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Valorization of Wheat Crop Waste in Araucanía, Chile: Development of Prototype of Thermal Insulation Material for Blowing Technique and Geographical Analysis

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Abstract: Houses in the operational stage consume around 40% of the world's energy, and most of it is consumed by air conditioning. This generates several problems, especially in cities, where biomass combustion is the most widely used form of heating. For this reason, environmental regulation works in parallel with energy efficiency, where efficient and low-impact thermal insulating materials are key to reduce the energy demand and fuel consumption to generate comfort in dwellings. This work considers the valorization of wheat straw from the Araucanía region of Chile, to develop a prototype for a thermal insulating material applied through the blowing technique. The results show the insulation potential of the fiber, which, in post-chopping conditions and at an average density of 80 [kg/m^3], has thermal conductivity of 0.034 [W/mK]. This value is much better than that of glass wool and other inorganic materials sold in the Chilean market. In addition, the developed material can be incorporated into partitions using the blowing technique, improving the execution time for the thermal insulation section. Finally, it is indicated that a good option to install a processing plant is in the central valley of the region, specifically in the communes of Victoria and Perquenco.

Keywords: blowing process; biomaterial; circular economy; fire behavior; natural fibers; thermal conductivity

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1. Introduction

Globally, the building sector consumes 40% of the total energy, generates resource depletion, and is responsible for more than 50% of greenhouse gas emissions [1,2]. Therefore, the design of energy-efficient buildings focuses on reducing energy consumption in all phases of their life cycle, from construction to demolition [3,4]. On the other hand, the residential sector is primarily responsible for particulate matter air pollution. The effects of these particles on the human body are widely recognized, reaching 3.3 million deaths in 2019 [5,6]. This reality originates mainly due to the process of burning wood to heat homes, releasing fine PM2.5 and PM10 particles. The accumulation of these compounds in the air threatens the health of the population because they penetrate the respiratory tract, increasing the indicators of premature mortality, lung cancer, and respiratory and cardiovascular diseases [7,8]. For this reason, European countries have been working on the development of thermal insulation materials for more than 30 years, as they allow reduced energy losses by transmission [9]. However, the thermal insulation market is dominated by inorganic materials, manufactured from petrochemical or natural sources, but, in the latter case, they have a large amount of contained energy [10,11].

Because of this, the main challenge in recent years has been to develop insulating materials with a low environmental impact that reduce energy losses through conduction, reduce the environmental impacts associated with the use of high-energy materials, and maintain a cost that allows them to enter and compete in today's market [12]. In this scenario, waste and residues from the food industry have favorable qualities for the development of thermal insulating materials, since their internal structure is porous, the environmental impacts are lower throughout their life cycle compared to traditional mass-marketed materials, and they are generated in large volumes [13,14]. In Chile, it is estimated that 60% of the food consumed in the country comes from the agricultural sector, where, only considering wheat, there is a sown area of more than 470,000 hectares and therefore the volume of waste generated is high and available for study [15,16]. However, in Chile, none of the waste is identified, neither in volume nor in geographical location. In Spain, progress was made in this context, valorizing organic waste for the development of thermal insulation materials, and, in parallel, they analyzed the availability of raw material and the coverage they could achieve. For example, corn by-products could be used to insulate up to 450 thousand homes per year [17].

These developments are limited from the production point of view since it has not been possible to scale them up to the production stage. The thermal conductivity of thermal insulation materials is variable and depends directly on the density [18,19]. For traditional materials, the values range from 0.03 to 0.05 [W/mK], while, for materials of organic origin, the values range from 0.03 to 0.1 [W/mK] [20,21]. Bakatovich et al. generated a biomaterial from cane fibers, straw, and a sodium silicate binder. The authors obtained a rigid panel with thermal conductivity values in the range of 0.057–0.066 [W/mK], placing it within an adequate material, but lower than other works, such as the one presented in this paper, which averages 0.034 [W/mK] [22]. It is important to highlight the effect (negative in most cases) that the binders in the mixtures, as well as the fiber composition, density, and humidity, have on the thermal conductivity for all insulation materials [23]. Inorganic and organic insulating materials are applied in dwellings by manual assembly. The blowing technique allows the filling of all empty spaces in building elements mechanically and homogeneously, e.g., paper cellulose has been used in housing projects, improving thermal performance. However, although the method is standard and benefits from great developments in equipment, it has not been widely studied with other types of insulating materials and has not been considered in scientific research. Recycled paper cellulose is an excellent material for study and its behavior in the building is very good; its average thermal conductivity is 0.040 [W/mK] and it has been applied via the blowing technique. However, being a material obtained from recycled newspaper, it is threatened by the low consumption of this product in recent years, replaced by digital news media [24,25]. Another topic of interest is the evaluation of the fire performance of thermal insulation materials. There is a challenge in improving the thermal properties of materials, but also in preventing their combustion. Organic materials, being the most widely used in building insulation, have been responsible for many deaths, since they release toxic gases harmful to human health. Some analyses of the fire behavior of these materials indicate that by incorporating fire-retardant additives, the ignition time and temperature of the material can be improved, but the generation of toxic gases cannot be avoided. For this reason, actions have been generated to develop organic materials, where adequate ignition times have been obtained; for example, strategies have aimed to carbonize wheat straw or to add a phase change material (PCM). However, in some cases, the latter could be counterproductive and increase the flammability of the material [26–28].

It is estimated that between 80% and 90% of the area with wheat stubble in the Biobío and Araucanía regions is managed by burning, generating respiratory problems for human health, a reduction in soil organic matter (which contributes to the degradation and loss of soil physical properties), and atmospheric pollution, among others [29–31]. In this sense, the development of materials from organic matter has presented advances; however, no research work has addressed the development of an agricultural waste material applied by the blowing technique. There are no antecedents regarding the physical properties or energy performance of a totally organic prototype, free of additives and applied in a prototype that simulates a real wall. In addition, in Chile, there are general data on the cultivated area of wheat and other cereals classified by region, but there are no specific data on the availability, volume, and location of residues. This makes recovery strategies for any waste difficult. Therefore, the purpose of this work was to evaluate the availability and quantity of wheat crops in the Araucanía region of Chile, identifying strategic points for the location of a processing plant for the valorization of wheat residues. A prototype of a thermal insulating material was generated with the residues, applied using the blowing technique, and the thermal conductivity, density, moisture, and fire behavior of this new material were measured. This development valorized a waste that is currently treated by burning, minimizing energy losses in homes, and contributing to point 13 of the Sustainable Development Goals (SDGs).

2. Materials and Methods

This section presents the methods associated with the availability and geographical analysis of the crops. In addition, the methods associated with the measurement of the following physical properties of the waste are presented: thermal conductivity, density, moisture, and the optimal variables for fiber blowing were determined, such as aperture, speed, and power.

2.1. Feedstock, Analysis, and Processing

The wheat straw was obtained through the company "Comasa", located in the commune of Lautaro, Chile, in the form of bales, which were transported to the energy efficiency laboratory of the Universidad de La Frontera. Figure 1a shows the straw bale at the university site to be subjected to processing.

Figure 1. Wheat straw in bales (**a**), biomass grinder equipment (**b**), blowing machine (**c**), test specimens for blowing the material (**d**).

Wheat straw production was determined in the following way: grain production [t/ha] × (1 − IC)/IC and its units are tons per hectare. The Chilean Agricultural Research Institute (INIA) estimated in 2018 that the average straw production is 7.5 [t/ha], a value very similar to that determined in 2015, through bulletin No. 308, which indicates that wheat straw production varies between 6.4 and 8.0 [t/ha] [32,33]. To determine the demand for thermal insulation materials and estimate what percentage could be covered with a material based on wheat straw, we use the data provided by the company "Servicios Integrales de Calidad Ambiental de Chile" (hereinafter SICAM), in relation to the diagnosis for the implementation of atmospheric decontamination plans in the central–south zone of Chile [34]. For the generation of the map and detection of points of interest for the location of the plant, the ArcGIS software version 10.2 was used and data from the land cover map of Chile were considered under the following criteria (limitations): (1) wheat crops within the region of La Araucanía, (2) crops within land titles in order to promote collaborative work with farmers, and (3) access to communities must be less than 1 km [35,36].

2.2. Sample Preparation and Material Application

The samples were prepared by processing the wheat straw using a biomass grinder, shown in Figure 1b. This equipment is composed of a system of rotating blades installed on a metal chassis, which rotates by means of a 1500 [W] electric motor, and then the material was sieved through a N° 12 sieve according to the "U.S. Standard Sieve" standard, which has an opening of 1.7 [mm].

For the blowing process, the X-FLOC equipment, model M99-DS, was used, which can be seen in Figure 1c. This equipment has a nominal power of 3.6 [kW], nominal blowing power of 440 [m^3/h] (adjustable 2 × 1.8 [kW]), and a variable opening range from 1 to 10". For the application of the material by means of the blowing technique, 2 × 4" pine wood specimens were used, whose dimensions were 60 × 40 × 9 [cm], length, width, and thickness, respectively. The specimens were built in these dimensions to simulate the actual span of a wood wall, as shown in Figure 1d.

2.3. Physical Characterization

2.3.1. Thermal Conductivity

The measurement was performed on three blowing specimens with processed material, measuring 4 points inside the sample, with the "KD2 Pro" instrument, which is a portable device that uses an interchangeable sensor that is inserted into the material to be measured and delivers a thermal conductivity value in a time that can vary between 2 and 10 min. The device measures in 1 s intervals during a 90 s heating and cooling cycle. The KD2 Pro meets the specifications of the IEEE 442–1981 standard and ASTM D5334-08 [37,38]. Figure 2a shows the equipment in the process of measuring the properties for one of the samples. To mitigate potential inaccuracies in readings resulting from the influence of convection on heat transfer, the procedures outlined in ASTM C518 were implemented. Specifically, samples with a minimum diameter and thickness of 75 [mm] and 25 [mm], respectively, were employed and met the dimensional criteria. Moreover, the manufacturer's instructions were strictly followed; readings were taken at 10 min intervals, and the laboratory was maintained at a controlled temperature and relative humidity of 20–22 °C and 55–60%, respectively.

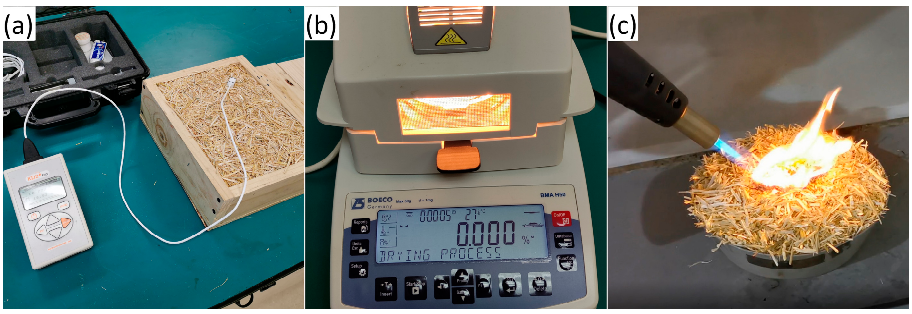

Figure 2. Thermal conductivity instrument (**a**), Boeco moisture analyzer (**b**), fire behavior tests (**c**).

2.3.2. Sample Density

This measurement considered the volume of the test specimens mentioned in Section 2.2 and the mass of material that was blown into the same volume. The mass was considered in kilograms with a universal precision balance of ±0.01 [kg]. The volume was calculated considering the interior measurements of the specimens, measured to the millimeter. Then, by means of the ratio between the mass that was blown into the test specimen and the volume of the specimen, the density was determined and reported in kilograms per cubic meter [kg/m^3].

2.3.3. Moisture

This measurement was performed using the Boeco moisture analyzer model BMA H50—"Moisture Analyzer". This equipment operates with a halogen light in a working temperature range of 10–40 °C and delivers results with accuracy of 0.001%. The analyzer used in the process of measurement is shown in Figure 2b.

2.3.4. Fire Behavior

An analysis of fire behavior, specifically flame reaction, was carried out for wheat straw at the optimum density presented in Section 3.3.2. This experimental test follows the procedures of European standard UNE 23-725-90 and operates as follows. Heat is applied at an average temperature of 1200 °C by means of a flame coming from a butane gas torch. The flame is maintained for 3 s at a fixed distance each time for a total of 3 min, and the flame duration time (from ignition to extinction) is recorded [39,40]. This experimental test allows an approximation of the fire behavior of the material, which will later be tested in an official laboratory in Chile. Figure 2c shows the above process applied to wheat straw samples.

3. Results and Discussion

3.1. Feedstock, Analysis, and Processing

According to data published by the Chilean National Institute of Statistics (INE), 470,882 [ha] of cereals were sown in Chile in the 2020–2021 agricultural year, of which 226,275 [ha] correspond to wheat. In the region of La Araucanía, 93,979 [ha] were sown, which is equivalent to 41.5% with respect to the national total of wheat cultivation [16]. Table 1 shows the area of all cereals cultivated in the Araucanía region for the period mentioned, where it can be seen that the region has larger areas for various types of crops, such as wheat, barley, oats, and triticale, compared to the national total. These data only indicate the crop area, and they do not specify the actual generation of residues, nor do they identify the areas in which they are being produced.

Table 1. Araucanía region crops.

Cereals	Surface [ha]	[%] With Respect to Chile
Wheat	93,797	41.45
Flour wheat	92,781	45.26
Wheat candeal	1016	4.77
Corn	53	0.08
Corn consumption	53	0.09
Seed corn	-	-
Barley	11,113	41.54
Malting barley	7646	44.22
Feed barley	3467	36.63
Rice	-	-
Oat	60,851	54.02
Triticale	9127	83.63
Other cereals	1494	36.23
TOTAL	176,435	–

According to the harvest index and the wheat crop area in the Araucanía region, it is estimated that for the period 2020–2021, 703,477 [ton] of wheat waste will be generated, which will be available for use. However, Hetz E., et al., in 2006, determined that between 20 and 50% of wheat stubble may remain in the soil, so that the volume of residue (for the most unfavorable scenario) would reach 351,738 [ton], which would be available for the development of materials for the production of new crops [41]. On the other hand, and to a lesser extent, wheat straw and other crops are used for animal fodder. However, the potential production of agricultural residues, especially wheat, is high, and, as will be presented in Section 3.2, a minimum percentage is required to insulate thousands of houses. The valorization and utilization of these residues is of great importance to reduce the environmental impacts associated with the treatment of these residues at present. Avoiding the burning of wheat straw stubble could have a very positive impact on air quality [29,30].

The modification of the thermal regulation requirements in Temuco and Padre las Casas through the atmospheric decontamination plan generated an increase in the demand for thermal insulation materials of approximately 300%. By 2020, the demand for thermal insulation materials was 25,470 [m^3/year], and by 2025, the figure is projected to reach 28,938 [m^3/year] [34]. It is important to note that the volume of wheat straw waste generated in the region could cover the thermal insulation needs of all the houses in Temuco, according to these housing projections. According to these data, and considering that the average density of wheat straw application in panels is 85 [kg/m^3], it is estimated that approximately 2460 [ton] of wheat straw would be required to cover the need of materials for the year 2025 in the Araucanía region, which, according to the data indicated in Section 3.1 of this document, is 0.7% with respect to the straw available at the regional level for the most unfavorable case of harvest.

The ranking of possible locations for the wheat straw processing plant to be located within the Araucanía region, in agreement with farmers, with accessibility less than 1 [km] (with respect to the layers of primary and secondary roads), is shown in Figure 3. The orange and red colors indicate a better location with respect to the entry criteria, where a clear trend is observed in the communes of Perquenco, Victoria, and Lautaro, all located in the central valley area of the region and at a distance of 30–50 [km] from the regional capital, Temuco, where the greatest demand for processed material is found. The map is of great help in generating strategic alliances with farmers in terms of the processing, storage, and possible distribution of the material. In this scenario, a real contribution was generated for the valorization of wheat straw residues, since the Chilean databases are not accurate in this information.

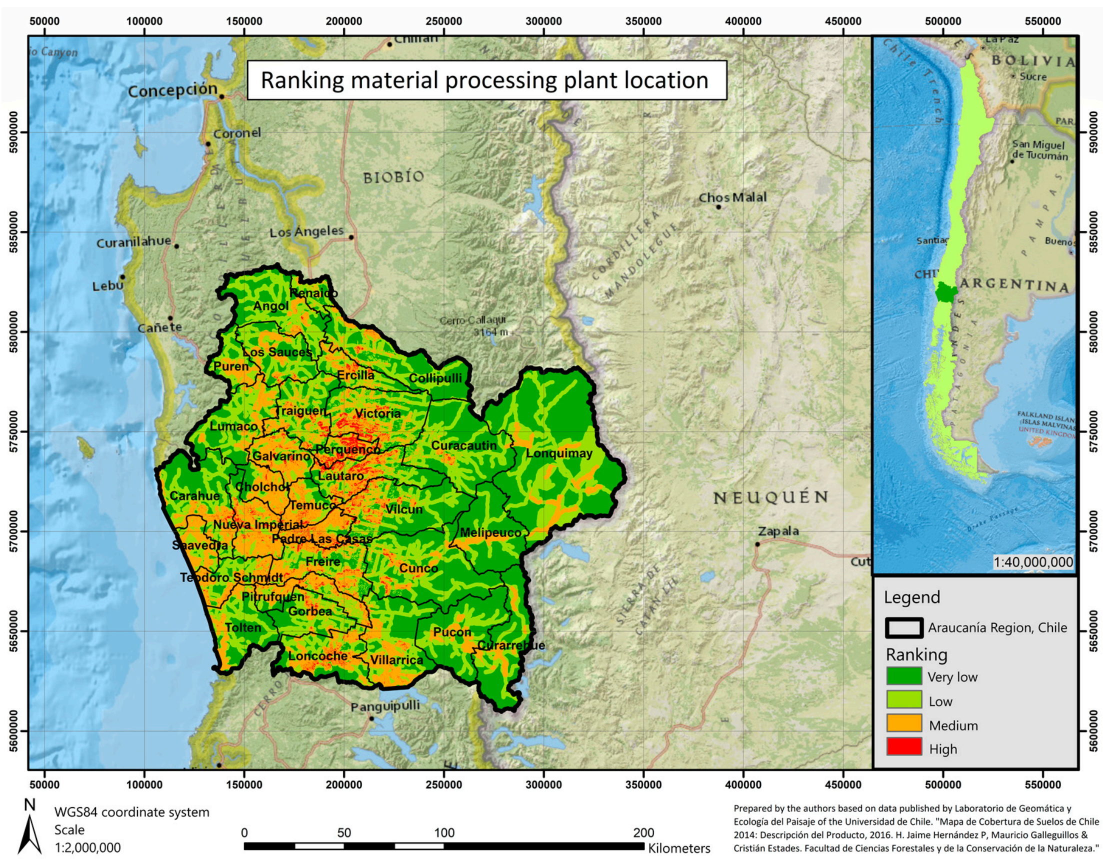

Figure 3. Ranking of optimal processing plant location.

3.2. Samples and Material Application

The bales of wheat straw subjected to the biomass grinder resulted in a homogeneous material whose dimensions varied between 1 and 2 [cm] in length, which can be seen in Figure 4a. This size of the fiber is ideal to be applied by the blowing technique since the exit duct of the equipment has a diameter of 2.5 [cm], thus avoiding agglomerations of material at that point and favoring the generation of internal air cavities. Since the experience with the blowing technique for this type of waste is low, precise combinations were generated to be able to blow the material into the empty spaces of a wall. The material is blown into the specimens at 60% of its nominal blowing power, where this process is completed in an average time of 60 s, for a sample volume of 0.022 [m^3], with an approximate material mass of 1.73 [kg], which is observed in Figure 4b, where the homogeneous distribution of the material at a density of 81.02 [kg/m^3] is highlighted.

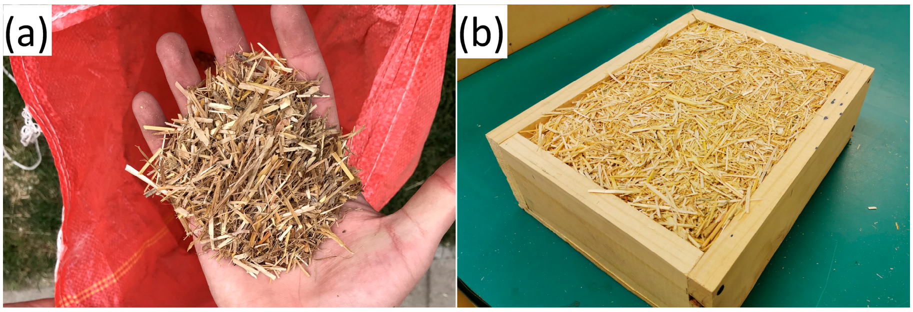

Figure 4. Wheat straw processed in the grinder (**a**), wheat straw applied by blowing technique on the specimens (**b**).

3.3. Physical Characterization

3.3.1. Thermal Conductivity

Table 2 shows the summary results of the thermal conductivity measurements [M] of the material processed and blown into the specimens, where it is observed that the average result is 0.034 ± 0.001 [W/mK]. This result is comparable and in a favorable position with respect to other traditional thermal insulation materials, such as glass wool, expanded polystyrene, and other organic materials, which are around 0.040 [W/mK] [42,43]. The result is comparable with other developments of low-environmental-impact materials. Several researchers have reported that the thermal conductivity value of this type of organic fiber material is around 0.045 [W/mK] [44–46]. In this context, it is important to note that the application of this material in housing construction is entirely viable from a thermal point of view. It is also important to emphasize that through the valorization of waste, it is possible to develop new materials. Additionally, it should be noted that the results obtained are directly associated with the application method. In previous works, the pulping method was used to develop a solid insulating material from wheat straw and corn husk; however, the thermal performance was lower, bordering 0.046 and 0.047 [W/mK], respectively [47].

Table 2. Summary of thermal conductivity results.

	Thermal Conductivity [W/mK]				**AVG**	**SD**
	M1	**M2**	**M3**	**M4**		
Sample 1	0.034	0.033	0.033	0.034	0.034	0.0006
Sample 2	0.034	0.032	0.034	0.035	0.034	0.0013
Sample 3	0.035	0.033	0.033	0.032	0.033	0.0013
					0.034	0.001

According to one of the objectives of the work, which was to valorize waste to develop a thermal insulating material, an interesting result regarding thermal conductivity was obtained. This is due to the fact that in the constructive solutions of a wall, floor, or roof, the thermal insulating material is responsible for the reduction of energy losses by transmission, eliminating a significant amount of energy consumption for the heating of the residential park [48]. In turn, this reduction in consumption reduces environmental impacts, since, worldwide, heating in homes is generated by primary energy extraction, biomass burning, or the use of fossil fuels [49,50].

3.3.2. Density of the Blowing Material

The average density of the samples was 81.02 ± 5.16 [kg/m^3]. This result is lower in respect to the values obtained for the same waste but worked with a wet method, whose average density was 110 [kg/m^3] [47]. Our results are comparable with other types of materials developed from lignocellulosic fibers. Eucalyptus bark materials are around 100 [kg/m^3] [51], Hydrangea Macrophylla natural polymer 60 [kg/m^3] [52], and bagasse fiber exceeds 1000 [kg/m^3] [53]. Regarding the variation in the densities obtained in the application stage of the material, it is possible to point out that a greater effect was not generated in the variation in thermal conductivity, which can be seen in Figure 5. This can be attributed to the fact that the blowing technique generates a homogeneous distribution in each application. However, when comparing the density of the material developed with other consolidated organic materials on the market, it is observed that our results are higher. For example, expanded polystyrene and glass wool vary in density in a range of 10–47 [kg/m^3]. Meanwhile, our results are similar to other organic materials currently on the market, such as extruded polystyrene foams and rock wool, with results of 35 [54] and 30–180 [55], respectively. In the same way, organic materials, in general, increase their thermal conductivity as their density increases (as demonstrated in this and other works). For this reason, it is essential to be able to calculate and report the optimal density at which to apply a material, especially if the blowing technique is being used [56–58].

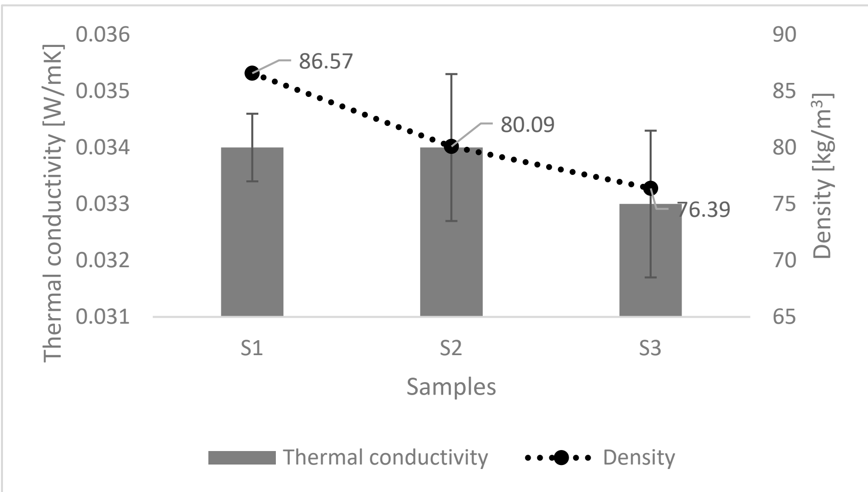

Figure 5. Relationship between density and thermal conductivity of samples.

It is important to note that traditional or natural thermal insulating materials are not structural elements, nor are they elements that must support loads within the construction elements of buildings, so their application is wide [59].

3.3.3. Moisture

The moisture test indicates that the samples have an average moisture value of 9.26% ± 0.12, which indicates that the moisture content is low. This figure is desirable for thermal conductivity measurements, since high moisture content in the samples could affect the results. It is important to understand that thermal conductivity varies with moisture content, as a high value for this property increases the thermal conductivity and reduces the thermal insulating performance [60]. This value is comparable with the moisture content results reported by other authors for lignocellulosic and conventional fiber materials and is also beneficial since high moisture content could affect the thermal performance of the construction solution and increase the probability of condensation and the appearance of pathologies in the interior coatings [61]. In this context, it is important to know the origin of the waste, since it can come from areas where the absolute moisture content is higher; therefore, air drying prior to transportation would be of great help to reduce the possible consumption of energy for the use of ovens.

3.3.4. Fire Behavior

Table 3 shows the results of the experimental test of the fire behavior of the material for 3 min, as described in Section 2.3.4. The data show a total flame duration time of 86 s in 18 flame applications, or an average of 4.8 s of flame presence per application. Other vegetable thermal insulating materials, such as rice husk, corn pith, or barley straw, under the same test method, have an average ignition duration of 9, 7, and 6 s, respectively [26]. In this case, barley straw stands out, whose composition for the development of the material included a binder, unlike this study, where wheat straw was not used with additives or binders, so the ignition result (flaming combustion) is acceptable.

Table 3. Results of the fire test.

Repetition	Ignition		Extinction		Total
	Minute	Second	Minute	Second	Duration [s]
1	0	2.94	0	5.90	2.96
2	0	9.73	0	14.18	4.45
3	0	17.59	0	21.60	4.01
4	0	25.57	0	29.05	3.48
5	0	32.74	0	34.32	1.58
6	0	38.44	0	42.19	3.75
7	0	45.28	0	57.85	12.57
8	1	4.78	1	6.40	1.62
9	1	10.61	1	14.23	3.62
10	1	18.35	1	22.58	4.23
11	1	26.63	1	29.71	3.08
12	1	33.54	1	38.40	4.86
13	1	42.42	1	48.33	5.91
14	1	49.27	1	52.00	2.73
15	1	56.74	2	10.51	13.77
16	2	19.05	2	23.25	4.20
17	2	32.00	2	36.18	4.18
18	2	49.04	2	54.26	5.22
				Total	86.22
				Average	4.79

Alternatives have been evaluated to improve the fire behavior of wheat straw; one of them is the carbonization of the material, which improves the fire performance by increasing the ignition temperature, but, at the same time, the internal porous structure of the fiber is altered, so the effect on thermal conductivity should be analyzed in detail [40,62].

4. Conclusions

The results of this work, associated with the valorization of wheat residues, show that the demand for materials in the Araucanía region versus the eventual production of thermal insulating material from wheat residues in the same region is highly viable. It is shown that the waste is found in abundance, with a greater presence in the central zone of the region, in the communes of Perquenco and Victoria, so, logistically, reaching only 1% of the waste in the region would allow us to cover the thermal insulation needs projected for

2025 in the regional capital. In addition, links could be generated for the operational work of the collection, storage, and transport of waste, avoiding the traditional disposal of this waste. Thermal insulation materials are key to reducing residential energy consumption worldwide, since the energy consumed in homes is mainly used for heating [63]. In this way, particle emissions associated with the use of fossil fuels for heating (combustion of biomass) and greenhouse gases are reduced. In this context, the characterization carried out in this work shows the competitive qualities of wheat straw for use in construction, where the average conductivity of the samples is 0.034 [W/mK], comparable to various materials used in the market. It is important to note that this value was obtained by generating an application process using the blowing technique. Other application methods, even from the same residue, vary this number, reaching 0.046 [W/mK]. The homogeneous application of the wheat straw inside the test tube is evident, confirming that the material can be used with this technique, which is currently widely used with cellulose paper. It is important to mention that in order to achieve this, the fiber must be subjected to a chopping process, in order to obtain a material with a maximum length of 2 [cm]; otherwise, the fiber would accumulate at the outlet of the duct and could not be applied with the technique of blowing to the interior of the partitions. Low moisture percentages were identified in the samples analyzed, and the challenges that are being addressed to complement this work are moisture adsorption tests and the variation in the thermal properties when cycles of rain, humidity, and heat occur. For its part, the reaction with the flame is encouraging, since, compared to other plant materials, wheat straw self-extinguishes in less time. It is important to mention that the material under study did not include any fire-retardant additive, binder, or phase change material, so any measure considered to improve the fire behavior would improve the material even further compared to other organic materials.

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