Life Cycle Assessments of bio-based insulating materials. A literature review

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Abstract

This paper presents a literature review on existing scientific studies on bio-based insulating materials focusing on their environmental analysis throughout all the phases of the building lifecycle. In respect of a circular thinking strategy and thanks to a Life Cycle Assessment method, the aim of this research is to understand how to estimate the potentials and limits of these materials and set the bases for future developments. Even if according to all the papers analysed natural materials appears to be environmentally friendly and have interesting insulating properties, LCA studies need to define more clearly the methodological assumptions in the context of the biogenic carbon sequestration and end of life scenario.

1. **Introduction**

The building sector is amongst the most cross-cutting industrial sectors. Transition towards sustainable building hence requires harmonization and interaction between diverse topics from security of the citizen to environmental impact, human health and resource efficiency (Allacker et al., 2014).

As a matter of fact, constructions play a major role on occupation of land, air pollution and influence of biodiversity (Aciu and Corbizan, 2013). But it is not limited to that. In fact, the building industry is responsible for the use of up to 40% of the materials produced globally and about 35% of the world's waste (Leising et al., 2018a). Within the EU, buildings currently account for 40% of total energy use and 36% of total GHG emissions (EU Commission, 2019). Therefore, several European Commission policies recognize the relevance of considering environmental impacts of buildings from a life cycle perspective with respect to resource efficiency, construction and demolition waste, and energy (EU Commission, 2011) (EU Commission, 2014). Furthermore, to achieve more sustainable production and consumption patterns, we must consider the environmental implications of the whole supply-chain of products, both goods and services, their use, and waste management, i.e. their entire life cycle from "cradle to grave", or even from "cradle to cradle". The "cradle to cradle" method has been proposed by Michael Braungart e William McDonough (McDonough and Braungart, 2002) and suggests, in a biomimetic approach, that the waste produced by one process could represent "food" for another one. This concept is at the base of the circular economy (CE), which is the instrument of achieving a resource efficiency in the European area proposed by the European Commission (EU Commission, 2015). Due to the huge contribution of the built environment on resource depletion, climate change and pollution (Leising et al., 2018a), CE could help in the redefinition of its whole life cycle.

The application of the concept of circular economy thinking in construction, which is in its early days, has been largely limited to construction waste minimization and recycling (Williams, 2019). Indeed, since 2008, the Directive 2008/98/EC on waste has set a target for increasing the rate of recovery of construction and demolition waste (C&D) that, by 2020, will have to be reused or regenerated in secondary raw materials (SRM) for at least 70% of their weight. On the other hand, circular strategies affecting also the other phases are needed in order to lower the overall building environmental impacts. This could be achieved by inserting the potential "wastes" of others production cycles into the building ones where they could represent a valuable element instead. Especially, construction applications made of natural materials usually need less energy in their production – when using local products –, and, in addition to their lower embodied energy in the manufacture, bio-based materials also capture CO_2 while growing through photosynthesis (Lawrence, 2015) and during the building use-phase (Lawrence, 2015; Pittau et al., 2019; Pretot et al., 2014) by the carbonation of lime, if present. According to Guest et al. (2013), temporary and permanent carbon storage from biogenic sources is seen as a way to mitigate climate change. Therefore, by using these biogenic materials as building component, also the building pressure on our planet could be reduced (Lawrence, 2015). Moreover, if these materials are used as insulations, they could also help in the reduction of the building in-use energy consumption (Aciu and Cobirzan, 2013). Consequently, by working on the supply chains of bio-based materials and closing potential production cycles, the CE concept could change the current consumption and production patterns of the built environment together with their environmental impacts (Leising et al., 2018). In this context, the use of the LCA methodology can be extremely useful to verify the environmental consequences and quantify the actual benefits of strategies related to the circular economy and bio-based materials.

2. Life Cycle Assessment in the building sector

The methodology of LCA has been applied in the construction sector since the 1990s and in European public policies, e.g., Environmental Product Declaration regulation or building labeling schemes (Lasvaux et al., 2015).

In construction sector, environmental impacts such as the Cumulative Energy Demand (CED) and the Global Warming Potential (GWP) are among the most commonly found in literature. On the other hand, to achieve more sustainable production and consumption patterns in the built environment, we must consider the environmental implications of the whole supply-chain of products, both goods and services, their use, and waste management, i.e. their entire life cycle. The lifecycle of buildings extends from the extraction of raw materials, through the construction and use phases, to demolition and eventual waste disposal and/or reuse of components or materials.

Moreover, recent LCA advances indicate that the global tendency is to erect buildings with lower energy demands in the operation stage owing to the international energy efficiency objectives (Franco et al., 2016); thus, the relationship between the materials' embodied energy and the operational energy (20%–80%) is changing in such a way that 40% of the impact is associated with materials and 60% is associated with the operational stage (Vilches, Garcia-Martinez, & Sanchez-Montã, 2017). Furthermore, some materials (typically insulation materials) can reduce the overall building impact throughout its life cycle. (Vilches et al., 2017). In fact, while choosing the materials for insulation, also other factors, such as carbon sink potential, renewability, local availability and occupants' wellbeing could be considered (Liu et al., 2017). At this regard, interest on natural materials is growing due to their environmental performances (reduced GHG emissions and create healthier buildings) and the possibility to activate new potential local markets remained so far untapped to foster the transition to a more circular economy.

3. Life Cycle Assessment of bio-based materials

Considering the increasing social emphasis on the environment issue, waste disposal and the depletion of non-renewable resources, bio-based materials constitute an interesting alternative to those obtained from fossil carbon. The main drive for their use is the substitution of conventional materials for sustainable ones. In this context, LCA strategies can provide a robust analysis for measuring the environmental impacts that occur over the life cycle of a product (Da Luz et al., 2018).

Nevertheless, other factors should also be considered to fully appreciate their sustainable use; including, the energy it takes to convert biomass to an usable product, emissions from transportation, runoff of agrochemicals into water bodies, soil erosion from crop production, etc. In other words, we should also be looking at the entire life cycle of products and services in order to avoid the shifting of burdens into other parts of the process (Cunan, 2003). Consequently, even if their use could seem interesting and environmentally friendly, LCA can help us understand the real sustainability of using them in the building world.

3.1 Bio-based materials definitions

Bio-based products in general are made of renewable resources, but this does not mean that they certainly will biodegrade and cause no harm to the environment (Sherwood et al., 2017). The term 'bio-based' means ' wholly or partly derived from biomass' (EN 16575: 2014). For instance, it is essential to characterize the amount of biomass contained in the element by its bio-based content or bio-based carbon content (EN 16760:2015). The fundamental attribute of a bio-based product is the proportion of renewable material actually contained within it. It is not necessarily true that a bio-based product is completely made of biomass or substances exclusively derived from biomass, e.g. for some bio-based products only require 25% bio-based content (Sherwood et al., 2017). They can be either material, intermediate, semi-finished or final products and biomass may be subjected to physical, chemical or biological treatment before being turned into a product (CEN, 2014). Hence, bio-based products are not necessarily biodegradable, and can be toxic just as fossil-derived products can for the environment.

3.2 **Research method**

This paper is a literature review, focused on the LCA studies on bio-based insulation materials. The aim is to understand the current knowledge on the topic, highlighting existing results and open gaps. We do not claim absolute completeness with respect to all published LCA studies. Instead, we seek to identify general patterns in the debate on a range of LCA studies on bio-based materials in other to understand the current problematics for future developments on this research field.

The study has been carried out by identifying existing scientific publications on LCA studies of bio-based insulation materials. To this end, the Scopus engine has been used with the following research query: (TITLE-ABS-KEY ("life cycle assessment") AND TITLEABS-KEY (bio-based material) AND TITLE-ABS-KEY ("building"), obtaining 17 publications. The choice to broaden the research avenues with the word "building" is due to the limited results we had at the beginning while using the word "insulation", which led to 7 papers. By checking out the final results, we can conclude that some of them are not directly relevant to this research, as a consequence of the extension made: two focus only on their structural applications (bamboo and substitution of concrete with wood); one discusses their condensation risks; few of them are not open access (abstracts of conference proceeding and papers, and one book chapter); while another one analyses a general product design and does not directly address to insulation applications.

In conclusion, only the following papers have been examined: [1] Heidari et al, 2019; [2] Pittau et al., 2018; [2] Pittau et al., 2019; [3] Da Luz et al., 2018; [4] Penolaza et al., 2016; [5] Lupíšek et al, 2015; [6] Lawrence, 2015; [7] Pretot et al., 2014; [8] Senga Kiessé et al., 2017.

3.3 **Results discussion**

All the papers analysed, highlight the necessity that a whole building LCA should take into account the impact linked to the production/construction, use and the end-of-life phases of buildings. By doing so, the real potentials and disadvantages of the bio-based transition of the built environment could be fully appreciate as part of the solution for the climate emergency. For this reason, the results will be here discussed in subparagraphs according to the main building phases.

In table 1, some key concepts have been noted and compared, in order to have a complete view of how they have been considered in the different papers.

Table 1: Comparison of papers analysis

	Environmental impacts considered	*Building lifespan*	*Type of LCA*	*Carbon sequestration by lime carbonation*	*Carbon sequestration from biomass regrowth or growth*	*End of life scenario*
[1]	They depend on the assessed study: ● Full LCA: Human health Ecosystem quality, Climate change, Resources. ● matrixLCA: Material Choice, Energy Use, Solid Residue, Liquid Residue, Gaseous Residue Comparison. ● Bilan Produit: Acidification, Aquatic Ecotoxicity, Climate Change, Energy consumption, Eutrophication, Human Toxicity, Photochemical pollution, Resources consumption	Not a building but a panel	Full LCA and streamlined LCA (SLCA): matrix LCA and Bilan Produit	Not considered	Not mentioned	Even if considered in the calculations, it is not clear which type of end of life scenario has been chosen
[2]	Global Warming Potential	60 years	Dynamic LCA	Accounted in in use-phase	Considered after the production process	Inert landfill, Sanitary landfill, Composting facility, Municipal incineration, Recycling
[3]	Primary Energy Demand, Global Warming Potential, Abiotic Depletion, Acidification, Eutrophication	Not a building but a composite	Standard LCA	Not considered	Considered before the production process	Reuse, Incineration, Recycling, Disposal in landfill

	Environmental impacts considered	*Building lifespan*	*Type of LCA*	*Carbon sequestration by lime carbonation*	*Carbon sequestration from biomass regrowth or growth*	*End of life scenario*
[4]	Global Warming Potential (GWP100)	Two scenarios: 50 years; 70 years.	Dynamic LCA	Not considered	Considered after the production process	Incineration, Disposal in landfill
[5]	Global Warming Potential, Ozone depletion, Acidification potential, Eutrophication potential, Photochemical ozone creation potential, Total use of non-renewable primary energy resources.	Service life of the panels of 30 years without replacement of the materials	Simplified LCA	Not considered	Considered after the production process	Not considered
	Environmental impacts considered	*Building lifespan*	*Type of LCA*	*Carbon sequestration by lime carbonation*	*Carbon sequestration from biomass regrowth or growth*	*End of life scenario*
[6]	Operational Energy, Embodied energy	60 to 100 years	Standard LCA	Not considered	Considered before the production process (allocated as negative carbon)	Biodegradation
[7]	Energy raw consumption, Exhaustion of resources, Water consumption, Photochemical ozone, Climate Change, Atmospheric Acidification, Air pollution, Water pollution, Eutrophication	100 Years	Standard LCA	Accounted in in use-phase	Considered before the production process (allocated as negative carbon)	Disposal in landfill, Recycling suggested
[8]	Climate change, Acidification, Eutrophication, Human toxicity, Ecotoxicity, Cumulative energy demand, Land competition	Not express since it only concentrates on the production phase (no in-use or end of life scenario)	Combination of LCA and sensitivity analysis	Not considered	Considered after the production process	Not considered

3.3.1. Production phase

One of the issue pointed out by Pretot et al. (2014) is that the buildings are unique and, usually, locally assembled. The geographical parameter is important for either the energy mix (Pretot et al., 2014) and the availability of local materials and their manufacturing technologies (Da Luz et al., 2018). At this regard, it is important to know all specific phases (procedures to obtain fibres, transportation, manufacturing process and chemicals used throughout the process). For example, for crops is quite hard to get reliable primary data or reliable secondary data from the literature that can accurately represent the system in term of culture cycle, time, chemical ingredients, land use and CO_2 uptake (Da Luz et al., 2018), that can also change according to each country regulations and location.

Several products can be obtained from natural materials (from each part constituting the natural element - e.g. seed, leaves, etc - we can realize composites, food, fuels, etc), raising up the necessity to add allocation in the model. This allocation can be based on mass, energy or economy (Da Luz et al., 2018). For example, the hemp production is not mainly assigned to the construction sector and it is rather oriented towards fibre production. Hence, in Pretot (2014), a mass allocation was used to account for co-production of fibre, shiv and seed, whereas both economic and mass allocations were used in Senga Kiessé (2017) for the co-production of straw and seed. It is thus important to insert these examinations in such analysis.

3.3.2. *In use-phase*

The carbon dioxide sequestration and emissions take place in different times and life cycle stages. Typically, biogenic carbon storage is not usually included in LCA calculation methods. In fact, forest and crops products are considered carbon neutral by virtue of full regeneration of biomass at the end of a rotation period (Pittau et al., 2018). Indeed, the ISO 14067:2018 reports that in the case of products containing biomass, the biogenic carbon content is equal to the carbon removal during plant growth. This biogenic carbon can be released in the end-of-life stage so, if calculated, shall be documented separately in the carbon footprint study report (ISO, 2018). In other methods for assessing the life cycle GHG emissions, e.g. the PAS 2050, for any biogenic component that is part of the final product, both emissions to the atmosphere and removals from the atmosphere shall be accounted for the overall GHG emissions of the product being assessed. In particular for the PAS 2050, the stored carbon within 100 years shall be recorded and accounted for in the carbon footprint calculations. Carbon storage might arise where biogenic carbon forms part or all of a product (e.g. wood fibre in a table), or where atmospheric carbon is taken up by a product over its life cycle (e.g. cement). While the potential source of storage in the forest management activities through the retention of forest biomass regrowth is not included in the scope of this PAS.

In the scientific literature here analysed, when it is considered, two ways of taking into account the carbon sequestration by bio-based materials have been found.

The first, in standard LCA analysis, by allocating it as negative emission of carbon dioxide and is calculated as the carbon dioxide required to create one kilogram of dry material (Lawrence, 2015; Pretot et al., 2014). Whilst performing the photosynthesis, plants absorb CO_2, using the carbon to make structural material (leaves, stem, etc.) and releasing the oxygen back into the atmosphere. Using stoichiometric calculation, it can be seen that CO_2 (44) is used to incorporate C (12) into the plant, releasing O_2 (32) into the atmosphere. Thus, every 12 kg of plant material has removed (sequestered) 44 kg of atmospheric CO_2, which is a conversion factor of 3.67. This quantity of carbon is considered sequestered within the material for its lifetime but no information regarding its emission at the end-of-life is mentioned in these papers.

The second, is the dynamic LCA, proposed by Levasseur et al. (2010).This approach takes into account the timing of carbon uptake and GHG emissions, which is quite important for bio-based products that temporarily store carbon and delay emissions (Pittau et al., 2018). Dynamic LCA allows to take into account the carbon embedded in the biomass that is fixated for as long as the product lifespan, and the one taken up by the forests and crop fields during their regrowth. In this way, the biogenic carbon exchanges from the natural cycle can be included in the inventory. In the dynamic method, the system boundaries include the forest as part of the product system for bio-based materials in the building (Da Luz et al., 2018).

Another interesting aspect, is the ability of fibre insulation materials to create breathable walls that absorb and release in their cavities moisture responding to relative humidity and vapour pressure modifications in the surrounding environment (Lawrence, 2015). This aspect favours buildings to use less energy for both heating and for air conditioning in their use-phase.

3.3.3 End-of-life-phase

As said before, also the end of life phase of elements can play an important role in the quantification of environmental impacts. In bio-based materials, their end-of-life can include vastly different scenarios: inert landfill, sanitary landfill, composting facility, municipal incineration, recycling (Da Luz et al., 2018; Peñaloza, Erlandsson, & Falk, 2016; Pittau et al., 2019). Indeed, these practices include: reuse after their first life cycle, incineration to generate electricity, recycling with economic reuse in another component and disposal in a landfill, with the possibility to biodegrade - if used as they are in their natural state without adding chemical products - or compost (Lawrence, 2015). Since they are quite new materials, the landfill disposal is the most commonly used due to few information to support their recycling or reuse, e.g. the hemp concrete seems possible to recycle but this practice is not yet developed (Pretot et al., 2014).

In dynamic LCA, the circumstance of releasing this biogenic carbon through incineration or keeping it stored through landfilling or recycling makes the end-of-life scenario even more relevant and not predictable without a clear model of its end-of-life (Peñaloza et al., 2016).

Another delicate point of bio-based materials is their durability because naturally biodegradable. In fact, in a complete analysis, this factor must be taken into account and compared to the building lifespan to see how many times they must be replaced. This information could definitely help in further decision make and economic considerations.

4. **Conclusions**

In the direction of make the built environment less energy consuming, the Ellen MacArthur Foundation (2015), suggests two directions of improvement: the first is to upgrade the energy management on existing buildings; the second is to move towards more passive buildings for the new-built segment. Since in developed countries, 85% of the buildings that will be standing in 2050 have already been built (Leising et al., 2018) retrofitting represents a key point in future European policies (Vilches et al., 2017). Moreover, thermal insulation is known to play a critical role in saving energy in the use phase of constructions (Binici et al., 2016). Thus, the individuation of sustainable insulation materials is of the utmost relevance since they can also affect other phases of the building lifecycle.

According to all the papers analysed, together with their good insulating properties, natural materials appears to be environmentally friendly materials. In their non-operational phase, biomaterials exhibit great interest while comparing, for example, concrete-based and wood framework buildings. In truth, the wood-based buildings lead to lower embedded energy and CO_2 emission than the concrete ones with similar insulation levels (Pretot et al., 2014).

Furthermore, these materials are capable of carbon sequestration during growth (photosynthesis) and, in lime-based materials, during carbonation.

Both Pittau et al. (2018) and Penaloza et al. (2016) use the dynamic LCA method in order to taking onto account the amount of carbon that is taken up in the forest or fields while their regrowth. Penaloza et al. (2016) mainly study the materials coming from forests and conclude that definition of the timing for the forest regrowth significantly affects the outcomes of this kind of studies. On the other hand, Pittau et al. (2018) analyse both forest materials and crop materials through a dynamic LCA, by concluding that the latter, fast-growing plantations, are the ones that can really help in the mitigation of climate change. Indeed, according to them the benefit from carbon uptake are effective when the carbon is rapidly reabsorbed in the crop fields, whereas the forests have a carbon cycle which is too long (40-120 years) compared to the building lifespan (from 30 to 100 years) (Peñaloza et al., 2016).

The end-of-life phase models need to be further improved in order to become a concrete actor in the understanding of building impacts of these materials (Da Luz et al., 2018).

Finally, Bio-based materials used for increasing the thermal insulation and temporary store carbon in construction elements might be a valuable opportunity that can contribute to lower the overall building environmental impacts. However, the benefits of replacing fossil fuel-based feedstock and reducing GHG emissions may have come at a cost of additional land use with the consequence of improving the pressure on the environment; an aspect that need to be further studied through a comparison with their conventional fossil fuels or mineral based counterparts (Brandão et al., 2012). Nonetheless, it is necessary to define more clearly the methodological assumptions in the context of carbon sequestration and end of life scenarios, as well as the identification of environmental “control” indicators (such as land use) to be put, in the assessment, besides the Global Warming Potential, with respect to which the organic supply chain is certainly favoured.

To conclude, the development of European policies that promote the use of bio-based materials requires the introduction of methodologies, as LCA, capable of assessing the environmental effects. Moreover, some of them also suggest that the LCA methods can be used as a support to lower the overall construction environmental impacts (EU Commission, JRC, 2010). Although, the existence of more than one declination of this methodology - as we can see in the “Type of LCA” column of Figure 1 - implies the need of a global unification and reinforcement in their objectivity to make them more trustworthy in the decision-making steps (Senga Kiessé et al., 2017). Indeed, it is possible to perceive this uncertainty in the column “Environmental impacts considered” reported in Figure 1, where both the number and the typology of environmental impacts change in the analyzed papers according to the practitioner’s choices. Moreover, Heidari (Heidari, et al., 2019) highlights that full LCA are far too time and cost intensive for industrial companies to implement during their production and consumption processes during the design stage. Therefore, there is an increasing demand for reliable simplifications to demonstrate a company’s resource efficiency potential without being data or time consuming.

5. **References**

Aciu, C, Cobirzan, N, 2013. Use of Agricultural Products and Waste in the Building Materials Industry. *ProEnvironment*, *6*, 472–478.

Allacker, K, Maia De Souza, D, Sala, S, 2014. Land use impact assessment in the construction sector: an analysis of LCIA models and case study application. *International Journal of Life Cycle Assessment*, 19, 1799–1809.

Binici, H, Aksogan, O, Demirhan, C, 2016. Mechanical, thermal and acoustical characterizations of an insulation composite made of bio-based materials. *Sustainable Cities and Society*, 20, 17–26.

Brandão, M, Hermann, B, Carus, M, Bringezu, S, Weiss, M, Haufe, J, Patel, MK, 2012. A Review of the Environmental Impacts of Biobased Materials. *Journal of Industrial Ecology*, 16, S169–S181.

BSI Group and Carbon Trust, 2008. PAS 2050:2008 : Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services.

CEN, 2014. European standards supporting the market for bio-based products, viewed 27 Mar 2019, <https://www.cen.eu/news/brochures/brochures/CEN_Bio-based-products_2014.pdf>.

CEN, 2014. EN 16575:2014 *Bio-based products-Vocabulary*.

CEN, 2015. EN 16760:2015 *Bio-based products-Life Cycle Assessment*.

Clift, R, Doig, A, Finnveden, G, 2000. The Application of Life Cycle Assessment to Integrated Solid Waste Management: Part 1—Methodology. *Process Safety and Environmental Protection*, 78(4), 279-287.

Cunan, MA, 2003. Do Bio-Based Products Move Us Toward Sustainability ? A Look at Three USA Case Studies. *Environmental Progress*, 22(4), 277–292.

Da Luz, SM, Magalini, V, De Sousa, Z, 2018. LCA modelling for natural fibre composites. *Int. J. Computer Aided Engineering and Technology*, 10 (1/2), 166-178.

Ellen MacArthur Foundation, 2015. *Growth within: a circular economy vision for a competitive europe*. *Ellen MacArthur Foundation*. viewed 27 Mar 2019, <https://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf>.

EU Commission, 2008. *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste.*

EU Commission, 2011. *Roadmap to a Resource Efficient Europe*. COM(2011) 571.

EU Commission, 2014. *Resource Efficiency Opportunities in the Building Sector*. COM(2014) 445.

EU Commission, 2015. *Closing the loop - An EU action plan for the Circular Economy.* COM(2015) 614.

EU Commission, 2019. Energy Performance of Buildings. viewed 27 Mar 2019, <https://ec.europa.eu/energy/ en/topics/energy-efficiency/buildings>.

EU Commission, JRC, 2010. *ILCD Handbook. General guide for Life Cycle Assessment - Detailed guidance Centre, Institute for Environment and Sustainability*. viewed 27 Mar 2019, https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-General-guide-for-LCA-DETAILED-GUIDANCE-12March2010-ISBN-fin-v1.0-EN.pdf

Franco, DVHK, De Langhe, R, Venken, J, 2016. Energy efficiency services in buildings: A tool for energy transition, in: Sojkova, K, Tywoniak, J, Lupisek, A, Hajek, P (Eds), *CESB 2016 - Central Europe Towards Sustainable Building 2016: Innovations for Sustainable Future*, Grada Publishing, pp. 732–740.

Guest, G, Bright, RM, Cherubini, F, Strømman, AH, 2013. Consistent quantification of climate impacts due to biogenic carbon storage across a range of bio-product systems. *Environmental Impact Assessment Review*, 43, 21–30.

Heidari, MD, Mathis, D, Blanchet, P, Amor, B, 2019. Streamlined life cycle assessment of an innovative bio-based material in construction: A case study of a phase change material panel. *Forests*, 10, 1–16

ISO, 2018. ISO14067: Greenhouse gases -Carbon footprint of products -Requirements and guidelines for quantification

ISO, 2006a. ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework.

ISO, 2006b. ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines.

Lasvaux, S, Habert, G, Peuportier, B, Chevalier, J, 2015. Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. *The International Journal of Life Cycle Assessment*, 20(11), 1473–1490.

Lawrence, M, 2015. Reducing the Environmental Impact of Construction by Using Renewable Materials. *Journal of Renewable Materials*, 3(3), 163–174.

Leising, E, Quist, J, Bocken, N, 2018. Circular Economy in the building sector: Three cases and a collaboration tool. *Journal of Cleaner Production*, 176, 976–989.

Levasseur, A, Lesange, P, Margini, M, Deschenes, L, Samson, R, 2010. Considering Time in LCA: Dynamic

LCA and Its Application to Global Warming Impact Assessments. *Environmetal, Science & Technology*, 44.

Liu, L, Li, H, Lazzaretto, A, Manente, G, Tong, C, Liu, Q, Li, N, 2017. The development history and prospects of biomass-based insulation materials for buildings. *Renewable and Sustainable Energy Reviews*, 69, 912–932.

McDonough, W, Braungart, M, 2002. *Cradle to cradle: remaking the way we make things*. North Point Press

Peñaloza, D, Erlandsson, M, Falk, A, 2016. Exploring the climate impact effects of increased use of bio-based materials in buildings. *Construction and Building Materials*, 125, 219–226.

Pittau, F, Krause, F, Lumia, G, Habert, G, 2018. Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls. *Building and Environment*, 129, 117–129.

Pittau, F, Lumia, G, Heeren, N, Iannaccone, G, Habert, G, 2019. Retrofit as a carbon sink: The carbon storage potentials of the EU housing stock. *Journal of Cleaner Production*, 214, 365–376.

Pretot, S, Collet, F, Garnier, C, 2014. Life cycle assessment of a hemp concrete wall: Impact of thickness and coating. *Building and Environment*, 72, 223–231.

Senga Kiessé, T, Ventura, A, van der Werf, HMG, Cazacliu, B, Idir, R, Andrianandraina, 2017. Introducing economic actors and their possibilities for action in LCA using sensitivity analysis: Application to hemp-based insulation products for building applications. *Journal of Cleaner Production*, 142, 3905–3916

Sherwood, J, Clark, JH, Farmer, TJ, Herrero-Davila, L, Moity, L, 2017. Recirculation: A new concept to drive innovation in sustainable product design for bio-based products. *Molecules*, 22(1).

Vilches, A, Garcia-Martinez, A, Sanchez-Montã, B, 2017. Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy & Buildings*, 135, 286–301.

Williams, J, 2019. Circular cities. *Urban Studies*.