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CLOSING THE LOOP OF TEXTILE: CIRCULAR BUILDING RENOVATION WITH NOVEL RECYCLED INSULATIONS FROM WASTED CLOTHES

Andrea Augello, Olga Beatrice Carcassi, Francesco Pittau*, Laura Elisabetta Malighetti, Enrico De Angelis

Politecnico di Milano, ABC Department, via Giuseppe Ponzio 31, 20133 Milano, Italy
* corresponding author: francesco.pittau@polimi.it

Abstract. The implementation of new energy policies and standards for NZEB is expected to lead to a significant reduction of GHG emissions from building use in Europe in the next decades. On the other side, the growing pressure on insulation materials risks to significantly contribute to the exhaustion of the remaining carbon budget due to the high carbon intensity of conventional insulation for material processing. Consequently, storing carbon in construction products and promoting circular economies able to generate up-cycling processes from industrial or post-consumption waste are the key strategies to promote an effective transition toward a carbon-neutral society. Fashion & clothing is one of the manufacturing sectors which mostly contributes to waste generation and fossil GHG emission. This paper presents the main outcomes achieved from RECYdress project, which focuses on the valorisation of wasted textile collected by municipal districts to develop novel thermal insulations for building applications. Three alternative conceptual manufacturing processes were defined at lab scale based on different treatment of textile fibres, with produced specimens tested for thermal characterization. Finally, the LCA results of an ETICS application for façade renovation were compared considering as functional unit 1 m^2 of façade with similar thermal resistance.

Keywords: Textile wastes, circular economy, life cycle assessment, sustainability, thermal conductivity, transient plane source method.

1. Introduction

To limit the high environmental impacts caused by the construction sector, the European Commission has promoted strategies and directives aimed at improving the energy efficiency of existing buildings, largely inefficient from an energy point of view. The European Green Deal constitutes one of the main issued strategies, which aims at the elimination of greenhouse gas production in Europe by 2050, through a gradual transition that will involve various sectors (transport, industry, agriculture, energy, etc.). Other instruments, such as the Renovation Wave, instead foresee an increase in the annual building renovation rate, currently between 0.4 and 1.2 %, over the next ten years, thus decarbonizing about 35 million buildings. To promote the circularity of the economy and reduce the environmental impacts associated with building materials, numerous authors have studied the possibility of integrating wastes of different nature within construction products. Among these, textile waste has been shown to have potential as thermal insulators, thanks to thermal conductivities comparable to traditional insulating materials; therefore, the use of these materials within the construction sector could constitute a possible solution to the problem of recycling textile waste, which ends up mainly in landfills (57 %) or incinerated (25 %) at the end of their life. Furthermore, the problem of textile waste in Europe is expected to increase in the coming years due to the restrictions imposed by the Waste Framework Directive, which imposes the mandatory separate collection of textile waste in all Member States by 2025, preventing landfill, incineration, or export of textile wastes to non-European countries. This paper summarizes the main results achieved from the RECYdress project, aimed at evaluating the development of thermal insulations based on recycled textile wastes. Different types of samples were analyzed, evaluating both their thermal and environmental properties, investigating the effect of parameters such as density, treatment, binder, and composition of the insulating material.

1.1. Textile-based insulation materials: a short literature review

The thermal properties of textile wastes of different compositions have been studied by many authors in the last years. Dieckmann et al. [1] tested the thermal properties of insulation panels based on waste chicken feathers mixed with bicomponent fibers: the lowest value of thermal conductivity measured, equal to 0.033 W/mK, was comparable with conventional insulation materials. Similar results were obtained by Mrajji et al. [2], who investigated the thermal properties of six nonwovens based on different amounts of chicken feathers, cotton, and wool produced with the needling technique: values between 0.0313 and 0.04465 W/mK were measured. The ther-

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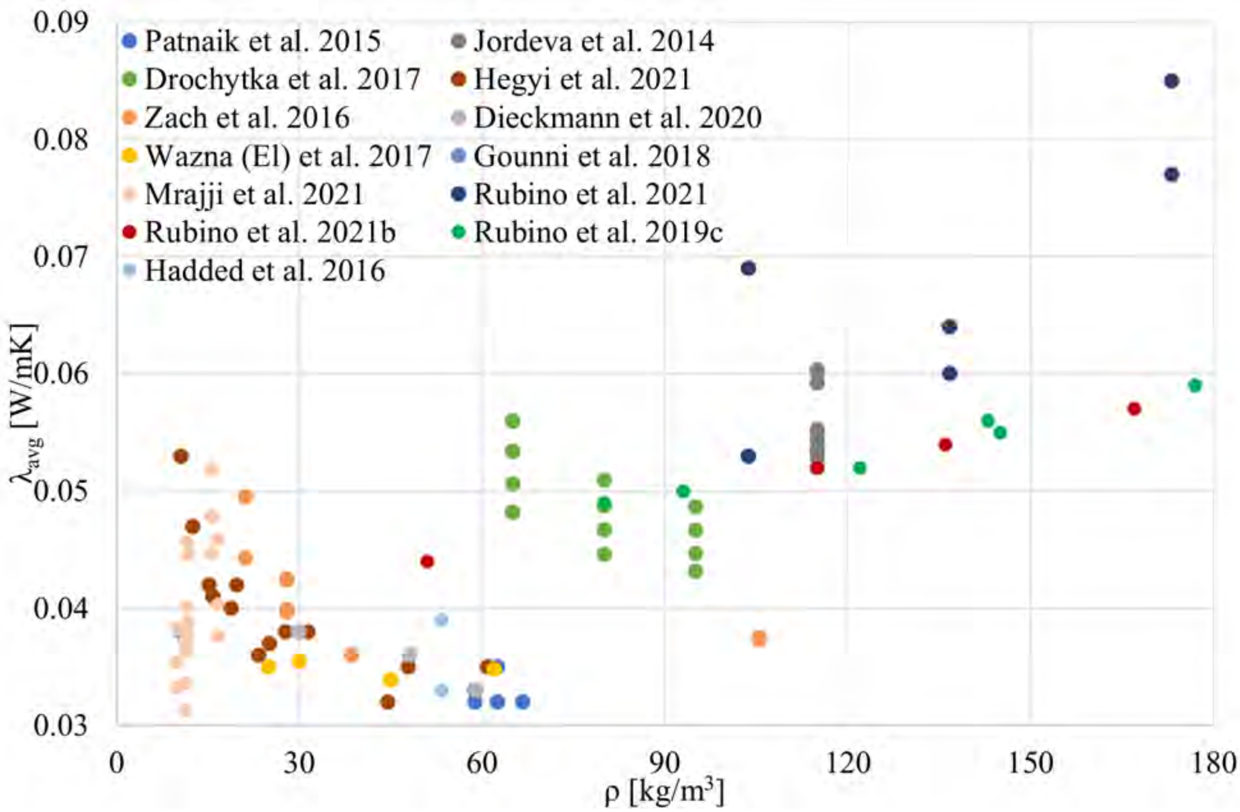

FIGURE 1. Thermal conductivity of textile wastes from literature.

mal properties of polyester fabrics were investigated by Jordeva [3], analyzing different types of polyester shredded and inserted in casings made of polypropylene: their measured thermal conductivity values ranged from 0.052 to 0.0603 W/mK. Good thermal performances of polyester-based materials were obtained by Drochytka et al. [4], who tested five samples based on polyester fibers mixed with synthetic bicomponent fibers produced with the airlay technology: values between 0.04319 and 0.05598 W/mK were measured. The same airlay technology was adopted by Zach et al. [5], manufacturing and testing five insulation materials based on flax, cotton, and polyester. The measured thermal conductivities ranged from 0.036 to 0.0443 W/mK, depending on density and composition. The use of recycled wool as thermal insulation was studied by Rubino et al. [6] on four samples based on Merino wool waste bound with chitosan: thermal conductivity values ranging from 0.049 to 0.06 W/mK were measured. These samples were later compared by Rubino et al. [7] with other specimens based on merino wool bound with Arabic gum: chitosan and Arabic gum samples showed similar thermal conductivity values. A few years later, Rubino et al. [8] analyzed five samples with different densities based on merino wool bonded with copolyester/polyester bicomponent fibers: lower values of thermal conductivity were obtained, going from 0.044 to 0.057 W/mK. Eventually, Rubino et al. [9] studied the combination of the previously investigated merino wool/Arabic gum samples with organic phase change materials. The measured thermal conductivities (between 0.053 and 0.085 W/mK) increased as function of the temperature and amount of PCMs, due to the increased connections among fibers and the reduction of the pore volume. The thermal performances of five samples based on wool and polyester were studied by Patnaik et al. [10]: the average values ranged from 0.032 to 0.035 W/mK, confirming that it is possible to manufacture insulation materials with a similar thermal conductivity as that of 100 % waste wool fibers.

The thermal behavior of wool and acrylic fibers was investigated by Wazna (El) et al. [11], producing four nonwovens based on acrylic and sheep wool wastes with the needling technique, characterized by low values of thermal conductivity (0.0339–0.0355 W/mK). Another acrylic nonwoven fabric was investigated by Gounni et al. [12], confirming its capability to significantly reduce the heat flux ($\lambda = 0.038$ W/mK). Hadded et al. [13] investigated the effect of the mechanical treatment on the thermal properties by considering two textile samples obtained through the same process but at different stages: both materials presented low density and high porosity, with similar thermal conductivities (0.033 and 0.039 W/mK). Hegyi et al. [14] investigated 13 samples made of different amount of recycled plastics, denim, or sheep wool mixed with bicomponent fibers; thermal conductivities between 0.032 and 0.053 W/mK were measured. The results obtained by the previously mentioned authors are reported in Figure 1.

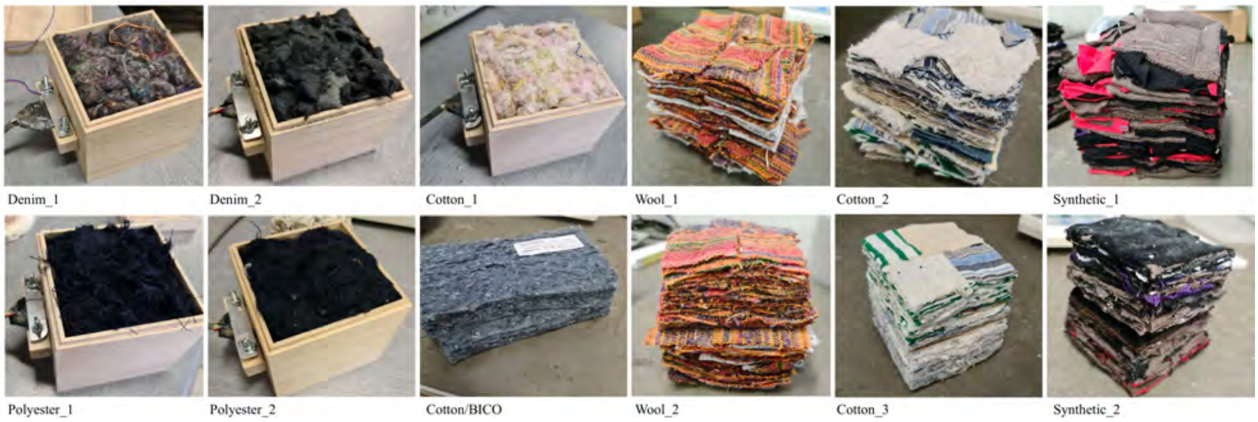

FIGURE 2. Tested textile samples. Dimensions: 10 cm^3.

2. Materials and methods

2.1. Tested materials

As shown in Figure 2, two different sizes of fibres were selected for thermal characterization:

(i) staple textile fibres, and

(ii) fabric strips with two alternative options to bind the layers: needle punched and vinyl adhesive.

In total, twelve types of wasted textile samples were prepared for testing, distinguished between:

(i) loose fibres (Denim_1, Denim_2, Cotton_1, Polyester_1, Polyester_2),

(ii) thermal treatment (Cotton/BICO), and

(iii) cut-out strips (Wool_1, Wool_2, Cotton_2, Cotton_3, Synthetic_1, Synthetic_2).

The effect of composition, density, treatment undergone by the materials, or binder on thermal conductivity values was investigated. All textile fibres used in the test campaign were provided by Vesti Solidale Società Cooperativa Sociale, an NGO operating in Northern Italy with a business core on collecting and sorting wasted clothes.

2.2. Test methodology

2.2.1. Thermal characterization: Transient Plane Source method

The measurements of the materials' thermal conductivity were carried out through the Transient Plane Source method, BS EN ISO 22007-2:2015, which is based on the use of a disk, called Hot Disk, which produces a thermal impulse on the material under examination and measures its change of thermal resistance; the model adopted by the software then allows to derive the thermal properties such as conductivity, diffusivity, specific heat, etc. For the loose textile wastes, the test methodology involves the use of some small wooden boxes (cube with a side equal to 10 cm) inside which the loose material to be tested is inserted; a hole located about halfway up the side allows the insertion of the disk in the middle of the sample; the dimensions of the boxes were chosen considering the need of guaranteeing an adequate sample thickness to avoid any edge effects that could alter the results. For the composite materials, the disk was simply inserted between two equal samples with a thickness of about 5 cm each.

At least six measurements were performed on each sample, to take into account the variability of the results; therefore, the reported thermal conductivities are intended as averages of six or more values. Besides, the uncertainties connected to the measurement method were evaluated by calculating the average standard deviations.

2.2.2. Life cycle assessment for carbon footprint calculation

The Life Cycle Assessment is a methodology used to estimate the environmental burdens associated with the entire life cycle of a product, process, or service, from raw material acquisition through production, use, end-of-life treatment (recycling or final disposal). The requirements and guidelines for carbon footprint of products are defined in the standard ISO 14067:2018. This methodology is used to evaluate the carbon footprint of the textile-based insulation materials, which will be compared with those of traditional ones, to highlight benefits or disadvantages. Two functional units were adopted: 1 kg of insulation material and 1 m^2 of panels with a thermal resistance of 2.22 m^2K/W. The chosen system boundaries from "cradle to gate" include the phases between the textile wastes collection to the final product manufacturing. Among the tested textile samples, only the environmental impacts of cotton waste (Cotton_1) were assessed, combining the loose material with different amounts of bicomponent fiber (5 % or 25 % in weight). The analysis was performed on SimaPro using the Ecoinvent 3.8 database as the main source of data by considering the Italian energy mix for electricity driven processes. Other relevant data about energy consumption of machinery used for the manufacturing process were collected onsite from a Italian company operating in the textile industry.

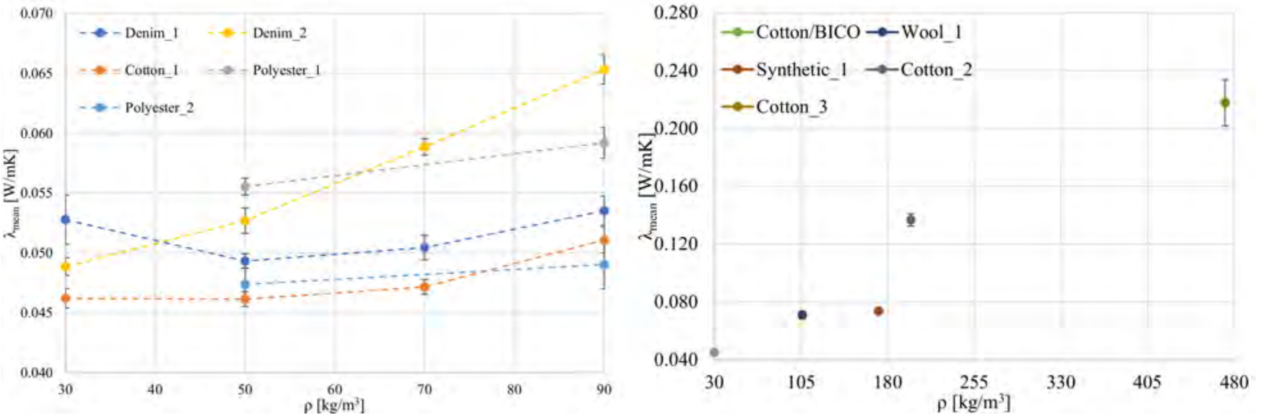

FIGURE 3. Thermal conductivity of the tested loose (left) and composite (right) materials.

3. RESULTS

3.1. THERMAL CHARACTERIZATION

The tested samples were stored in the laboratory under a controlled environment before starting the measurements. The moisture content of some textile samples was evaluated using a moisture analyzer (PCE-MA100), which measured an average moisture content of 8–9 %.

The thermal conductivity values measured on the tested samples are reported in the following scatter plot (Figure 3), having the materials' density as x-axis; the error bars represent the calculated thermal conductivity's uncertainties. All the loose textile materials showed low values of thermal conductivity, almost always lower than 0.06 W/mK, which makes them suitable as insulating materials; on the contrary, the Cotton/BICO sample is the only tested composite material that could be applied as insulation material. All the tested parameters, i.e. density, treatment, binder, and composition have a not negligible effect on the samples' thermal properties. The thermal conductivity increases with the increasing density for four of the five tested loose materials: only the sample "Denim_1" has an opposite trend, i.e. a decreased thermal conductivity, going from 30 to 50 kg/m^3. The treatment undergone by the materials, investigated by comparing the two types of polyester, seems to have a not negligible effect too: we registered a decrease of 16 % (in average) of the thermal conductivity for Polyester_2 on both the tested densities. For what concerns the effects of the binder on the thermal performances, the needled samples do not have excellent thermal performances: Wool_1 and Synthetic_1 have the best results, with conductivity values lower than 0.075 W/mK; on the contrary, Cotton_2 has a thermal conductivity value completely outside the range of the insulating materials ($\lambda = 0.137$ W/mK). In the case of adding glue to the samples, there is a further sharp decrement in thermal conductivity: for the Cotton_3 sample, an average value of 0.218 W/mK is measured (+ 59 % compared to the needled Cotton_2 sample), i.e. an unsuitable conductivity for an insulating material; furthermore, measurement uncertainties are much greater than those calculated for the other tested materials. These problems are probably attributable to the nature of the chosen binder and to the large amount of water contained in it, which keeps the sample to be tested partially moist even for several weeks and which therefore could have had a not negligible effect on the thermal conductivity measurement. For these reasons it was not possible to evaluate the performance of the other two composite materials (Synthetic_2 and Wool_2) as they were excessively wet and with results not consistent with what was expected as they were probably influenced by the initial materials conditions. This problem could represent the big disadvantage of the recycled textile wastes, since for many building applications it is necessary to guarantee a minimum water-repellent behaviour.

3.2. CARBON FOOTPRINT ASSESSMENT

3.2.1. PRODUCTION PROCESSES

The functional unit chosen to calculate the global warming potential due to the production process of the two textile wastes (Cotton/BICO 95/5 and Cotton/BICO 75/25) is equal to 1 kg of insulation material. The production process was divided into the following sub-processes:

(1.) Collection and shredding. It includes:
- (a) Transport of textile wastes to the collection site located in Cinisello Balsamo (average distance of 15 km)
- (b) Production of low-density polyethylene for packaging (volume of 0.25 m^3)
- (c) Transport of textiles to the production site located in Recanati (distance of 460 km)
- (d) Electricity consumption for textile shredding of 515 kWh
- (e) Water consumption of 160 l/h
- (f) Lubricant consumption of 10–20 l/h
- (g) Flame retardant consumption of 30–40 l/h
- (h) Allocation of the production of machinery used in this sub-process

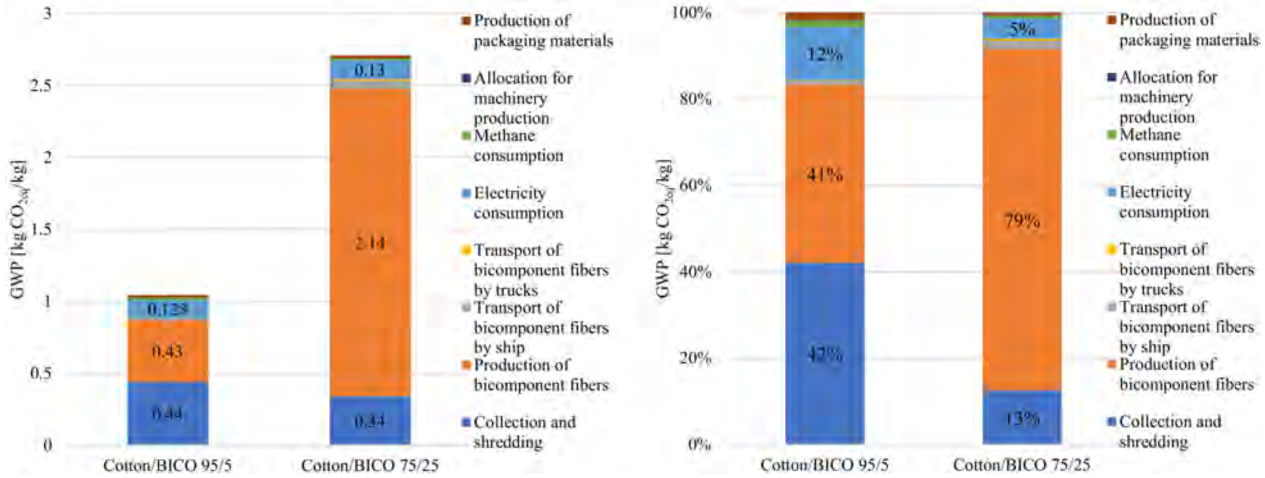

FIGURE 4. GWP, in kg CO_2eq per 1 kg of insulation, of the two textile alternatives.

Material	λ [W/mK]	Thickness [mm]	Density [kg/m^3]	R_T [m^{2}K/W]
Cotton/BICO 95/5	0.045	100	50	2.22
Cotton/BICO 75/25	0.045	100	50	2.22
EPS	0.035	78	20	2.23
Rockwool	0.035	78	60	2.23
Glasswool	0.032	71	50	2.22
Woodfibre	0.040	89	50	2.22

TABLE 1. Properties of the analysed insulation materials.

(2.) Production of textile-based insulation. It includes:
   (a) Production of bicomponent fibers in South Korea
   (b) Transport of bicomponent fibers by ship to the Port of Genoa (distance of 18 000 km)
   (c) Transport of bicomponent fibers by trucks to the production site located in Recanati
   (d) Electricity consumption for textile thermopressing of 293 kWh
   (e) Methane consumption of 35 m^3/h
   (f) Allocation of the production of machinery used in this sub-process
   (g) Production of packaging materials

The global warming potential of the two insulations is represented in Figure 4, expressed as kg CO_2eq/kg and as percentages respectively. The sample composed of 25 $\%_m$ of bicomponent fibres presents the highest GWP-value, thus impacting 2.5 times more than the other sample made with 5 % of bicomponent fibres. This difference is mainly caused by the higher amount of bicomponent fibres and thus by their impacting production process, which represents 79 % of the total GWP of the 75/25 sample.

3.2.2. Comparison with traditional insulation materials

After calculating the impact associated with the production process, a comparison with traditional insulation materials is performed (Table 1). The thermal resistance is adopted as functional unit, taking into account the differences in terms of thermal performances: 1 m^2 of panels with a thermal resistance of around 2.2 m^{2}K/W. Furthermore, the benefits of the recycled and natural insulation materials are highlighted, calculating the amount of CO_2 stocked by each kg of dry material obtained multiplying the carbon content and finally by converting carbon into CO_2, through the mass equivalent coefficient 3.67.

As already discussed in the previous paragraph, a higher amount of bicomponent fibres negatively affects the carbon footprint of textile-based materials. The quantity of stocked CO_2 is affected by the percentage of bicomponent fibres too, growing with their decreasing content: thanks to its low amount of bicomponent fibres, the sample Cotton/BICO 95/5 is characterized by a negative net GWP value.

4. Discussion

The methodology adopted for the thermal characterization of the insulation materials presents some criticalities and uncertainties related to the test parameters adopted (time, voltage, hypothesis, etc.) and to the measurement method itself. It is known that the thermal conductivity measured by the Transient Plane Source method could be overestimated by about 10 % with respect to real values, as demonstrated by Colinart et al. [15]. Therefore, a comparison with other measurement methodologies (e.g., heat flowmeter, guarded hot plate etc.) could help for the valida-

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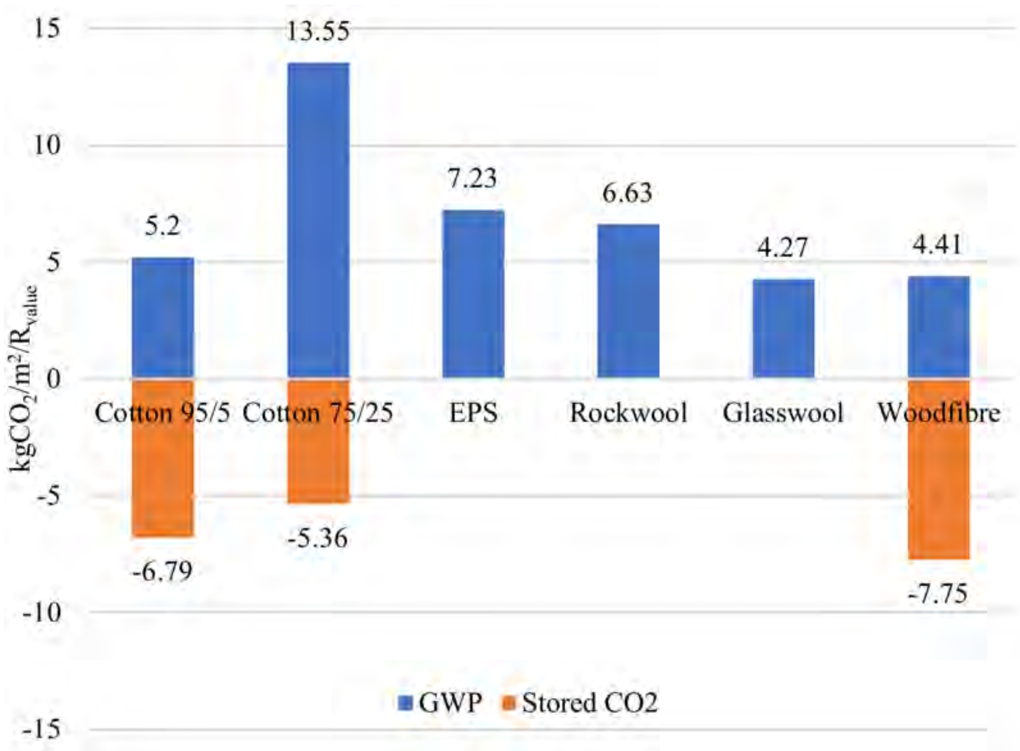

FIGURE 5. Carbon footprint (GWP) and CO_2 stored in $1\,m^2$ of textile and conventional insulation materials with a $R_T = 2.2\,m^2K/W$.

tion of the reported results.

For what concerns the carbon footprint assessment, as shown in the following Figure 5, results are largely sensitive to the share of BICO used to bind the fibres though a thermal treatment. Nowadays, the EU demand of bicomponent polyester fibres (BICO) is almost fully covered by South Korea. The long distant transportation and the high-carbon intensity for Country-specific energy generation largely affects the GWP of the final product. Investigation of possible alternative fibres, resulting from pet recycling process, should be investigated in order to define alternative low-carbon solutions for manufacturing the insulation panels.

5. Conclusions

This article summarizes the main results obtained in the "RECYdress project", which aimed at investigating the properties of textile-based insulations, proposing alternative ways to recycle a material whose end of life is mainly constituted by landfill or incineration. The main findings of this research were:

- textile wastes could be applied as insulation materials thanks to their low thermal conductivity values
- as verified by many authors, the thermal conductivity increases with the increasing material's density
- the treatment undergone by the textile wastes affects their thermal performance
- the chosen binder, i.e. glue, negatively affects the materials' thermal conductivity, due to the high amount of water contained
- the GWP value of textile-based materials is mainly affected by the amount of bicomponent fibers and their production process; besides, the Cotton/BICO 95/5 sample is characterized by a negative net GWP value, thanks to its low amount of bicomponent fibers.

Furthermore, future investigations could involve the measurement of the thermal properties of the tested materials with other methodologies, comparing and validating the obtained results. Besides, an additional analysis could concern the analysis of other types of textile materials, trying to improve both their thermal and environmental performances.

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References

[1] E. Dieckmann, R. Onsiong, B. Nagy, et al. Valorization of waste feathers in the production of new thermal insulation materials. *Waste and Biomass Valorization* **12**(2):1119–1131, 2021. https://doi.org/10.1007/s12649-020-01007-3.

[2] O. Mrajji, M. E. Wazna, Y. Boussoualem, et al. Feather waste as a thermal insulation solution:

Treatment, elaboration and characterization. *Journal of Industrial Textiles* **50**(10):1674–1697, 2021. https://doi.org/10.1177/1528083719869393.

[3] S. Jordeva, E. Tomovska, D. Trajković, K. Zafirova. Textile waste as a thermal insulation material. *Tekstil* **63**(5-6):174–178, 2014. https://hrcak.srce.hr/file/210294.

[4] R. Drochytka, M. Dvorakova, J. Hodna. Performance evaluation and research of alternative thermal insulation based on waste polyester fibers. *Procedia Engineering* **195**:236–243, 2017. https://doi.org/10.1016/j.proeng.2017.04.549.

[5] J. Zach, J. Hroudová, A. Korjenic. Environmentally efficient thermal and acoustic insulation based on natural and waste fibers. *Journal of Chemical Technology & Biotechnology* **91**(8):2156–2161, 2016. https://doi.org/10.1002/jctb.4940.

[6] C. Rubino, M. Bonet-Aracil, S. Liuzzi, et al. Thermal characterization of innovative sustainable building materials from wool textile fibers waste. *Tecnica Italiana – Italian Journal of Engineering Science* **63**(2-4):277–283, 2019. https://doi.org/10.18280/ti-ijes.632-423.

[7] C. Rubino, M. Bonet Aracil, J. Gisbert-Payá, et al. Composite eco-friendly sound absorbing materials made of recycled textile waste and biopolymers. *Materials* **12**(23):4020, 2019. https://doi.org/10.3390/ma12234020.

[8] C. Rubino, M. Bonet Aracil, S. Liuzzi, et al. Wool waste used as sustainable nonwoven for building applications. *Journal of Cleaner Production* **278**:123905, 2021. https://doi.org/10.1016/j.jclepro.2020.123905.

[9] C. Rubino, S. Liuzzi, F. Martellotta, et al. Nonwoven textile waste added with PCM for building applications. *Applied Sciences* **11**(3):1262, 2021. https://doi.org/10.3390/app11031262.

[10] A. Patnaik, M. Mvubu, S. Muniyasamy, et al. Thermal and sound insulation materials from waste wool and recycled polyester fibers and their biodegradation studies. *Energy and Buildings* **92**:161–169, 2015. https://doi.org/10.1016/j.enbuild.2015.01.056.

[11] M. El Wazna, M. El Fatihi, A. El Bouari, O. Cherkaoui. Thermo physical characterization of sustainable insulation materials made from textile waste. *Journal of Building Engineering* **12**:196–201, 2017. https://doi.org/10.1016/j.jobe.2017.06.008.

[12] A. Gounni, M. El Wazna, M. El Alami, et al. Thermal performance evaluation of textile waste as an alternative solution for heat transfer reduction in buildings. *Journal of Solar Energy Engineering* **140**(2):021004, 2018. https://doi.org/10.1115/1.4038786.

[13] A. Hadded, S. Benltoufa, F. Fayala, A. Jemni. Thermo physical characterisation of recycled textile materials used for building insulating. *Journal of Building Engineering* **5**:34–40, 2016. https://doi.org/10.1016/j.jobe.2015.10.007.

[14] A. Hegyi, C. Bulacu, H. Szilagyi, et al. Waste management in the context of the development of sustainable thermal insulation products for the construction sector. *International Journal of Conservation Science* **12**(1):225–236, 2021. https://ijcs.ro/public/IJCS-21-16_Hegyi.pdf.

[15] T. Colinart, M. Pajeot, T. Vinceslas, et al. How reliable is the thermal conductivity of biobased building insulating materials measured with hot disk device? In *Bio-Based Building Materials*, vol. 1 of *Construction Technologies and Architecture*, pp. 287–292. Trans Tech Publications Ltd, 2022. https://doi.org/10.4028/www.scientific.net/CTA.1.287.

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