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Analysis of the Possible Use of Straw from Agriculture as an Environmental Insulation Material in Buildings

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Abstract: Straw has been used as a building material since time immemorial and has been considered as a waste product from the agricultural sector, usually used for feed, bedding, or fertilization. Nowadays, the construction industry strives to reduce greenhouse gas emissions and is focusing on renewable materials; hence, straw seems to be an attractive, low-energy option. Straw bales or blown insulation are common uses, with limited detailed knowledge regarding the properties of different straw types. Straw is made up of the dry stems of crops. Straw's chemical composition will differ with different crops and can have a great impact on its effectiveness. As a renewable material, straw also has the potential to be used in buildings, enhancing thermal insulation and reducing environmental impacts. This study considers four kinds of straw: barley, oats, oilseed rape, and triticale, regarding their possible usage in insulation materials. The thermal conductivity, bulk density, and dust generation of each type were tested in the laboratory. Among them, the best performance was shown by the barley straw treated with mechanical pulping using a knife mill at 4000 rpm for 60 s, which showed the lowest bulk density and thermal conductivity and generated the least dust. It is thus proven to be an environmental insulation material with significant implications for sustainable construction and energy-efficient building design, further helping in maintaining environmental sustainability in building construction.

Keywords: green insulation material; straw; ecological material; low energy production; agriculture waste; recycling

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Academic Editors: Jairo Andrade and Edna Possan

Received: 24 February 2025
Revised: 7 April 2025
Accepted: 12 April 2025
Published: 16 April 2025

Citation: Peterková, J.; Korjenic, A.; Zach, J.; Bydžovský, J.; Halásová, S.; Sesto, E. Analysis of the Possible Use of Straw from Agriculture as an Environmental Insulation Material in Buildings. *Sustainability* **2025**, *17*, 3589. https://doi.org/10.3390/su17083589

1. Introduction

In recent years, the construction industry has been moving towards more sustainable and eco-friendly alternatives to traditional building materials. With growing concerns about climate change and resource depletion, the demand for renewable materials that reduce environmental impact has taken center stage. Insulation, which plays a crucial role in cutting energy use and boosting a building's energy efficiency, is one area in which this shift is evident. Common insulation options like expanded polystyrene (EPS), extruded polystyrene (XPS), and mineral wool, although widely used, are made from petrochemical sources, require energy-intensive production, and contribute to long-term environmental waste [1]. In response, natural fiber-based insulation materials are gaining popularity due to their renewability, biodegradability, and lower carbon footprints [2].

In addition to this, more and more emphasis is placed on ecological sustainability and reducing the environmental burden. Regarding the gradual reduction in the energy demand of building structures, the importance of built-in CO_2 emissions in the production of building materials is gradually increasing. In connection with the new requirements under the Green Deal for Europe [3] to reduce greenhouse gas emissions by 55% and aim for zero emissions by 2050, it is necessary to look for new alternative ways to achieve a balanced and environmentally friendly approach to the construction and operation of buildings and the production of building materials. In the area of building structures, the above requirements are reflected in the new amendment of the EPBD (Energy Performance of Buildings Directive) [4]. Therefore, there is a demand for new, ecological heat-insulating materials, without which buildings cannot achieve favorable energy properties.

Agricultural residues like straw from various crops are among the natural fibers being explored for use in thermal insulation [5,6]. These straws, which are by-products of cereal and industrial crop farming, offer an innovative way to reduce agricultural waste while supporting circular economy practices. Abundant and renewable, these straws also have valuable characteristics—a low density as well as good mechanical and thermal insulation properties—that make them promising options for producing effective insulation materials [7].

Prior research has shown that agricultural residues, especially cereal straws, can be effectively used in the development of construction materials [8,9].

Barley straw (Hordeum vulgare) is one of the most widely available agricultural residues, particularly in regions where it is cultivated for animal feed or human consumption [10]. The world's largest barley producer is Russia, while the western provinces of Canada and the southern states of Australia are also important global producers. Within the EU, the key barley producers are mainly France, Germany, and Spain [11]. In 2024, a total of 19.3 million tons of barley were produced in Russia, and in 2023, 20.5 million tons were produced [12]. Studies have demonstrated that barley straw, with its relatively high cellulose content of 36–43%, can be mechanically processed into fine particles suitable for insulation material, offering a lightweight structure and favorable thermal insulation properties [13].

Similarly, oats (Avena sativa), another cereal crop commonly cultivated in temperate regions, produces straw with a cellulose content of approximately 31–35% [7]. One of the main producers of oats within the EU is Poland, followed by Scandinavian countries (Finland and Sweden). In 2024, 2.27 million tons of oats were produced in Poland [14]. Other major producers worldwide are Russia and Canada [11]. Oat straw has been examined in research focused on its potential as a fibrous material in thermal insulation, in which its mechanical properties and low density make it an attractive alternative to synthetic fibers [15].

Oilseed rape (Brassica napus), known for its industrial use in oil production, also generates significant quantities of straw as a by-product. Canada is one of the world's largest producers of rapeseed (with 22.011 million tons produced in 2024); within the EU, France, Germany, Poland, and the United Kingdom are significant producers [11,16]. With a cellulose content ranging from 49 to 52%, oilseed rape straw has shown potential as a bio-based insulation material [7,17]. Research has indicated that when processed correctly, oilseed rape straw can achieve a comparable thermal conductivity to that of conventional insulants, making it an intriguing option for sustainable building applications [18].

Triticale (Triticosecale), a hybrid cereal crop derived from the crossbreeding of wheat and rye, produces straw with a high cellulose content of around 48–50% [13]. The world's largest producer of this crop is Poland, followed by France and Germany [19]. In 2023, 5.28 million tons of this crop were produced in Poland [20]. Triticale straw's mechanical properties and fibrous structure have been the subject of various studies aimed at evaluating its suitability for thermal insulation [21–23]. In particular, triticale's higher lignin content compared to other cereal straws can contribute to improved moisture resistance, a desirable characteristic in insulation materials.

Thermal insulation plays a vital role in minimizing energy losses during a building's operation. It is necessary to move to more sustainable models of building construction and renovation. The substitution of synthetically produced materials with insulating materials based on natural fibers, especially on the basis of lignin–cellulose fibers, represents a very promising path.

The decreasing demand for straw in traditional agricultural uses, like livestock bedding and feed, has opened the door for exploring new ways to utilize this abundant by-product [24]. With large amounts of straw produced each year and its relatively low market value, there is a strong case for repurposing it as a sustainable raw material for the construction industry. In particular, straw from barley, oat, oilseed rape, and triticale stalks is an underutilized resource due to its lower use in agriculture, which has great potential for conversion into cellulose-based insulation materials. Straw from these crops represents an alternative raw material source for wood, flax, and hemp [25]. The price of straw from these agricultural crops in the Czech Republic is significantly more favorable than the prices of flax and hemp, and it can therefore be stated that it is also suitable from an economic point of view for use in construction as an insulating material. Rapeseed straw is the cheapest, with a price ranging from 25 to 40 EUR/ton, followed by barley, whose straw has a market value of around 150 EUR/ton, and the prices of oat and triticale straw are similar, around 200 EUR/ton. The prices of flax and hemp are higher, with flax in particular ranging from 300 to 1000 EUR/ton and hemp around 210 EUR/ton [26].

This study builds on previous research and focuses on the development of sustainable, cellulose-based thermal insulation materials from agricultural residues, specifically straw from barley, oats, oilseed rape, and triticale.

The primary objective is to investigate the suitability of these raw materials by analyzing their physical properties—loose density, particle size distribution, and thermal conductivity—following mechanical processing using a knife mill. By evaluating these characteristics, the research aims to identify the optimal processing conditions for producing insulation materials with performance comparable to traditional insulants such as expanded polystyrene (EPS), extruded polystyrene (XPS), and mineral wool.

The methodology for this study involves mechanically pulping the straw samples under a controlled knife mill rotation speed and grinding time. A range of laboratory tests, including a sieve analysis and thermal conductivity measurements, are conducted to assess the effectiveness of each straw type as an insulant. By comparing the results across barley, oats, oilseed rape, and triticale straw, this research seeks to determine which material performs best in terms of insulation properties.

Previous research has highlighted the potential of agricultural residues as a source of cellulose for insulation materials [27–29], but few studies have directly compared multiple straw types under uniform processing conditions. This study aims to fill that gap by providing a comprehensive analysis of the most suitable straw type, while also offering insights into the processing parameters that influence the final product's performance. The research findings will contribute to the ongoing development of eco-friendly building materials, promoting the use of renewable agricultural by-products in sustainable construction.

2. Materials and Methods

2.1. Selection of Suitable Input Raw Materials

Based on the research carried out, potentially suitable raw material sources for the production of cellulose-based thermal insulation materials were selected. These were agricultural feedstocks, specifically straw from various crops. The reason for this choice was the observation that, as a result of the decreasing share of litter farming in recent years, the possibilities for using straw in this sector are decreasing. On the basis of the shares of each crop type in the agricultural area in 2024 in the Czech Republic and the cellulose content, three cereal types and one representative industrial crop were selected; see Table 1 and Figure 1. These were straws from barley (the sown area in the Czech Republic in 2024 was 317,119 10ths. m^2), oats (the sown area in the Czech Republic in 2024 was 52,618 10ths. m^2), oilseed rape (the sown area in the Czech Republic in 2024 was 343,380 10ths. m^2), and triticale (the sown area in the Czech Republic in 2024 was 44,048 10ths. m^2); see Figure 2. In 2023, 153,400 tons of oats were harvested in the Czech Republic with an average yield of 3.79 t/ha, 995,000 tons of barley with an average yield of 5.23 t/ha, more than a million tons of oilseed with an average yield of 5.3 t/ha, and 211,300 tons of triticale with an average yield of 5.34 t/ha [30].

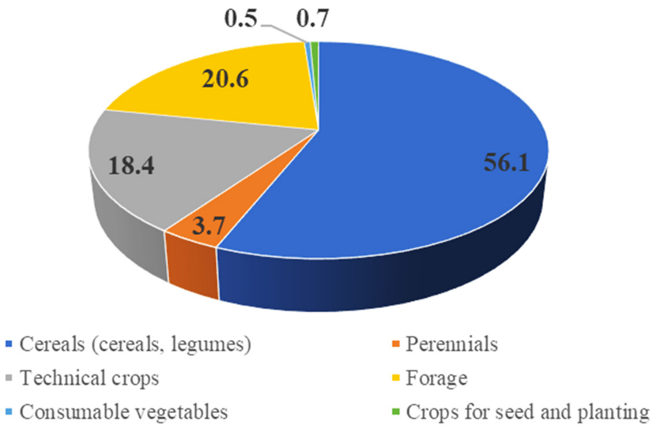


Figure 1. Share of each crop type in the total area sown in 2024 in Czech Republic (%) (2,416,064 ha) [31].

(**A**) (**B**)

Figure 2. *Cont.*

(C) (D)

Figure 2. Selected types of agricultural raw materials: (**A**) oats; (**B**) barley; (**C**) oilseed rape; (**D**) triticale.

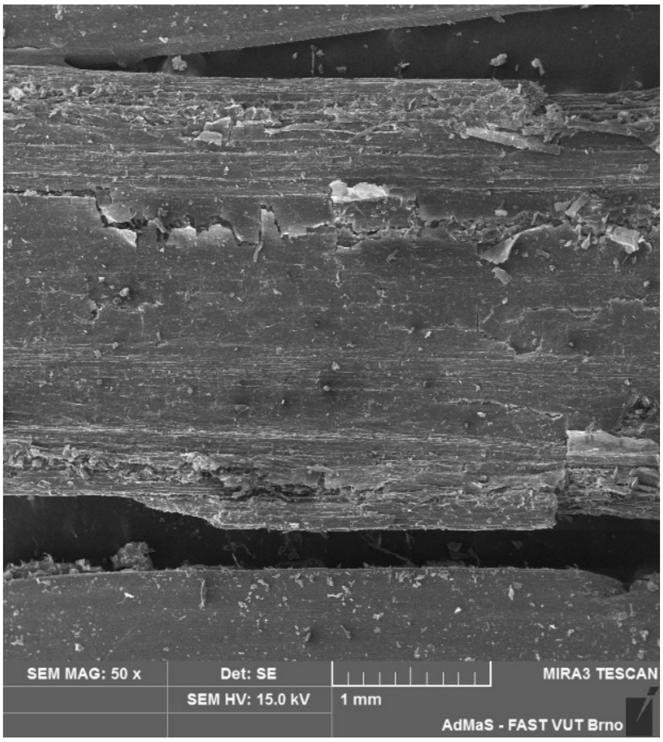
Table 1. Chemical composition of selected natural materials [32–37].

Raw Materials	**Percentage Content [wt.%]**		
	Cellulose	**Hemicellulose**	**Lignin**
Sorghum	32–35	24–27	15–21
Barley	36–43	24–33	6–9
Oats	31–35	20–26	10–15
Wheat	35–39	23–30	12–16
Triticale (hybrid cereal—wheat and rye)	48–50	25–27	15–17
Oilseed rape	49–52	12–15	16–19
Sunflower	34–42	13–33	12–30
Hemp	64–71	17–24	6–8
Flax	65–75	13–26	5–7
Coniferous wood	33–42	22–40	27–32
Deciduous wood	38–51	17–18	21–31

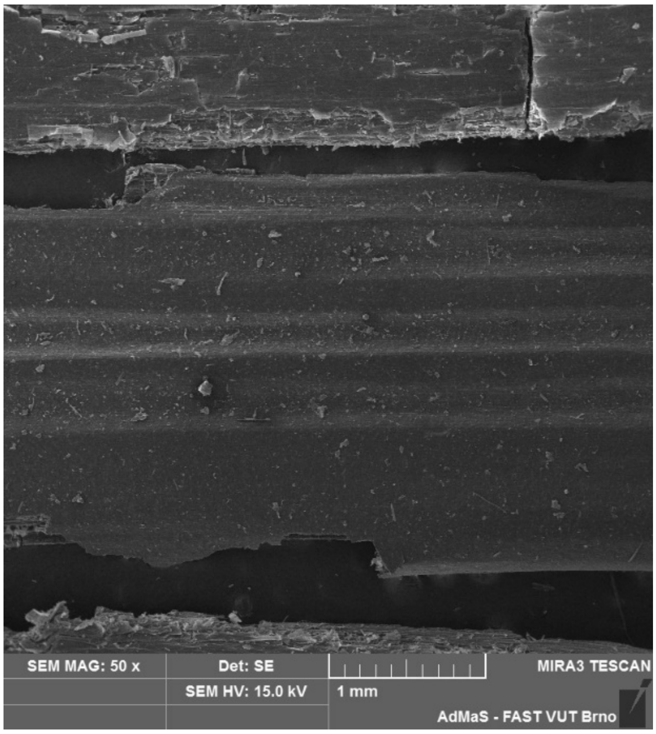
The straws selected based on the research were supplied by local farmers for this study. Straw harvesting took place in 2 phases: in the first phase, the upper parts of the crops were collected by a combine harvester, and the straws were dried in the field and then collected with a volume of at least 100 L for further laboratory testing. The actual preparation of samples for testing selected properties was carried out according to EN 15101-1 [38].

The SEM images, as shown in Figure 3, show the surface structure of each crop type. From the images, it can be seen that, in the case of oats, the surface of the straw particles is more open and porous. On the other hand, the oilseed rape and triticale straw particles are the most compact.

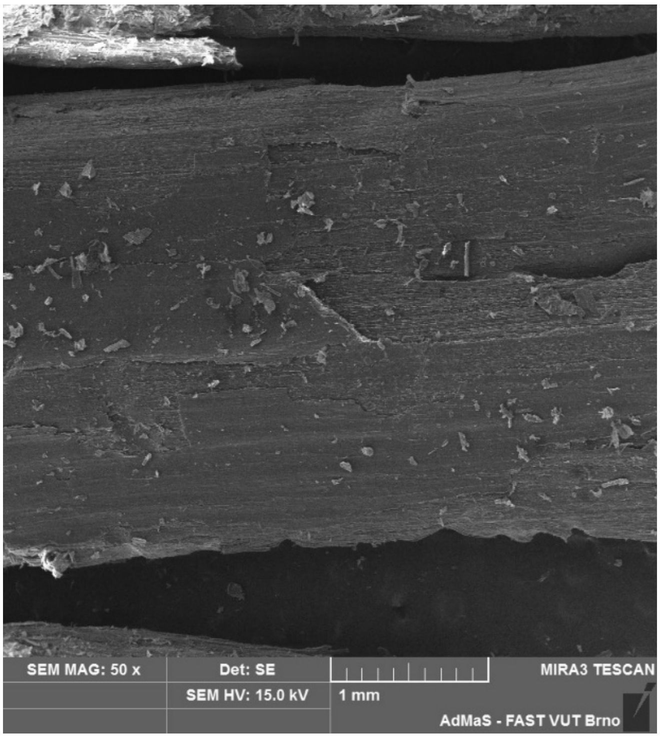
Initially, representative straw samples were stored in laboratory conditions at 23 °C and 50% relative humidity until the weight stabilized. Then, the straw samples were subjected to the following tests: moisture determination using a drying balance, ash determination according to the Tappi T 211 om-02 standard [39], and basic analytical tests to determine the chemical composition, i.e., determination of the contents of polysacharides (cellulose and hemicellulose) and polyphenols (lignin). The determination of the cellulose content was carried out by the nitration method according to Kürschner–Hoffer, the determination of the hemicellulose content was carried out by extraction of holocellulose according to Wise with 5% and 24% NaOH [40], and the determination of the lignin content was carried out by Klason according to the Tappi T 222 om-11 standard [41].



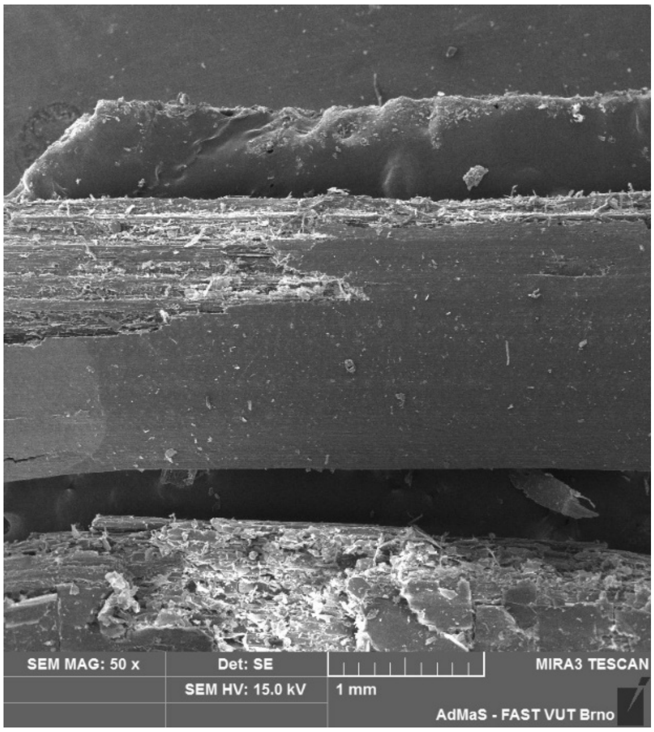
OAT



BARLEY



OILSEED RAPE



TRITICALE

Figure 3. Images of straw from electron microscope TESCAN MIRA3 XM (Brno, Czech Republic), magnification 50×.

The evaluation of these analyses is presented in Table 2 below. The highest polysaccharide content was found in the triticale straw sample, while the highest lignin content was analyzed in oilseed rape straw. The remaining components of straw, such as pectin, fats, nitrogenous substances, silicon dioxide, and minerals, have not been determined.

Table 2. Overview of measured values for straw (polysaccharides and lignin).

Straw	Percentage Content (wt.%)				
	Moisture	Fly Ash	Cellulose	Hemicellulose	Lignin
Oats	7.375	9.5	32	22	13
Barley	8.587	6.0	39	28	6
Oilseed rape	8.791	6.1	51	13	17
Triticale	7.485	6.8	50	26	15

The aim was to research the possibility of using these agricultural residues in the construction industry in the form of insulation materials. In the first stage of sample preparation, the different types of straw were cut by shearing to a length of about 3 cm, taking into account the maximum recommended length of 4 cm of ground material for a given type of knife mill. They were then mechanically pulped in a Pulverisette 11 knife mill (producer: FRITSCH, Weimar, Germany) under the given conditions (for the grinding interval and speed of the grinding knife); see Figure 4. Table 3 below lists the samples and their markings, including their preparation process—frequency and grinding time. These are 4 test sets of different types of straw, each set containing 7 test samples according to their treatment—pulping.

Figure 4. Knife mill Pulverisette (FRITSCH, Weimar, Germany).

Table 3. Overview and designation of test samples according to their preparation.

BARLEY			OATS		
Sample Designation	**Grinding Frequency (rpm/min)**	**Grinding Time (s)**	**Sample Designation**	**Grinding Frequency (rpm/min)**	**Grinding Time (s)**
J-2/120	2000	120	O-2/120	2000	120
J-4/60	4000	60	O-4/60	4000	60
J-4/120	4000	120	O-4/120	4000	120
J-6/30	6000	30	O-6/30	6000	30
J-6/60	6000	60	O-6/60	6000	60
J-8/60	8000	60	O-8/60	8000	60
J-10/60	10,000	60	O-10/60	10,000	60
TRITICALE			**OILSEED RAPE**		
Sample Designation	**Grinding Frequency (rpm/min)**	**Grinding Time (s)**	**Sample Designation**	**Grinding Frequency (rpm/min)**	**Grinding Time (s)**
T-2/120	2000	180	R-2/120	2000	120
T-4/60	4000	60	R-4/60	4000	60
T-4/120	4000	120	R-4/120	4000	120
T-6/30	6000	30	R-6/30	6000	30
T-6/60	6000	60	R-6/60	6000	60
T-8/60	8000	60	R-8/60	8000	60
T-10/60	10,000	60	R-10/60	10,000	60

2.2. Laboratory Testing Methodology

The loose density of the material was determined for all straw test samples (barley, oats, triticale, and oilseed rape), and sieve analysis was also carried out. As straw is a material for which precise testing procedures are not currently established in the Czech Republic, these tests were carried out according to normative procedures for aggregates. On the basis of loose density, particle size in each fraction, and visual assessment, one sample from each set was selected for which the thermal conductivity was determined.

- Determination of loose density

The determination of the loose density was carried out according to EN 1097-3 [42] for the determination of the bulk density and the spacing of loose aggregate. A watertight cylindrical container with a capacity of 1.0 L was used for the test. The determination of the loose density was carried out by filling a cylindrical container of known weight with a test sample of straw up to the rim, and the excess of the sample above the rim of the container was cut with a steel ruler so that compaction did not occur. The sample container was weighed, and the weight was recorded. This procedure was used to determine the weight three times for each sample.

The loose density was calculated according to the following relationship:

$$\rho_l = \frac{m}{V} \tag{1}$$

where:

- ρ_l—loose density of straw [kg/m^3];
- m—weight of test samples [kg];
- V—volume of testing container [m^3].

- Determination of grain size by sieve analysis

The test was carried out according to the EN 933-1 [43] standard for the determination of aggregate grain size, while the part involving washing the input material was skipped due to the different nature of the test sample. Measurements were performed 3 times for each straw sample.

A standard set of sieves with mesh diameters of 125 mm; 63 mm; 31.5 mm; 16 mm; 8 mm; 4 mm; 2 mm; 1 mm; 0.5 mm; 0.25 mm; 0.125 mm; and 0.063 mm is used for the determination of the grain size. For the purpose of testing straw fibres, the 0.25 mm mesh sieve was replaced by a 0.20 mm mesh sieve.

Before testing, the standard set of sieves was stacked in a column with the smallest diameter at the bottom and the largest diameter at the top. The bottom was fitted under the smallest-diameter sieve, and the lid was fitted over the largest-diameter sieve. The sample was weighed to the required quantity and poured onto the prepared set of sieves. The column was further mechanically shaken on a shaking table for 1 min. After shaking, the sieve column was disassembled, and the balances on each sieve were weighed. Grain size curves were generated from the measurements.

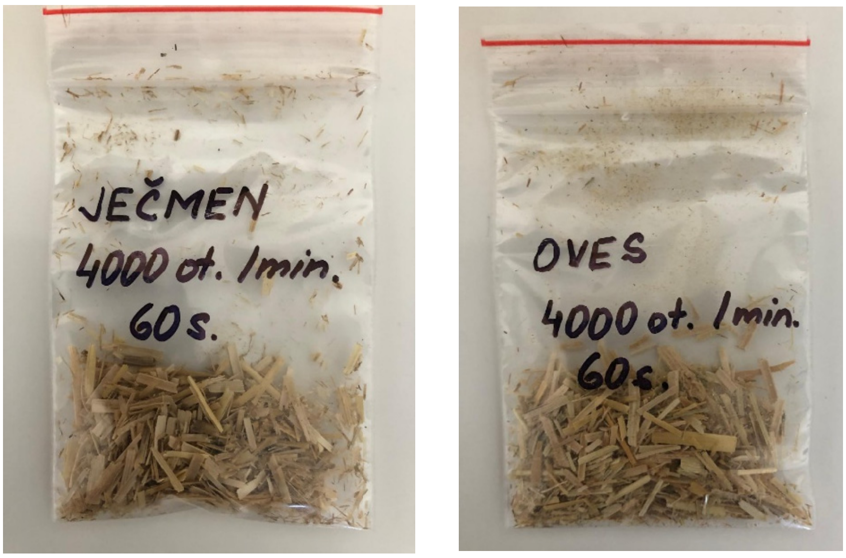
- Determination of thermal conductivity

Determination of the thermal conductivity was carried out according to EN 12667 [44] according to ISO 8301 [45] (heat flux meter method). Measurements were taken using a Lambda 2300 device (Holometrix Micromet Inc., Bedford, MA, USA). Straw samples with dimensions of 300 mm × 300 mm (conditioned under laboratory conditions of 23 °C and 50% relative humidity) were placed between the heating and cooling plates of the device and the voltages on the heat flux meters were measured. Five measurements of the thermal conductivity at a mean temperature of 10 °C and a temperature gradient of 10 K were taken for each sample, after which the test sample was removed, the material was replenished and compacted by gently pushing it into the frame, and a series of three measurements were taken again.

3. Results

In the samples of individual straw types after mechanical pulping in the knife mill, it was evident that with increasing grinding time and with increasing speed of the knife mill, the individual straw particles were shorter and the samples also contained more dust fractions, which then negatively affect the thermal insulation function of the materials.

On the basis of the macroscopic assessment and results for the loose density, the samples mechanically pulverized at 4000 rpm with a grinding time of 60 s were selected as optimal; see Figure 5.



BARLEY *OATS*

Figure 5. *Cont.*

OILSEED RAPE *TRITICALE*

Figure 5. Test samples of straw pulped at 4000 rpm and a grinding time of 60 s.

3.1. Evaluation of the Results of the Loose Density Determination

From the determined values of the loose densities according to the standard EN 1097-3, which are given in Table 4 below, it can be concluded that the loose density increases with increasing grinding time and also with increasing speed of the knife mill.

Table 4. Summary of determined loose densities for all samples.

Type of Straw	Sample	Loose Density (kg/m^3)	Type of Straw	Sample	Loose Density (kg/m^3)
BARLEY	J-2/120	50	OILSEED RAPE	R-2/120	83
	J-4/60	72		R-4/60	152
	J-4/120	91		R-4/120	185
	J-6/30	75		R-6/30	144
	J-6/60	89		R-6/60	165
	J-8/60	108		R-8/60	168
	J-10/60	117		R-10/60	156
OATS	O-2/120	79	TRITICALE	T-2/120	79
	O-4/60	124		T-4/60	96
	O-4/120	151		T-4/120	132
	O-6/30	123		T-6/30	98
	O-6/60	156		T-6/60	107
	O-8/60	173		T-8/60	112
	O-10/60	187		T-10/60	110

This fact is confirmed by the fact that, for all the straw types, the lowest loose density was recorded for the samples mechanically pulped at a frequency of 2000 rpm and a grinding time of 2 min. On the other hand, the highest loose density values were recorded at 10,000 rpm and a grinding time of 60 s for barley and oat straw. In the case of oilseed rape straw and triticale straw, the highest loose density values were for the samples obtained at a grinding frequency of 8000 rpm for 60 s. According to these facts, it can be assumed that an increase in the speed of the knife mill and the grinding time of the raw material leads to an increase in the fines in the samples, which causes an increase in the bulk density, which then has a negative impact on the thermal insulation function of the material.

A comparison of the samples pulped at 4000 rpm and a grinding time of 60 s (see Figure 6), as selected by the macroscopic assessment, shows that the lowest bulk density values were measured for the barley straw sample, while the highest values were obtained for oilseed rape.

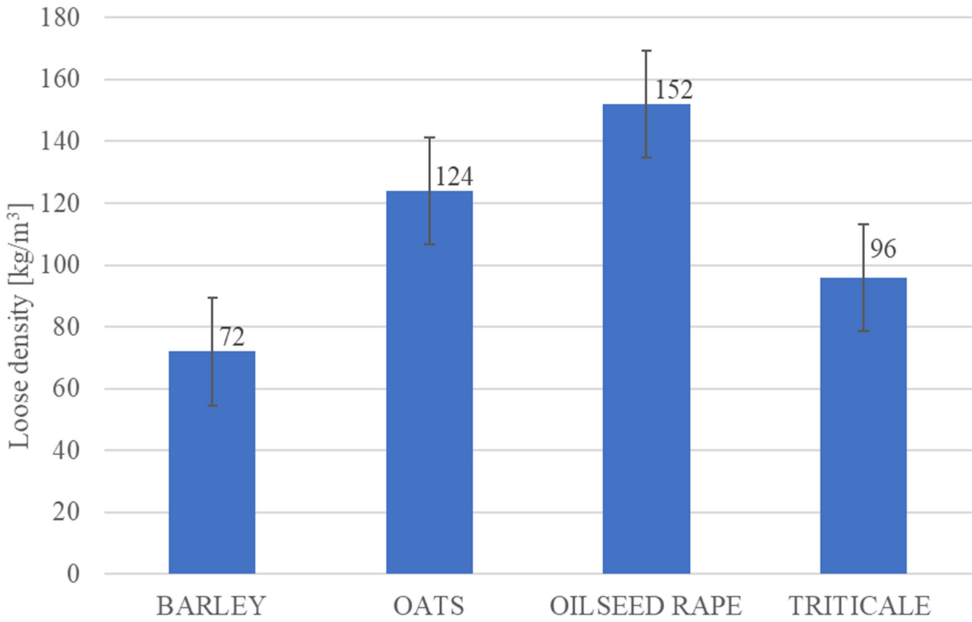


Figure 6. Comparison of bulk weights of individual straw samples pulped at 4000 rpm and grinding time of 60 s.

3.2. Evaluation of the Results of Sieve Analysis

The sieve analyses of individual straw samples were carried out according to EN 933-1. The resulting grain size curves for the individual straw samples are presented in Figures 7–10. Based on these sieve analyses, it can be stated that the grinding time and grinding frequency have a significant effect on the fineness of the obtained materials. Our expectation was confirmed: with a higher grinding frequency and a higher grinding time, there is a higher proportion of fine particles in the straw samples. It can be observed that the samples ground at the highest frequency (10 thousand revolutions per minute) from barley and triticale straw show 100% collapse only at a sieve mesh size of 2 mm, in comparison to oat and rapeseed straws, which show 100% collapse already at a sieve size of 1 mm; i.e., they contain finer fractions.

In addition, the mean particle sizes of the individual samples were calculated, and the weight fractions of fine particles with a maximum grain size of 1 mm were determined. The grain size of 1 mm was chosen as the decisive grain size for the determination of the fine fractions because particles below 1 mm exhibit high dustability and are the reason for the higher loose density.

The obtained data are summarized in Tables 5 and 6, which confirm the assumption that with increasing speed and longer grinding time, the proportion of fine fractions in the material increases, while, conversely, with decreasing speed and a shorter grinding time interval, the proportion of coarser particles increases. Considering the achieved values, the mean value for the particle size, and the proportion of grains up to 1 mm, barley straw appears to be optimal, which has the smallest proportion of fine particles at 4000 rpm and a grinding time of 60 s, 32%, which is also closely related to the chemical composition of this straw (with a high content of polysaccharides and low content of lignin). Figures 11 and 12 present the results for the mean value of the particle size and proportion of grains up to 1 mm for the best barley straw sample. Graphical evaluation for all other straws is given in the Appendix A, Figures A1–A6.

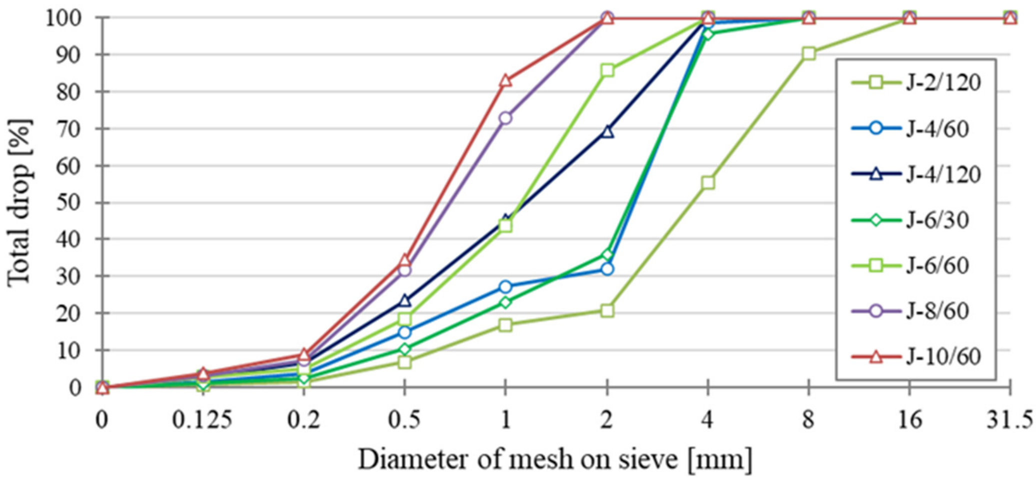


Figure 7. Sieve analysis of barley samples.

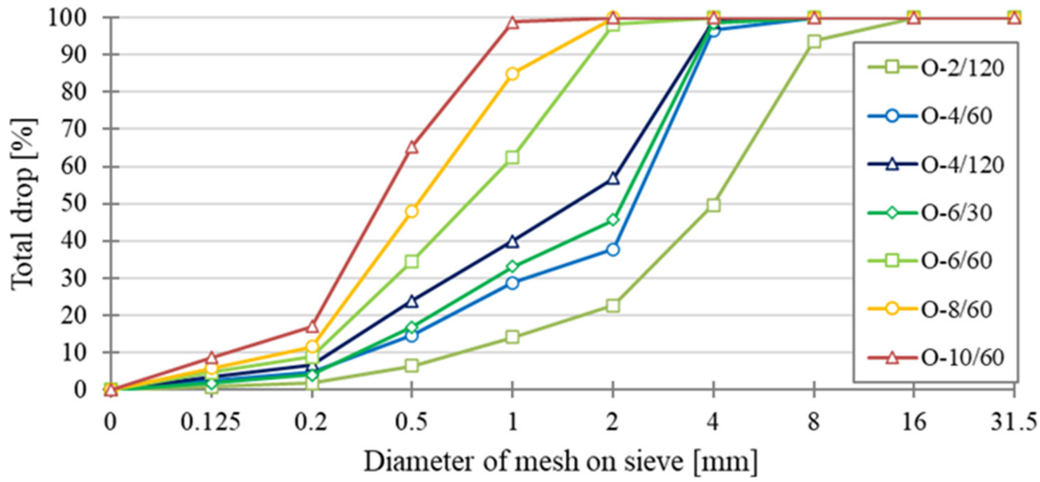


Figure 8. Sieve analysis of oat samples.

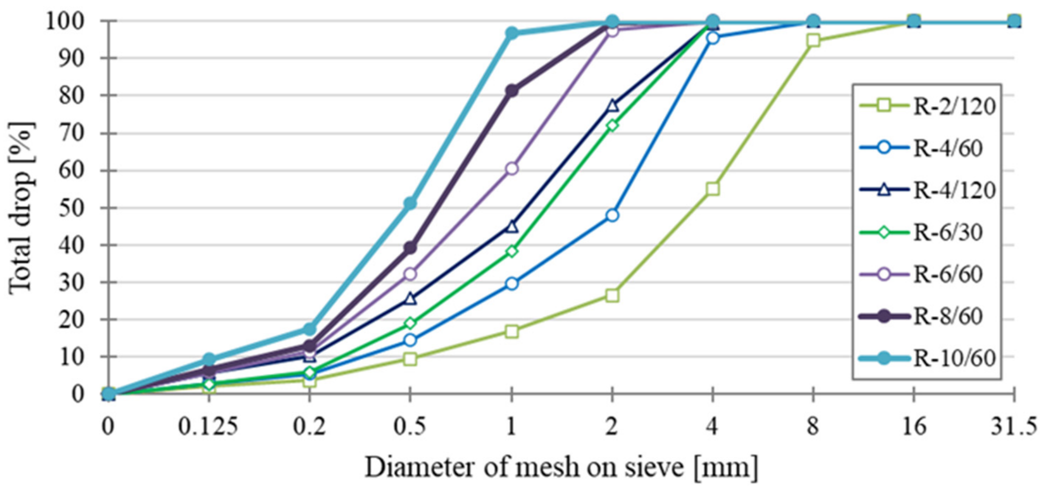


Figure 9. Sieve analysis of oilseed rape samples.

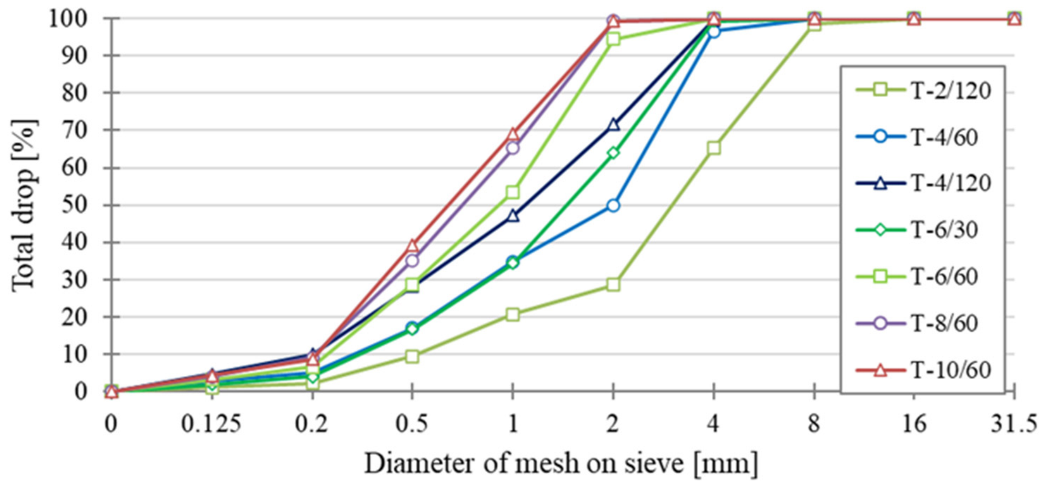


Figure 10. Sieve analysis of triticale samples.

Table 5. Overview of mean values of particle size (mm).

Raw Material Processing (Grinding Frequency in ths. rpm/min/time in s)	BARLEY	OAT	OILSEED RAPE	TRITICALE
2/120	2.97	2.94	2.72	2.33
4/60	1.52	1.50	1.41	1.34
4/120	1.00	1.17	0.92	0.96
6/30	1.58	1.35	1.02	1.15
6/60	0.86	0.59	0.61	0.69
8/60	0.53	0.42	0.46	0.56
10/60	0.47	0.29	0.34	0.53

Table 6. Overview of proportion of grains up to 1 mm (wt.%).

Raw Material Processing (Grinding Frequency in ths. rpm/min/time in s)	BARLEY	OAT	OILSEED RAPE	TRITICALE
2/120	21	23	27	29
4/60	32	38	48	50
4/120	69	57	78	72
6/30	36	46	72	64
6/60	86	98	98	94
8/60	100	100	100	99
10/60	100	100	100	99

Based on the sieve analyses and determination of the fines content, the samples mechanically pulverized at 4000 rpm and a grinding time of 60 s, containing up to 50 wt.% of fines, were selected as the optimum samples for the thermal conductivity determination; see Figure 13. Thus, the same samples were selected as those for the loose density.

3.3. Evaluation of Determination of Thermal Conductivity

The determination of the thermal conductivity was carried out according to EN 12667 and ISO 8301 (the heat flux meter method) on the samples of all types of straw pulped at 4000 rpm and a grinding time of 60 s, which was selected as optimal according to the determination of loose densities and the sieve analyses. Two series of three measurements of the thermal conductivity coefficient were taken for each of the samples, the first series of measurements taken for a sample of loose material and the second series taken for compacted material (the material was placed in a frame made of extruded polystyrene with internal dimensions of 200 × 200 mm and the thermal conductivity coefficient was measured in this frame for its thickness). In parallel with these measurements, the thicknesses of the individual layers of material were determined, from which the loose densities for that series of measurements were then calculated. The measured and calculated values are shown in Table 7 below.

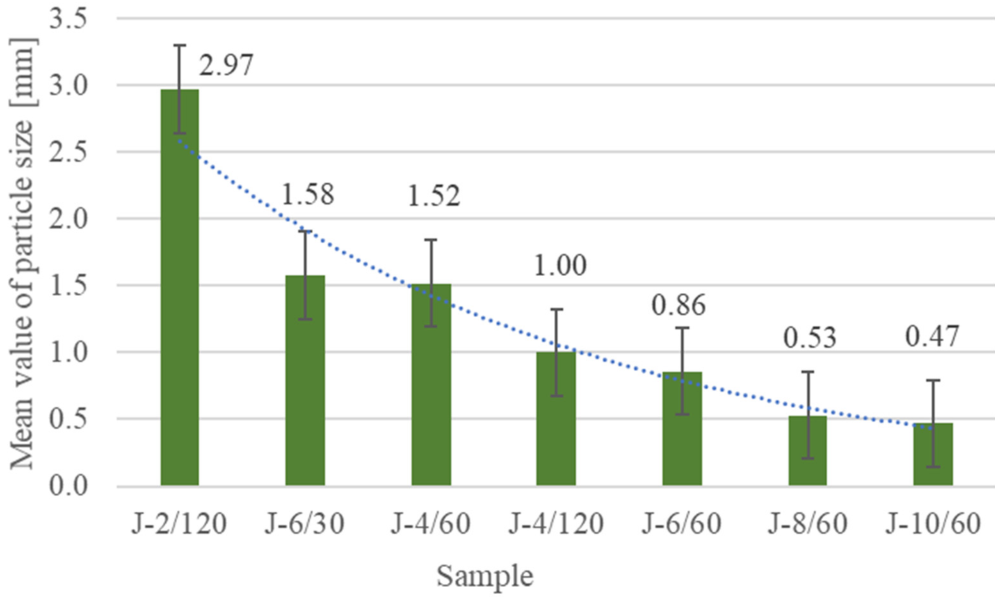


Figure 11. Comparison of mean particle sizes of barley samples.

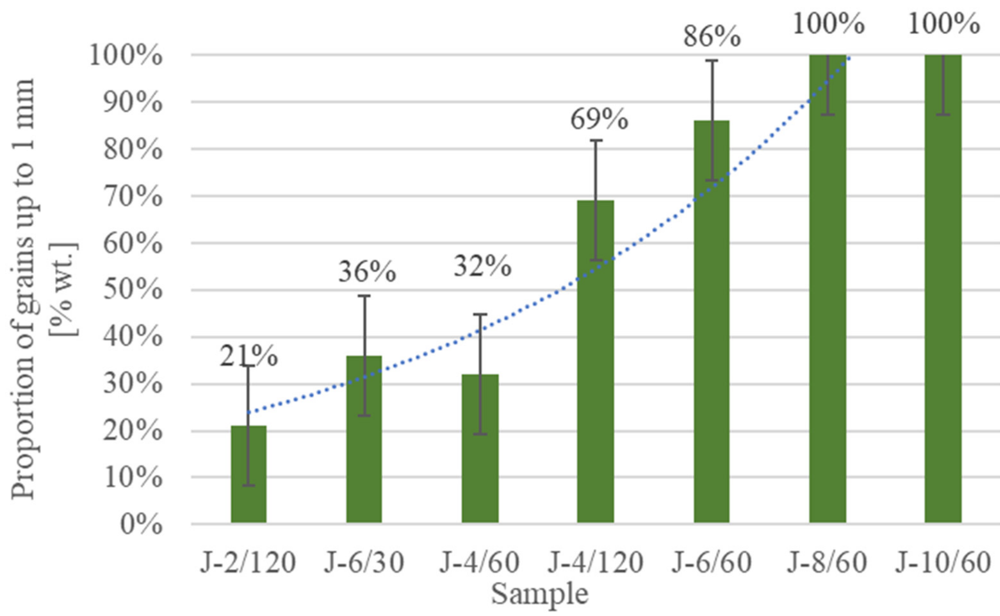


Figure 12. Comparison of mass fractions of particles below 1 mm in barley samples.

According to the resulting values and their comparison in Figure 14, the barley straw sample achieved the lowest values of the thermal conductivity in the loose and compacted state, while the oilseed rape straw sample achieved the highest values in both states. The barley straw also had the lowest bulk density, while the rapeseed straw had the highest bulk density. An interesting feature of the barley straw, in addition to having the lowest thermal conductivity, was that the thermal conductivity decreased with increasing bulk density for the sample in the compacted state. For the remaining samples, an increase in thermal conductivity was also observed with an increase in bulk density. From the point of view of their thermal insulation properties, it can be stated that an effective treatment was chosen, which achieved significantly better thermal insulation properties, especially for barley straw, than the researchers from Eindhoven University of Technology, who determined that the thermal conductivity coefficient in the dried state at a bulk density of 100 kg/m^3 was 0.052 W/(m·K) [46].

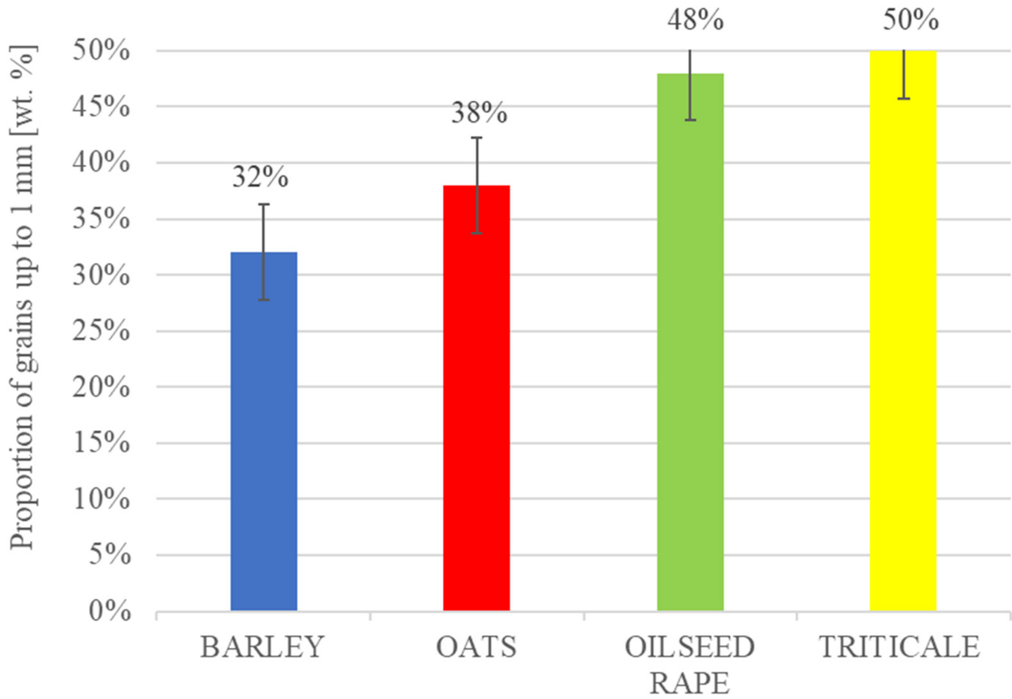


Figure 13. Comparison of the fines content of samples pulped at 4000 rpm and 60 s.

Table 7. Overview of determined values of thermal conductivity.

Type of Straw		OATS		BARLEY		OILSEED RAPE		TRITICALE	
Sample		**O-4/60**		**J-4/60**		**R-4/60**		**T-4/60**	
State		**Loose**	**Compacted**	**Loose**	**Compacted**	**Loose**	**Compacted**	**Loose**	**Compacted**
Dimensions (mm)	**a**	198.00							
	b	208.00							
	t	23.20	23.58	22.71	23.15	23.98	24.61	22.86	23.50
Weight (g)		122.68	151.32	55.31	65.68	136.73	165.16	115.29	130.23
Loose density (kg/m^3)		128	156	59	69	138	163	122	135
Thermal conductivity (W/(m·K))		Measurement 1							
		0.0420	0.0429	0.0367	0.0361	0.0451	0.0466	0.0424	0.0428
		Measurement 2							
		0.0418	0.0429	0.0367	0.0359	0.0448	0.0465	0.0421	0.0427
		Measurement 3							
		0.0415	0.0428	0.0363	0.0359	0.0446	0.0464	0.0421	0.0426
		Average value of thermal conductivity							
		0.0418	0.0428	0.0366	0.0360	0.0448	0.0465	0.0422	0.0427

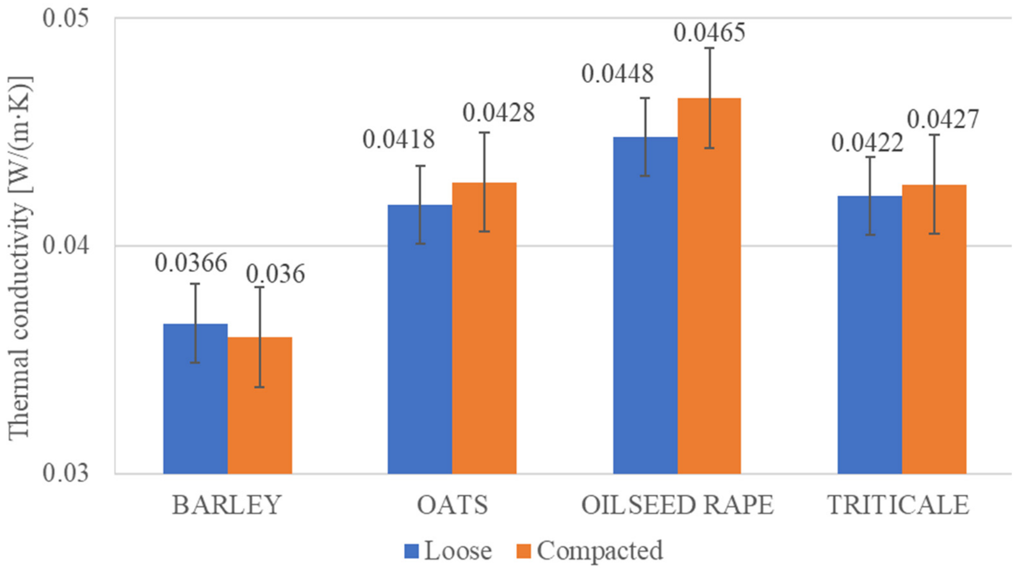


Figure 14. Comparison of thermal conductivities of free-flowing and compacted samples (mechanically pulverized at 4000 rpm and a grinding time of 60 s).

4. Discussion

Based on the selection of suitable input raw material sources from agriculture, tests were carried out on four types of straw, namely barley, oat, oilseed rape, and triticale straw. The different types of straw were mechanically pulped with a knife mill under given conditions (knife rotation speed and grinding time) and then subjected to laboratory tests, the determination of their loose density, a sieve analysis, and the determination of their thermal conductivity.

In the first phase of the work, a macroscopic assessment of the particles was carried out on individual samples of each straw type, looking for optimal grinding intervals so that the sample mainly contained particles from the interval of about 1–3 mm. The upper limit of the interval was chosen so that the particles were not too long to process. The lower limit of the interval was chosen so that the particles would not dust and increase the loose density of the material.

Next, the loose densities were determined, and the resulting values were compared. According to this comparison, it can be generally concluded that with increasing speed of the grinding equipment and a longer grinding time, the fineness increases, resulting in an increasing trend in the loose density. Furthermore, according to the comparison of the individual loose density, a selection of samples potentially suitable for the production of thermal insulation materials was made. For all types of straw, samples mechanically pulped at 4000 rpm and a grinding time of 60 s were selected. The lowest loose density of 72 ± 0.24 kg/m^3 was achieved by this pulping method for the barley straw sample. This was followed by the triticale straw sample with a loose density of 96 ± 1.29 kg/m^3 and the oat straw sample with a loose density of 124 ± 0.47 kg/m^3. The highest loose density value of 152 ± 0.73 kg/m^3 was achieved by the oilseed rape straw sample. The obtained values fully correspond to the content of fine particles, in which the loose density increases with increasing fine particle content.

The sieve analysis and determination of fines content below 1 mm confirmed the above statement that fines increase with increasing speed and grinding time. In this case, the samples pulverized at 4000 rpm and 60 s were chosen as the optimum, as in the determination of the bulk density. This choice was made on the basis of an evaluation of the percentages of fines, and these samples reached a fines content of up to 50 wt.%. The lowest fines content of 32 wt.% was recorded for the barley straw sample with a mean particle size of 1.52 mm, followed by the oat straw sample with 38 wt.% and a mean particle size of 1.50 mm and the oilseed rape sample with 48 wt.% and a mean particle size of 1.41 mm. The highest fines content of 50 wt.% was achieved by the triticale sample with a mean particle size of 1.34 mm. The reason for these laboratory-obtained characteristics is the lower lignin content of barley and oat straw compared to that of rapeseed and triticale straw. The lignin content improves mechanical properties, especially compressive strength, but the consequence is an increase in the brittleness of the straw, which then leads to an increase in the amount of fines during crushing.

Based on the determination of loose densities and the sieve analyses, the samples pulverized at 4000 rpm and 60 s were subjected to a determination of their thermal conductivity. The lowest thermal conductivity in the loose state was obtained by the barley sample, 0.0366 W/(m·K), followed by the oat sample 0.0418 W/(m·K) and the triticale sample 0.0422 W/(m·K). The highest thermal conductivity was obtained by the oilseed rape straw sample: 0.0448 W/(m·K). After compaction, the measured values for barley were 0.0360 W/(m·K), triticale 0.0427 W/(m·K), oats 0.0428 W/(m·K), and oilseed rape 0.0465 W/(m·K). Interestingly, the barley showed a decrease in thermal conductivity after compaction compared to the loose-fill condition (this is typical for conventional thermal insulation materials). Thus, it can be seen that the bulk density optimum is higher than the bulk density in the loose-fill state, which is very advantageous in terms of the deposition of this insulator in the structure, as it is possible to compact the material without deteriorating the thermal insulation properties and thus limiting its settlement in a vertical or inclined structure. Based on the obtained thermal conductivity data, it can be stated that the barley straw showed values very close to those of the blown insulation commonly used today on the EU market; for example, the Climatizer Plus (CIUR, Brandýs nad Labem, Czech Republic) product has a thermal conductivity coefficient of 0.038 W/(m·K) at a density of 30–90 kg/m^3 and the Climawood product (STEICO, Feldkirchen, Germany) has a thermal conductivity of 0.038 W/(m·K) at a density of 36–60 kg/m^3.

The laboratory tests show that the most suitable raw material for mechanical pulping with a knife mill is barley straw, while the optimal pulping process is at a frequency of 4000 rpm and a grinding time of 60 s. The raw material pulped in this way achieves the lowest loose density and the lowest thermal conductivity. It also achieves the lowest amount of fines, which ensures lower dustiness values of the material. As the material is light and low-dust, blown insulation technology appears to be the optimum technology for processing this type of material. The advantage in this case is that barley straw has a lower thermal conductivity in the compacted state, which has a beneficial effect in the event of the settling of the blown-in thermal insulation. For the complete development of the thermal insulation material, the material would need to be further treated against the effects of fire, moisture, mould, and pests. However, existing methods that do not significantly affect the thermal insulation properties of the blown-in material are suitable for this purpose [47].

5. Conclusions

This paper was devoted to the development of thermal insulation materials based on natural raw materials: different types of straw. On the basis of our experience and knowledge acquired from research on the subject, raw material sources for the production of cellulose-based thermal insulation materials from the agricultural sector were selected. Specifically, these were barley, oat, triticale, and oilseed rape straw. Mechanical pulping on a knife mill was carried out on these raw materials and the samples were then subjected to a bulk density determination, sieve analysis, and a determination of their thermal conductivity coefficients.

Barley straw, prepared by mechanical pulping with a knife mill at a frequency of 4000 rpm for 60 s, appears to be the most suitable raw material for the production of thermal insulation materials from the samples examined. The barley straw achieved the lowest loose density of all the samples, 72 kg/m^3, the lowest proportion of fine particles, 32 wt.%, with a mean particle size of 1.52 mm, and the lowest thermal conductivity. In the free-flowing state, a thermal conductivity of 0.0366 W/(m·K) was obtained, and in the compacted state, a thermal conductivity of 0.0360 W/(m·K) was obtained. Due to the nature of the material and its properties, blown thermal insulation technology was chosen as the optimum technology for the use of this raw material.

From the measured values of thermal conductivity coefficients, which ranged from 0.0363 W/(m·K) to 0.0457 W/(m·K) for the different straw types, it can be concluded that these materials are potentially suitable for thermal insulation materials. The thermal insulation materials most commonly used in building practice, EPS, XPS, and mineral wool, have thermal conductivity coefficients of approximately 0.036 W/(m·K), 0.034 W/(m·K), and 0.036 W/(m·K), respectively. These values indicate that, given the appropriate pulping method and production technology, straw can be used to produce thermal insulants with properties approaching those of materials commonly used in building practice.

On the basis of the research activities carried out and the results achieved, it is possible to state that thermal insulation materials from barley straw represent ecological, easily renewable materials with a low carbon footprint [2,5,7,24,28]. Based on the results of the laboratory measurements, it can be stated that these insulators have significant future potential as blown insulation for buildings.

Author Contributions: Conceptualization, J.P. and J.Z.; methodology, J.Z., J.P., J.B. and A.K.; formal analysis, J.P., S.H. and E.S.; investigation, J.Z.; resources, S.H., J.P. and E.S.; data curation, J.P., J.Z., J.B., S.H. and A.K.; writing—original draft preparation, J.P., J.Z. and S.H.; writing—review and editing, J.P. and E.S.; visualization, J.P. and E.S.; supervision, J.P., J.Z., J.B. and A.K.; project administration, J.P., J.B. and A.K.; funding acquisition, J.P., J.B. and A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This paper was elaborated within the bilateral research project between the Czech Republic and Austria (Czech Science Foundation: 23-06542K, FWF Austrian Science Fund: I 6398-N) “Study of the hygroaccumulative effect of natural based materials and their influence on the moisture stability of the indoor environment of buildings” and project of Ministry of Education Youth and Sports: 8J23AT012 “Study of heat and moisture transport in the structure of materials based on natural and secondary fibers”.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

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

Abbreviations

The following abbreviations are used in this manuscript:

SEM	Scanning electron microscopy
EPS	Expanded polystyrene
XPS	Extruded polystyrene
EPBD	Energy Performance of Buildings Directive

Appendix A

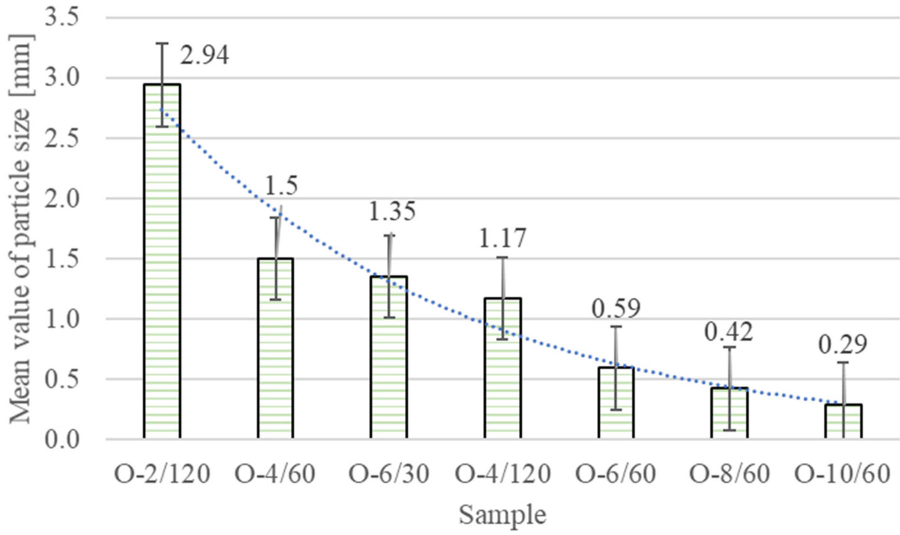


Figure A1. Comparison of mean particle sizes of oat samples.

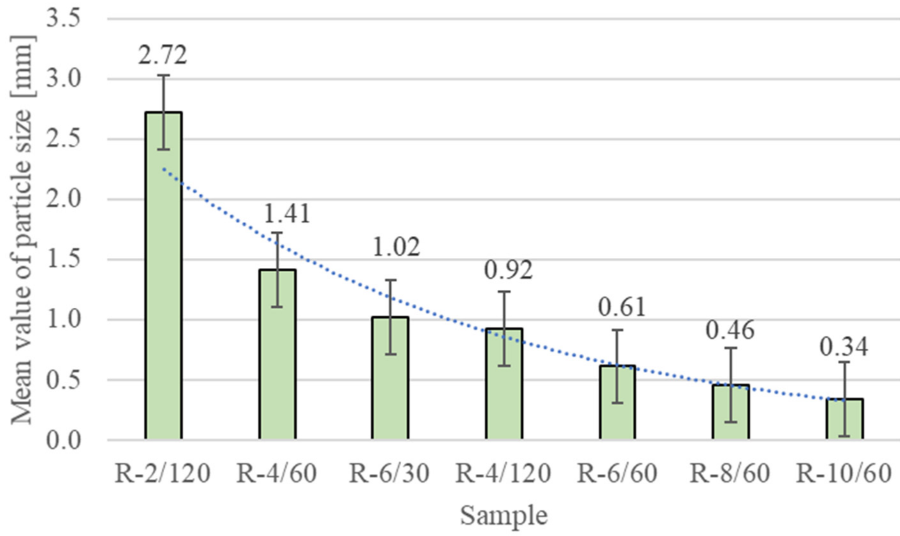


Figure A2. Comparison of mean particle sizes of oilseed rape samples.

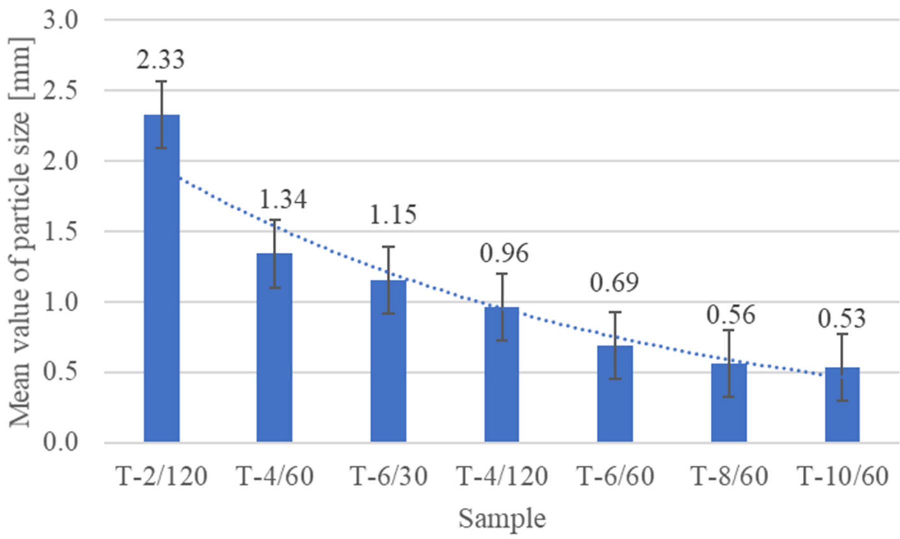


Figure A3. Comparison of mean particle sizes of triticale samples.

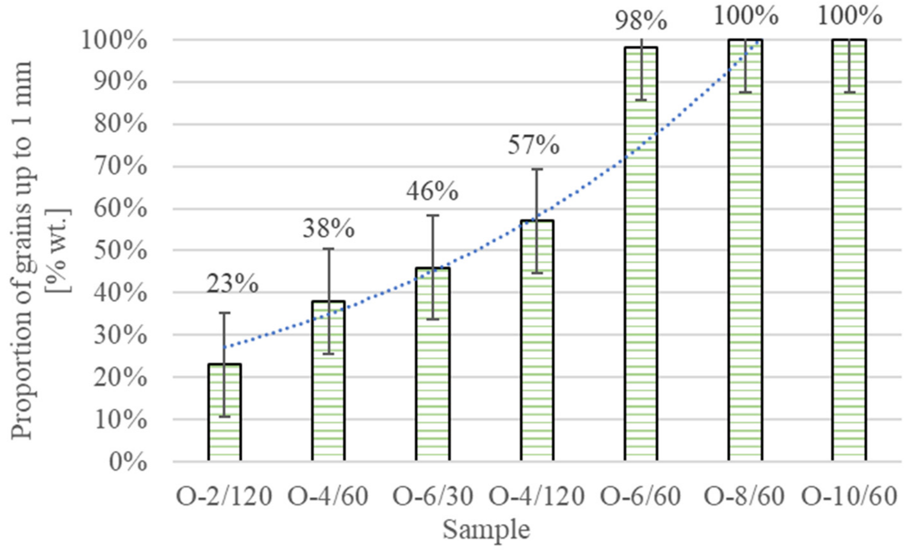


Figure A4. Comparison of mass fractions of particles below 1 mm in oat samples.

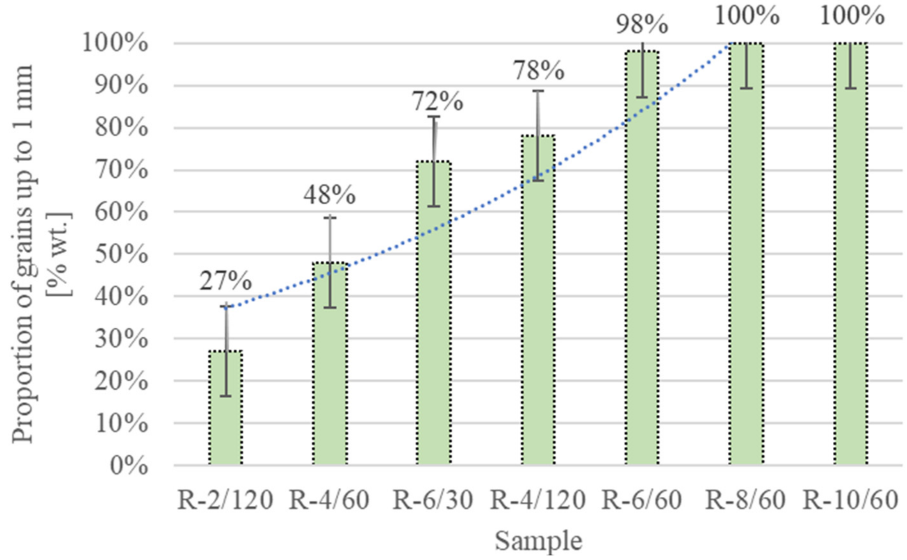


Figure A5. Comparison of mass fractions of particles below 1 mm in oilseed rape samples.

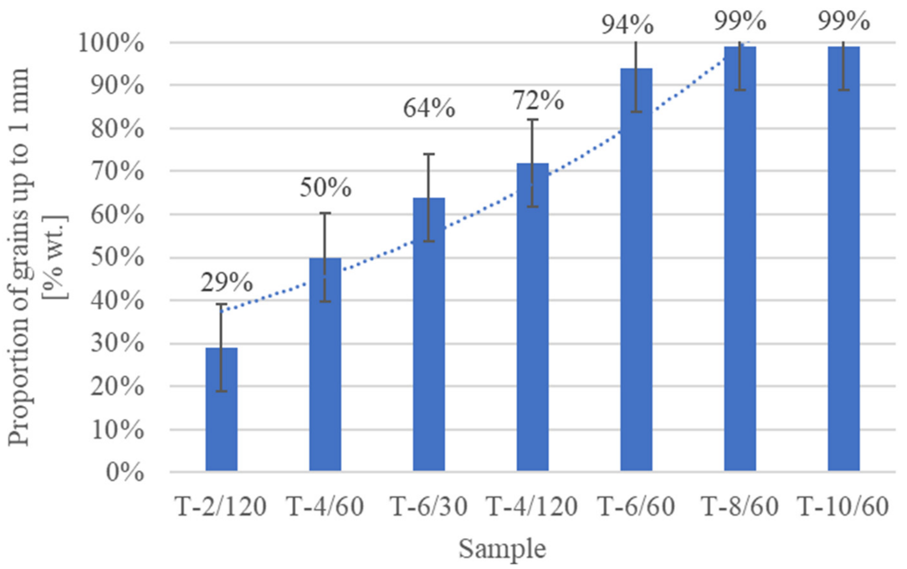


Figure A6. Comparison of mass fractions of particles below 1 mm in triticale samples.

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