sustainability

MDPI

Article

Comparative Studies of Thermal Conductivity Determination in Synthetic Wood with Recyclable Waste Content Using an Experimental Design Approach

Loredana Judele [1], Eduard Proaspăt [2], Razvan Ionut Teodorescu [3], Daniel Lepadatu [1,2,*] and Daniel Bucur [4]

[1] Faculty of Civil Engineering and Building Services, Gheorghe Asachi Technical University of Iasi, 700050 Iasi, Romania; loredana-emanuela.judele@academic.tuiasi.ro

[2] Transport Infrastructure Engineering Department, Faculty of Urban Planning and Architecture, Technical University of Moldova, 2028 Chisinau, Moldova; eduard.proaspat@iit.utm.md

[3] Department of Environment and Land Improvements, Faculty of Land Improvements and Environmental Engineering, University of Agronomical Sciences and Veterinary Medicine of Bucharest, 59 Marasti Blvd., 011464 Bucharest, Romania; razvan.teodorescu@usamv.ro

[4] Department of Pedotehnincs, "Ion Ionescu de la Brad" Iasi University of Life Sciences, 700490 Iasi, Romania; dbucur@uaiasi.ro

* Correspondence: daniel.lepadatu@iit.utm.md

Abstract: Waste has become an everyday subject, especially its efficient recycling due to the increasing decline in the planet's primary resources. Therefore, their recovery is intended to be total and with minimal energy consumption. Biomass waste is fully recoverable in raw or processed states and in combination with other compatible waste types (including wastewater from construction, polymers, and sunflower seeds). It represents the basic elements for obtaining synthetic wood to replace natural wood, which is very expensive and difficult to obtain (lasts for several years). This paper proposes three methods to determine the thermal conductivity of these new materials (synthetic wood) to guarantee and optimise their thermal characteristics. The determination of thermal characteristics in insulating materials is usually performed experimentally in a double climate chamber or more simply using a special instrument of the ISOMET type, but under these conditions, the sample must meet certain conditions imposed by the manufacturer to be tested. Thus, two experimental investigation methods are used to which a numerical method is added, which consists of modelling by the finite element method with an adequate programme of heat transfer through these materials. Four samples with variable content of recyclable waste obtained through combinations resulting from six different experimental design plans with two controlled factors were analysed to optimise synthetic wood recipes for the efficiency of their hygro-thermal characteristics. The content of the tested samples varied relative to the quantity and number of recyclable wastes included in the final recipe. Thus, the thermal conductivity obtained was different for each sample but close to that of similar synthetic wood-type materials and natural wood.

Keywords: thermal conductivity; recycled waste; synthetic wood; experimental design; finite element method

check for updates

Citation: Judele, L.; Proaspăt, E.; Teodorescu, R.I.; Lepadatu, D.; Bucur, D. Comparative Studies of Thermal Conductivity Determination in Synthetic Wood with Recyclable Waste Content Using an Experimental Design Approach. *Sustainability* **2023**, *15*, 15481. https://doi.org/10.3390/su152115481

Academic Editor: Mostafa Ghasemi Baboli

Received: 17 September 2023
Revised: 20 October 2023
Accepted: 26 October 2023
Published: 31 October 2023

1. Introduction

Efficient waste recycling management is an important challenge for each administration but is mandatory for the environment, leading to a significant reduction in greenhouse gases. Solid waste, especially from construction but also from wood biomass, is an acute problem through the large areas it occupies, contributing to soil contamination and affecting groundwater when non-compliant. The recycling of biomass waste by re-introducing it into the economic circuit is a concern of all countries through multiple research teams that have obtained biogas from burning it in specialised installations [1,2] and ash as an addition to cement [3–5].

According to the EU report on waste management [6], a solid comparative analysis between 2010 and 2020 (Figure 1) shows that the best-ranked country is Finland with almost 20 t/capita. In contrast, Croatia or Turkey produce almost 2 t/capita, which is 10 times less. Romania is above the EU average of 5 t/capita, but this value has decreased compared to 2010 when it was almost 10 t/capita.

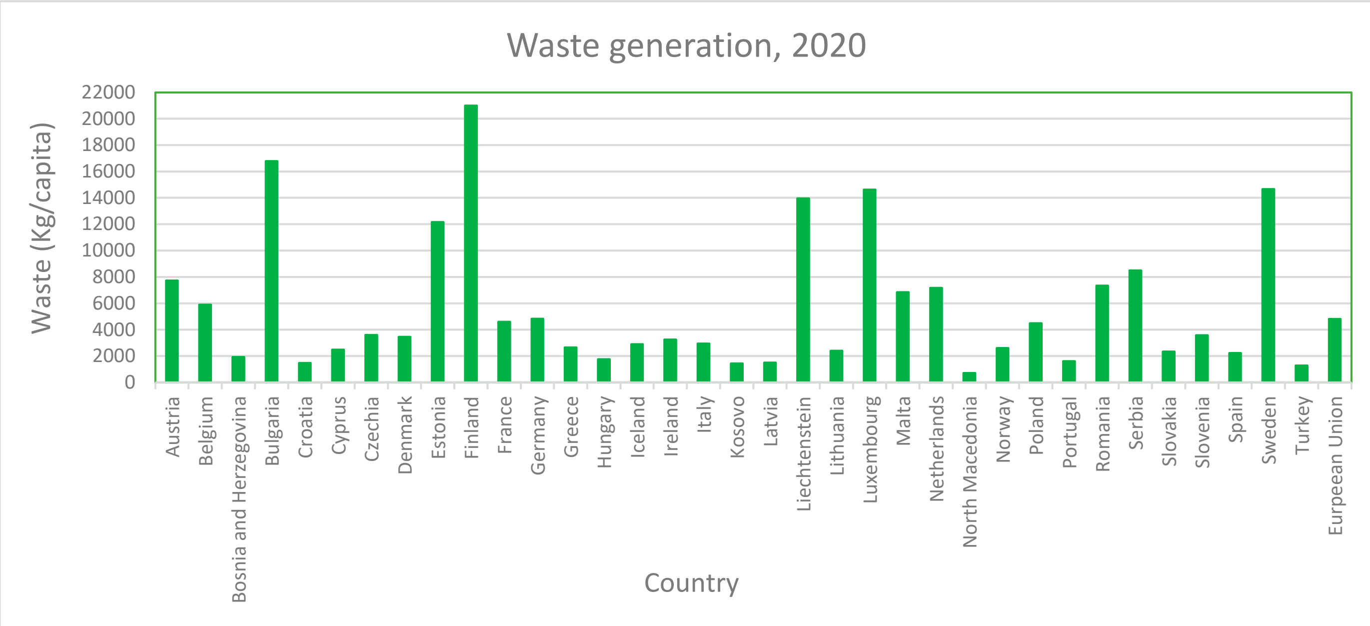


Figure 1. Waste recycling rates in Europe by country (in accordance with Eurostat data [6]).

Products obtained through recycling and whose main component is wood waste or derived products, the so-called Wood Plastic Composite (WPC) [7], are being used more and more frequently throughout the world [8–10]. Winandy et al. [11] enumerated some of these products obtained in the USA, but this market experienced an exponential rise in all countries, especially in developed ones [12,13].

Some researchers [14] have studied the chemical composition and nutrient stocks in two mountainous regions in western Bulgaria on four types of beech waste of different types (stumps, standing, and lying dead wood) which they called wood dead. Thus, they determined that they contained predominantly carbon, hydrogen, and nitrogen and that the quantities in the studied regions differed. This study highlights the stocks of carbon, hydrogen, nitrogen, and other elements existing in wood biomass in a mountainous region of Bulgaria.

The economic impact of the use of various wastes as constituent elements of the WPC was studied in Ref. [15]. This study was based on a comparison of composite materials containing different fractions of their waste mass with those obtained with virgin materials. However, no significant cost differences were found between them. From this, we can conclude that it is increasingly important to recycle all types of waste as much as possible by reintroducing them into the economic circuit and with beneficial effects on the environment.

A study [16] aimed to recover cellulose from wastewater sludge, serving as a substitution for WPC elements. To improve the properties of the new material, maleic anhydride (MA) and vinyltrimethoxysilane (VTMS) were added. Analyses have shown an increased efficiency of MA compared to VTMS in the refinery of interfacial bonding. Thus, cellulose obtained from wastewater can be a viable alternative to WPC production.

Using rubber waste to obtain WPC is a challenge and has been introduced by Zhou et al. In their study [17] with a new rubber-wood-plastic formula (RubWPC), they insisted on the use of malleated and silane coupling agents.

Nano wood is another concept that is being used more frequently [18,19]. This consists of the introduction of nanoparticles in the recipe of the new wood material to improve its physical–mechanical characteristics.

Researchers in China have developed a wood-derived product with a polymer-type binder called resol [20], which is similar to lignin. It is obtained from woody biomass waste through heat treatment developed by other researchers [21–23]. In the first version, the resol binder is light and has the advantage of good fire and acid resistance, while thermolignin is a biodegradable product with very good hygrothermal properties.

The thermal treatment of the new material is another essential component of this process of obtaining synthetic wood [17,24], with improved and high-performance properties superior to the natural one. In ref. [17], researchers focused on the effects of ultraviolet (UV) radiation. The results showed that there was a change in colour for WPC when exposed to UV.

In this study, the thermal treatment of the mixture from which the synthetic wood was obtained was beneficial because this heat treatment accelerated the reaction process/drying and facilitated the creation of chemical connections between the various components of the recipe. The objective of the study was to present a wood-type material, called synthetic wood, obtained mainly from wood biomass waste combined with other compatible types of waste (such as polymers, cellulose, rubber, and sunflower) that is capable of preserving at least part of the properties of natural wood but is environmentally friendly. It was obtained in the laboratory and had a thermal conductivity close to the category of thermal insulation materials, such as the values of the agglomerated slabs of wood (PAL), located between 0.05 for porous pal and 0.14 for insulating boards. Knowing that obtaining it naturally is much more expensive and long lasting, the optimisation of recipes to achieve these requirements is the goal of these studies.

Some researchers [25] have used biomass to produce biogas through the pyrolysis process. Thus, two types of processes are presented: thermochemical and a mix of biological and chemical or physical processes that depend on several parameters, such as the type of biomass, humidity, and the production process.

Plastic waste is an inexhaustible and indefinitely recyclable source because its lifespan is very long. Cinelli et al. [26] identified an innovative method for accelerating the degradation of plastic waste from agriculture by applying a biotic approach. These were subjected to attacks with enzymes and larvae. Over time, an acceleration of the degradation was found depending on the type of polymer subjected to this test.

Many other studies have addressed the topic of liquid wood [27–29]. These are pure biopolymers, such as lignin (e.g., Arboform), or hybrid mixtures with other biocompatible waste, and they use specific characteristic injection modelling in an almost liquid form due to thermal processing [17,27].

2. Materials and Methods

2.1. Design of Experiments (DoE) Method

Considering that obtaining new materials with characteristics that are sometimes superior to existing ones requires many experimental trials, the proposed technique is old-fashioned. It was first used in agriculture by the statistician Sir R. A. Fisher [30–34], primarily to reduce their number and especially to study the variability of these experiments with the help of statistics, that is, by analysing the variance of the experimental results with the help of an analysis of variance (ANOVA) table [30–34].

The design of the experimental method is an advanced method of planning, analysis, and optimisation [30,34] of complex problems such as a black box in which things happen without being directly controlled but which, thanks to this technique, can identify both influential variables and mathematical models for the optimisation process.

For this study, multiple experimental plans of the two-parameter factorial type [30–34] were planned and developed to vary, on sets of four samples, different factors [30–34] that were part of the synthetic wood recipes and that were inventoried and chosen with the help of Poisson's diagram (Figure 2).

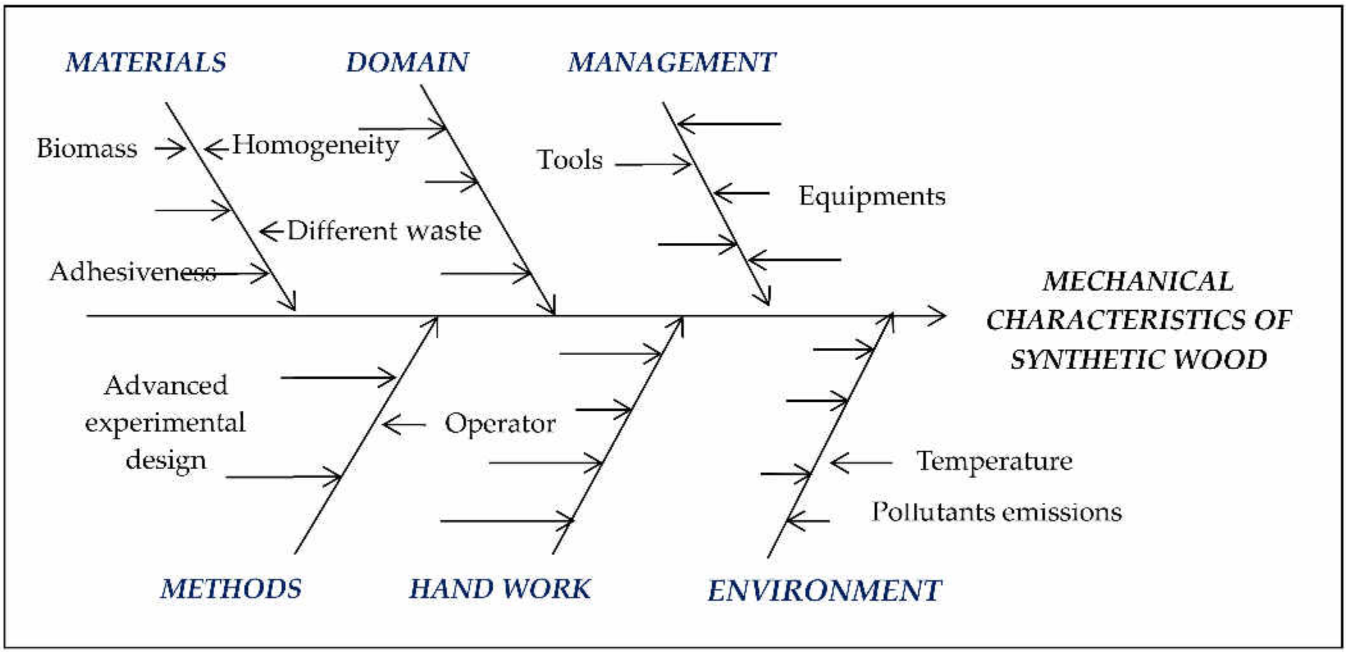


Figure 2. Ishikawa diagram for synthetic wood.

Thus, six sets of plans (DoE_1–DoE_6) with two variable factors, X_1 (Recycled polystyrene), X_2 (Sunflower husk waste), were studied, for example (Tables 1 and 2, with four samples each (Table 3) for a total of twenty-four samples (Tables 4–9). Some of these were then tested using a double climate chamber to determine the thermal conductivity in situ (Y_i) (Table 3).

Table 1. Experimental design and variable parameters (DoE_1–DoE_3).

Experimental Design No.	DoE_1		DoE_2		DoE_3	
Waste/Additive	Alcohol (mL)	Ceresit (g)	Fly Ash (mL)	Polymer (g)	Rec. Polystyrene (g)	Sunflower Husk (g)
min	20	10	13	10	3.5	25
max	40	20	26	20	7	50

Table 2. Experimental design and their variable parameters (DoE_4–DoE_6).

Experimental Design No.	DoE_4		DoE_5		DoE_6	
Waste/Additive	Plastic Waste (mL)	Recycled Cement (g)	White Cement (g)	Sodium Silicate (g)	Rubber Waste (g)	Sulphuric Acid (mL)
min	20	10	30	25	10	20
max	40	20	70	50	20	40

Table 3. Experimental design for two factors.

No.	X_1	X_2	Response
1	0	0	Y_1
2	1	0	Y_2
3	0	1	Y_3
8	1	1	Y_4

Table 4. Mixture composition of sample no. 1.

No.	Mixture Component	Percent (%)	Sample
1	The wood waste fine part	0.17	
2	Wood waste coarse part	0.30	
3	Adhesive tip urelit	0.30	
4	Cement	0.03	
5	Recycled meal	0.06	
6	Alcohol	0.06	
7	Additive hardener	0.01	

Table 5. Mixture composition of sample no. 2.

No.	Mixture Component	Percent (%)	Sample
1	Wood waste fine part	0.17	
2	Wood waste coarse part	0.30	
3	Adhesive tip urelit	0.30	
4	Cement	0.03	
5	Recycled fly ash	0.09	
6	Alcohol	0.07	
7	Polymer	0.03	
8	Additive hardener	0.01	

Table 6. Mixture composition of sample no. 3.

No.	Mixture Component	Percent (%)	Sample
1	Wood waste fine part	0.32	
2	Recycled polystyrene	0.02	
3	Sunflower husks waste	0.13	
4	Adhesive tip urelit	0.21	
5	Recycled cement	0.10	
6	Sodium silicate	0.05	
7	Alcohol	0.10	
8	Polymer	0.05	
9	Additive hardener	0.01	

Table 7. Mixture composition of sample no. 4.

No.	Mixture Component	Percent (%)	Sample
1	Wood waste fine part	0.28	
2	Wood waste coarse part	0.06	
3	Fly ash	0.10	
4	Recycled plastic	0.02	
5	Adhesive tip urelit	0.19	
6	Recycled cement	0.01	
7	Sodium silicate	0.10	
8	Alcohol	0.10	
9	Polymer	0.10	
10	Additive hardener	0.05	

Table 8. Mixture composition of sample no. 5.

No.	Mixture Component	Percent (%)	Sample
1	Wood waste coarse part	0.20	
2	Sunflower husks waste	0.03	
3	Recycled polestyrene	0.03	
4	Adhesive tip urelit	0.39	
5	White cement	0.12	
6	Sodium silicate	0.09	
7	Meal waste	0.07	
8	Sulphuric acid	0.06	
9	Additive hardener	0.01	

Table 9. Mixture composition of sample no. 6.

No.	Mixture Component	Percent (%)	Sample
1	Wood waste fine part	0.11	
2	Wood waste coarse part	0.11	
3	Rubber	0.03	
4	Sunflower husks waste	0.04	
5	Adhesive tip urelit	0.30	
6	Recycled cement	0.07	
7	White cement	0.07	
8	Sodium silicate	0.09	
9	Meal waste	0.05	
10	Sulphuric acid	0.07	
11	Alcohol	0.07	
12	Additive hardener	0.01	

This study investigated synthetic wood samples obtained from the combination of wood mass waste or biomass with adhesive (urellite type) and other types of compatible waste (Tables 4–9).

Thus, they were mixed using experimental planning and several factorial plans with two factors each from which one sample was chosen to make a comparative analysis in determining the thermal conductivity of these samples.

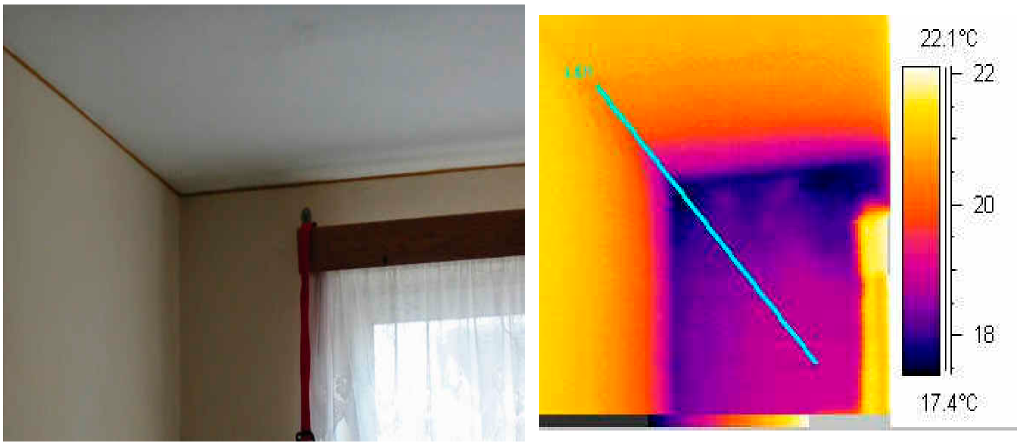
The samples chosen for the analysis were based on wood waste in which other types of recyclable waste were introduced in turn, such as meal (sample no. 1), fly ash (sample no. 2), sunflower husks, recycled polystyrene (sample no. 3, sample no. 5), recycled cement, plastic (sample no. 4), and rubber (sample no. 6).

This modern method of experimental planning was chosen to control two parameters on each plane and trace their influence on the physical–mechanical characteristics of the synthetic wood. In particular, the aim was to preserve, if not improve, their thermal conductivity.

Our goal was to identify as many solutions as possible, with variations between compatible parameters for such a recipe (synthetic wood) so that we could incorporate as much recyclable waste as possible with minimal costs.

2.2. *Thermovision and Thermography of the Thermal Field*

Thermal imaging cameras [35] are a powerful tool for identifying and analysing the existing thermal flow between two premises or environments at different temperatures (Figure 3a) through an intelligent detection system that obtains an optimal and high-quality image. The usefulness of this method in highlighting the critical areas, as well as the identification of the points of interest in the temperature range with high precision, has been proven by the ability of this technique. It reproduces, with high precision, a complete image of superior quality with the related heat losses and possible non-conformities in the structure or even for a quick localisation of areas with high humidity and an obvious risk of mould (Figure 3b).



(**a**) (**b**)

Figure 3. Heat loss identification with a thermovision camera. (**a**) Testing condensation areas; (**b**) Heat loss in the insulated wall.

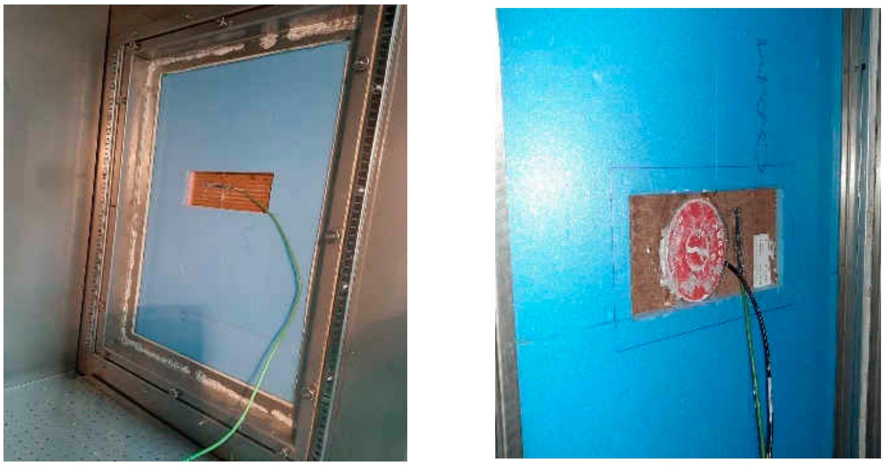
2.3. Double Climate Chamber Environmental Simulation for Conductivity Determination

Thermal conductivity was determined using a climatic installation with a double chamber (Figure 4), whose technical characteristics were as follows [36]:

- Test volume room: 630 dm^3;
- Temperature range variation: −10 °C/+40 °C;
- Humidity range variation: 50–95%.

Figure 4. Double climate chamber in the work.

The sample whose geometric dimensions were 23 cm length, 11 cm width, and 1.5 cm height was introduced into the climatic chamber. The gap left between the two enclosures of the climatic chamber was filled with polystyrene. For condition test permanent monitoring, a thermal flow sensor and a temperature sensor were installed on the sample (Figure 5).



Climate chamber no. 1—hot face

Temperature sensor

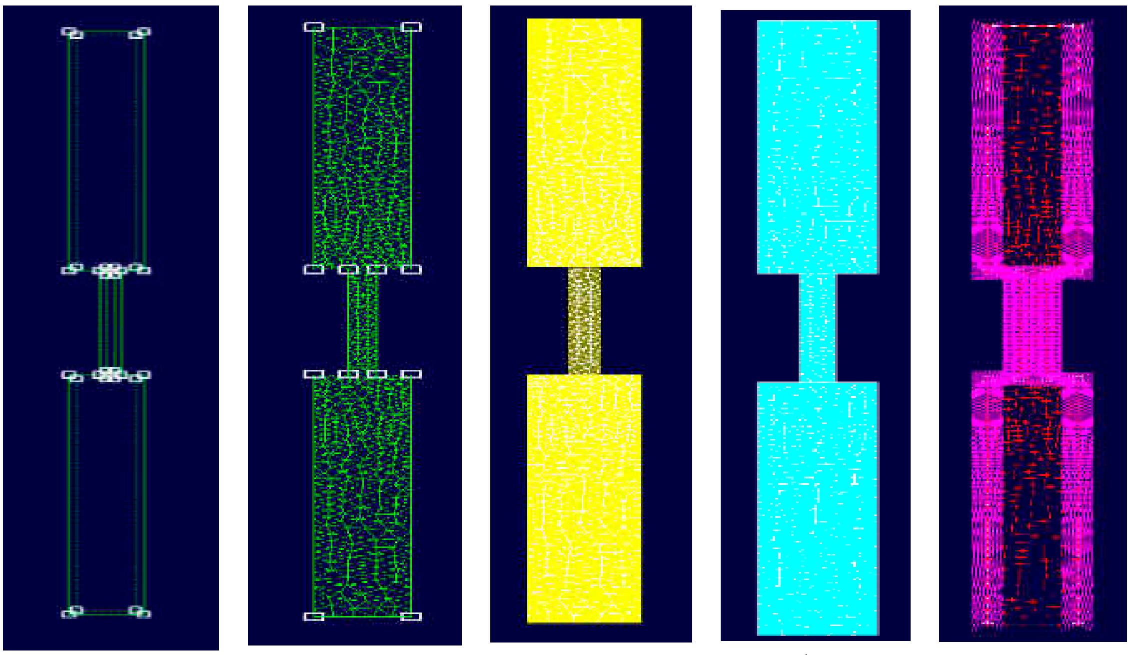
Climate chamber no. 2—cold face

Temperature sensor and thermal heat flow sensor

Figure 5. Sample preparation inside climate chambers.

2.4. Numerical Simulation for Conductivity Estimation

Numerical modelling was performed using RDM v7.04 software [37]. Figure 6 shows the stages of numerical modelling, such as the definition of the geometry (a), the structural discretisation (b), the definition of the physical–mechanical properties of the materials (c) and assigning the thickness of the whole (d), and the imposition of the contour conditions (e).



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 6. Numerical simulation stages of the sample. (**a**) definition of the geometry, (**b**) the structural discretisation, (**c**) the definition of the physical–mechanical properties of the materials, (**d**) assigning the thickness of the whole, (**e**) the imposition of the contour conditions.

Structural discretisation was performed automatically by the RDM v7.04 programme, with planar triangular elements. For the colours in the Figure 6, the meaning is as follows: the green in Figure 6a represents the geometry of the part, with the highlighting in the dotted line of the areas to be discretized in triangular planar finite elements that can be found in Figure 6b. In Figure 6c, the materials used are represented in different colours: yellow—polystyrene, brown synthetic wood or pink in Figure 6d and the contour conditions with the hygrothermal characteristics of the thermal loads on the two sides of the sample are highlighted.

Mathematical Model of Numerical Conductivity

The mathematical model of numerically shaped thermal conductivity is directly proportional to the thermal flow and thickness of the material and inversely proportional to the temperature difference between the two enclosures.

The mathematical equation is given by [38]:

$$\lambda = \frac{\phi \cdot d}{T_e - T_i} \quad (1)$$

where λ is the thermal conductivity, ϕ is the thermal flux obtained by numerical stimulation, d is the weight of the sample, and T_e and T_i are temperatures.

2.5. Experimental Thermal Conductivity Determination

2.5.1. Measurement Tool Description

The Isomet 2114 device [39] is a handheld device for the direct measurement of heat transfer properties. It measures a wide range of materials, including those considered insulators. It applies a dynamic measurement method, which allows the measurement time to be reduced compared to other experimental steady-state measurement methods.

2.5.2. Principle of the Measurement Method

The evaluation of thermal conductivity and volumetric heat capacity was based on temperature records at regular time intervals, provided that heat propagation took place in a continuous environment and with infinite duration. These values were recorded in the device memory as a weighted average of these values. The operation was repeated at least twice to increase the precision and the final average of these values. Its measurement accuracy was between 5% and 10%.

3. Results and Discussion

3.1. Relevance of This Study

The aim of this study was to experimentally determine the thermal conductivity of some new synthetic materials in a double climate chamber, mainly from wood biomass waste [40] with various additions of other wastes whose compatibility [41] was close to that of wood. The novelty of other studies is highlighted by the fact that these materials were obtained from various combinations based on advanced experimental planning using an experimental design method, which allowed us to take a modern approach to organising and making a varied mix of recyclable waste. Comparative numerical analysis using finite element modelling with RDM 7.04 software or the double climate chamber and Isomet 2114 hand tool for thermal conductivity determination confirmed that the results obtained experimentally were correct. The secondary objective of this study was to identify combinations of parameters that optimise the thermal characteristics of this material with varying contents of recyclable waste and that meet the requirements for strength and durability with beneficial effects on the environment, considering its recyclable waste content.

3.2. Synthetic Wood Thermographic Images

To highlight the thermal flux (Figure 7) with its variations on the partition wall of the double climate chamber, we employed a thermographic camera, Testo 870 [35], with a thermal sensitivity of 0.05 °C.

(**a**) (**b**)

Figure 7. Thermographic test preparation in a double climate chamber. (**a**) Thermal image of sample no. 1; (**b**) Double climate chamber—test preparation.

The variation in the thermal flux of the samples subjected to heat transfer was observed in the thermal image (Figure 8) with the identification of temperature boundary zones and their contours. To determine temperatures in predefined areas of interest or other parameters (including emissivity and reflected temperature), they were marked by points (marked with Mi) on the thermal image. Using Testo IRSsoft 5.0 software, we obtained the desired values and even their evolution through the thickness of the element (Table 10).

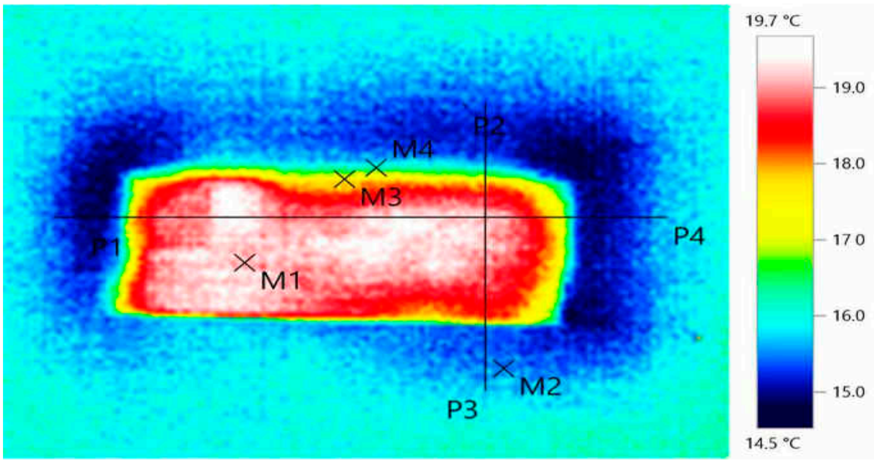


Figure 8. Thermal image of sample 1 points marked with Pi.

Table 10. Temperature variation of sample 1.

Measurement Objects	Temperature (°C)	Emissivity	Reflected Temperature (°C)
Measure point 1	19.1	0.93	20
Measure point 2	15.6	0.93	20
Measure point 3	17.4	0.93	20
Measure point 4	16.0	0.93	20

As shown in Figure 9, the average values of the temperatures on the halves of the plate between the two rectangles were almost identical, with a difference of only 0.1. This is due to the thermal isotropy of the material.

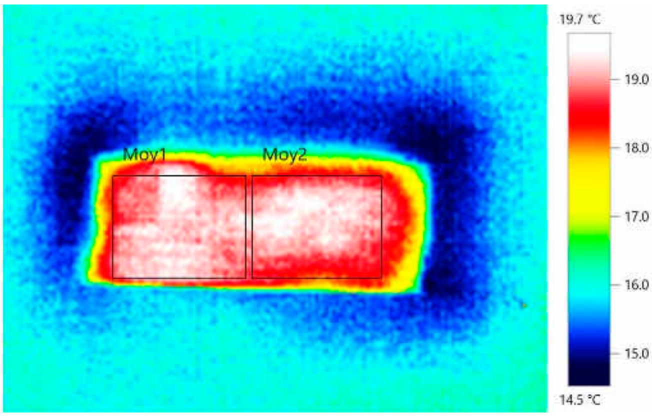


Figure 9. Thermal isotropy material of sample 1.

3.3. Experimental Conductivity Results

Most of the building materials were not necessarily homogeneous; their structure was capillary porous, which allows the migration of air or water but especially vapours through this network of capillaries and pores. Consequently, the heat flow was transmitted in several forms, but we were interested in the one through conduction, which is a characteristic of these materials. Quantitative evaluation of this phenomenon was difficult based on mathematical equations, so we chose its appreciation on an experimental basis to reflect the complexity of these heat transfer processes. The following factors are known to affect conductive transfer:

- temperature;
- air humidity;
- material thickness;
- density and porosity.

Six samples with different characteristics were used due to the various waste contents (Tables 4–9). The temperature difference between the two enclosures was 10 °C (+15 °C for the left chamber and +25 °C for the right chamber). The experimental results for each sample were recorded every 10 min in the climate chamber for at least 4 h and an average of these values was calculated (over 25 recordings). These are presented in Table 11.

Table 11. Experimental and numerical results of conductivity.

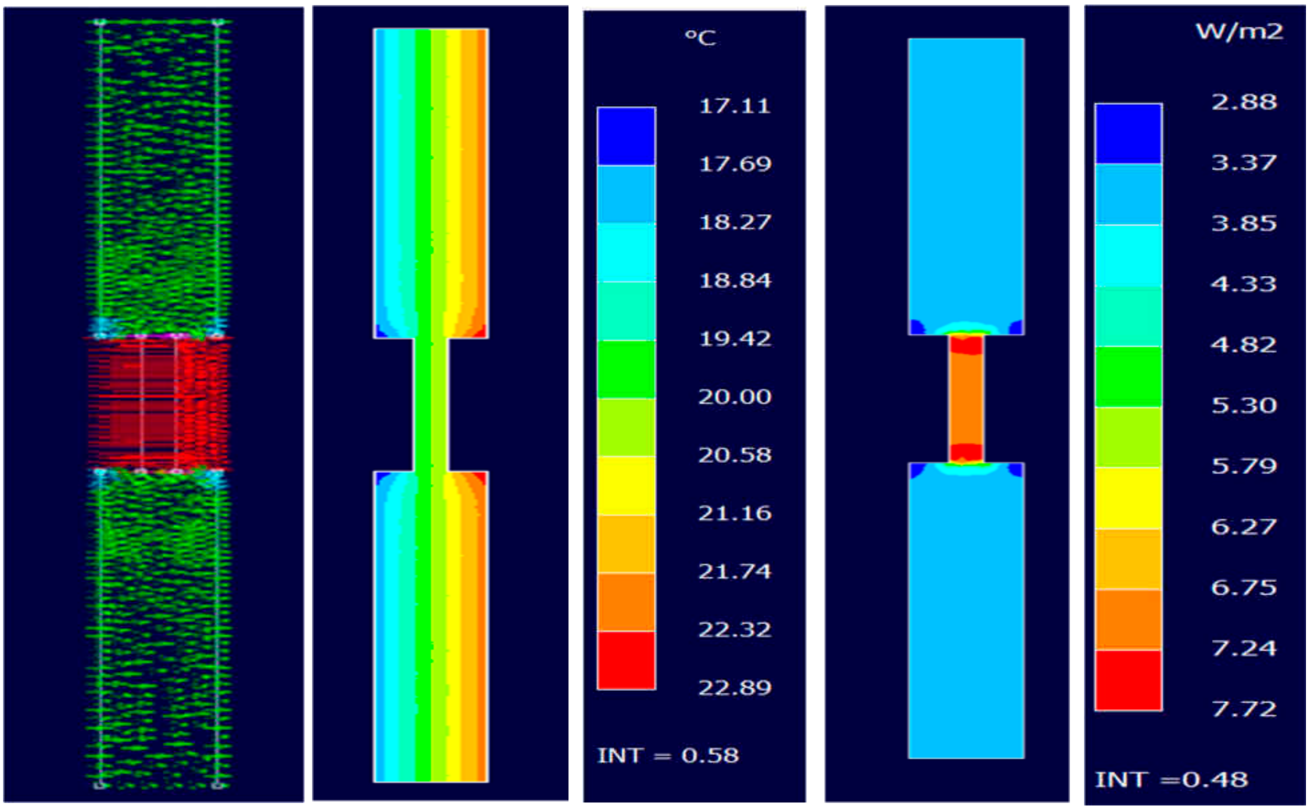
No.	Sample	Sample Thickness (m)	Double Climate Chamber Thermal Conductivity (W/mk)	Numerical Thermal Conductivity (W/mk)	Manual Thermal Conductivity (W/mk)
1	Sample 1	0.0155	0.107	0.109	0.155
2	Sample 2	0.0163	0.118	0.121	0.126
3	Sample 3	0.018	0.102	0.127	0.124
4	Sample 4	0.019	-	0.139	0.147
5	Sample 5	0.023	-	0.185	0.189
6	Sample 6	0.021	-	0.140	0.142

3.4. Numerical Results of Conductivity

Numerical modelling on a finite element is a numerical method that shapes physical phenomena with certain hypotheses and constraints but which is very close to the real phenomenon. Instead, it is always at much lower costs, with the results being comparable and close in size.

In the hygrothermal calculation of the tire elements or of the building in its entirety, the thermal flow is considered stationary and its transmission is made by conduction between two different environments (air-solid-air) by a temperature difference of at least one Celsius degree. The stationary regime is defined by the constant in time of the temperature field. However, variations in indoor/outdoor temperature can be sinusoidal with periods of 6, 12, or 18 h or days. They can also be given by polynomial functions or conventional variations by discrete measurements [41].

The results of the numerical analysis are presented graphically in Figure 10, where a represents the thermal flux density, b represents the temperature isotherms, and c represents the thermal flux passing through the sample.



(**a**) (**b**) (**c**)

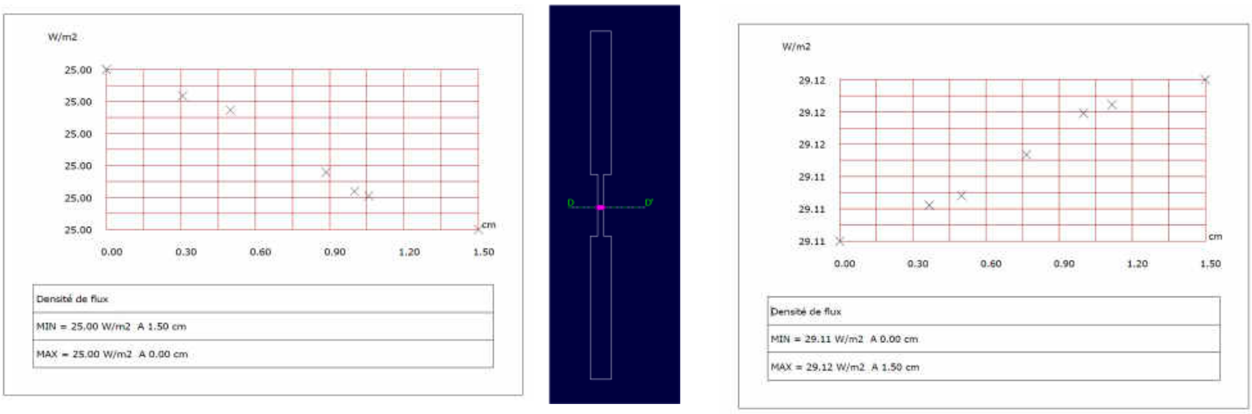
Figure 10. Numerical conductivity of sample 6. (**a**) Flux density; (**b**) Temperature; (**c**) Thermal flux.

Considering that the connecting element of these two approaches (numerical modelling and the experimental one) was thermal conductivity, in numerical modelling, we aimed for the two thermal flows to be as close as possible to reality.

Figure 10 shows that the temperature is evenly distributed on the two sides of the sample, with values between 19.42 and 20.58 °C. For the thermal flow, we observed a concentration of it in the sample area with maximum and moderate values in the rest.

Because thermal conductivity [42,43] is a characteristic of the material, its values are very different depending on its nature and properties. Thus, for porous materials, the conductivity decreases with an increase in porosity, while it increases linearly with an increase in temperature. Metals have the highest thermal conductivity, which is proportional to electrical conductivity.

Figure 11 shows the flux density and its variation on the cross section D–D′ (Figure 11) for sample no. 1 (Figure 11a) and sample no. 3 (Figure 11b).



(**a**) (**b**)

Figure 11. Numerical results of the sample. (**a**) Flux density of sample 1; (**b**) Flux density of sample 3.

3.5. Microstructural Analysis

From the samples obtained, cores with a diameter of 3 cm were extracted and analysed with the help of a BX51M (PA-USA) electronic microscope [44] with a magnification of up to 1000, which allowed for a microstructural exploration of the connections created between the various wastes and binders in the analysed recipes (Figure 12a–c).

(**a**) (**b**) (**c**)

Figure 12. Microstructural image for sample 2 at different magnitudes. (**a**) 100× magnitude; (**b**) 200× magnitude; (**c**) 500× magnitude.

Analysing the images studied at different magnitudes (Figure 12), we noticed that the images for sample 2 showed a microstructure with good homogeneity and adhesion between the wood fibres and the binder.

3.6. Analysis and Interpretation of Results

The results obtained and presented in Table 11 show us the concordance between the three approaches and strengthen our conviction that both the experimental tests and numerical modelling prove that the hypotheses considered in the numerical modelling of the heat transfer phenomenon, as well as the protocol of the experimental tests in the double-climatic enclosure, were perfectly viable. However, the determination of thermal conductivity inside the climate chamber was much more precise but more expensive; thus, we tested all samples with the Isomet 2114 manual device. The results are shown in Table 11.

Our interest in the hygrothermal characteristics of synthetic wood was also to exploit the heating behaviour of lignin, generally obtained from wood biomass, namely at a strict temperature range of 180–230 °C. When lignin acts as a thermoplast adhesive, "melting" and constituting in a strong binder achieves acceptable internal cohesion and creates the possibility of replacing the obsolete urelite adhesive. It was observed that in the case of the analysed samples, we have a good heat transfer with the ones containing recycled pollen (sample 3) and fly ash and/or sunflower seeds (sample 2), while those containing cement and sodium silicate (sample 5) have worse conductivity.

The synthetic wood discussed in this paper through the presented recipes can have multiple applications [45–48], depending on the physical–mechanical characteristics obtained through the tests. However, the replacement of the urea-type adhesive (which also has harmful effects on the environment; adhesives made from urea formaldehyde resins are more dangerous) was a constant concern of ours during this research. Thus, our proposal (including within the ongoing EFECON project [49]) for the future would be to replace it with the one obtained by melting lignin under certain conditions. In these cases, since it is a thermoplastic polymer, we have a problem with uneven dispersion in the newly created matrix in the manufacturing process of the new cellulosic materials, implicitly resulting in a more complex technological process with increased electricity consumption to overcome this inconvenience. This in no way diminishes the value of this idea. We have not yet fully implemented a synthetic wood production system to quantify the effects on its thermal performance.

In this paper, we presented the microscopic characteristics of synthetic wood, a biomaterial with huge potential for the absorption of biomass waste and more. Thus, the combination of different biomass waste with binders and other types of recyclable construction waste can generate a product with superior characteristics to natural wood, primarily related to the average duration of its production but also to properties such as superior mechanical resistance, weight, and low conductivity comparable to insulating materials or resistance to water absorption.

4. Conclusions

In this paper, we carried out a comparative study to analyse the thermal conductivity of a new synthetic wood-type material obtained with the addition of various recyclable materials. The main purpose was to highlight the thermal characteristics of the new material but also to experimentally, manually, and numerically validate these sizes. Thus, we tested several specimens in the double climate chamber, determining the value of the energy flow that crosses the new material.

The experimental design method used in this work is a modern method of experimental planning, analysis, and optimisation that allowed us to investigate a minimal set of experimental samples to obtain different configurations of parameters with very good results, benefiting from such specificity.

The values obtained for thermal conductivity by the three analysed methods were between 0.107 and 0.118 for the samples analysed with a double climate chamber, 0.109 and 0.185 for those determined by numerical modelling, and 0.124 and 0.189 for those determined manually with the Isomet 2114 (BL-SK) (Made by Applied Precision Ltd., Stavitelska 1, 83104 Bratislava, Slovakia) device, which places it in the category of insulating materials and is very good considering that its rigidity is quite good and can be used for both thermal and/or sound insulation and perimeter closures.

Lignin acts as a thermoplastic adhesive, "melting" in the range of 180–230 °C and forming a strong binder, achieving acceptable internal cohesion, and it can partially or totally replace the urellit-type adhesive frequently used to obtain wood-type derivatives.

The thermal imaging camera helped us to identify the imperfections in the synthetic wood structure, determine the temperature differences on a surface, check the isotropy of the material, and view the thermal field on its entire surface. Infrared investigations are a particularly useful tool for architects, construction engineers, and installers. The use of thermography always clarifies aspects of major interest and allows for great reductions in expenses by easily detecting problems that require much more expensive investigations using other methods.

Applications of liquid wood patented by TECNARO are multiple in all fields with very good results and they are also biodegradable. However, there could also be microstructural,

structural, and chemical incompatibilities that we have not yet encountered or that have not yet been discovered.

Our goal is to obtain synthetic wood that incorporates as much recyclable waste with compatible characteristics from a physicochemical point of view but that ultimately meets the resistance and hygrothermal requirements so that it can be used not only in construction but also in the wood processing industry.

Considering the global objectives of the whole world, the benefits of using biomass waste and other compatible materials to produce synthetic wood are multiple: horizontally, by removing them from zones that are crowded/are used for storage and then returning these areas to agriculture; and vertically, by replacing natural wood, which is much harder to obtain, with synthetic wood, which can be produced, distributed, and used rapidly.

The perspectives offered by the synthetic wood solution are very encouraging and achievable, considering the increased interest in the reuse of all recyclable waste, as well as the fact that the natural one has a very high growth/development rate, and has major implications for the natural ecosystem (see illegal deforestation especially in Romania).

The optimisation and analysis of these experimental tests were initiated with the experimental design method to obtain the first information on the influence of the parameters on the physical–mechanical characteristics of synthetic wood. We aim to use the same modern method to identify the configuration that corresponds to the needs of the operator, depending on the type of use.

Author Contributions: Conceptualization, D.L. and L.J.; methodology, D.L.; software, D.L.; validation, D.L., L.J. and D.B.; formal analysis, E.P.; investigation and material characterization, L.J. and E.P.; writing—original draft preparation, D.L.; writing—review and editing, D.L. and L.J.; visualization, D.B.; supervision, D.B.; project administration, D.L.; funding acquisition, R.I.T. All authors have read and agreed to the published version of the manuscript.

Funding: The research related to numerical modeling, comparative analysis and interpretation of results was supported by the project 7PFE/2021 "Circular economy in USAMV farms—whole use of by-products resulting from fermentation processing", Program 1—Development of the national research-development system, Subprogram 1.2—Institutional performance—Institutional development projects—Projects to finance excellence in RDI.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The research related especially to experimental tests and conductivity determination by double climate chamber of this paper were realized with the support of project EFECON—Eco-innovative products and technologies for energy efficiency in construction, POC/71/1/4—Knowledge Transfer Partnership, Cod MySMIS: 105524, ID: P_40_295, Project co-financed by the European Regional Development Fund.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kasinath, A.; Fudala-Ksiazek, S.; Szopinska, M.; Bylinski, H.; Artichowicz, W.; Remiszewska-Skwarek, A.; Luczkiewicz, A. Biomass in biogas production: Pretreatment and codigestion. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111509. [CrossRef]
2. Kourdourli, F.; Estel, L.; Taouk, B.; Abdelouahed, L. Modeling of hydrogen production from biomass bio-digestion under Aspen Plus. *Comput. Chem. Eng.* **2023**, *175*, 108273. [CrossRef]
3. Mohamaed, A.; KMuduli, K. Utilization of Biomass Flyash in Cementitious Application. *J. Phys. Conf. Ser.* **2021**, *2129*, 012005. [CrossRef]
4. Kusuma, R.T.; Hiremath, R.B.; Rajesh, P.; Kumar, B.; Renukappa, S. Sustainable transition towards biomass-based cement industry: A review. *Renew. Sustain. Energy Rev.* **2022**, *163*, 112503. [CrossRef]
5. Kim, K.W.; Park, K.T.; Ates, F.; Kim, H.G.; Woo, B.H. Effect of pretreated biomass fly ash on the mechanical properties and durability of cement mortar. *Case Stud. Constr. Mater.* **2023**, *18*, e01754. [CrossRef]
6. Waste Recycling in Europe, Rapport UE. Available online: https://www.eea.europa.eu/ims/waste-generation-and-decoupling-in-europe (accessed on 2 July 2023).

7. Nuryawan, A.; Hutauruk, N.O.; Purba, E.Y.S.; Masruchin, N.; Batubara, R.; Risnasari, I.; Rahmawaty, F.K.S.; Baysuni, M.; McKay, D. Properties of wood composite plastics made from predominant Low Density Polyethylene (LDPE) plastics and their degradability inature. *PLoS ONE* **2020**, *15*, e0236406. [CrossRef]
8. Gardner, D.J.; Han, Y.; Wang, L. Wood–Plastic Composite Technology. *Curr. Forestry Rep.* **2015**, *1*, 139–150. [CrossRef]
9. Dubey, N.; Purohit, R.; Rana, R.S. Manufacturing of Wood Polymer Composites. In *Wood Polymer Composites. Composites Science and Technology*; Mavinkere, R.S., Parameswaranpillai, J., Kumar, M.H., Siengchin, S., Eds.; Springer: Singapore, 2021. [CrossRef]
10. Zhou, Y.; Wang, Y.; Fan, M. Incorporation of tyre rubber into wood plastic composites to develop novel multifunctional composites: Interface and bonding mechanisms. *Ind. Crops Prod.* **2019**, *141*, 111788. [CrossRef]
11. Winandy, J.E.; Stark, N.M.; Clemons, C.M. Consideration in recycling of wood plastic composites. In Proceedings of the 5th Global Wood and Natural Fibre Composites Symposium, Kassel, Germany, 27–28 April 2004.
12. Najafi, S.K. Use of recycled plastics in wood plastic composites—A review. *Waste Manag.* **2013**, *33*, 1898–1905. [CrossRef]
13. Lin, J.; Tan, T.H.; Yeo, J.S.; Goh, Y.; Ling, T.C.; Mo, K.H. Municipal woody biomass waste ash-based cold-bonded artificial lightweight aggregate produced by one-part alkali-activation method. *Constr. Build. Mater.* **2023**, *394*, 131619. [CrossRef]
14. Damyanova, S.; Dimitrova, V. Chemical Composition and Stocks of Nutrients in Dead Wood of Beech (*Fagus sylvatica* L.) Forests. *WSEAS Trans. Environ. Dev.* **2023**, *19*, 465–471. [CrossRef]
15. Keskisaari, A.; Kärki, T. The use of waste materials in wood-plastic composites and their impact on the profitability of the product. *Resour. Conserv. Recycl.* **2018**, *134*, 257–261. [CrossRef]
16. Zhou, Y.; Stanchev, P.; Katsou, E.; Awadn, S.; Fan, M. A circular economy use of recovered sludge cellulose in wood plastic composite production: Recycling and eco-efficiency assessment. *Waste Manag.* **2019**, *99*, 42–48. [CrossRef] [PubMed]
17. Kuka, E.; Andersons, B.; Cirule, D.; Andersone, I.; Kajaks, J.; Militz, H.; Bicke, S. Weathering properties of wood-plastic composites based on heat-treated wood and polypropylene. *Compos. Part A Appl. Sci. Manuf.* **2020**, *139*, 106102. [CrossRef]
18. Hanzhou, Y.; Asante, B.; Schmidt, G.; Krause, A.; Zhang, Y.; Yu, Z. Eco-friendly geopolymer-wood building materials: Interactions between geopolymer and wood cell wall. *J. Clean. Prod.* **2023**, *420*, 138381. [CrossRef]
19. Kong, X.; Wei, Z.; Xia, S.; Jia, B.; Gan, L.; Han, S. The characterizations of nanofluid type urea formaldehyde resins. *Int. J. Adhes. Adhes.* **2023**, *126*, 103451. [CrossRef]
20. Resol. Available online: https://physicsworld.com/a/making-artificial-wood-on-the-large-scale/ (accessed on 2 July 2023).
21. Kalami, S.; Chen, N.; Borazjani, H.; Nejad, M. Comparative analysis of different lignins as phenol replacement in phenolic adhesive formulations. *Ind. Crops Prod.* **2018**, *125*, 520–528. [CrossRef]
22. Börcsök, Z.; Pásztory, Z. The role of lignin in woodworking processes using elevated temperatures: An abbreviated literature survey. *Eur. J. Wood Prod.* **2021**, *79*, 511–526. [CrossRef]
23. Windeisen, E.; Wegener, G. Behaviour of lignin during thermal treatments of wood. *Ind. Crops Prod.* **2008**, *27*, 157–162. [CrossRef]
24. Lepadatu, D.; Isopescu, D.; Judele, L.; Cucos, I.; Antonescu, I.; Alecu, I.-C. Particularities of synthetic wood—A biomaterial with recycled waste. *Environ. Eng. Manag. J.* **2021**, *20*, 585–592.
25. Patania, F.; Gagliano, A.; Nocera, F.; Agrifoglio, A. An Applied "energy System" (ES) to Produce Energy by Wasted Biomass (Part One). *Des. Constr. Maint.* **2022**, *2*, 74–83. [CrossRef]
26. Cinelli, P.; Barbani, N.; Filippi, S.; Strangis, G.; Sandroni, M.; Pratelli, A.; Lopez, M.J.; Barranco, P.; Cabello, T.; Castillo, P.; et al. Innovative Biotic Symbiosis for Plastic Biodegradation to Solve their End-of-Life Challenges in the Agriculture and Food Industries. *WSEAS Trans. Environ. Dev.* **2022**, *18*, 1276–1282.
27. Nägele, H.; Pfitzer, J.; Näegele, E.; Inone, E.R.; Eisenreich, N.; Eckl, W.; Eyerer, P. Arboform—A Thermoplastic, Processable Material from Lignin and Natural Fibers. In *Chemical Modification, Properties and Usage of Lignin*; Hu, T.Q., Ed.; Springer: Cham, Switzerland, 2002; pp. 101–117.
28. Burkhardt-Karrenbrock, A.; Seegmüller, S.; Burk, R. Liquid wood—A review. *Holz Als Roh Und Werkst.* **2001**, *59*, 13–18. [CrossRef]
29. Favier, L.; Simion, A.I.; Hlihor, R.M.; Fekete-Kertész, I.; Molnár, M.; Harja, M.; Vial, C. Intensification of the photodegradation efficiency of an emergent water pollutant through process conditions optimization by means of response surface methodology. *J. Environ. Manag.* **2023**, *328*, 116928. [CrossRef]
30. Montgomery, D.C. *Design and Analysis of Experiments*, 8th ed.; John Wiley & Sons, Inc.: New York, NY, USA, 2013.
31. Box, G.E.P.; Draper, N. *Empirical Model Building and Response Surfaces*; Wiley: New York, NY, USA, 1987.
32. Box, G.E.P.; Hunter, W.; Hunter, J.S. *Statistics for Experimenters*; Wiley: New York, NY, USA, 1978.
33. Lepadatu, D.; Judele, L.; Antonescu, I. Advanced Experimental Design and Optimization Methods for New Building Materials Developed in Civil Engineering. In *Sustainable Industrial Processing Summit SIPS2018 New and Advanced Materials and Technologies*; Kongoli, F., Marquis, F., Chen, P., Prikhna, T., Chikhradze, N., Eds.; FLOGEN Star Outreach: Montreal, QC, Canada, 2018; Volume 6, pp. 263–286.
34. Bliuc, I.; Lepadatu, D.; Iacob, A.; Judele, L.; Bucur, R.D. Assessment of thermal bridges effect on energy performance and conden sation risk in buildings using DoE and RSM methods. *J. Eur. J. Environ. Civ. Eng.* **2017**, *21*, 1466–1484.
35. Testo Termographic Camera. Available online: https://static-int.testo.com/media/c9/6e/651946818e07/testo-870-Instruction-manual.pdf (accessed on 2 September 2023).
36. Double Climate Chamber. Available online: https://www.feutron.de/en/double-climate-test-chamber/ (accessed on 2 September 2023).
37. RDM Software v. 7. Available online: https://iut.univ-lemans.fr/ydlogi/rdm_version_7.html (accessed on 2 September 2023).

38. Lepadatu, D.; Stefanescu, D.; Velicu, C. *Elements of Building Physics and Hygrothermal Calculation*; PIM: Iasi, Romania, 2017; p. 180.
39. Isomet. Available online: https://www.appliedp.com/product/isomet/ (accessed on 2 September 2023).
40. Mishra, K.; Siwal, S.S.; Nayaka, S.C.; Guan, Z.; Thakur, V.K. Waste-to-chemicals: Green solutions for bioeconomy markets. *Sci. Total Environ.* **2023**, *887*, 164006. [CrossRef]
41. Lerman, P.; Scheepers, G. Determination of a mass-transfer coefficient for wood drying by means of thermography. *Wood Mater. Sci. Eng.* **2023**. [CrossRef]
42. Bruma, B. Comparative Numerical Studies on the Thermal Performance of Building Envelope Elements. Ph.D. Thesis, Technical University of Cluj Napoca, Cluj-Napoca, Romania, 2015.
43. Gavrilă, L. *Transfer Phenomena. Heat and Mass Transfer*; Alma Mater: Bacău, Romania, 2000.
44. Electronic Microscope. Available online: https://microscopecentral.com/products/olympus-bx51m-metallurgical-microscope (accessed on 2 September 2023).
45. Kaimeng, X.; Guanben, D.; Siqun, W. Wood Plastic Composites: Their Properties and Applications. In *Engineered Wood Products for Construction*; Gong, M., Ed.; IntechOpen: Rijeka, Croatia, 2021; p. 12. Available online: https://www.intechopen.com/chapters/77629 (accessed on 2 September 2023).
46. Sommerhuber, P.F.; Wang, T.; Krause, A. Wood-plastic composites as potential applications of recycled plastics of electronic waste and recycled particleboard. *J. Clean. Prod.* **2016**, *121*, 176–185. [CrossRef]
47. Elsheikh, A.H.; Hitesh, P.; Shanmugan, S.; Muthuramalingam, T.; El-Kassas, A.M.; Ramesh, B. Recent progresses in wood-plastic composites: Pre-processing treatments, manufacturing techniques, recyclability and eco-friendly assessment. *Clean. Eng. Technol.* **2022**, *8*, 100450. [CrossRef]
48. Arboform, Application Areas and Series Products. Available online: https://www.tecnaro.de/en/anwendungen/ (accessed on 2 September 2023).
49. EFECON, Eco-Innovative Products and Technologies for Energy Efficiency in Construction. European Researcher Project. Available online: https://www.efecon.tuiasi.ro/ (accessed on 2 September 2023).