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Lignocellulosic Industrial Waste as a Substitute for Virgin Hemp for a More Sustainable Hempcrete Material

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Abstract

Although hempcrete is a more sustainable alternative to most conventional thermal insulation materials, it still requires virgin hemp for its production. In this context, lignocellulosic industrial waste emerges as an attractive alternative to replace the virgin hemp. Accordingly, this work analyzed the use of eucalyptus pinchips and hemp waste as a replacement for virgin hemp in the production of hempcrete. For this, an integral methodology is applied to evaluate not only the technical properties of the mixtures but also to assess the corresponding environmental impacts. In particular, the mechanical properties of the mixtures were analyzed with percentages of replacement between 40% and 100% of virgin hemp by eucalyptus pinchips and/or hemp waste. The density of the mixtures was measured in a time frame between 0 and 28 days, and their compressive strength at 28 days of curing. Finally, life cycle assessments were performed for each mixture. As all mixes reached higher values of compressive strength than the ones with virgin hemp, basically, the differences are concentrated in the environmental impacts. From that perspective, the lime-based mixture with 100% hemp waste reduces the environmental impacts, particularly the emissions for respiratory and carcinogenic/non-carcinogenic effects, which are 10% and 20%, respectively.

Keywords: lignocellulosic waste; hempcrete; eucalyptus pinchips; hemp waste; life cycle assessment; thermal insulation

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1. Introduction

The building construction industry significantly contributes to greenhouse gases, accounting for 37% of the global energy-related emissions. About 10% of these emissions are due to the manufacture of building construction materials [1]. Conventional thermal insulation materials have the disadvantage of consuming large amounts of energy during production, together with the release of pollutants or volatile compounds into the environment [2,3]. This contributes to the increment of the greenhouse gas emissions of the buildings and can lead to further health problems [4–6]. In addition, these materials have practically no reuse and recycling processes, generating waste once their life cycle ends [7,8].

In order to reduce the environmental impact generated by conventional insulating materials, alternative and sustainable options have been developed, such as those from plant origin, which have good environmental performance, both in their production and lifespan [3]. Examples of plant-based materials or recycled materials are cork [9], flax [10,11], hemp [12–14], kenaf fibers [15], miscanthus [16–19], sugar palm fiber composites [20], corn cub [21], sunflower stalks [22], wheat [23], wood fiber [12], and wood strands [24].

Nevertheless, hemp fibers seem to be the best option to use as a partial replacement for insulation materials due to their lower environmental impact compared to kenaf and cork fibers, as they require less water during the growing process of the plant [25]. Specifically, hempcrete, a composite construction material made out of lime, water, and hemp, is an attractive and promising alternative for use as insulation in residential construction due to its low thermal conductivity. The nature of hempcrete is not structural, as it has low compressive strength, for instance. The compressive strength for a mixture with a ratio of binder–hemp of 2 and 1.5 oscillates between 0.2–0.12 MPa and 0.11 MPa, respectively [26–29]. In terms of thermal conductivity, the previous mixtures have values between 0.06 and 0.115 W/m-K [27,30], which are within the range of traditional insulation materials [31]. The factors that affect the thermal conductivity of these types of materials are the size of the hemp chips and their density [32]. Furthermore, the thermal conductivity of hempcrete depends not only on its density but on the water content as well [33].

Regarding its workability, there is no standardized evaluation methodology for hempcrete, and mixture stability is subjectively measured in situ by molding a sphere with the hand and applying pressure with the fingers [30]. Similarly, the compaction of hempcrete mainly depends on the operator experience, presently reaching up to 1 MPa of compaction pressure [34]. Although favorable characteristics of the hempcrete material exist, there are still challenges regarding its evaluation.

On the other hand, the wood industry produces a considerable amount of waste. These residues have a high potential to be used in construction as a sustainable alternative due to their properties and carbon sequestration. Furthermore, the production of industrial hemp also generates lignocellulosic waste, which can be useful to replace virgin hemp for building materials, such as hempcrete.

Specifically, the wood industry in Chile generates an important amount of subproducts or residues, such as those from eucalyptus in the Region of Biobío, and industrial hemp in the Region of Maule [35]. One such significant wood residue, known as pinchips, has particles between 3 and 9 mm in length, which are disregarded in the pulping process of wood due to their small dimensions [36]. In addition, industrial hemp core is a lignocellulosic residue with a similar chemical composition to wood but with no major end application in the production chain of hemp strands and seed; it is the least valuable part of the plant [37–39]. Therefore, exploring plant by-products is vital for sustainability, reducing new land use, minimizing competition with food crops, and diversifying farmers' income sources.

Accordingly, this work aims to evaluate the use of eucalyptus pinchips and hemp waste as a replacement for virgin hemp in the production of hempcrete. Particularly, the mixtures' characteristics, mechanical properties, density, and insulation capacity were analyzed, followed by the development of a compaction methodology for the mixtures. The environmental benefits of the mixtures were also compared and quantified by performing a life cycle assessment. Hence, the article applies an integral approach to evaluate not only the technical properties of the mixtures, but also the assessment of the corresponding environmental impacts, which is crucial to define if a proposed novel material alternative is more sustainable than the traditional one. Then, those are the mixtures that can allow an effective and practical use of waste streams, contributing to the development of a sustainable thermal insulation building material.

2. Materials and Methods

2.1. Experimental Plan

Given the numerous combinations of cases in this work, and in order to obtain the most meaningful information possible about the behavior of the samples, the experimental program was organized in three consecutive stages.

This strategy was chosen to narrow down the scope of the study based on the results obtained in previous stages. Thus, for the first stage, eucalyptus pinchips were evaluated as the replacement material, using two mixing proportions and wet densities based on a literature review, in order to determine which dosage provides the best results. The material originates from forest areas in the Biobío Region, Chile. Since the results did not allow for distinguishing between the two dosages, in the subsequent stage 2, work was performed with the incorporation of a new residue, aiming to reduce the final density of the specimens while maintaining compression strength and exploring different combinations among them. Additionally, in this stage, the compaction method was validated.

2.1.1. Stage 1

The dosages of the mixtures were obtained from specialized literature on hempcrete. In effect, for mixtures with medium densities, there are two types of proportions in weight of hemp, binder, and water: 1:1.5:1.5 and 1:2:2 [40]. With these proportions, average densities of 250 to 350 kg/m^3 are obtained, which are used as thermal insulation for walls.

In stage 1 (see Figure 1) of sample preparation, only eucalyptus pinchips were used, with a humidity of 90%. Table 1 presents the two mixtures used with the respective percentages by weight of each of the materials in the permitted range. It is important to note that the eucalyptus pinchips have a high moisture content, and no pre-treatment, such as drying, was carried out. This is because the replacement materials should be usable as is, in terms of both their mechanical and environmental properties.

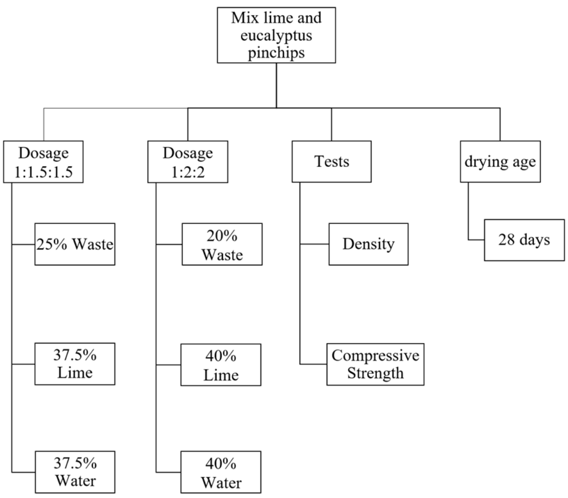

Figure 1. Flow chart stage 1.

In stage 1, a total of 24 specimens (we considered more specimens than the statistical minimum) were fabricated, 12 of them with a dosage of 1:1.5:1.5, from which 6 specimens were prepared at a packing density of 500 kg/m^3, and the other 6 specimens with a density of 700 kg/m^3. Similarly, 12 specimens were fabricated with a dosage of 1:2:2 and equally divided between densities of 500 and 700 kg/m^3. Finally, the densities of the 24 specimens and 28-day compressive strength tests were performed. The selection of packing densities between 500 kg/m^3 and 700 kg/m^3 is because, after 28 days of drying, the specimens should have reached an average density similar to that of hempcrete for the same dosages [40].

Table 1. Mix proportions by mass in stage 1.

Density (kg/m^3)	Mixtures	Eucalyptus Pinchips	Binder	Water
Mix a (700 kg/m^3)	1:1.5:1.5 1:2:2	25% 20%	37.5% 40%	37.5% 40%
Mix b (500 kg/m^3)	1:1.5:1.5 1:2:2	25% 20%	37.5% 40%	37.5% 40%

2.1.2. Stage 2

In stage 2 (see Figure 2), the results of the previous stage were considered. In order to achieve lower densities than those already obtained, dry residues were used, with eucalyptus pinchips, hemp residue, and mixtures of both, following the proportions indicated in Table 2. In addition, during this stage, the validation of the compaction process was carried out using virgin hemp.

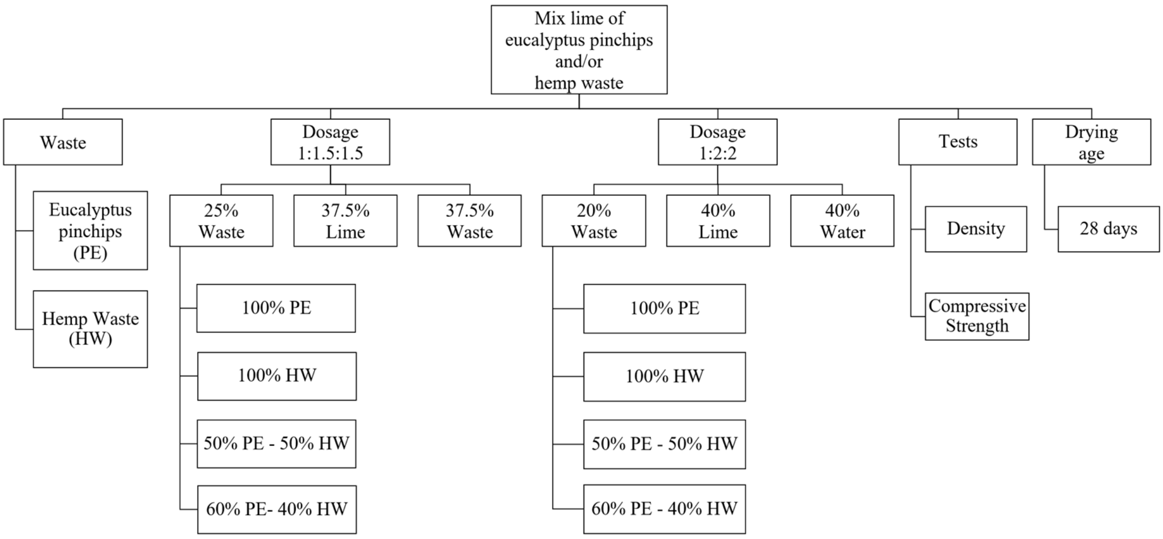

Figure 2. Flow chart stage 2.

Table 2. Mix proportions by mass in stage 2.

Dosage	Materials	Mix 1 (Eucalyptus Pinchips)	Mix 2 (Hemp Waste)	Mix 3 *	Mix 4 **	Mix 5 (Virgin Hemp)
1:1.5:1.5	Waste	25%	25%	12.5%, 12.5%	15%, 10%	25%
	Binder	37.5%	37.5%	37.5%	37.5%	37.5%
	Water	37.5%	37.5%	37.5%	37.5%	37.5%
1:2:2	Waste	20%	20%	10%, 10%	12%, 8%	20%
	Binder	40%	40%	40%	40%	40%
	Water	40%	40%	40%	40%	40%

*: 50% eucalyptus pinchips–50% hemp waste; **: 60% eucalyptus pinchips–40% hemp waste.

During stage 2, a total of 60 test specimens were prepared following the mixtures indicated in Table 3. Of these, 12 specimens corresponded to mixture 1, distributed in 6 test specimens with the dosage 1:1.5:1.5 and 6 specimens with the dosage 1:2:2:2. For mixture N° 2, 12 specimens were prepared, distributed similarly to the above-mentioned dosages.

This same pattern was repeated for mixes 3, 4, and 5, each with 12 test specimens, divided in equal parts according to the indicated dosages.

Table 3. Physical properties of each material.

Properties	Hemp Waste	Eucalyptus Pinchips	Traditional Hemp [26]
Bulk density (kg/m^3)	90	170	98
Porosity (%)	83	84	84

Finally, the density of the 60 specimens was determined, and 28-day compressive strength tests were carried out.

2.2. Materials

Eucalyptus pinchips and hemp residues were generated from forestry residues and agricultural residues, respectively. Virgin hemp wood was used to develop and validate the compaction methodology, and to compare the strength behavior of each mixture with traditional hempcrete.

Drinking water was used for all tests. The grain size distribution curve for each material is given in Figure 3, based on ASTM C136 [41]. The virgin hemp and hemp residue used in this study are located between the upper and lower ranges given in the literature [28,34]. Eucalyptus pinchips are located at the lower range of commonly used virgin hemp. It is important to note that the virgin hemp used in this study is not the same as that commonly used for the manufacture of hempcrete; however, its properties are very similar to those from the literature, as shown in Table 3. Also, the particle sizes of the materials used in this study are maintained within the range given in Figure 3.

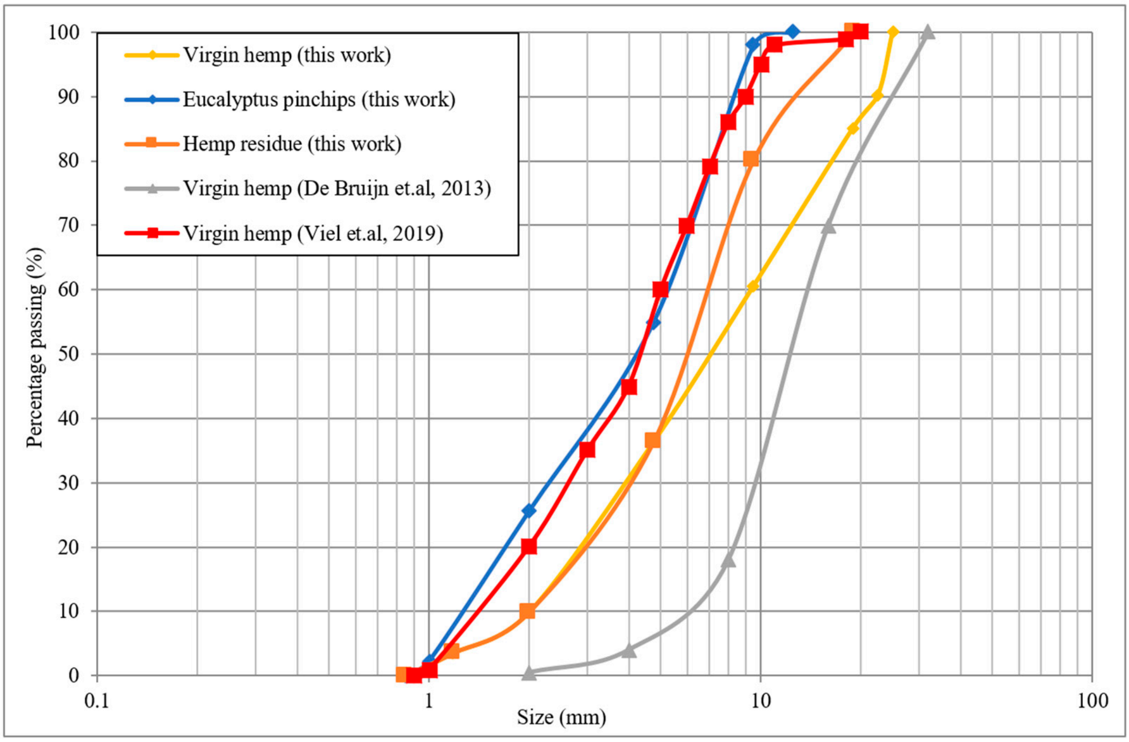

Figure 3. Grain size distribution curve for each material used in this work, in comparison to virgin hemp used in other studies [42,43].

Figure 4 shows each material in its initial state. Scanning electron microscopy (SEM) images for hemp residue and eucalyptus pinchips are shown in Figure 4d,e, respectively, showing similar porosity microstructure despite their high difference in density as mentioned in Table 3. That is congruent with other authors; for example, Jiang et al. [44] characterize the intrinsic physical parameters of hemp shives, mentioning that their microstructural features are like hardwoods, such as *Eucalyptus* sp., which are classified. In both materials, a large part of the volume is occupied by empty spaces (cell lumens, gaps between fibers, vessels). Still, hemp cell walls are thinner and have less lignin, resulting in lower weight per unit volume. However, eucalyptus has thick, lignified cell walls that provide more mass to volume, resulting in a higher density.

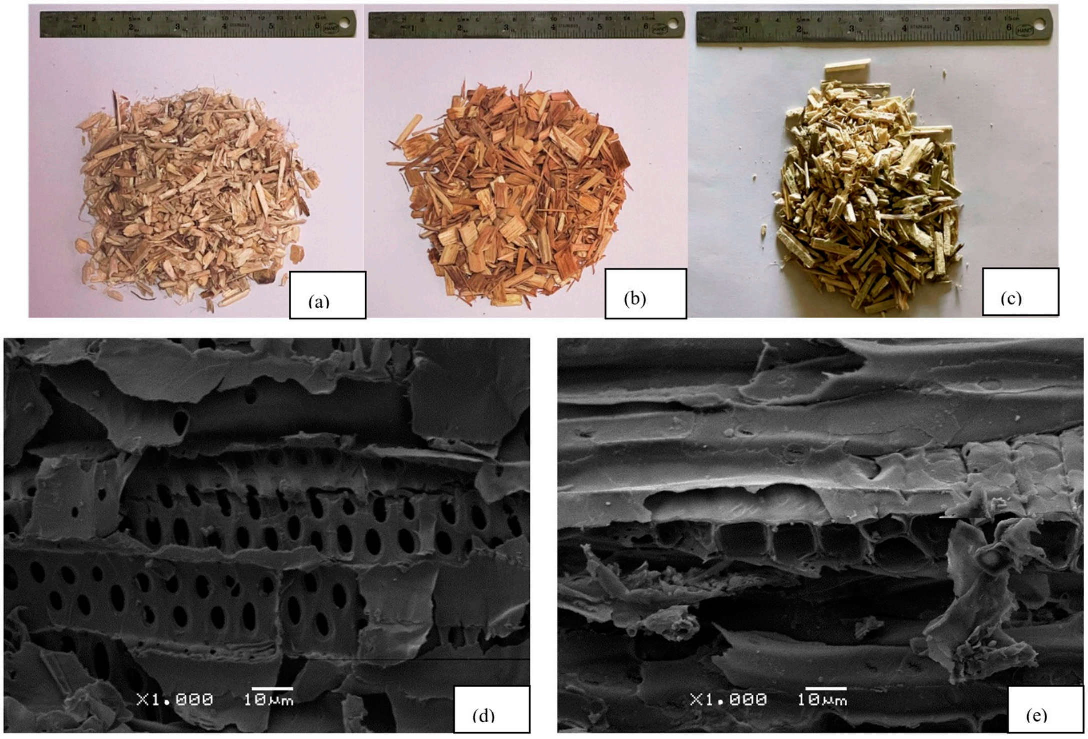

Figure 4. Visual images of materials: (**a**) hemp residue; (**b**) eucalyptus pinchips; (**c**) virgin hemp; (**d**) microscopic photography of hemp; (**e**) microscopic photography of eucalyptus pinchips.

2.3. Binder

Hydrated lime was used as a binder complying with the characteristics of natural hydrated lime NHL2, required by UNE-EN 459-1 [45].

2.4. Mixture Preparation and Testing

The preparation, compaction, and drying of the mixtures based on eucalyptus pinchips, lime, and/or hemp residue were carried out following the procedure proposed by Magwood [40].

According to the dosage indicated in Section 2.1.2, the material corresponding to each mixture was weighed, and the dried elements, i.e., lime with eucalyptus pinchips and/or hemp residue, were homogenized for 1 min. During this process, the elements were completely covered with lime. Water was then added at regular intervals and mixed for 5 min until a homogeneous mixture was achieved.

To verify the consistency of the mixture, the suggestion corresponding to the sphere and finger test of Stanwix and Sparrow [30] was performed for all mixtures before pouring them into the molds, ensuring consistency. After consistency was assessed, the mixture was re-homogenized for an additional minute. Then, the molds were filled in a single layer, avoiding the application of compaction force.

Once the molds were filled, compacting equipment designed for small specimens was used (see Figure 3). Once the specimens were compacted, they were placed in an incubator at 20 °C and 50% relative humidity [28,46–50] for 3 days before demolding. Then, they were re-entered into the chamber once demolded to carry out the density evaluation at 7, 14, and 28 days. Finally, the compressive strength was evaluated at 28 days.

2.5. Design of Compaction Equipment

The compaction equipment was specifically designed for use on small laboratory specimens (see Figure 5). Since the compaction pressure in the field is unknown, the methodology of Viel et al. [34], who applied various compaction pressures, was used as a reference. For the compaction of specimens, a steel plate of dimensions 95 mm × 95 mm and a weight of 4.8 kg was designed, whose theoretical compaction pressure corresponds to 0.05 MPa, which was applied to each specimen for 1 min. Subsequently, the dimensions of each specimen were measured to determine the densities and then tested in compression, resulting in minimal differences from those proposed by Cerezo [27]. The previous procedure was followed for all mixtures.

Figure 5. (**a**) Compacting device; (**b**) compaction of specimens.

2.6. Compressive Strength and Density Test

The mass and dimensions of the specimens were recorded in order to determine the dry density (kg/m^3) according to ASTM C138 [51]. The compressive strength evaluation was carried out at 28 days of curing, in accordance with ASTM [52]. A total of 84 specimens were tested.

2.7. Life Cycle Assessment

The estimation of the environmental impact of the material production, use, and end-of-life cycle was performed following the methodology proposed by ISO 14040 [53]. The approach is based on a Streamlined Life Cycle Assessment (SLCA), focusing on life cycle stages with significant differences due to modifications in the design of a product [54].

In the case of this study, blends based on pinchips, lime, and/or hemp residue could reduce environmental costs. However, there is no record of the extent of environmental savings compared to hempcrete.

Input and output data for the materials used in the manufacture of the mixtures were adopted from the open-access inventory of the European Life Cycle Database ELCD 3.2v2, AGRIBALYSE, and ECOINVENT [55]. The first comprises life cycle inventory data from EU-level trade associations and other key material sources, energy carriers, transport, and waste management. The second comprises life cycle inventory data from the agriculture and food sector provided by ADEME in France. The third comprises data from five Swiss research institutes providing well-documented data for thousands of products worldwide.

The databases are incorporated into the freely available sustainability and Life Cycle Assessment software OpenLCA 1.11. This software was developed by GreenDelta in Berlin, Germany, and uses the sum-of-processes approach to assess the sustainability of materials and activities. In this study, the OpenLCA software models the following processes:

- Raw material: At this stage, eucalyptus pinchips and/or hemp residue are purchased, then dried and sieved.
- Production of the material: In this stage, the mixture is differentiated, quantifying the amount of each raw material to be used, that is, the residues, binder, and water.
- Manufacture of the product: In this phase, the product is manufactured in the field, with differences in density and compressive strength between the mixtures for the functional unit of 1 m^3.

The end product and end-of-life stages are assumed to be the same for each mixture since the differences occur only until the manufacture of the product (compressive strength and density). And, in order to ensure impartiality, the transport was assumed equivalent and then not included in the Streamlined LCA [54]. In this way, the environmental differences are due to the raw material, the material production, and the manufacture of the product.

From the output results, the OpenLCA software generates impact analyses using the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2.1) tool developed by the U.S. Environmental Protection Agency. For mixture ratios, TRACI quantifies the impact of any process using specific environmental categories.

3. Results

3.1. Laboratory Results

The results considering the mixture based on wet eucalyptus pinchips and lime (Stage 1) are shown in Figure 6. Each bar corresponds to the average compressive strength of the six specimens tested, and their standard deviation. For the mixture of dosage 1:1.5:1.5 at 28 days, a compressive strength of 0.0924 and 0.094 MPa was obtained for mixes a and b, respectively. Similarly, the results of mixtures with a dosage of 1:2:2 at 28 days indicate a compressive strength of 0.0968 and 0.098 MPa for mixes a and b, respectively.

Figure 7 indicates the evolution of density through time for both dosages. Each curve corresponds to one specimen tested at stage 1. Figure 7a,b show the results of dosage 1:1.5:1.5 for mixes a and b, with a reduction of 26.7% and 9.8%, respectively, in dry density after 28 days. Also, Figure 7c,d show the results of specimens at a dosage of 1:2:2, with a reduction of 26.1% and 5.0% of their initial dry density for mixes a and b, respectively.

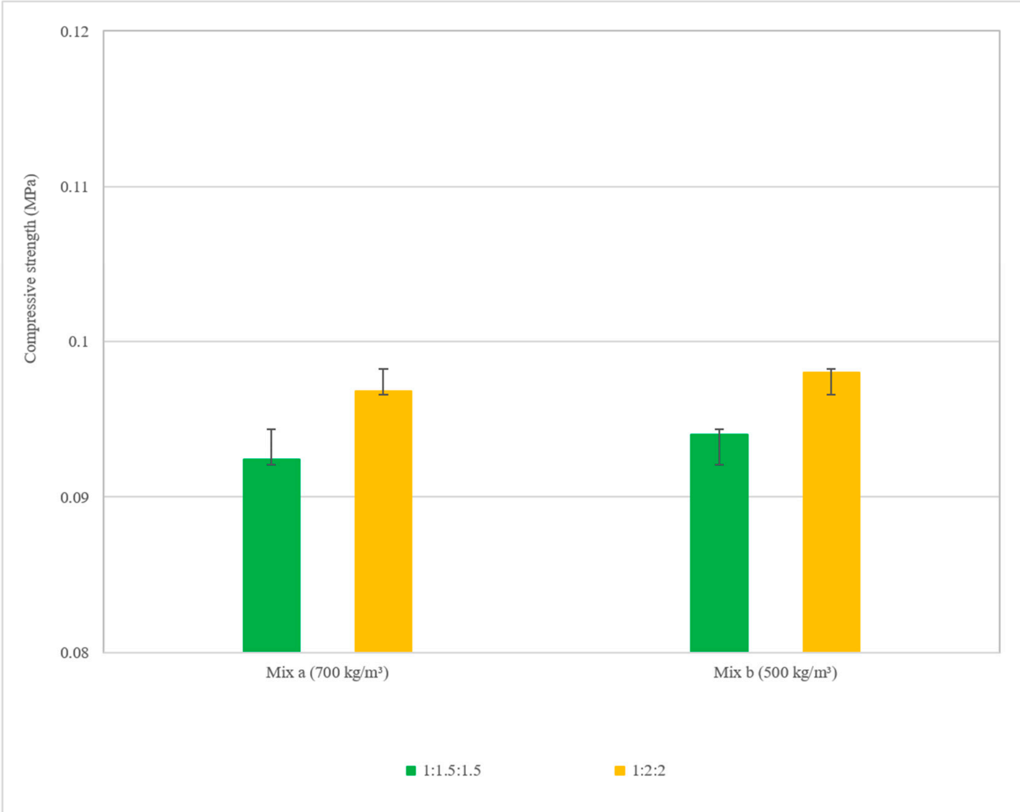

Figure 6. Stage 1 compressive strengths of eucalyptus pinchips dosages 1:1.5:1.5 and 1:2:2.

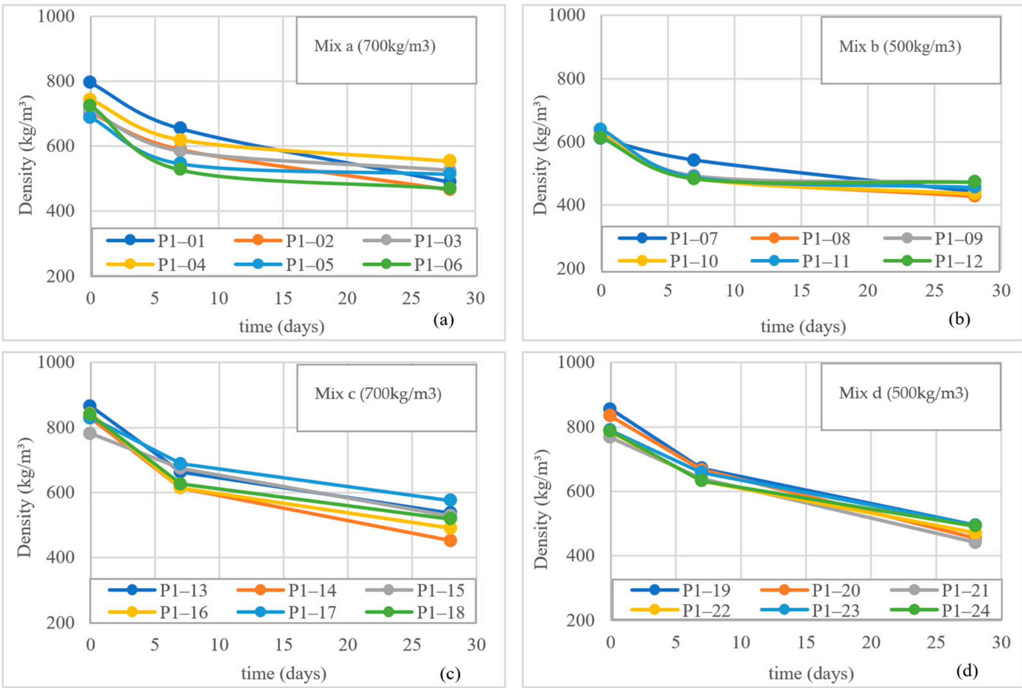

Figure 7. Stage 1 density evolutions: (**a**) 700 kg/m^3 packing density for the dosage 1:1.5:1.5; (**b**) 500 kg/m^3 packing density for the dosage 1:1.5:1.5; (**c**) 700 kg/m^3 packing density for the dosage 1:2:2; (**d**) 500 kg/m^3 packing density for the dosage 1:2:2.

The previous results reveal that both sets of dosages have densities too high to be considered as thermal insulator materials. However, in both mixtures, eucalyptus pinchips were used in a wet state, which resulted in an excess of water in the mixture. A higher amount of water and binder is observed in the mixture dosage 1:1.5:1.5 compared to dosage 1:2:2.

These findings highlight the importance of the mixture design, and consequently, a new mixture was evaluated in order to obtain a lower density. In addition, the use of dry eucalyptus pinchips was considered for better moisture control in the mixtures.

Figure 8 shows the results of the compressive strength at stage 2 (Table 2), obtained on mixtures at 1:1.5:1.5 and 1:2:2:2 dosages. Each bar corresponds to the average compressive strength obtained for six specimens. The standard deviation is indicated above each bar. Mix 1 obtained the highest compressive strength of 0.112 MPa, while mix 3 and mix 4 achieved a compressive strength of 0.101 MPa. These results suggest that the material used does not significantly influence the resistance, since the compressive strength ranges are within the standards established by Cerezo [27].

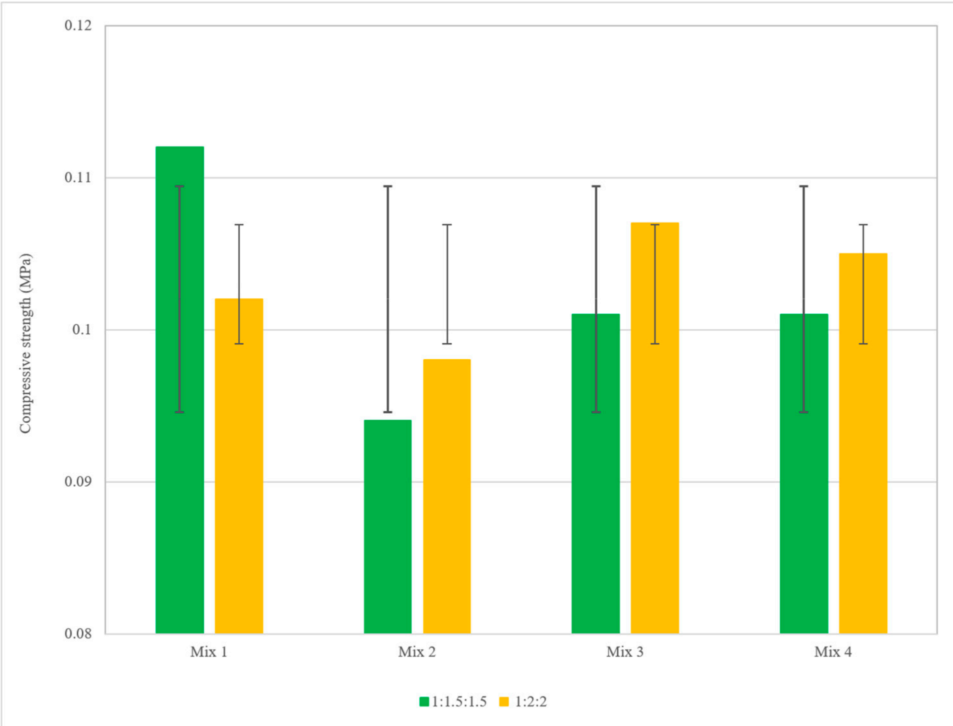

Figure 8. Stage 2 compressive strengths for mixtures based on eucalyptus pinchips and/or hemp waste dosages 1:1.5:1.5 and 1:2:2.

As for mix 2, a compressive strength of 0.094 MPa was obtained, well within the values established by Abdellatef et al. [56] for medium-density walls. However, it is important to consider that the 1:2:2 dosage has a higher content of binder and water, which resulted in a minimal increase in compressive strength compared to the previous mixes.

It is noteworthy to indicate that mix 3 presented the best performance in compressive strength (0.107 MPa), while the one that presented the lowest strength was the mixture based only on hemp residue.

The results of the density evolution with time corresponding to the 1:1.5:1.5 mixture are presented in Figure 9a, while those corresponding to the 1:2:2 mixtures are presented in Figure 9b. Each curve corresponds to the average results of the six specimens tested. Both figures show the decrease in density over the drying period of the specimens. A noticeable decrease is observed during the first 14 days, followed by a more gradual decrease after 21 days. In some mixtures, a steady trend in dry densities is observed.

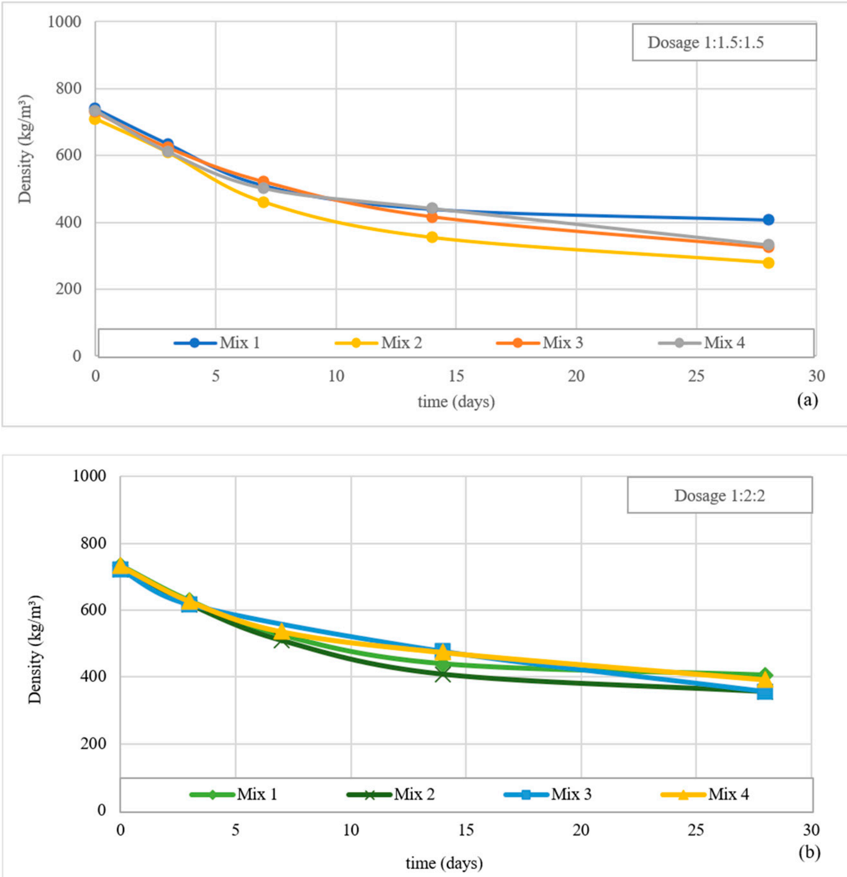

Figure 9. Stage 2 density evolutions: (**a**) mixture based on eucalyptus pinchips and/or hemp waste dosage 1:1.5:1.5; (**b**) mixtures based on eucalyptus pinchips and/or hemp waste dosage 1:2:2.

Density is reduced during the drying process under controlled conditions of temperature (20 °C) and humidity (50% RH), which is a fundamental step in the hardening process and consolidation of the mixtures. This reduction is primarily due to the evaporation of water present in the initial mix, and it is a behavior observed in other hempcrete mixes as well [47].

The mixtures with the lowest densities were those containing mix 2, reaching values of 279 kg/m^3 for the 1:1.5:1.5 mixture and 350 kg/m^3 for the 1:2:2:2 mixtures. These results indicate that these mixtures have a good thermal insulation capacity in terms of density.

Figure 10 shows the average compressive strength of six specimens for mixtures with virgin hemp, using the new compaction method implemented. For the dosage mixtures of 1:1.5:1.5 and 1:2:2:2, a compressive strength of 0.091 MPa and 0.098 MPa was obtained. In both cases, a minimal difference was observed, considering the standard deviation, which may be attributable to the binder and water content. The previous results are similar to those obtained by De Bruijn et al. [28] and Viel et al. [34].

In terms of density, Figure 11 represents the density variation with time for specimens prepared at stage 2 with virgin hemp and two dosages. Both results indicate a significant decrease during the first 21 days of drying, under conditions of 20 °C and 50% relative humidity. Therefore, the compaction pressure established in this research coincides with the standards for average densities established by Magwood [40], since no significant differences are obtained in the compressive strength and densities with both dosages.

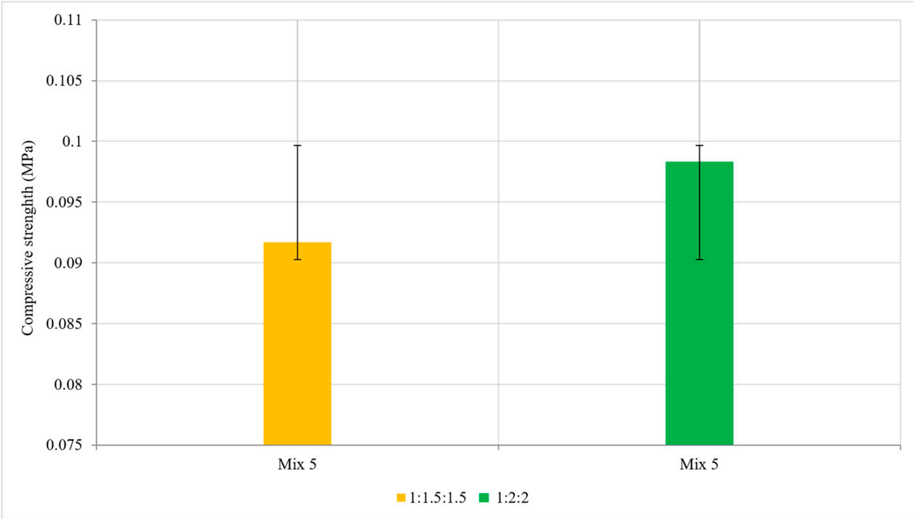

Figure 10. Stage 2 validation of compaction with virgin hemp dosages 1:1.5:1.5 and 1:2:2.

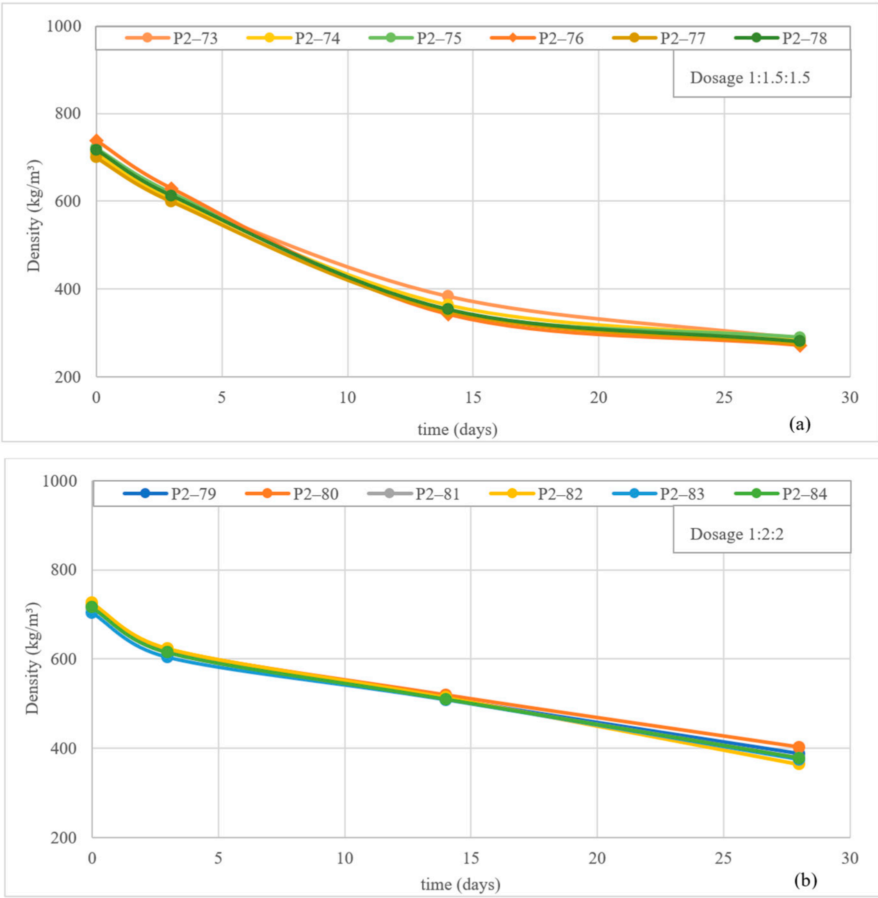

Figure 11. Stage 2 densities in the density compaction method: (**a**) dosage 1:1.5:1.5; (**b**) dosage 1:2:2.

On the other hand, the newly developed compaction method is validated through the previous results since the pressure that was applied to each specimen did not generate a major difference between the compressive strength of the mixtures and their densities.

3.2. Life Cycle Assessment of Mixture

The results of the life cycle assessment are divided into two main categories: environmental impact and human health. Environmental impacts include acidification, ecotoxicity, eutrophication, global warming, and ozone layer depletion. On the other hand, the human health category includes aspects related to carcinogenic, non-carcinogenic, and respiratory effects.

Figure 12 represents the results of the mixtures for the 1:1.5:1.5 dosage, while Figure 13 shows the results of the mixtures for the 1:2:2 dosage in each of the categories analyzed.

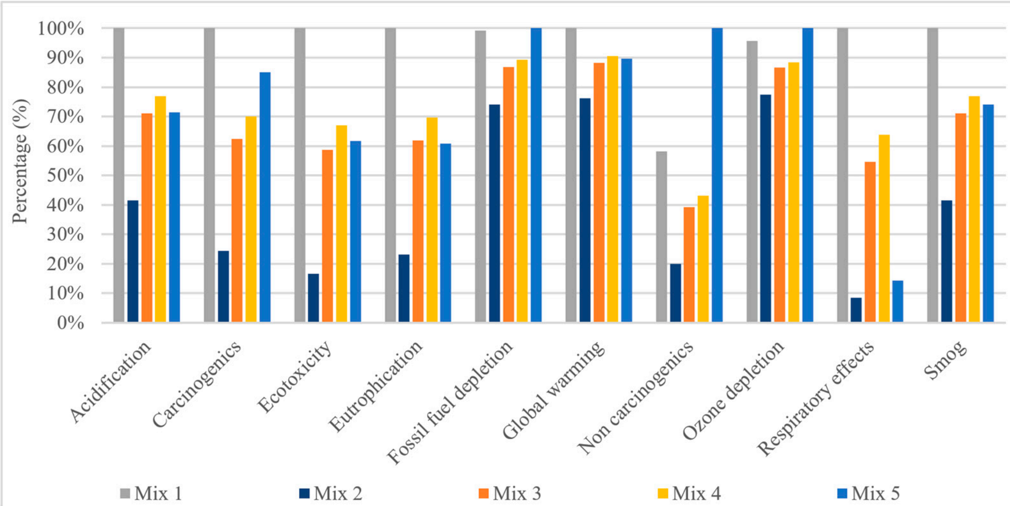

Figure 12. Comparison of the environmental burdens of dosage 1:1.5:1.5. The material with the highest impact in a category represents 100%.

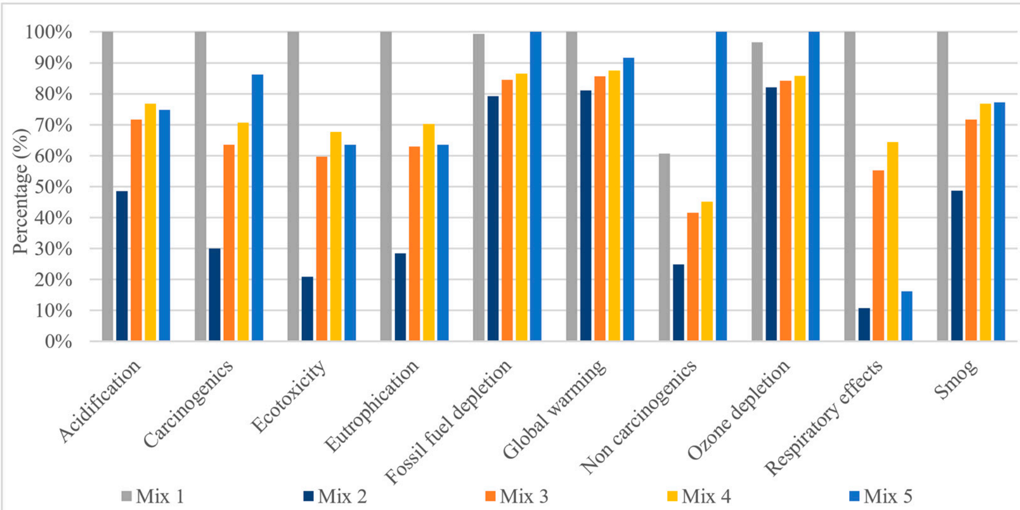

Figure 13. Comparison of the environmental burdens of dosage 1:2:2. The material with the highest impact in a category represents 100%.

As can be seen, in each of the impact categories, mixture 2 obtained low percentages in the environmental and human health impacts. This is due to the fact that, since it is a waste product, it does not entail an environmental load that implies the generation of more emissions, since no pre-treatment is performed. On the contrary, by using it in this type of mixture, the CO_2 captured during its growth stage remains stored, which indicates that it could contribute to the possible replacement of traditional insulators, and even to the replacement of hempcrete.

Mix 1, on the other hand, shows percentages close to 100% in nine categories. This result is attributed to the prior drying process of the material in ovens that are connected to electricity before being incorporated into the mixture, thus generating a significant environmental load.

In relation to mix 5 (virgin hemp), values close to 100% are observed for fossil fuel depletion, non-carcinogenic elements, and ozone layer depletion. This situation is mainly attributed to the fact that, being a virgin product, it requires a series of agricultural operations, including the application of fertilizers, sowing, irrigation, cutting, and storage. These processes are linked to electricity generation and oil consumption.

As for mixtures 3 and 4 (eucalyptus pinchips and/or hemp residue), it is suggested to consider them as viable alternatives, given that they exhibit superior environmental performance compared to virgin hemp and eucalyptus pinchips separately.

The previous trend was maintained in Figure 13, showing only minimal increases in each of the categories. This is due to this type of mix containing more lime and less eucalyptus pinchips and/or hemp residue. These findings support the viability of lime-based blends as more sustainable and environmentally friendly options compared to using only virgin hemp or eucalyptus pinchips.

4. Discussion

This research proposed the use of four mixtures based on lime with eucalyptus pinchips and/or hemp residue as thermal insulation in housing walls, as an alternative to hempcrete. These mixtures were subjected to mechanical analysis, evaluating compressive strength and density, and environmentally evaluated using Life Cycle Assessment. In effect, the article applies an integral approach to evaluate not only the technical properties of the mixtures, but also the assessment of the corresponding environmental impacts, which is crucial to define if a proposed novel material alternative is more sustainable than the traditional one.

The results of the mechanical properties and environmental impacts indicate the valuable possibilities of using lignocellulosic waste as a virgin hemp replacement for a more sustainable thermal insulation building material. In effect, when the technical performance of the material is adequate, the use of lignocellulosic industrial waste has an immediate reduction of the environmental impacts, generating benefits from raw material production and product manufacturing, contributing to a more sustainable construction industry and building sustainability.

The integral approach adopted in this article is relevant because it not only allows the identification of the mixtures with adequate technical performance but also those assuring the reduction of environmental impacts. Then, those mixtures will allow an effective and practical use of waste streams, taking advantage of abundant resources and avoiding their underutilization or deposition in landfills, particularly in the case of the hemp waste, which nowadays does not have practical applications in Chile. Then, this solution contributes to the development of a sustainable thermal insulation material using a low-cost, abundant raw material.

As the lignocellulosic industrial waste captures CO_2 during its growth, it becomes a building element that functions as carbon storage. Therefore, the solution proposed in this document not only makes a valuable contribution to the reduction of the climate change phenomenon, but it also provides a practical alternative for waste valorization, assuring the quality of thermal insulation in homes, benefiting their inhabitants. In effect, the Life Cycle Assessment highlighted that the mixture with hemp waste presented emissions close to 10% in the respiratory effects indicator and 25% in the other indicators related to human health. These findings emphasize the human health benefits derived from the use of lime-based blending techniques with hemp residue.

What has been presented agrees with the basis of a circular economy, defined as a model of production and consumption where materials are reused and recycled as often as possible with the objective of increasing resource efficiency and lowering demand for virgin raw materials [57,58]. In this regard, the by-products and waste streams can be converted into value-added products such as thermal insulation building materials. For instance, in the particular case of Chile, according to the Camara Chilena de la Construcción [59], approximately 12.2 million m^2 of houses and buildings are constructed per year. Assuming that all dwellings use insulation materials, as required by the Chilean standards [60], the demand for insulation would be approximately 12 million m^2. That scenario represents a potential practical utilization of the lignocellulosic industrial waste studied in this article.

The integral approach applied in this article can be replicated for the analysis of other waste streams for the development of more sustainable thermal insulation building materials. For instance, the same approach can be applied in future research analyzing the (partial) replacement of lime by pozzolanic materials as waste derived from used glass, biomass ash, or thermoelectric fly ash. Due to the scope of the current research, which is focused on the replacement of the virgin hemp, this was not included. However, the incorporation of pozzolan waste can reduce reliance on lime as a binder, thereby reducing CO_2 emissions to the environment.

5. Conclusions

This research analyzed the technical and environmental benefits derived from the incorporation of forestry industry by-products, such as eucalyptus pinchips, and agricultural industry residues, such as hemp, in the manufacture of medium-density thermal insulation for housing walls. As all mixes reached higher values of compressive strength than the ones with virgin hemp, basically, the differences are concentrated in the environmental impacts. Therefore, the main conclusions of this integral approach are summarized as follows:

- The most promising application from a technical and environmental point of view is mixture 2. Outstanding mechanical properties were evidenced, with reductions of between 10% and 20% in emissions for respiratory and carcinogenic/non-carcinogenic effects, respectively. Then, it is a very interesting alternative for the practical use of lignocellulosic industrial waste and for reducing the environmental impacts of the hempcrete material, making it even more attractive in comparison with the conventional thermal insulation materials.
- On the other hand, mix 1 proved to be the most unfavorable option in environmental terms. Environmental emissions were close to 100%, attributable to the moisture content of the by-product and their need for drying before incorporation into the mixes.
- Mixes 3 and 4 presented consistent technical results in terms of density and compressive strength. However, to improve their environmental impact, it is suggested to modify the drying process of the eucalyptus pinchips, since this was identified as a critical point that generated emissions close to 40% in all the categories analyzed.
- The results of the lime-based mixes for the specimens indicate that the designed compaction system is adequate. Strengths close to the minimum are achieved and could even be better, but this is attributed to the use of a different binder than the one used in the hempcrete. In addition, the density of the mixes is within the ranges studied in the design of mixes. Therefore, the compaction equipment designed with 0.05 MPa pressure is suitable for the manufacture of lime-based mixes developed during the research.
- The environmental assessment of these applications is crucial when considering the use of by-products and waste in construction. Since research into new materials in-

volves significant costs, a practical recommendation is to determine the environmental viability even before making substantial experimental investments.

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