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COMPARING THE CARBON FOOTPRINT OF BIO-BASED AND CONVENTIONAL INSULATION MATERIALS

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ABSTRACT
In this article we report the results of a study using Life Cycle Assessment methods to evaluate the Global Warming Potential (GWP) of five bio-based materials (mycelium, flax, sheep's wool, cellulose, wood fibre and cork) and two non-renewable insulation materials (mineral wool and PUR). This research demonstrated that sheep's wool can have a GWP lower than competing non-bio-based materials. However, other bio-based materials, though made using renewable resources, can have higher GWP than non-renewable insulation. The aim of this paper is to share information on the GWP of bio-based materials to inform the selection of sustainable building products.

KEYWORDS
Bio-based, life cycle assessment, Global Warming Potential.

INTRODUCTION
Bio-based insulation materials offer several benefits in comparison with more established non-renewable alternatives. Advantages of bio-based materials include that they: (1) have a renewable supply chain when sustainably and responsibly managed; (2) are often fast-growing, (3) can often be recycled or can be reintegrated into the biosphere as compost or fertiliser, and (4) can offset carbon emission through the photosynthetic carbon stored within them (Dams et al., 2021; van Dam et al., 2005).

Bio-based materials are widely marketed as sustainable. However, a comprehensive environmental impact assessment of the production, usage, and disposal of these materials is not always available. Life Cycle Assessment (LCA) is an established technique that assesses the environmental impact associated with all stages of a product's life (ISO 14040, 2006). To perform LCAs, detailed information on energy use, emissions and resource use are necessary (EN 15804, 2012 + A2, 2019). Some bio-based materials are newly commercially available with little or no data publicly available to assess their environmental impacts. In other cases, it is possible to find Environmental Product Declarations (documents that summarise an LCA) (del Borghi, 2013), but information may be limited only to the manufacturing process or be based on outdated standards (such as EN 15804, 2012 + A1, 2013) .

Comparative studies on insulation materials were performed (Murphy & Norton, 2008; Pargana et al., 2014; Schmidt et al., 2004; Schulte et al., 2021). Pargana et al. (2014) based their study on conventional insulation materials and demonstrated that by defining a thermal resistance of 1 m^2K/W, lightweight materials with high thermal performances have the lowest environmental impact. However, this study is based only on manufacturing impacts, and it is based on the outdated EN 15804 (2012) + A1 (2013).

Schmidt et al. (2004) and Schulte et al. (2021) compared the environmental impact of plant-based insulation materials to conventional materials. Both Schmidt et al. (2004) and Schulte et al. (2021) performed a cradle to grave LCA based on ISO 14040 (2006) and defined the thermal resistance value as the functional unit. Schulte et al. (2021) did not use scenarios to investigates variations on the environmental impacts of the insulation but provided single value results based on a single scenario for transportation, end-of-life, and materials properties. Schmidt et al. (2004a) took a different approach by looking at the influence of the improvement of manufacturing processes at the end-of-life scenarios. Schmidt et al. (2004a) demonstrated that product development can increase the recyclability and reduce some impacts. However, uncertainties in product developments (especially on the development of agricultural techniques) makes it complex to establish if there are significant differences between scenarios.

Murphy & Norton (2008) investigated the environmental impacts of natural fibre insulation materials. Murphy & Norton (2008) used a cradle to grave approach with a functional unit of 0.16 W/m^2K (thermal conductance). Similar to Schmidt et al. (2004a), Murphy & Norton (2008) demonstrated that improvement in the manufacturing process can reduce the whole life environmental impacts. An end-of life scenario analysis compared the environmental impacts of products when landfilled, incinerated or composted. Results from the study are, however, not comparable with EN 15804 (2012) + A2 (2019) based LCA and EPDs.

The presented work here analysed the Global Warming Potential (GWP_{100}) of five bio-based insulation materials. The environmental benefit and loads of each material were investigated, and results were compared with two common non-renewable insulation materials. GWP was assessed through LCA based on EN 15804 (2012) + A2 (2019). Manufacturing, use, and disposal data were collected from insulation manufacturers and supplemented through a thorough literature search. Results are first analysed using a declared unit, with no reference to material properties and material functionality. Afterwards the carbon footprint (GWP_{100}) is put into context by defining a target thermal conductance (0.15 W/m^2K). Several end-of-life and transportation scenarios were also considered. The use of scenarios and different units provides a range of information that can be adapted or directly used in the building material selection process.

METHODS

Materials

Five commercially available bio-based (mycelium, flax, sheep's wool, cellulose, wood fibre and cork) and two non-renewable insulation products (mineral wool and PUR) were assessed. Table 1 shows the density and thermal conductivity of the materials. The actual value represents the properties of the material as provided from the producers, while the minimum and maximum were collected through a literature review. The densities of all materials (excepted mycelium) and the corresponding thermal conductivity for the selected densities were taken from Hung Anh & Pásztory, (2021). For mycelium properties were collected from .Elsacker et al. (2019); Xing et al. (2018); Yang et al. (2017).

Table 1 Insulation materials properties

Products		Density (kg/m³)			Thermal Conductivity (W/mK)		
		Actual	Min	Max	Actual	At min density	At max density
Bio-Based	Mycelium	140	50	260	0.06	0.08	0.06
	Flax	23	20	80	0.038	0.045	0.03
	Sheep wool	18	10	40	0.038	0.045	0.033
	Cellulose	52	30	80	0.038	0.045	0.038
	Wood fibre	140	30	270	0.038	0.09	0.038
	Cork	165	110	170	0.04	0.05	0.037
Non-Renewable	Mineral wool	45	30	180	0.039	0.045	0.033
	PUR	35	30	100	0.025	0.03	0.024

Life cycle assessment

The aim of the LCA is to use Global Warming Potential as a tool to compare and select the most sustainable insulation material. The LCA follows the EN 15804 (2012) + A2(2019). For each material, a cradle to grave life cycle assessment was performed. The service life of the insulation was assumed to be 60 years, which is the typical life span for buildings (Athina Papakosta, 2017). Figure 1 represents the life cycle Modules and processes considered in this study (Module A to C). Module D was not included in the study as there are many uncertainties on the loads and benefits of recycling and on the calorific energy produced by bio-based materials when incinerated. Module A includes the assessment of products manufacturing, transportation and installation on site, Module B includes the use stage of the building which includes maintenance, eventual replacement of the product, but also the energy and water use of the building. Because this study has no reference to a specific building and environment, the impact of the insulation on energy and water usage was omitted. For most of the insulation materials, producers stated a life span of 60 years, so no maintenance and replacement are necessary. However, for cellulose the life span is 30 years, which means that the insulation needs to be removed and replaced at least once during the life span of the building. For mycelium, which is not yet a widely established material, no data that indicate possible life span is available, but it was assumed a life span of 60 years. Module C includes the demolition, waste sorting and end-of-life scenarios (incineration, landfill, and recycling). Figure 1 also represents the system boundary for the LCA. As EN 15804 (2012) + A2 (2019) prescribes, the LCA includes the extraction and manufacturing of raw materials, while the impacts that involve the pre-processing of recycled waste materials were omitted, as they belong to the system that generated that waste (the 'cut-off' approach).

Functional Unit

In the first part of the results, mass was used as declared unit (kg). This provides a general overview of the impact of the material without considering its functionality and material properties.

In the second part, a functional unit was defined. It was set that 1 m^2 of insulation needs to achieve a thermal conductance of 0.15 W/m^{2}K. To achieve the target, data on thermal conductivity and densities of the materials were collected in Table 1 Insulation materials properties. The use of a functional unit gives another perspective to the carbon footprint of the materials, as it gives the context of a real application.

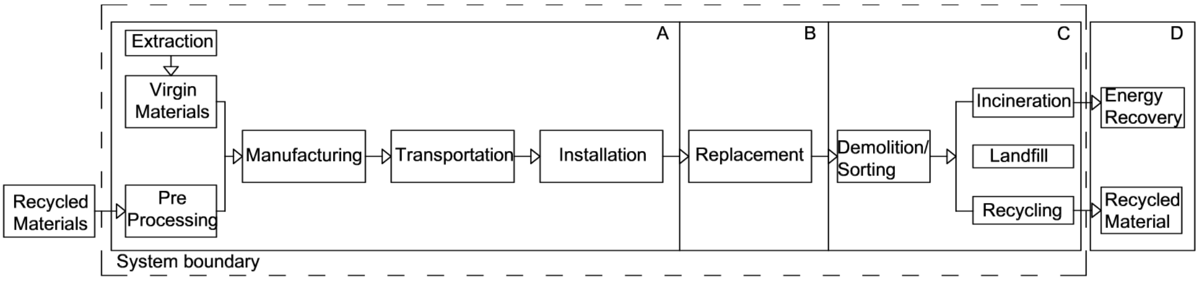

Figure 1 System boundary for the insulation materials

LCA and impact assessment
The LCA study was conducted using an attributional framework. LCA was modelled using openLCA version 1.10.3. For background data and, when necessary, for foreground data, ecoinvent 3.6 implemented in EuGeos 15804+A2 IA v4. Unit Processes (Eugeos, 2020) was used, to enable life cycle impact assessment (LCIA) according to the EN 15804 (2012) + A2 (2019) standard. LCIA prescribed in EN 15804 (2012) + A2 (2019) was implemented using EuGeos impact assessment method (Eugeos, 2020). Total, biogenic, fossil and land use and land use change (LULUC) GWP were analysed. GWP estimates how much energy the emissions of 1 ton of a gas will absorb over 100 years, relative to 1 ton of carbon dioxide. The GWP does not consider only carbon dioxide, but all anthropogenic greenhouse gasses, including methane, nitrous oxide, and chlorofluorocarbons emissions.

Material Modelling
Process modelling for mycelium, flax, sheep's wool, mineral wool and PUR are reported in (Cascione et al., 2022).
For cellulose, wood fibre and cork manufacturing processes, the ecoinvent database was used, as shown in Table 2. The carbon content was calculated by multiplying the amount of plant-based content present in the insulation (e.g., fibreboard is composed of 96% wood fibre) by the carbon content present in the biogenic constituent (calculated in base of lignin, cellulose, and hemicellulose present in the plant-based constituent). The amount of plant-based content and carbon content are provided with the ecoinvent database.

Table 2 Manufacturing processes and carbon content

Material	Process	Plant based content (kg)	Carbon content ($kgCO_2/kg$)
Cellulose	cellulose fibre production, blowing in | CH	0.2	0.8
Wood fibre	fibreboard production, soft | Europe	0.96	1.81
Cork	cork slab | RER	1	1.81

Cellulose is assumed to be replaced after 30 years. The replacement process involves the extraction of the existing cellulose by using a blown machine that consumes 18.5E-3 kWh of electricity per kg of material (Kellenberger et al., 2007)
The end-of-life and sorting of waste insulation were based on UK statistics on waste management in 2016 (DEFRA, 2016). For mycelium, flax, sheep's wool, mineral wool and PUR, the waste treatment methods are reported in (Cascione et al., 2022), while for cellulose, wood fibre and cork, wastes are sorted as in Table 3.

Table 3 Sorting of waste at the end-of-life

Material	Incinerated	Landfill	Recycling
Cellulose	86%	14%	0%
Wood fibre	34%	4%	62%
Cork	9%	91%	0%

For recycling it was assumed that wood fibre and cork are shredded before leaving the system, while for cellulose only the energy necessary to extract the insulation is considered as only action necessary for recycling.

When landfilled in the UK, materials go into sanitary landfills and if incinerated, UK plants are provided with a fly ash extractor (DEFRA, 2013; Gani, 2018).

The emissions generated by landfilling and incineration were assumed to be similar to paperboard for cellulose, while cork is considered similar to untreated wood waste. Wood fibre is considered a mix of untreated wood waste and polyurethane waste, as shown in Table 4.

Table 4 Characterization of insulation waste

Material	Quantity	Flow
Cellulose	1	waste paperboard
Wood fibre	0.96	waste wood, untreated
	0.035	waste polyurethane
Cork	1	waste wood, untreated

Scenarios

As shown in Table 1, insulation can be available in different densities and thermal conductivities. By analysing only one typology of insulation, LCA does not give a comprehensive overview of the environmental impacts. Variations on thermal conductivities require changes in the thickness and the overall volume of the materials to achieve the same thermal conductance, while changes in density lead to modification of the overall weight of the insulation. For this reason, variations in the GWP depending on material properties were investigated. It is important to highlight those variations in densities and thermal conductivities may affect the manufacturing process and, consequently, the results of the LCA. However, as the LCIA was based on data available in literature, there are lots of unknown to further address. For this reason, there is the necessity to look further into the sensitivity and uncertainty analysis and to have detailed data from manufacturers to have more precise predictions on the carbon footprint.

Life cycle assessment requires to include transportation from the manufacturer to the construction site. Transportation can have a significant impact on the carbon footprint. To have wide view on the impacts of materials, several manufacturing locations were assumed to deliver material to the UK. For UK producers it was assumed that materials are transported by lorry from a manufacturer placed 300 km away. For insulation delivered from the rest of Europe, it was assumed that lorries need to cross the channel by train or that materials are sent by plane. Five scenarios will be used to estimate the impact of transportation on the GWP of the insulation materials (Table 5).

Table 5 Transportation means and distances (km)

Location	Lorry	Train	Plane
UK	300	-	-
Northern Europe	300	50	-
Southern Europe	1000	50	-
Southern Europe	-	-	900
Overseas	-	-	8000

RESULTS

Table 6 shows the GWP breakdown (fossil, biogenic, land use and change). In most of the materials fossil GWP are the highest. This is due to the carbon emissions produced by human activities necessary to process and transport materials and wastes. For all materials, fossil GWP is the highest at manufacturing. Fossil GWP at the end-of-life is generally smaller than at manufacturing, because in the UK most of the wastes are recycled, and when incinerated and landfilled wastes are treated to reduce emissions (DEFRA, 2013; Gani, 2018).

Biogenic carbon is highly present in plant-based materials, as plants and trees store carbon dioxide from the air during their growth (negative value) and release carbon back at the end of their service life when materials are incinerated, landfilled, or recycled. When summing up the biogenic carbon emission from production, replacement, and end-of-life, the sum is close to zero, as EN 15804 requires that biogenic carbon dioxide stored at manufacturing is modelled as released at the end-of-life. In all materials a small positive number for biogenic GWP was found that represents methane emissions emitted by biogenic materials. LULUC GWP is relatively insignificant at less than 5 % of the total emissions in all cases.

The total GWP indicates that wood fibre and cork present a net negative GWP at the manufacturing stage, as carbon dioxide absorbed by plant-based material outweighs the fossil GWP. All other materials present positive total GWP values at manufacturing, showing fossil GWP is greater than biogenic GWP. However, it is important to highlight those biogenic emissions are modelled as being re-emitted at a later stage (end-of-life), regardless of whether wastes are recycled, incinerated, or landfilled. However, if materials are recycled, the biogenic carbon content is still retained in the subsequent product, and if landfilled the release of carbon and other gases depends on the degradation timeframe of the waste (Morris et al., 2021). The total emissions of biogenic carbon at the end-of-life, is, however, prescribed by the EN 15804 (2012) + A2 (2019). to avoid double counting of biogenic carbon across different product systems. This approach can be considered conservative, as the release of carbon dioxide at the end-of-life does not highlight the advantage of reusing or recycling bio-based materials when compared to non-bio-based materials (Figure 3). Module D should highlight this difference, but the modelling of Module D for bio-based materials involves the application of many assumptions on potential recycling and reuse of materials. An alternative approach would be to represent the temporal aspects of the carbon sequestration within the cradle to grave product life, as shown by Morris et al. (2021).

Table 6 GWP (kgCO_2eq/kg) breakdown. Bio based materials are in green and non-renewable in orange. Service life for all materials is 60 years, except cellulose that is replaced after 30 years.

Materials	Process	GWP total	GWP LULUC	GWP fossil	GWP biogenic
Mycelium	A	1.9	5.0E-3	3.5	-1.6
	C	1.9	6.2E-6	31.0E-3	1.9
Flax	A	1.6	3.5E-3	2.7	-1.1
	C	1.4	10.0E-6	132.1E-3	1.3
Sheep Wool	A	1.8	48.9E-3	1.4	281.8E-3
	C	577.0E-3	11.3E-6	156.4E-3	420.5E-3
Cellulose	A	254.0E-3	900.0E-6	409.0E-3	-155.7E-3
	B	581.0E-3	910.0E-6	456.0E-3	124.0E-3
	C	487.0E-3	12.8E-6	47.0E-3	439.9E-3
Wood Fibre	A	-608.0E-3	1.8E-3	1.1	-1.7
	C	1.8	7.5E-6	57.0E-3	1.8
Cork	A	-40.7E-3	3.6E-3	1.3	-1.7
	C	1.8	7.4E-6	56.0E-3	1.8
Mineral Wool	A	1.4	807.4E-6	1.4	25.2E-3
	C	31.9E-3	5.8E-6	31.8E-3	91.3E-6
PUR	A	6.1	3.6E-3	6.0	148.6E-3
	C	717.6E-3	17.7E-6	716.8E-3	771.9E-6

By comparing the cumulative total GWP over Modules A-C, it is evident that PUR is the most impactful material (Figure 2). Meanwhile, mineral wool has a relatively low total GWP (1.4 kgCO_2e/kg) as the material itself does not need much processing. Mineral wool is composed of 25% recycled content. As it is mainly composed by inert at the end-of-life mineral wool can be recycled and, if landfilled, does not generate significant emission (Cascione et al., 2022). Only cellulose and wood fibre present slightly lower values than mineral wool (both 1.2 kgCO_2e/kg). Mycelium presents the highest GWP among the bio-based materials (3.9 kgCO_2e/kg). Even though mycelium is composed by 100% bio-based materials, it was estimated that fossil GWP at manufacturing is two times higher than the sequestrated biogenic carbon. This is due to the energy necessary to maintain optimal conditions for the growth of mycelium for prolonged time (Dorr et al., 2021; Robinson et al., 2019).

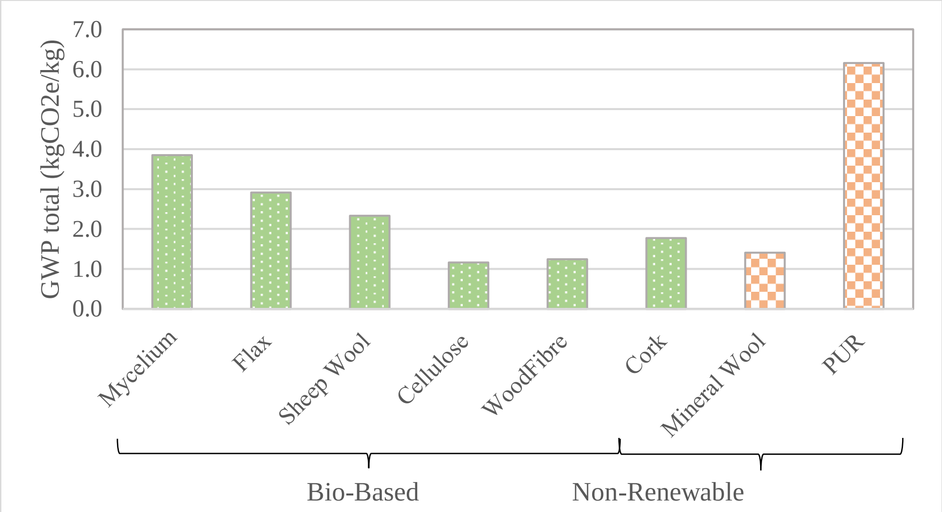

Figure 2 Comparison of the total GWP of the insulation (A to C)

In Table 6 and Figure 2 UK based end-of-life scenario was shown, which is a combination of recycling, landfill and incinerator depending on the material sorting and recycling capacity in the UK. In Figure 3 scenarios in which materials are 100% recycled or 100% incinerated or 100% landfilled are presented to give an overview of the impacts of each process on the whole life carbon footprint. The scenarios do not include the energy recovery from incineration and the recycling of wastes after they become secondary resources in a new system, as usually included in Module D as described in the .EN 15804 (2012) + A2 (2019).

Figure 3 shows that there is not a general trend that suggests recycling, incineration or landfilling are overall less impacting. PUR, sheep's wool and flax incineration released, respectively, 40%, 31% and 18% more emissions than landfilling, due to the release of fossil carbon dioxide from the plastic component. For cellulose, landfilling is 65% higher than incineration and recycling due to the release of methane in paper-based materials. In mycelium, wood fibre, cork, and mineral wool no significant differences were observed between scenarios. Overall, a similar trend to Figure 2 is observable for most materials. PUR is the worst material, whilst mycelium is the worst among the bio-based insulation, regardless of how materials are disposed with exception of flax and sheep's wool that can have similar or higher impacts when incinerated. Cellulose that presented the lowest GWP in the UK scenario (Table 6), but if 100% landfilled it releases higher emissions than wood fibre, cork, and mineral wool (Figure 3).

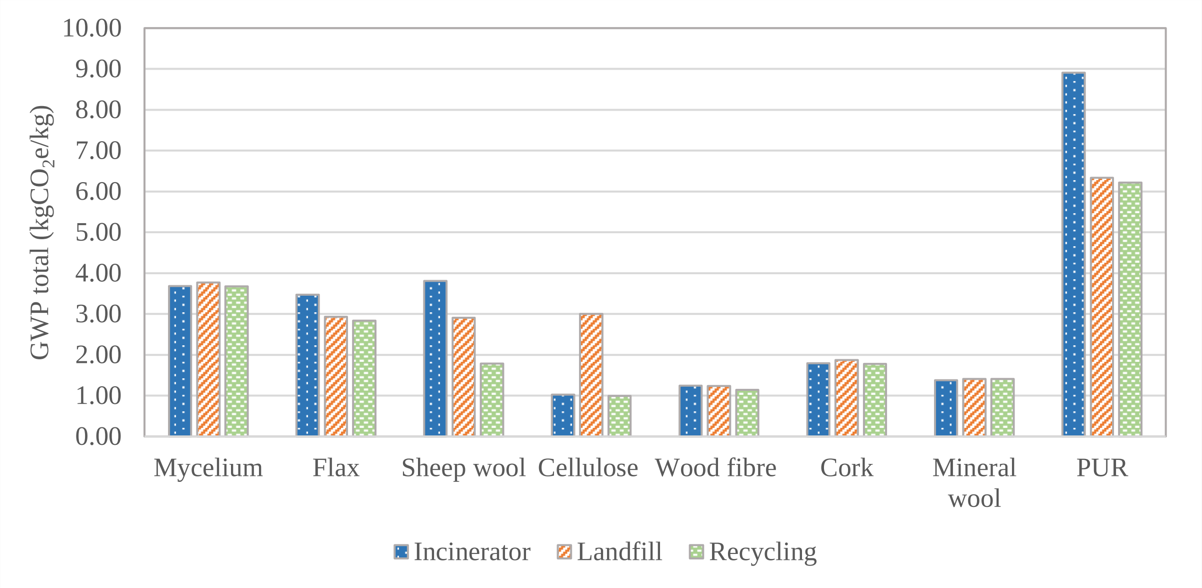

Figure 3 End-of-life scenarios (Module C) impacts on the whole life GWP (Module A-C). In dotted blue 100% incineration, in striped, orange 100% landfill and in green trellis 100% recycling

When the functionally of materials is considered, material properties become relevant to the A-C GWP estimation (Table 7). Density and thermal conductivity of each material influence the amount of material necessary to achieve a thermal conductance of 0.15 W/m^2K, which consequently impact the GWP. Table 7 indicates that materials like PUR with low density and high thermal resistance (first two columns in Table 7) impact overall less than mycelium because the amount of PUR necessary to manufacture an insulation up to the specification (6-16 kg) is significantly less than the quantity of mycelium necessary to achieve the target thermal conductance (27-104 kg).

In Table 7 mycelium presents the highest GWP, followed by cork, wood fibre and PUR. Mineral wool, flax, sheep's wool, and cellulose are overall the least impacting, when low density and higher thermal resistance products are preferred.

It is, however, important to highlight that the ranking in Table 7 is affected by which impact categories are considered. The present study focuses on GWP_{100}, but the inclusion of other impacts categories, such as depletion of resources and eutrophication) may change the rankings.

Table 7 A to C total GWP of the insulation when thermal conductivity and density of materials are considered. UK base scenario was used. Red represents the highest impact and dark green the lowest.

Products	Total GWP/m^2		
	Actual	At min density	At max density
Mycelium	215.6	550.6	77.0
Flax	17.4	17.5	46.6
Sheep's Wool	10.9	7.0	20.5
Cellulose	15.7	10.5	24.2
Wood Fibre	45.3	22.4	87.3
Cork	90.3	76.4	89.5
Mineral Wool	16.5	12.7	55.8
PUR	36.6	36.9	98.5

Transportation can also be a significant contributor to the GWP. Table 8 shows a systematic increase in the carbon emission when transportation distances increase. By assuming that manufacturing impacts do not change across countries, the farthest the manufacturer, the highest impacts. However, optimised manufacturing processes (high recycled content, low energy use) can reduce the overall impacts of a product that may results in lower carbon emissions for products coming overseas than local alternatives.

The impact of transportation is also strictly related to the overall weight of the material and its properties. Transportation impacts are higher in heavier and thicker materials than in light weight and higher performing ones. As an example. mycelium that is overall the heaviest presented significantly higher transportation impacts (215.5-379.4 $kgCO_2e/m^2$) than sheep's wool (10.9-29.6 $kgCO_2e/m^2$).

Table 8 A-C Total GWP ($kgCO_2e/m^2$) for transportation scenarios from manufacturer to construction site (UK). The scenarios in orange are the impacts considered for the base scenario (UK scenario from Module A to C)

Products	Transportation scenarios				
	UK	Northern Europe	Southern Europe	Southern Europe	Overseas
	by lorry			by plane	
Mycelium	215.5	**215.6**	223.2	230.0	379.4
Flax	17.4	**17.4**	18.5	19.5	41.2
Sheep wool	**10.9**	10.9	11.8	12.6	29.6
Cellulose	16.8	**15.7**	18.2	20.5	69.5
Wood fibre	45.2	**45.3**	52.0	58.0	190.1
Cork	93.7	82.3	**90.3**	97.3	253.0
Mineral wool	**16.5**	16.5	18.7	20.6	63.1
PUR	**37.1**	79.7	37.8	81.9	103.9

DISCUSSION

Figure 4 summarises all GWP variations when end-of-life, transportation, and material properties scenarios are combined. Mycelium presents the highest variations, as it is still a material that is not yet strongly present on the market and still needs to go through a production optimisation process (Robertson et al., 2020). Moreover, depending on the substrate used, material properties may significantly change (Robertson et al., 2020). Other materials showed smaller variation because they already went through manufacturing optimization, but wide GWP variations can be seen due to variety of products commercially available (Figure 5). Sheep's wool presents the lowest variation (between 5.4 to 52.2 $kgCO_2e/m^2$), as it showed smaller variations of weight and thermal conductivity. However, end of life scenarios can impact the overall GWP of sheep's wool (Figure 3). Cellulose, mineral wool, flax present overall higher GWP variations than sheep's wool (between 24 and 136 $kgCO_2e/m^2$). Cork and wood fibre have higher variation than other insulation materials but lower than mycelium (20.4 to 256.3 $kgCO_2e/m^2$).

Overall, it is complex to establish whether bio-based materials are better than non-biobased. From this study sheep's wool is in most cases a better choice than mineral wool and PUR, whilst flax and cellulose can have lower impacts than mineral wool and PUR, but it is necessary to choose the best performing products (lowest thermal conductivity and less dense) and to avoid landfilling of cellulose or incineration for flax (Figure 3). Wood fibre and cork can have higher GWP than mineral wool and PUR. |However, the choice of lighter and highly insulating wood fibre and cork products can lower the overall GWP.

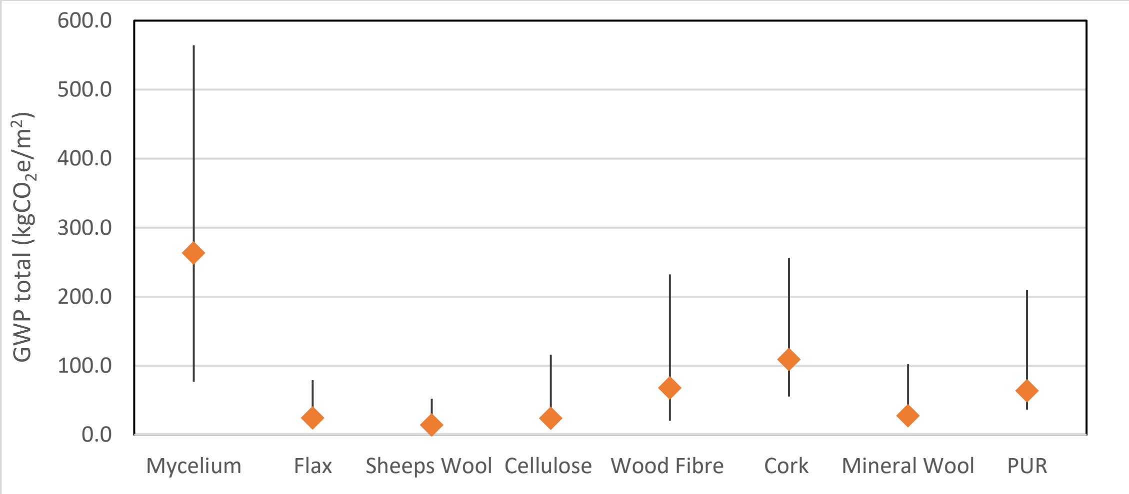

Figure 4 A to C Total GWP range. In orange the UK base scenario GWP. The black line represents the maximum and minimum GWP obtained in all the scenarios investigated.

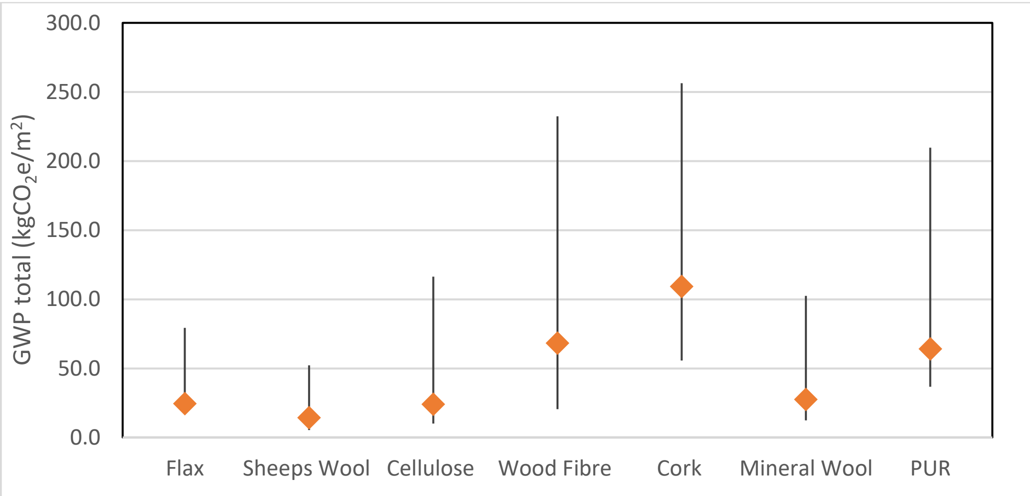

Figure 5 A to C Total GWP range excluded mycelium. In orange the UK base scenario GWP. The black line represents the maximum and minimum GWP obtained in all the scenarios investigated.

CONCLUSIONS

This paper demonstrated that a cradle-to--grave LCA (Modules A to C) can be used to assess the carbon footprint of insulation products to guide the selection of the most sustainable material. Module D was omitted as no sufficient data on the recyclability and energy recovery of bio-based materials was available.

This research demonstrated that some bio-based materials have a lower total GWP than conventional products; for example, the total GWP of sheep's wool was on average three times lower than PUR, and two times lower than mineral wool, depending on materials properties. Other bio-based materials, even though they are made using renewable resources, can have four times higher total GWP (mycelium and cork) than non-renewable insulation materials due to the manufacturing process or end of life scenarios. However, scenarios analysis demonstrated that the GWP is heavily influenced by the product functionality, material properties, transportation, and end-of life scenarios. Variations in scenarios showed how also established bio-based materials (wood fibre, flax, cork) can have higher GWP variations than non-renewable insulation materials. It is important to highlight that the ranking of the insulation materials is only based on GWP. When considering other environmental impacts as described in EN 15804 (2012) + A2 (2019), a different perspective on material sustainability can be highlighted. As an example, mineral wool may deplete a higher quantity of non-renewable resources

than mycelium. In this circumstance mycelium may show a better ranking than when only considering GWP.
Overall, it can be stated that bio-based insulation materials can be a low carbon option, but it is important to tailor the choice of materials to a specific location and product. Moreover, it is necessary to consider temporal aspects and the carbon storage capacity of bio-based materials. In this study a conservative approach was applied to follow the EN 15804 (2014) + A2 (2019). However, in future investigation the advantaged of bio-based materials to outweigh fossil emission and be net negative at the manufacturing stage should be better represented. The carbon sequestration can be relevant when it is necessary to reduce carbon levels in the air in the present by delaying carbon emission in the future when the net-zero carbon target will be achieved. At the end-of-life the modelling of biogenic carbon should also be revised to better represent the benefit of reuse and recycling, due to the preservation of carbon within the product. This approach will better show the benefit of using bio-based martials over non-bio-based products.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.