Bio-based Building Material Solutions for Environmental Benefits over Conventional Construction Products - Life Cycle Assessment of Regenerative Design Strategies (1/2)

Lise Mouton  
KU Leuven, Faculty of Engineering Science, Department of Architecture, Leuven, BE  
https://orcid.org/0000-0002-9387-2224

Karen Allacker  
KU Leuven, Faculty of Engineering Science, Department of Architecture, Leuven, BE  
https://orcid.org/0000-0002-1064-0795

Martin Röck  
KU Leuven, Faculty of Engineering Science, Department of Architecture, Leuven, BE  
https://orcid.org/0000-0003-2940-1230

Research Article

Keywords: Bio-based materials, comparative LCA, embodied impacts, embodied carbon, biogenic carbon, hotspot analysis, decarbonization, climate change, mitigation

Posted Date: October 25th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2199019/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.  
Read Full License
Abstract

The focus in reducing environmental impacts of buildings is shifting from the operational stage to the full life cycle, with particular attention to embodied greenhouse gas (GHG) emissions of construction materials. The application of bio-based construction materials is promoted for potentially reducing material-related embodied GHG and even enabling carbon fixation.

In part one of this study (1/2), we apply life cycle assessment (LCA) to critically examine regenerative design strategies, starting by investigating embodied GHG emissions as well as other environmental impact indicators of different bio-based building element variants – assessing timber-, straw- and hemp-based solutions - in a European context.

The results show that bio-based building elements tend to have considerably lower embodied GHG emissions than conventional solutions, e.g., brick or concrete-based elements. Analyzing the environmental hotspots across the life cycle of selected bio-based construction options, we identify their most contributing environmental indicators to be global warming potential (GWP), particulate matter (PM) and land use (LU); and the most important life cycle stages to be material production, maintenance and replacement, particularly of finishes. To investigate carbon removal potentials, we calculated biogenic carbon contents of selected bio-based options, identifying straw-based building elements as the most promising solution due to high biogenic carbon content and fast (yearly) re-growth cycles.

Our study highlights the environmental potentials of using bio-based construction solutions to substitute conventional building materials. In addition, the study identifies important environmental trade-offs within bio-based material alternatives that demand consideration and further study in future research.

1 Introduction

In 2020, building construction and operation accounted for 36% of global final energy use and 37% of energy-related carbon dioxide (CO₂) emissions [1]. Hence, in order to mitigate climate change, the building sector urgently needs to implement strategies to drastically reduce its energy and resource use. Over the past years, measures to reduce the environmental impact of buildings have mainly targeted the operational impacts. While those measures have been successful, they only relate to the use stage of buildings and thus do not consider impacts during any of the other life cycle stages. These energy-saving measures have even caused an increase in embodied impacts [1–7], and consequently, in so-called embodied greenhouse gas (GHG) emissions [1, 8] both absolute and relative to the total impacts. Therefore, to further reduce the building sector’s environmental impacts, embodied impact reduction should be addressed more extensively. To this extent, the life cycle assessment (LCA) methodology is typically applied. In a building LCA, the environmental impacts are generally divided into operational and embodied impacts. The operational impacts are related to the operational energy and water use, i.e. covering indoor activities and providing the desired indoor environment. Embodied impacts occur in all
other life cycle stages and are related to material production, transport, end of life processing as well as maintenance and replacements [9, 10].

To enhance the reduction of the building sector’s impacts, the development of environmental targets for buildings has been emerging. One approach to define such targets is by top-down allocation of global environmental goals or policy targets. Examples of goals and targets that have been allocated are the Earth environmental carrying capacity [11], global carbon budgets [12–14] or Planetary Boundaries [15]. The approach results in target values for buildings that reflect how high their impacts can be in order for them to be sustainable in an absolute sense. However, as such targets are developed and compared to existing buildings’ impacts, it appears that current construction practices are not able to achieve them [11, 13–16]. This diagnosis is supported by recent analyses on EU building stock development, which stress the importance of developing and implementing strategies for monitoring and effectively reducing building-related environmental impacts [17]. In this context, regenerative design strategies aim at minimizing negative impacts (such as GHG emissions) while enabling environmental benefits (like biogenic carbon fixation) based on a holistic perspective with the environment at its core.

A potential strategy to reduce the embodied impacts of buildings is to substitute conventional, fossil fuel-based construction materials with bio-based alternatives [1]. Nowadays it is possible to produce construction materials from biomass that achieve similar mechanical, thermal, acoustic etc. properties as conventional construction materials and, on top of it, that provide better environmental performance during their life cycle [18–22]. Some even enhance atmospheric carbon reduction through their potential of storing carbon in the construction product [23]. However, these conclusions are often drawn from cradle-to-gate LCA studies excluding impacts occurring after the product has left the factory.

This paper aims at evaluating the life cycle environmental impact of bio-based construction materials for the building structure and envelope in the Belgian context. Our analysis focuses on GHG emissions, i.e. the GWP indicator, as this is the main reason bio-based construction materials are promoted. To identify potential environmental trade-offs, we further carry out an environmental hotspot analysis based on a comprehensive set of environmental indicators for identifying the most important impact indicators, life cycle stages and most contributing processes. This paper offers a comprehensive assessment of GWP and other environmental impacts across the full life cycle of bio-based construction solutions. The study highlights the potential of bio-based solutions to reduce GWP impacts as well as identifies environmental hotspots and trade-offs that should be the focus in further research.

The paper is structured as follows. Firstly, a state-of-the-art review is conducted to select bio-based materials and products that are relevant for the Belgian construction sector to date. Secondly, the environmental performance of multiple building elements containing the selected products is assessed through an LCA from cradle-to-grave. Thirdly, their environmental performance is compared to the impact of conventional building element compositions. Fourth, environmental hotspots are identified, i.e. the most important impact indicators, life cycle stages and processes. Finally, the biogenic carbon content of bio-based options is calculated and the overall results compared to the literature for contextualization.
2 State-of-the-art For Bio-based Construction Materials

A review of the state-of-the-art of bio-based construction materials was performed, consisting of two parts. First, the state-of-research was investigated by means of a systematic literature review (SLR) [24]. Second, a web search was performed to explore which bio-based materials and products are available on the European market and which ones are typically used in Belgium. The full state-of-the-art review is included in the Supplementary Data.

In the SLR the databases ScienceDirect and Scopus were searched for: ["bio-based materials" OR "biobased materials") AND (buildings OR construction)]. The initial search resulted in a total of 80 papers when duplicates were removed. From this initial gathering, a selection was made using following criteria: it presents one or more bio-based materials; the material is applicable for a residential or mixed-use building’s structure or envelope; the paper addresses the embodied impacts of the construction material. This resulted in 23 research papers for a detailed reading

Figure 1 (left) shows hemp is studied the most (i.e. 12 times), especially hempcrete (i.e. nine times). Eight of those papers assessed hemp at building element level and one paper at building level. All papers are positive about the application of hemp as eco-friendly construction material. Moreover, out of all bio-composites in the papers, hempcrete appears to be the only one which has proven to be an adequate construction material, whereas other composites are still being modified and experimented with at material level. Structural timber appeared seven times as the structural frame in a hempcrete wall, so little attention was given to its properties or environmental performance. However, it can be concluded that it works well with bio-based infill materials. The third most studied materials are straw and cork, i.e. both four times. Cork is considered out of scope, however, because of its relatively larger transportation distance. Straw was found in the form of traditional straw bales, pressed straw or combined with clay. However, it is noted that straw construction techniques are currently being modernized to keep up with industrialization [25]. In general it is argued that the traditional construction techniques of some bio-based materials (e.g. traditional straw bale construction) are not able to compete with newly developed techniques in terms of applicability, quality assurance, labor intensity and overall cost effectiveness [25, 26]. That is why new materials and techniques such as bio-composites and engineered bio-based products are being developed. These provide low-impact products that can compete with industrial materials and techniques (e.g. steel, concrete).

Based on this initial review, we decided to look further into the state of application in construction practice for timber, hemp and straw.

We researched multiple construction product manufacturers and building stakeholders who work with timber, hemp and straw to get an overview of relevant construction products and to gather material to inform the composition and modeling of building elements. An overview table was compiled and is included in the Supplementary Data. It shows that straw and hemp construction products are currently gaining popularity in Belgium. Both materials are applied in different types of products, e.g. in the form of insulation mats, prefabricated blocks or building elements, for both new construction and retrofitting.
However, a comparison of the environmental impacts from both these uprising materials seems to be lacking thus far.

Straw is most often applied in the form of traditional straw bales, although newly developed straw-based construction techniques are gaining territory. Two promising examples are blowing in straw and prefabricated straw-based elements. Hemp is typically used either in hemp-based thermal insulation or in hempcrete. The latter knows multiple application techniques, of which hempcrete blocks and cast hempcrete are most common in Belgium [27].

Timber is already considered a common construction material because it has been around for centuries and its application possibilities and issues are well-known. Many different kinds of timber products can be found, including both traditional and innovative products. Today, both traditional timber frame construction and modern, prefabricated mass timber solutions such as cross laminated timber (CLT) are gaining importance on the Belgian market [28].

The analysis of the state-of-the-art reveals a strong interest in construction materials based on harvested wood products (HWP), e.g. timber-based construction, as well as construction materials made from agricultural residues, such as hemp or straw fibers. However, especially for the latter we observe a lack in studies actually investigating the environmental impacts of straw-based construction products. This is a clear research gap, as some recent research suggested high potentials of using straw-based construction materials, e.g. as insulation material for building retrofit, and indicate beneficial effects of reduced embodied GHG emissions as well as carbon fixation effects [29].

Based on this analysis of the state-of-the-art, the LCA study presented in this paper focuses on the environmental assessment of construction options utilizing three main bio-based materials, albeit in different applications:

- **Timber**: timber frame, mass timber,
- **Straw**: straw bales, prefabricated straw panels, blow-in straw,
- **Hemp**: hemp insulation, hempcrete blocks, hempcrete cast in situ.

### 3 Materials And Methods

**Life cycle assessment**

**Modeling approach**

The building elements are modeled with the MMG-tool by KU Leuven. The KU Leuven MMG-LCA-tool is an excel-based LCA tool for buildings that is developed specifically for the Belgian building sector [31]. Figure 2 shows the hierarchical structure of the modeling procedure in the tool: materials – work sections – building elements – buildings. First, materials are modeled by specifying their $\lambda$ (heat transmission
coefficient) and \( \rho \) (density) and linking to LCI background data for stages production (A1-A3) as well as transport (A4) and end-of-life stages (C2, C3, C4), respectively, based on scenarios for the Belgian context. Second, work sections are defined by their material composition and respective quantities per unit of work section (e.g. m² wall). The work section definition includes scenarios for construction process (A5), cleaning, maintenance and replacements (B2, B4) and deconstruction (C1), respectively. Third, building elements are modeled as a set of work sections. Since this study is limited to the building element level, the final upscaling to buildings is not included in this paper. The MMG-LCA method version 2020 includes the CEN and CEN+ environmental impact indicators as defined by the Belgian Royal Decree of 14.07.2014 regarding environmental product declaration of construction products [32]. The CEN indicators are in line with the European standard EN 15804+A1:2013 [33] while the CEN+ indicators are additional ones in line with the ILCD recommendations [34]. All impacts in MMG are modeled according to the life cycle stage they occur in. A full documentation of the method is available in [31]. The LCA background database used in this study is ecoinvent 3.3 [35]. The life cycle scenarios are elaborated specifically for Belgium [31]. Materials that are not available in the MMG database are modeled in SimaPro and respective impacts implemented in MMG as new material records.

Assessment methodology

<table>
<thead>
<tr>
<th>FU</th>
<th>What?</th>
<th>How much?</th>
<th>How well?</th>
<th>How long?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Building element variants for external walls (EW), internal walls load-bearing (IW-LB) and non-load-bearing (IW-NLB), ground floors (GF), internal floors (IF), flat roofs (FR), pitched roofs (PR)</td>
<td>1 m of building element</td>
<td>Structural properties: All element variants are dimensioned for use in residential and mixed-use buildings of up to 5 floors and comply with relevant requirements for moisture-protection. Thermal and acoustic properties: ( U = 0.15 ) W/m K (EW, GF, FR and PR) ( R = +/- 41 ) dB (IW-LB) and +/- 38 dB (IW-NLB)</td>
<td>Reference study period (RSP): 60 years</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reference flow 1 m of building element including its structure, insulation, internal and external finishing, water and vapor barriers, supporting layers; as used for building in a Belgian context over 60 years.


Table 1: Scope of the life cycle assessment in this study.
Table 1 summarizes the scope of the LCA. The different components are discussed in more detail below.

**Goal and scope:** The aim is to compute the life cycle environmental impacts of the selected technologies for the various building elements: external walls (EW), internal walls (IW), ground floors (GF), internal floors (IF), flat roofs (FR) and pitched roofs (PR). For every type, impacts are compared to each other as well as to conventional solutions. This way an overview is obtained of how the bio-based materials perform in each impact category relative to conventional materials, and which aspects (i.e. life cycle stages and work sections) contribute the most to each category.

**Functional unit:** For EW, GF, FR and PR the functional unit (FU) is 1 m² of the respective building element with $U = 0.15 \text{ W/m}^2\text{K}$, which is compliant with the passive house standard [36]. For IW, however, there are no regulations concerning thermal transmittance. So instead, the FU is 1 m² of building element with similar sound insulation, i.e. a sound reduction index of approximately 41 dB and 38 dB for load-bearing and non-bearing walls respectively.

Furthermore, the structural components are sized so that all elements are structurally feasible for their respective use in the case studies (CS) presented later. Lastly, building physics is considered, meaning that water and vapor barriers are applied as needed to avoid infiltration and internal condensation.

**Reference flow:** Every building element is composed of a structural component, insulation (either thermal or acoustic), foils for air, water and vapor tightness, and support structures (e.g. boards or battens), where needed, as well as finishing layers. The specific parts included in each building element including their respective classification according to BB/SfB-plus codes [37] are provided in Supplementary Information.

The reference study period (RSP) is 60 years, which is typical for residential and office buildings LCA modeling and in line with the MMG method [31]. During the RSP, no renovations are planned. When the service life of certain materials or work sections are shorter than 60 years, their replacements are considered.

**System boundaries:** Life cycle stages considered are in line with EN 15978:2011 [9] and consist of A1-A3 (Product stage), A4-A5 (Construction process stage), B2 (Maintenance), B4 (Replacement) and C1-C4 (End of life stage). B2 is subdivided in B2.1 (Cleaning), B2.2 (Small maintenance) and B2.3 (Big maintenance). B4 is at the building element level only B4.1 (Replacement of work section). A visual overview is presented in Supplementary Information.

**Biogenic carbon flows:** Biogenic carbon is an increasingly relevant consideration for bio-based construction materials. In our study, we apply the 0/0 approach, i.e. neither biogenic carbon uptake nor release are modeled in the life cycle assessment’s GWP indicator. However, a simple, static calculation of biogenic carbon content in the building elements is done, based on the kg of bio-based material per building element found in literature. The calculation only considers biogenic C in the bio-based structures and insulations, hence excluding finishes and support structures. The C contents that are applied are the following:
Timber: 0.5 kgC/kg<sub>timber</sub> [40]
Straw: 0.4 kgC/kg<sub>straw</sub> [41]
Hemp shiv: 0.45 kgC/kg<sub>hemp</sub> [42]

The biogenic carbon content of timber actually ranges across different species, but 0.5 kgC/kg<sub>timber</sub> is a common assumption [40].

**Hotspot analysis**

To systematically identify environmental hotspots for the different building elements investigated in this study, we apply a protocol inspired by the hotspot analysis suggested in the respective Environmental footprint (EF) guide [38] and applied previously in the PEF4Buildings study on testing the implementation of the Product EF (PEF) method to buildings [39]. The protocol suggests a step-by-step investigation of: 1) most important environmental indicators, based on normalized and weighted impacts; 2) the most important life cycle stages; and finally 3) the most important processes, which in our case are work sections and construction materials within building elements. In each consecutive step, the items cumulatively contributing 80% to total impacts are hotspots and hence considered in the next step of the hotspot analysis.

**Life cycle inventory**

**Building elements**

For each building element type, multiple compositions are defined, each containing at least one of the selected bio-based construction techniques. For all element types, it is opted to define a composition for every selected technique, though in some cases no relevant solution could be found. First, the building elements of three real case study (CS) buildings are modeled. The CS are: CS1 – A mass timber mixed-use building in Switzerland (SolarHouse, N11 Architects, 2014); CS2 – A strawbale single family house in Austria (EFH Gladik, 2016); and CS3 – A hempcrete single family house in Belgium (under construction at time of writing) (jtB, BLAF Architecten, 2022). A more elaborated description of the CS is included in the Supplementary Information. The work section thicknesses of the original building elements are adjusted to obtain the required U-value or sound insulation. Second, variations of these elements are defined, generally by changing the insulation material. For the timber frame EW, a variant including a doubled frame is always defined (i.e. elements EWXX.2 in Figure 4 to Figure 7, and Table 2 and Table 3) to have elements that are structurally feasible for the five-story building CS1. Third, additional compositions are derived from product catalogs and via building stakeholders that were found during the web search mentioned in section 2. Where needed, extra layers are added to avoid moisture-related issues.
Inventory modeling

Figure 3 presents by example the detailed composition and hierarchically modeled LCI of the external wall EW01. For all elements, the input parameters and scenarios are categorized under the respective level (i.e. work section or material) in which they are implemented in the MMG method. The input data for materials and processes that were modeled in SimaPro are provided in the Supplementary Information. In addition, the Supplementary Information presents an overview of all bio-based elements modeled, including information on materials used in structure and insulation/infill as well as further information on the references including mentioned CS buildings. Further information, such as the detailed inventory data of all of these building elements, are provided in the Supplementary Data. Existing conventional element options were used from the MMG database, the details are also available in Supplementary Data.

4 Results And Discussion

Life cycle embodied GHG emissions of all building elements

Figure 4 shows the GWP results for the different building elements investigated in this study. Results are grouped by building element type. The bars show the GWP, expressed in kgCO$_2$eq/m$^2$ building element, across the full life cycle, with colored sections showing the contribution of different life cycle stages. The color shaded underlay used here and in other sections differentiates the main material focus of the specific element options, where: gray = conventional (e.g. using reinforced concrete, fired clay bricks); brown = timber-based; yellow = straw-based; green = hemp-based. The dash-dotted lines show the mean values of the different element types, and the dashed lines show the mean values for the different material subgroups.

Figure 4 reveals a great variation in total impacts between the different building element types as well as within every type. Overall, the lowest embodied life cycle GHG emissions per m$^2$ are observed for IW-NLB, around 42 kgCO$_2$eq/m$^2_{BE}$, and IW-LB, with about 52 kgCO$_2$eq/m$^2_{BE}$. The EW, IF, FR and PR show embodied life cycle GHG emissions on a similar order of magnitude with mean values of 107 kgCO$_2$eq/m$^2_{BE}$ (EW), 112 kgCO$_2$eq/m$^2_{BE}$ (IF), 107 kgCO$_2$eq/m$^2_{BE}$ (FR), and 130 kgCO$_2$eq/m$^2_{BE}$ (PR), respectively. The emissions per m$^2$ GF are about double, i.e. around 239 kgCO$_2$eq/m$^2_{BE}$.

For all building element types and material variants, both bio-based and conventional, the most contributing life cycle stage is the production stage (A1-A3), albeit to a different degree, depending on the element type, service life and related use stage scenarios.

Further, for EW, IF and FR it strikes that for some bio-based elements the total impact is lower than the lowest of the conventional elements (i.e. timber frame with stone wool or cellulose), while other bio-based elements’ impact are higher than the highest conventional ones (i.e. with a concrete or fired clay brick structure). In case of the IW, all bio-based solutions perform better than the conventional solutions with
the exception of the timber frame with hempcrete blocks wall IW-LB05. On the other hand, the bio-based PR all have higher impacts than the conventional PR except for the prefabricated straw-timber panel PR03, which has nearly the same impact as the conventional timber frame with stone wool roofs MMG01-02. Similarly, for the GF, the floor with straw bales GF04 is the only one that performs better than the floors with conventional insulation such as PUR foam or board.

Overall the building elements with the same bio-based material have similar total impacts within the building elements, with some exceptions for the EW and PR. For the mass timber EW it strikes that the walls with hempcrete insulation EW03 and EW06 have a much higher impact than the ones with hemp or straw insulation. Similarly, the timber frame walls with hempcrete blocks or cast hempcrete EW11 and EW12 have a much higher impact than a frame wall filled with hemp insulation EW09.

Timber-focused elements: The GWP of mass timber elements in general highly depends on the insulation material that is used in the composition, making it either higher or lower than straw compositions. For the EW for example, the elements that contain hemp insulation (EW01 and EW04) have a GWP that is 6-11% higher than the elements with blow-in straw insulation (EW02 and EW05), while the GWP of the ones with hempcrete blocks (EW03 and EW06) is 1.6 to 2 times as high as the ones with straw. Regarding the mean values, it strikes that among the PR, the mean GWP of the timber-focus elements is lowest of the bio-based elements, while for IF and FR it is the highest of all. For the EW and IW the timber elements' mean values fall in between straw (lower) and hemp (higher), and are in both cases lower than the overall mean of the respective building element. Yet, the GWP of the elements with hempcrete insulation (EW03 and EW06) are higher than the overall mean of the EW.

Straw-focused elements: The straw-based building elements have the lowest GWP. This is in line with a finding in the SLR, namely that a straw-based wall's GWP is only half of that of a hempcrete wall [43]. In general, it holds that the total GWP of straw-based elements is lower or only slightly higher than the GWP in A1-A3 of timber and hemp elements. For all element types, the mean value of the straw-focus elements is lower than the overall mean of the respective type, ranging from 7.5% lower than the PR's mean value to 66% lower than the IW-LB's mean value. Moreover, the mean values of the straw elements are for every element type the lowest except for the PR, where the mean value of the timber-focus elements is just 2% lower.

Hemp-focused elements: The hempcrete elements often have the highest GWP of the bio-based compositions, in several cases higher than conventional compositions. However, it should be noted that carbon sequestration of hemp is not considered in this analysis, which would otherwise induce a reduction in its impact. For the hempcrete walls EW11-12, the impact in A1-A3 alone is already higher than the total impact of seven out of the eleven conventional EW. Moreover, for all EW containing hemp, whether as insulation layer or as infill in frames, A1-A3 is higher than the total impact of the other bio-based elements. Then again, these other bio-based elements' total impacts are lower than the A1-A3 impact of eight of the conventional EW. For all building element types except for the IW-NLB, the mean
value of the hemp-focused elements is higher than the overall mean. Moreover, for all element types except for the IF and FR, the mean value of the hemp elements is the highest.

Environmental hotspot analysis of selected bio-based building elements

In a next step, we analyze the different element options considering the full range of environmental indicators assessed in the LCA. To stay within reasonable page limits, we focus our analysis on the environmental hotspots, benefits and trade-offs for a selection of bio-based building material options. In the following, we hence present the analysis of a selection of building elements which have a high potential to apply bio-based alternatives over conventional construction methods in practice. We selected the "best" building element for each material type from four element types based on GWP results. Table 2 presents the building element variants selected for in-depth study and discussion. Nonetheless, we conducted a full life cycle assessment and detailed analysis of the full set of environmental indicators for all building elements in this study. The respective results are provided in Supplementary Data.

<table>
<thead>
<tr>
<th>Element category</th>
<th>Timber-focus</th>
<th>Straw-focus</th>
<th>Hemp-focus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>External wall (EW)</strong></td>
<td>EW05: CLT + blow-in straw; EW09.1: Timber frame + blow-in straw</td>
<td>EW10.1 Timber frame + hemp insulation;</td>
<td></td>
</tr>
<tr>
<td><strong>Internal wall (IW)</strong></td>
<td>IW-LB01: Mass timber; IW-LB04: Prefabricated straw-timber panel;</td>
<td>IW-LB05: Timber frame + hempcrete blocks</td>
<td></td>
</tr>
<tr>
<td><strong>Internal floor (IF)</strong></td>
<td>IF02: Mass timber + EPS; IF05: Timber beams + blow-in straw;</td>
<td>IF06: Timber beams + hempcrete aggregate</td>
<td></td>
</tr>
<tr>
<td><strong>Flat roof (FR)</strong></td>
<td>FR01: Mass timber + hempcrete blocks; FR04: Timber frame + straw bales;</td>
<td>FR06: Timber frame + hempcrete aggregate</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Bio-based element variants selected for further investigation and hotspot analysis.

As a first step, we analyze the most important environmental impact indicators based on characterized results weighted by their environmental cost in line with the MMG method. The environmental cost represents an external cost based on damage and prevention costs [44].

Figure 5 presents the contribution of different environmental impact categories per m² of the selected bio-based material options, based on the total environmental cost. Overall, the it shows that commonly, the highest contribution to the external environmental cost for the selected bio-based building elements
stems from GWP, particulate matter (PM), land use (LU), and human toxicity - non-cancer effects, where positive effects, i.e., negative impact values, are observed. The Supplementary Information shows that this also holds largely true for the other building elements.

The Supplementary Information includes tables showing both absolute and relative values of the contribution of the impact indicators. For the timber and straw-focus elements, GWP, PM and LU make up 80-87% of the total environmental cost, except for roof FR04 (67%). For the elements containing hemp, i.e. the hemp-focus elements as well as roof FR01, we obtain a cumulative contribution of 82-88% when human toxicity (non-cancer effects) is also included. However, it is remarkable that for the elements that contain straw, this indicator shows negative values. Examination of straw in SimaPro showed that the negative values seem to be correct and are due to straw stocking up pollutants from the soil. Nevertheless, if these pollutants return to the environment at the end of life, this effect might be reversed [45]. While this effect of negative human toxicity is interesting and deserves further investigation, we decided to exclude it from our further analysis due to the effect only showing for straw-based elements, but not for other bio-based options.

Within different options for the same building element type (i.e., EW, IW-LB, IF, FR) the straw-based elements generally have the lowest overall weighted impact. Moreover, the straw elements have the lowest weighted cost for GWP, except for the EW variant (EW09.1), where the mass timber solution has a slightly lower GWP cost, albeit higher weighted impact overall. For both EW and IW wall types, the hemp-based elements have the highest GWP cost, and for the IF and FR the mass timber elements have the highest GWP cost. The environmental costs for PM and LU are overall the highest for the mass timber solutions.

Figure 5 further illustrates that, logically, the external building elements (EW and FR) have higher total costs than their internal equivalent (IW and IF), and that the horizontal building elements (IF and FR) have higher costs than the vertical building elements (EW and IW).

**Most important life cycle stages**

Figure 6 shows the absolute results for the different building elements and the contribution from different life cycle stages (a) as well as the relative contribution of different life cycle stages, (b) for the selected bio-based building elements, based on their most important environmental indicators (GWP, PM, and LU).

Figure 6 shows that for all selected elements the product stage (A1-A3) has the largest contribution, i.e. around 50% to as much as 95% of life cycle impacts. Analyzing which stages are the most important and that together contribute up to 80% of the total life cycle impact, we find that the product stage (A1-A3) consistently ranks as the most important life cycle stage across all elements and environmental indicators.
For LU, the dominance of product stage-related impacts goes so far that the most important life cycle stage (i.e., related to at least 80% of impacts) is mostly just the product stage (A1-A3) with its contribution ranging from 90 to 95% except for roof FR06 (Timber frame + hempcrete aggregate), where A1-A3 makes up just below 80%, with the second most relevant contribution from the replacement stage (B4.1), contributing another 20% to whole life cycle impacts.

For GWP and PM, the replacement stage (B4.1) falls in the top 80% of all straw elements except for the timber beam floor IF05 where no replacement of the insulation layer was modeled. Similarly, for hemp-based wall IW-LB05 and roof FR06 that stage also falls within the top 80% for GWP and PM. Floor IF05 instead has relatively larger impacts from B2.1 cleaning for GWP (i.e. 20%), and C1 deconstruction, demolition and B2.2 small maintenance for PM (respectively 9.5% and 7.4%). The same holds for floor IF06 which has a very similar composition.

Results from all three impact categories suggest that the production of mass timber appears to be rather impact intensive as for the mass timber elements A1-A3 represents over 80% of the three categories. The only exceptions are the GWP and PM of roof FR01, which are just slightly lower than 80%, as well as the GWP of floor IF02. FR01 also includes A5 construction and installation in its most important stages of GWP and PM. However, for both impact categories, A5 only represents around 4% of the total. Further, FR01 is the only element for which A5 is by definition amongst the most important stages.

Mass timber elements overall have fewer stages that are identified as most important than timber frame elements. For all timber frame walls (EW09, EW10, IW-LB04, IW-LB05) and timber beam floors (IF05, IF06) stage C1 deconstruction and demolition belongs to the most important stages of PM, yet this is limited to only 5-12% of the total PM.

Finally, there are some stages that are less frequently among the most important ones. C4 waste disposal belongs to the most important stages of the GWP of mass timber floor IF02, straw floor IF05 and straw roof FR04, representing respectively 29%, 8% and 7.4% of the total GWP. A4 transport to site is included in the most important stages of the GWP of the prefabricated element IW-LB04. However, that element was modeled as if it were constructed on site, hence in reality its transport impacts will be different. The stages that are never identified as most important are B2.3 big maintenance, C2 waste transport and C3 waste processing.

**Most important processes**

Table 3 includes the selected elements’ most important work sections for GWP, PM and LU. Overall, the bio-based material or work section of focus is always included. This is no surprise since those materials are always used as structural or insulating components. Nevertheless, the insulation that is applied in the mass timber elements is only a few times among the most important work sections. For example, the blow-in straw in EW05 is the largest contributor to the LU (49%) but is not considered important for its GWP and PM. The mass timber elements often include less work sections among their most important
ones than the timber frame elements (i.e. the elements with straw or hemp focus). The mass timber work section itself often represents a large part of the impacts, while for the work sections consisting of a timber structure with straw or hemp-based infill there is more variation in how much it contributes to the total impacts. Note that wall IW-LB01 only consists of a mass timber wall that accounts for 100% of the impacts, so it is not further considered in the discussion.

Global Warming Potential (GWP): The GWP of elements containing hempcrete (IW-LB05, IF06, FR01, FR06) are dominated by the hempcrete work section. In IF06 and FR06 it accounts for 40%, in IW-LB05 86%, and in FR01 (which is in the first place a timber-focus element) the hempcrete blocks account for 62% of the GWP. The work section with hemp mats in wall EW10.1 is relatively less important for GWP, accounting for 21%.

Walls - For the EWs, the structure, insulation and external finishing are generally responsible for the largest shares of impacts. For all three EW, the external finishing is always among the most important work sections for GWP and PM. The lime plaster of EW09.1 and the fired clay bricks of EW10.1 even contribute the most to the total GWP, i.e. representing 61% and 47% respectively. In case of the lime plaster, this is linked to the high impact in the replacement stage of EW09.1 as noted in the section 4.2.2. In EW09.1, the structural frame with blow-in straw comes after the finishing with 16% and next is OSB with 10% contribution. In EW10.1 the timber frame with hemp mats only comes third with 21%, while the wood fiber board accounts for 24% of the GWP. In EW05 the largest contribution to the GWP comes from the CLT structure (54%) and then the cork finishing (30%). The timber frame internal walls IW-LB04 and IW-LB05 consist of just the frame with bio-based infill and a clay plaster on both sides of the wall. The frame with infill has for all three indicators the highest impact. However, when adding up the contribution of both plaster layers, these become the larger contributor (53%) to the GWP of IW-LB04.
<table>
<thead>
<tr>
<th>Indicator</th>
<th>EW05</th>
<th>EW09.1</th>
<th>EW10.1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GWP</strong></td>
<td>54% CLT 30% Cork finish</td>
<td>61% Lime plaster 16% Blow-in straw + frame 10% OSB</td>
<td>47% Fired clay bricks 24% Wood fiber board 21% Hemp mats + frame</td>
</tr>
<tr>
<td><strong>PM</strong></td>
<td>73% CLT 17% Cork finish</td>
<td>49% Blow-in straw + frame 25% Lime plaster 11% Clay plaster</td>
<td>40% Hemp mats + frame 29% Fired clay bricks 23% Wood fiber board</td>
</tr>
<tr>
<td><strong>LU</strong></td>
<td>49% Blow-in straw + frame 35% CLT</td>
<td>96% Blow-in straw + frame</td>
<td>57% Hemp mats + frame 23% Wood fiber board</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indicator</th>
<th>EW05</th>
<th>EW09.1</th>
<th>EW10.1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GWP</strong></td>
<td>100% Mass timber</td>
<td>47% Straw-timber panel 26% Clay plaster (x 2)</td>
<td>86% Hempcrete blocks + frame</td>
</tr>
<tr>
<td><strong>PM</strong></td>
<td>100% Mass timber</td>
<td>57% Straw-timber panel 21% Clay plaster (x 2)</td>
<td>71% Hempcrete blocks + frame 13% Clay plasters (x 2)</td>
</tr>
<tr>
<td><strong>LU</strong></td>
<td>100% Mass timber</td>
<td>99.7% Straw-timber panel</td>
<td>96% Hempcrete blocks + frame</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indicator</th>
<th>EW05</th>
<th>EW09.1</th>
<th>EW10.1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GWP</strong></td>
<td>33% EPS board 30% Parquet (hardwood) 21% Mass timber</td>
<td>48% Parquet (hardwood) 23% Cement screed 12% Blow-in straw + beams</td>
<td>40% Hempcrete aggr. + beams 33% Parquet (hardwood) 15% Cement screed</td>
</tr>
<tr>
<td><strong>PM</strong></td>
<td>67% Mass timber 23% Parquet (hardwood)</td>
<td>42% Parquet (hardwood) 33% Blow-in straw + beams 14% Cement screed</td>
<td>45% Hempcrete aggr. + beams 34% Parquet (hardwood) 11% Cement screed</td>
</tr>
<tr>
<td><strong>LU</strong></td>
<td>82% Mass timber</td>
<td>79% Blow-in straw + beams 12% Parquet (hardwood)</td>
<td>40% Hempcrete aggr. + beams 35% Parquet (hardwood) 12% OSB (x 2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indicator</th>
<th>EW05</th>
<th>EW09.1</th>
<th>EW10.1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GWP</strong></td>
<td>62% Hempcrete blocks 21% Mass timber</td>
<td>20% Wood fiber board 15% Straw bales + beams 12% EPDM 12% Softwood board 11% Battens &amp; counter battens (x 2)</td>
<td>40% Hempcrete aggr. + beams 17% Plywood 15% Steel profiles</td>
</tr>
<tr>
<td><strong>PM</strong></td>
<td>61% Mass timber 25% Hempcrete blocks</td>
<td>20% Straw bales + beams 20% Softwood board 15% Battens &amp; counter battens (x 2) 11% Wood fiber board</td>
<td>51% Plywood 18% Hempcrete aggr. + beams 10% Sloping profiles (softwood) 10% Steel profiles</td>
</tr>
<tr>
<td><strong>LU</strong></td>
<td>99% Mass timber</td>
<td>79% Straw bales + beams 9% Softwood board</td>
<td>38% Plywood 27% Hempcrete aggr. + beams 22% Sloping profiles (softwood)</td>
</tr>
</tbody>
</table>

Table 3: Most important work sections for the selected elements (i.e. cumulatively 80% impact or more) and their relative contributions.
Floors - For the IF, the impacts are dominated by the structure and the floor finish. Note that all IFs are finished with hardwood parquet on a cement screed. For GWP the parquet is even more impactful than the mass timber slab in IF02 and the timber beams with blow-in straw in IF05. In floor IF06 it comes second after the timber beams with hempcrete infill for all three indicators (40-45%), but still represents one third of each. As illustrated in Figure 6, the cleaning stage is an important reason for this. In the beam floors IF05 and IF06, the screed is also an important work section for GWP and PM, accounting for about 11-23%. In the mass timber floor IF02, the largest contributor to the GWP is the EPS insulation (33%), followed by the parquet (30%) and the mass timber element (21%). The screed is not identified as an important work section in this floor. The EPS is the work section responsible for the high C4 waste disposal impact in Figure 6. In this case substituting the EPS board by a lower impact alternative would have great effect on the total GWP of floor IF02.

Roofs - For mass timber roof FR01, the bio-based work sections lead all three impact indicators: for GWP the hempcrete blocks are highest (62%) followed by the mass timber element (21%), while for PM it's the other way around (i.e. 25% and 61%). On the other hand, the timber beam roofs FR04 and FR05 have relatively low contributions from the beam with infill work section. For the GWP of FR04, and the PM and LU of FR06, the most important work sections are the timber-based boards, followed by the beam with infill work section. For the GWP of FR06 and PM and LU of FR04 it is the other way around. Both FR04 and FR06 include multiple timber boards and timber and steel substructures in their most important work sections for the three indicators, and even EPDM for GWP. Important to note is that the plywood board in FR06 is always among the highest, while the OSB board in FR04 is not spotted in the most important work sections, although they are used for similar purposes. In fact, in FR06 the plywood is responsible for a large part of replacement impacts, while in FR04 the replacement of the EPDM and the softwood board underneath become relatively more important because a lower-impact OSB board is applied. Hence, the low contribution of the beams with straw bales in FR04 is more related to the fact that straw is fairly low-impact, while the relatively low contribution of the beams with hempcrete in FR06 can be ascribed to the fact that plywood appears to have a relatively high impact.

Particulate Matter (PM): PM impacts are always dominated by work sections that contain or that fully exist of timber. For mass timber elements EW05, IF02 and FR01 the mass timber work section (i.e. CLT or mass timber) is responsible for 73%, 67% and 61% respectively. Also important here are the cork finishing (17%), parquet finishing (23%) and hempcrete blocks (25%). In the timber frame elements, the first most important work sections for PM include the timber frame with infill work section (18-71%), the parquet for the IF (34-42%), and timber boards and profiles for the EW and FR (10-51%).

Hempcrete is also an important contributor to the PM impacts. For example the frame with hempcrete blocks in wall IW-LB05 is responsible for 71% of the total PM, while for wall IW-LB04 the frame with straw accounts for 47%, even though it has a larger timber to infill ratio (i.e. 24% instead of 9%; both IW further contain the same work sections). The non-bio-based work sections that are important in PM are the lime plaster (25%) and fired clay bricks (29%) in the EWs, the clay plaster in the EWs (11%) and IWs (13-21% x2
layers), the screed in the IFs (11-14%) and the steel profiles in FR06 (10%). These are also layers that drive the B4.1 replacement and C1 deconstruction impacts shown in Figure 6.

**Land use (LU):** As expected, the most important layers responsible for LU are all plant-based. For all elements with straw focus, LU impacts are largely covered by the straw-based work section (i.e. 79-99.7%). Furthermore, in the mass timber wall with blow-in straw insulation EW05, straw represents half of the LU, whereas the CLT accounts for 35%.

In the other elements, the largest part of LU comes from either mass timber or hemp in a timber structure. For the hemp-focus elements the most important layers of LU additionally include timber boards and substructures and parquet finishing. In roof FR06 for example the most important layers for LU are plywood (38%), timber beams with hempcrete aggregate (27%), and then timber profiles for the roof slope (22%). The high impact of the plywood is related to the high B4.1 replacement impact of FR06 presented in Figure 6.

In our modelling, Hemp shows to have lower LU impacts than straw. Floors IF05 and IF06 for example have, except for the bio-based infill material, exactly the same composition. In IF05, however, the beams with straw work section is responsible for 79% of the LU, while the beams with hempcrete in IF06 are only 40% of the LU. Moreover, in roof FR01, which contains mass timber and hempcrete blocks, the mass timber roof element accounts for 99% of the LU. A consideration here is that the high LU impacts of straw could be due to an allocation issue. Straw is in fact a by-product of agricultural crops [46], which means the majority of impacts during production should be allocated to the crops instead of the straw. Hence, if this is not the case, the impact of straw is overestimated. The same holds for hemp, because multiple products are derived from hemp plants.

Further analysis of the most important processes for the production stage A1-A3 impacts is provided in Supplementary Information Table 4. Therein we observe overall the same important work sections and with a similar order of magnitude, with some shifts in their ranking for GWP and PM. Generally, the bio-based work sections of focus (i.e. mass timber, straw or hemp) are responsible for higher shares of A1-A3 impacts than for the full life cycle impacts. For GWP, the larger importance of these work sections is mainly because of the exclusion of the replacement (B4.1) of external wall finishing, cleaning (B2.1) of floor finishing, and waste disposal (C4) of the timber boards in roofs. The increased importance of their PM impact is explained by the exclusion of the often high deconstruction (C1) impacts of wall or ceiling finishing or cement floor screeds. For LU, the ranking of the importance of work sections does not change and their shares do not differ more than 4%, except for hempcrete roof FR06. In FR06, the hempcrete aggregate and softwood sloping profiles are responsible for higher shares of the LU because no replacement is foreseen of the high-impact plywood embedded in the construction.

**Biogenic carbon analysis**
Figure 7 shows the biogenic carbon content in the structural and insulating materials. The carbon content in the elements varies from 11.94 for hemp wall IW-LB05 to 62.10 kgC/m²BE for timber roof FR01. The GWP of the building elements is for all elements higher than the carbon fixation, except for walls IW-LB01 and IW-LB04. Note, however, that it is not evident to directly compare biogenic carbon to the GWP due to the temporal nature of carbon uptake and emissions [47]. Yet, while the carbon fixation effects are beneficial, they do not compensate for the process-related emissions across the life cycle of the building elements. Overall there remains a net emission and hence the building elements do not act as actual carbon sinks. Figure 7 highlights that mass timber elements can fixate two to five times as much carbon as straw or hemp-based elements. On the other hand, there is no such clear pattern for which building element type has in general the highest or lowest fixation. Further, although straw and hemp-based elements contain more straw and hemp in volume than timber, for about half of these elements the timber frame fixates more carbon than the straw or hemp. The hemp elements always fixate the least carbon, though the difference with straw is no more than 8.4 kgC/m²BE. It is important to note that differences in growth cycles and rotation times until harvest of the different bio-based materials (one or few years for straw and hemp, to several decades for timber) influence both their availability and carbon fixation potential at the macroscale. On this aspect, recent studies have shown clear benefits for fast-growing bio-based materials such as straw, for enabling an effective, temporary carbon sink from use of bio-based building materials [29, 48].

Table 4 presents for the selected elements the results of the biogenic carbon calculation next to the GWP in the different life cycle stages. Table 4 shows that overall the elements with the lowest carbon fixation, i.e. the hemp elements, have the highest total GWP. So although their carbon fixation is only slightly lower than for straw, the straw elements will compensate for a much higher share of their GWP than the hemp elements. For example for the FR, the GWP of straw roof FR04 is almost four times as high as its carbon fixation, while for hemp roof the GWP is more than ten times as high. Timber elements will compensate for an even higher share of their GWP, even though the GWP of these timber elements is always higher than for straw elements. For roof FR01 for example the GWP is less than three times as high as the carbon fixation, yet its GWP is 70% higher than the GWP of the straw element.
### Table 4: Biogenic carbon content and GWP of the selected building elements.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Biogenic carbon content [kgC/m²BE]</th>
<th>Global Warming Potential (GWP) [kgCO₂eq/m²BE]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1-A3</td>
<td>A4-A5</td>
</tr>
<tr>
<td><strong>External Wall</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EW05</td>
<td>41.98</td>
<td>52.81</td>
</tr>
<tr>
<td>EW09.1</td>
<td>20.87</td>
<td>36.85</td>
</tr>
<tr>
<td>EW10.1</td>
<td>13.33</td>
<td>91.94</td>
</tr>
<tr>
<td><strong>Internal Wall - Load Bearing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IW-LB01</td>
<td>47.70</td>
<td>25.66</td>
</tr>
<tr>
<td>IW-LB04</td>
<td>12.69</td>
<td>7.48</td>
</tr>
<tr>
<td>IW-LB05</td>
<td>11.94</td>
<td>47.02</td>
</tr>
<tr>
<td><strong>Internal floor</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IF02</td>
<td>47.70</td>
<td>62.00</td>
</tr>
<tr>
<td>IF05</td>
<td>17.69</td>
<td>47.97</td>
</tr>
<tr>
<td>IF06</td>
<td>16.29</td>
<td>85.06</td>
</tr>
<tr>
<td><strong>Flat roof</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FR01</td>
<td>62.10</td>
<td>109.98</td>
</tr>
<tr>
<td>FR04</td>
<td>21.38</td>
<td>51.35</td>
</tr>
<tr>
<td>FR06</td>
<td>12.95</td>
<td>84.30</td>
</tr>
</tbody>
</table>

**Contextualization with results from scientific literature**

The studies identified in the SLR were found to vary significantly in terms of assessment method, FU and system boundaries, which makes direct comparison to the literature challenging. Only one study, i.e. by Pittau et al [43], was found to have the same scope, i.e. cradle-to-grave LCA of a 1 m² of a full building element. In Figure 8, the GWP (y-axis) and biogenic carbon (dot sizes) of the exterior walls with straw and hemp focus are plotted, together with results from that study. Note, however, that the U-value differs, namely U = 0.125 W/m²K. The Pittau study includes one EW with pressed straw, and one EW with hempcrete blocks and cast hempcrete, and both are assessed with three different disposal scenarios. The GWP results for straw are more in line with the other study than the results for hempcrete. The GWP of the straw walls from our study (71-83 kgCO₂eq/m²BE) all fall within the range of the other study (70-90 kgCO₂eq/m²BE). On the other hand, all hempcrete elements’ GWPs are higher for our study (155-180 kgCO₂eq/m²BE) than in the Pittau study (84-120 kgCO₂eq/m²BE). Specifically, the mean value of the GWP is 74% higher than it is for the other study. The biogenic carbon is for both the straw and hempcrete walls...
lower than in Pittau et al, even though they applied the same biogenic carbon contents as our study. Specifically, their biogenic carbon can be up to three times as high for both the straw and hempcrete walls. However, the difference in the walls’ total biogenic carbon fixation can be explained by the fact that theirs contain more material, which is reflected by the lower U-value. Still, a difference of a factor of three is surprisingly high.

**Limitation of the study**

Since the increased use and manufacturing of novel bio-based construction materials is a recent development, the information that could be gathered about the environmental performance as well as practical matters was limited. There are not many bio-based construction product manufacturers yet and hence LCA studies of market-available products are limited. For example, for the prefabricated elements no information could be retrieved about the impacts during the production stages of the product. Furthermore, since the application of bio-based products in practice is relatively recent, not much information was available about maintenance and replacement. The biogenic carbon calculation was limited to a simple static calculation as it was not the main interest of this study. However, although a dynamic calculation would have induced more challenges to be dealt with, it is argued that such calculation delivers more reliable results [47, 49]. In addition, it should be kept in mind that biogenic carbon content and GWP are not directly comparable, which is why this study did not subtract values but rather shows results side-by-side.

**5 Conclusion And Outlook**

Prior to the LCA, the state-of-the-art review revealed that there is an increasing interest in timber, straw and hemp-based construction materials in Belgium. Nevertheless, there is currently a lack of studies that compare the environmental performances of these materials and their applications. Therefore, this study investigated multiple building elements consisting of various timber, straw and hemp applications.

In terms of global warming potential (GWP) there is great variation in how the bio-based elements perform compared to conventional such as concrete, brick or timber frame elements. For the external walls (EW), internal floors (IF) and flat roofs (FR) some bio-based elements have higher GWP than the highest conventional elements (i.e. hempcrete walls EW11.1/2 and mass timber floors IF02-03 and flat roof FR02), while others have lower GWP than the lowest conventional options (i.e. all straw-based walls EW07-09 and IW-(n)LB03-04 and straw-based ground floor GF04 and pitched roof PR03). The bio-based internal walls (IW) perform better in GWP than the conventional options, while overall the ground floors (GF) and pitched roofs (PR) perform worse. Generally, the mean values for GWP of elements containing hemp are for every element type but the IW (i.e. IW-(n)LB05) higher than both the overall mean as well as the mean of the conventional elements of that type. For straw, all GWP mean values are the lowest of all mean values except for the PR (i.e. the mean of PR03-04). The mean GWP of the timber-focus walls
(EW01-06, IW-(n)LB01-02) is lower than the mean GWP for the conventional walls, but the mean of the timber floors (IF01-03) and roofs (FR01-02, PR01-02) is higher than for the conventional ones.

The hotspot analysis of the bio-based elements illustrated that the weighted environmental impacts are highest for global warming potential (GWP), particulate matter (PM) and land use (LU), and that the majority of these impacts occur during the production stage A1-A3. The total impact of building elements with mass timber is highly subject to the insulation type it contains (i.e. blow-in straw, hemp mats, hempcrete blocks or conventional EPS board), particularly for GWP and LU. Depending on the insulation, these building elements’ GWP is either higher or lower than for conventional solutions. Yet, a large share of the impacts of these elements comes from the production of the mass timber work section. On the other hand, PM impacts are always driven by mass timber and any work section that contains timber in general. Straw-based building elements have the lowest GWP and PM as well as the lowest total environmental costs. Their total GWP is often even lower than the GWP in A1-A3 alone of timber and hemp-based elements. Because straw production impact is so low, its contribution to the total impact is overruled by the production (A1-A3) and replacement (B4.1) impacts of the boards and plasters they contain. These layers however are required to keep the straw dry and protected and cannot be simply replaced by any other low-impact finishing. In contrast to how positive the papers in the SLR were about hempcrete, its GWP turned out to be unexpectedly high. Building elements containing hempcrete often have higher GWP than various conventional options. However, biogenic carbon was not taken into account, which could significantly lower its GWP. The largest part of hempcrete's impact comes from the lime binder, which also explains why hemp-based insulation performs better than hempcrete.

Logically, the bio-based materials focused on (i.e. mass timber, straw and hemp) were always among the most important work sections of the building elements. Nevertheless the hotspot analysis revealed that the production (A1-A3), maintenance (B2) and replacement (B4.1) of finishing and supporting layers can represent a large part of the total impacts as well. This indicates the importance of being aware of the possible high influence of some layers on the total impacts when comparing different building element compositions. However, it is worth noting that while some work sections could easily be replaced by alternatives (e.g. plywood by OSB), others are considered essential for the work section being compared and do not have many alternatives (e.g. lime plaster on a straw bale wall).

The modeling of bio-based building elements for the LCA was based on the best available information and data. Nevertheless, limited information was obtained about the replacement and maintenance of the applied work sections in relation to the bio-based materials. The LCA results, however, illustrated that such impacts can represent large parts of the total impacts of building elements. This study therefore emphasizes the importance of accurate replacement and maintenance data for refining the modeling of the materials.

**Declarations**

Data availability
In addition to the contents presented in this article, we provide the following supplementary information:

- Supplementary Information (.doc)
- Supplementary Data (.xls)

Author information

CRediT author contributions

**Lise Mouton**: Conceptualization; methodology; formal analysis; data curation; visualization; writing – original draft. **Karen Allacker**: Conceptualization; methodology; writing – review and editing; supervision. **Martin Röck**: Conceptualization; methodology; investigation; data curation and visualization; writing – original draft; writing – review and editing; project administration; supervision.

ORCID

- Lise Mouton - https://orcid.org/0000-0002-9387-2224
- Karen Allacker - https://orcid.org/0000-0002-1064-0795
- Martin Röck - https://orcid.org/0000-0003-2940-1230

Funding and acknowledgements

The authors thank the architects of three case study buildings that provided input and relevant information for modeling the bio-based building elements in this study, namely Sascha Schär of N11 architects (CS1: N11 SolarHouse, 2014); Dominik Gladik (CS2 – Straw-based SFH Gladik, 2016); and jtB, BLAF Architecten (CS3 – Hempcrete SFH in Belgium (under construction at time of writing)). We thank Damien Trigaux for supporting this study by providing previous LCA modeling on hemp-based construction materials for further analysis. Martin Röck received funding through a DOC Fellowship of the Austrian Academy of Sciences (OeAW) [2019/1].

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Abbreviations**
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full term</th>
</tr>
</thead>
<tbody>
<tr>
<td>BE</td>
<td>Building element</td>
</tr>
<tr>
<td>C</td>
<td>Carbon</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>CO$_2$eq</td>
<td>Carbon dioxide equivalent</td>
</tr>
<tr>
<td>CLT</td>
<td>Cross laminated timber</td>
</tr>
<tr>
<td>CS</td>
<td>Case study</td>
</tr>
<tr>
<td>EF</td>
<td>Environmental footprint</td>
</tr>
<tr>
<td>EW</td>
<td>External wall</td>
</tr>
<tr>
<td>FR</td>
<td>Flat roof</td>
</tr>
<tr>
<td>FU</td>
<td>Functional unit</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas (emissions)</td>
</tr>
<tr>
<td>GF</td>
<td>Ground floor</td>
</tr>
<tr>
<td>GWP</td>
<td>Global warming potential</td>
</tr>
<tr>
<td>HWP</td>
<td>Harvested wood product</td>
</tr>
<tr>
<td>IF</td>
<td>Internal floor</td>
</tr>
<tr>
<td>IW-LB</td>
<td>Internal wall – load-bearing</td>
</tr>
<tr>
<td>IW-NB</td>
<td>Internal wall – non-load-bearing</td>
</tr>
<tr>
<td>LCA</td>
<td>Life cycle assessment</td>
</tr>
<tr>
<td>LCI</td>
<td>Life cycle inventory</td>
</tr>
<tr>
<td>LU</td>
<td>Land use</td>
</tr>
<tr>
<td>MMG</td>
<td>Environmental Performance of Materials used in Buildings and Building Elements (NL: Milieugerelateerde Materiaalprestatie van Gebouw(element)en)</td>
</tr>
<tr>
<td>PEF</td>
<td>Product environmental footprint</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate matter</td>
</tr>
<tr>
<td>PR</td>
<td>Pitched roof</td>
</tr>
<tr>
<td>RSP</td>
<td>Reference study period</td>
</tr>
<tr>
<td>SLR</td>
<td>Systematic literature review</td>
</tr>
</tbody>
</table>

References


Supplementary Material

Supplementary Information and Data not available with this version.

Figures

**Figure 1**

*Bio-based materials identified in the systematic literature review (SLR) (left) and level of assessment in the reviewed papers (right).*

**Figure 2**

*Hierarchical structure of the four levels used in the KU Leuven MMG-LCA-tool (figure adopted from [30]).*
<table>
<thead>
<tr>
<th>Building element</th>
<th>Work section</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cork finish</td>
<td></td>
<td>Cork slab {RER} production</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fibreboard, soft, bitumised {RER} production</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chromium steel, screws {RER} production</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hemp insulation, packed {RER} production</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Softwood, untreated timber {BE} production, MIX</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Softwood, untreated prefabricated structural product {BE} production, MIX</td>
</tr>
</tbody>
</table>

**Figure 3**

*Example of the hierarchically modeled life cycle inventory for external wall EW01.*
Figure 4

Comparison of GWP results for conventional and bio-based internal and external walls, expressed per m² building element [kgCO₂eq/m² BE].
Figure 5

Analysis of the contribution from different environmental impact categories to the weighted results (environmental cost) of the selected bio-based building elements.
Figure 6

Impact assessment results for the selected bio-based building elements and their most important environmental indicators GWP, PM and LU, showing: (a) absolute contribution of different life cycle stages, and (b) relative contribution of different life cycle stages
Figure 7

Biogenic carbon content in the selected building elements.
Comparison of results with the literature

Figure 8

Comparison of the GWP and biogenic carbon results of exterior walls with Pittau et al [43]. The dot sizes express the biogenic carbon.