urban forest as a source of raw materials for the production of nonstructural construction materials could open interesting and decisive scenarios for urban greening's care and maintenance, following a circular economy approach.

Sustainable management of urban forestry should be a fundamental goal to achieve for every public administration, as the Trees for Seattle (City of Seattle, 2018) experience seems to demonstrate. There are many obstacles to overcome to reach this goal, in some nations more than others, but one of the steepest slopes for all to climb is economical. This fact clearly shows in the novel approach of cutting down urban trees as a response to the overall economic hardship of municipalities and a general quest for urban safety (Rotherham and Flinders, 2019). To exploit the by-products of maintenance processes could represent the key to unlock those monetary resources indispensable for adequate caretaking of the urban arboreal patrimony. There is a strong need to find a different approach in this regard, and that entails investments in personnel, techniques, and equipment.

Tilia sp., even if one of the most predominant, is only one of the various tree species used in urban forestry.

The potentialities of using by-products of pruning residues could be affected by various conditions such as the peculiar environment, needs, and availability of source material.

These considerations must be taken into account before even thinking about scaling up the process to the industrial stage.

The technological process for the production of composite materials made of wood fibers and binders already exists, the novelty of the proposed material must be searched in the nature of its source. In this regard, for understanding the commercial viability of the process would be of considerable significance to know the volumes of raw materials available per year per municipality, and this would entail having a precise knowledge of the arboreal patrimony of each territory.

In many situations, like for instance, in many Italian Municipalities, this is often not the case. More specifically, the number of linden trees, their characteristics, and in general, all the parameters that provide the framework to set up an adequate management scheme are often unknown. This consideration translates into an unclear general situation in which it is not possible, at least where there this lack of information, to assess the economic feasibility of producing this material, even at a small scale commercial level.

Furthermore, the same amount of material would not be collected every year, since the management necessity for an average plant in good conditions does not foresee a yearly pruning. The management practice that has to be carried out every year is the removal of the suckers growing near the root collar, which are not lignified enough to be shredded.

We imagine that it could be possible to consider even other tree species' pruning residues and also mixtures of different wood wool, but this has still to be demonstrated. The work of our research team is now focused on appraising various species separately, next one will be Platanus sp., and then to determine the potentialities on mixtures of different wood wool and different binders, and not only as nonstructural construction materials but also explore other potential uses.

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