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Review

The Evolution of Crop-Based Materials in the Built Environment: A Review of the Applications, Performance, and Challenges

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Abstract: The use of bio-based building materials as an alternative to replacing concrete or insulation materials is called to become a growing trend in the construction industry. On Science direct, publications concerning "bio-based materials" have increased from 4 in 2002 to 1073 twenty years later, demonstrating a growing interest in these materials However, among bio-based materials, crop or plant-based materials are not as popular. Due to their relative novelty, little is known about their potential applications, physical characteristics, and environmental impacts. The aim of this review is to qualitatively investigate the technical and environmental viability of crop-based materials in modern building applications. The specific objectives of the study consider greenhouse gas (GHG) emissions using life cycle assessment (LCA) approaches, contribution to the circular economy, and physical and hygrothermal characteristics. Another objective is to examine the progress of crop-based materials' R&D, current bottlenecks, and a future roadmap for their evolution in state-of-the-art renewable buildings. The paper is broad enough to capture a large readership rather than experts in the domain. The review reveals that crop-based materials have the potential to replace traditional, highly emissive building materials. They offer low environmental impacts, in all stages of their life cycle.

Keywords: crop-based materials; building applications; life cycle assessment (LCA); biogenic carbon; thermo-hygro-mechanical characteristics; R&D challenges; viability

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1. Introduction

In the last two decades, global environmental issues have emerged at an alarming rate. Improving energy efficiency and reducing greenhouse gas emissions have become key concerns across all industries. The construction sector is particularly highlighted as it is one of the most energy-intensive industries [1]. The built environment alone accounts for 40% of energy consumption and 36% of carbon emissions in the EU [2]. Embodied energy, which represents a significant portion of a building's carbon emissions (approximately 10–30%) [3–5], has only recently started to receive the attention it deserves.

Currently, there is a noticeable trend in construction practices towards bio-based building materials. In comparison to the common and traditional practices the commonly utilize materials such as concrete, steel, and plastics, these materials are reported to have a range of advantageous properties such as low toxicity, durability, low level of GHG and other pollutants emissions, high local recycling potential, local availability, minimal processing requirements, and low embodied energy [6]. Moreover, in the context of a desired shift from zero-energy buildings (ZEB) to life-cycle ZEBs (LCZEB), bio-based materials could be the key approach to address sustainability issues [7]. The resources used to produce these materials could comprise agricultural crops and residues, forest materials, animal wastes, and post-consumer biological wastes [8].

In this context, the aim of this paper is to present a review of bio-based materials in the context of building applications, specifically on crop-based materials. The specific objectives are to review their environmental impact, building applications, and performances, and to address their specific challenges for the upcoming years. The overall goal is to conclude their viability to replace traditional materials.

The review is structured as follows. In the next section, the review methodology is presented. Section 3 involves the life cycle assessment (hereafter LCA) of crop-based materials while Section 4 presents the possible building applications and related performance of these materials. While Section 5 introduces the current and upcoming challenges, Section 6 is a global discussion involving summary-tables of the previous sections. Finally, the conclusion reminds the context, objectives, and methodology of the review before it provides a summary of the results and a few recommendations. Moreover, appendices are used to extract and present peripheral notions required by the neophyte from the essential discussions. Appendix A gives a few basic notions about crop-based materials for readers who are new to the subject and who want to start a research project on this topic. Appendix B provides information to help distinguish the different approaches to life cycle assessment and also refers to standards, frameworks, and eco-labels related to crop-based materials. Appendix C pertains to LCA as it presents the basics of the subject.

2. Review Methodology

Based on their structure and formulation, the literature reviews are broadly classified as:

- Narrative Reviews—This is the classic literature review that summarizes the collated literature relevant to a specific subject at a given time.
- Scoping Reviews—Scoping reviews involve systematic searching of all the material on the topic. This enables the researcher to fill in any gaps that appear in the results.
- Systematic Reviews—It is a methodical approach to collating and synthesizing all relevant data about a predefined research question.

Here, the authors propose a narrative review. Section 6 presents summary tables of the articles, classified according to predetermined categories in order to help readers wishing to undertake research in one or other of the possible directions cited in the article.

A comprehensive review approach should involve the following four categories: environmental considerations, thermo-hygro-mechanical characteristics, social aspects, and economic feasibility and affordability [9]. However, although the paper discusses all issues, it focusses on the first two categories. Hence, this research addresses the current state of knowledge in the development of crop-based materials, regarding the technical and environmental viability of crop-based building materials in modern buildings, focusing on their physical characteristics, environmental impacts, and potential to replace traditional energy-intensive building materials. This study focuses on a range of crop-based materials starting from clay-based monolithic walls to more advanced agglomerates of crops and binders, to showcase their potential in building construction

The relevant concepts, keywords, and search themes include crop-based building materials, related keywords of physical characteristics, environmental impacts, life cycle assessment, circular economy, renewable buildings, and keywords pertaining to standards and regulations. Except for some parts related to LCA in the manufacturing of crop-based materials, there has been more attention focused on plant-based bio composites in this study. There is also no geographical exclusion to the review, although the focus is mostly on Europe and North America, either in addressing technical development or exploring standards in the building industry. In the category of physical characteristics, there are several studies on the same properties that are filtered based on the proximity of materials and selected experimental procedures.

The review was carried-out in a three-step process:

1. The authors screened titles and abstracts of the retrieved studies focusing on embedded concepts, keywords, and specific terms. They first gathered any relevant research, most of them published mainly after 2015 until 2022 and excluded all research before 2015. Then, the authors also reviewed selected papers from previous years and added them to the database. After discussions and reviews by external researchers, the review has been reduced to the current status. The consulted databases include Elsevier (42.8 percent), Springer (10.7 percent), MDPI (9.5 percent), Taylor and Francis (5.9 percent), and Sage Journals (4.8 percent).
2. Then the full texts of the selected studies from Step 1 were reviewed to extract detailed data, considering parameters including physical characteristics, environmental impacts, the role of suggested ideas to replace traditional energy-intensive building materials, life cycle assessment, and their contribution to the circular economy. A short and relevant description and a reference for each contribution were written at that stage.
3. In the final step, a qualitative assessment of the data extracted from stage 2 was conducted to identify common themes, trends, and patterns across the studies. furthermore, the studies were grouped based on their detailed focus areas and analyzed the findings within each group. Finally, the key findings from each study were summarized and they are presented in tables. These tables stress any knowledge gaps or inconsistencies in the discussion part (Section 6).

3. Life Cycle Assessment Stages

EN 15804 (CEN (2012b)) [10] describes the common core of product category rules (PCR) for Type III environmental declarations relating to any construction product and service. It provides a comprehensive definition of the material life cycle, which encompasses raw material cultivation and harvesting to manufacturing, construction, operation, demolition, and final disposal [2,9,11]. Each of these stages includes sub-stages that are associated with different procedures, boundaries, and functional units, which are listed in Table 1. EN 15804 involves four main stages (product, construction process, use, and end-of-life stages) which in turn cover supply, transport, manufacturing, construction installation, use, maintenance, repair, replacement, refurbishment, deconstruction, waste processing, and disposal. Moreover, it accounts for reuse, recovery, and recycling potentials. The discussion below follows these global categories.

Table 1. Boundaries of the study in building's life cycle assessment [2].

Building Life Cycle Information													
A 1–3			**A 4–5**		**B 1–7**					**C 1–4**			
Product stage			Construction Process stage		Use stage					End of life stage			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4
Raw material supply	Transpor	Manufacturing	Transport	Construction Installation Process	Use	Maintanance (incl. transport)	Repair (incl. transport)	Replacement (incl. transport)	Refurbishment (incl. transport)	De-construction /Demolition	Transport	Waste processing	Disposal
			Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario
					B6 Scenario	Operational energy use							
					B7	Operational water use							
					Scenario								

3.1. Product Stage

In this category, although most of the literature focuses on biomass or other materials capable of producing ethanol throughout their life time, some studies have explored the cultivation of fiber crops, which are the main source of material in the bio-construction industry [12]. Cultivation of crop-based materials varies significantly with forest materials since most of the crops utilized in crop-based bricks or infills are perennial plants, so recurring cultivation could happen during annual periods. The quantification of LCA is conducted in cumulative A1 to A3 stages (Table 1), which is the combination of the entire process from cultivation to the end of the manufacturing process. Therefore, the quantified comparison is discussed in the manufacturing (A3) paragraph below.

In this stage of life cycle assessment for forest and agriculture products, life cycle measures are defined in terms of main products, additives-preservatives, and recycled products. Detrimental environmental effects in this phase include the burning of fossil fuels during exploitation, fertilizer application, and resulting eutrophication, pesticide use and related toxicity issues, and the impact of land and water use. Furthermore, for wood-based materials, forest's beneficial CO_2 removal and carbon sequestration are identified as the environmental advantages [11,13]. In addition to the environmental impacts, the cultivation of perennial plants for the production of crop-based materials is a critical issue due to its potential impact on increasing soil organic carbon (SOC) sequestration. This, in turn, will result in a significant decrease of carbon foot print in the life cycle of crop-based materials [14].

In this respect, the underlying issue is that there are some impact factors, which are not discussed extensively in the literature. For instance, acidification is often included in the LCAs, while other impact categories, such as eutrophication or land use change, may be overlooked [15]. Specifically in agriculture/animal products, a major environmental effect called Indirect Land Use Change (ILUC), has been introduced but has not been studied widely. ILUC accounts for the fact that production plants establishment on former agriculture lands result in spreading cultivation to areas such as grasslands, which in turn are crucial for mitigation of CO2 levels and even in some cases heat islands. Consequently, by diminishing vegetation, detrimental pollution effects will be rising up. Bioenergy projects can have complex impacts on land use, including both direct and indirect land use change. These changes can affect greenhouse gas balances in both positive and negative ways, making it difficult to assess bioenergy's contribution to climate change mitigation [16,17]. Direct and indirect land use change, are examples of rebound effects in the progress of crop-based or waste-based technologies [18]. One obstacle to quantifying these impacts is the complex interplay between environmental factors and market dynamics in the specific case studies being evaluated. The use of consequential LCA (CLCA) in these studies can further complicate the assessment of multi-functional systems due to complex overlap between system boundaries, inputs, and outputs [19–21].

That being said, there are other phenomena such as water resource depletion, threats to biodiversity, ecosystem quality, etc. These are specific side effects of the development toward more utilization of crop-based resources [15,22]. Overexploitation of agricultural materials, resulting from the growth in the crop-based economy is another life cycle issue that falls within this category, leading to agricultural intensification and land use change [18,23–25]. Moreover, compared to forest products, higher levels of fertilizer, pesticides, and fuels are used, in agro-based products due to the higher annual cultivation cycle. The importance of recycled products in attenuating detrimental impacts has to be considered. For instance, there are products similar to wood beams and timbers that do not need any recycling process, which will be crucial in the life cycle process of crop-based building materials [2]. On the other hand, agro-sourced products (such as sugarcane) end up producing residues that can be used to manufacture wood-agro-based products [26,27]. In the waste-based economy which encompasses a significant percentage of this practice, LCA studies have to consider co-production since the main plan and its waste serve different purposes. Although co-production essentially leads the system to contribute to supporting circular economy (schematically depicted in Figure 1), defining a reference scenario can be challenging since the purposes and outputs are not the same and different defined systems are diverging in some sense [18]. To assess waste-based systems, the literature often employs input-based life cycle assessment [28–30].

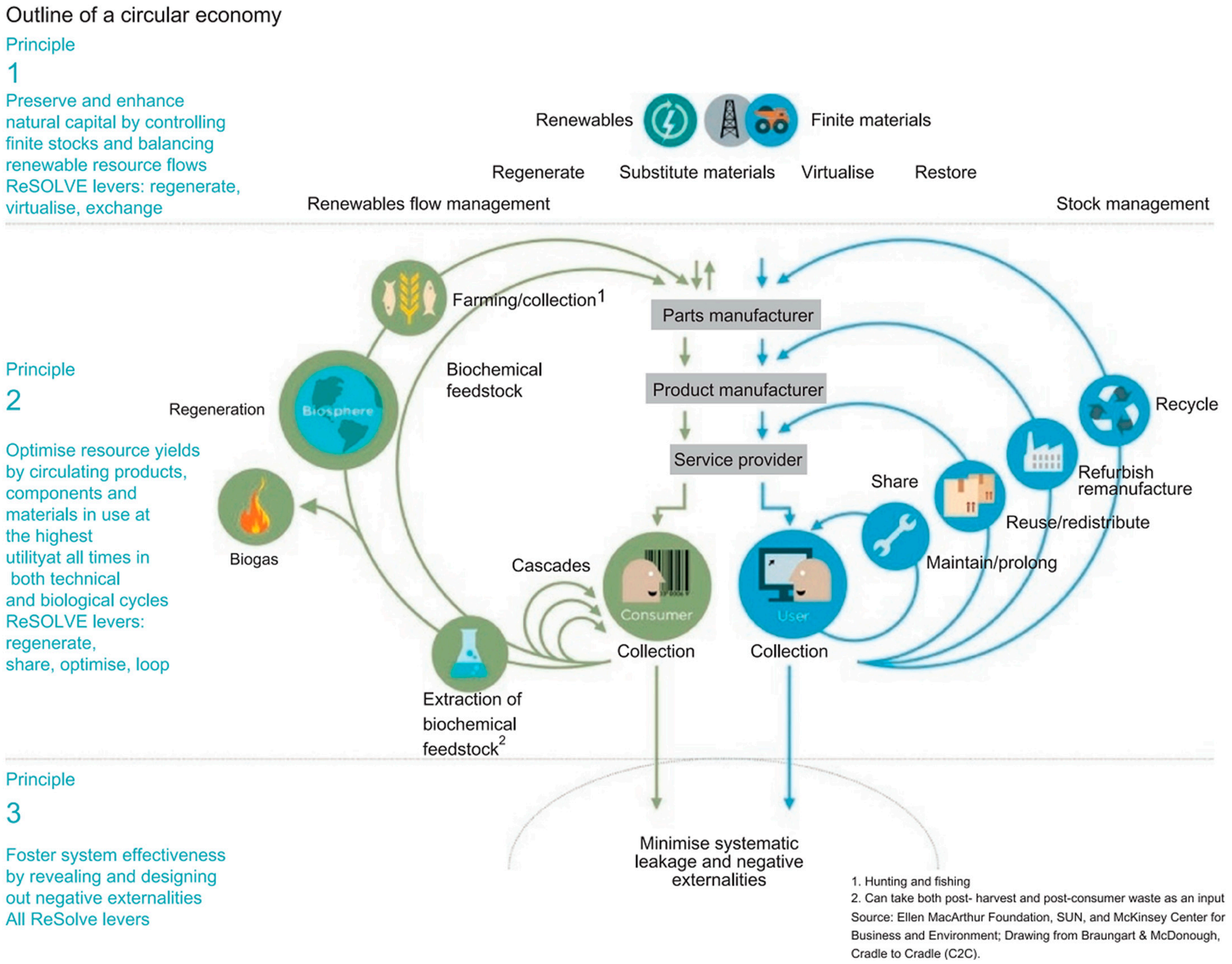


Figure 1. Illustration of the circular economy [2].

The manufacturing (A3 in Table 1) life cycle is a critical part of the supply chain of crop-based resources. At this stage of the building materials' life cycle, concrete has been a crucial source of debate in terms of its energy-intensive manufacturing cycles. It is vastly investigated, concerning its major effect on GHG emissions. Despite the use phase of building, in which the most share of energy consumption occurs, a major portion of the embodied energy of the building materials is discussed in the manufacturing stage. The vast scope of the literature focused on the embodied energy of buildings.

Asif et al. [31], conducted an LCA study of a detached house. The result demonstrates that concrete alone consumes most of the total embodied energy by 60%, along with having the highest environmental impacts among other constructing elements. Finally, geographical location's related parameters of 'climate' and 'upstream energy' significantly influence the life cycle's emissions. However, while this stage's emission is quite sensitive to material/fuel choice and energy performance, its subsequent emission is also highly tied to available construction practices in the short term [32].

Peñaloza et al. [33] present a comparative traditional (common) and dynamic LCA on the effects of increasing the crop-based material content in the manufacturing process under scenarios with variations in four key assumptions: service life, end-of-life scenario, timing of forest carbon sequestration and time horizon of the impact assessment. The varying content of crop-based materials are assumed to be: a concrete design (0% crop-based in mass), a conventional cross-laminated timber (CLT) structure (50% crop-based in mass), and another CLT structure with higher crop-based material content (69% in mass). This study concludes that increasing the crop-based content of the material resulted in climate impact reductions in almost every studied scenario, but the differences between designs varied and were highly sensitive to the assumptions explored.

In the manufacturing phase, drying and gluing are critical processes due to the involvement of fossil fuel combustion; and its consequences on acidification, climate change, CO_2 emissions and photo-oxidation, along with the consumption of abiotic resources [34]. Several studies claimed that by incorporation of a closed loop carbon cycle [35], i.e., consuming burning fuel from production waste (e.g., wood shavings and saw dust) and accumulated biogenic carbon, these materials become climate neutral [2,9,17]. Gluing activities, on the other hand, consume energy. Their impacts, therefore, depend on energy generation sources. The major emissions of traditional concrete occur in the production of clinker, which is the foundation of cement as the binder of concrete [36]. Cement is not a popular agent in crop-based concretes. Instead, lime has been used as the base binder for traditional crop-based concrete or insulation infills. The hemp-lime compound is the most common type of concrete in this category. Nonetheless, lime mixture usually yields low strength. Attempts are made to introduce new binders. In this regard, Bumanis et al. [37] analyzed gypsum, starch, and a type of geopolymer and compared the results with lime characteristics. The resulting material delivered lower density and thermal conductivity, as well as the same impact in LCA, though they did not examine the mechanical strength. There are also studies on wood-based products, which developed crop-based and eco-efficient adhesives for this sort of product [38–40]. This is a neglected area of research, which could lead to more enhanced thermo-physical characteristics of crop-based building materials.

As for other processing stages in building materials modifying forest products requires thermal treatment and impregnation infrastructures, as well as their associated chemical and energy consumption- related impacts [34]. The manufacturing process of crop-based boards including particle board, medium density fiberboard (MDF), light density fiber board (LDF), oriented strand board (OSB), and plywood are in similar processing categories, in which high-temperature pressing for wood layers demands combustion of fuels, and consumes electricity to veneer wood layers [2,41].

3.2. Construction Stage

Within the construction stage, most of the LCA studies focus on the effect of equipment use (broken down by different tasks in construction project management) as well as the long-term environmental impacts of the utilized material in the use stage of the building [42]. A majority of the impacts of the construction phase are caused by the production of ancillary materials, and transportation. In the aforementioned processes, operations such as the on-site cut-to-fit, packaging, etc., generate wastes that affect the life cycle regarding their disposal process; however, their impact is less than the aforementioned operations [2,9,11].

A key feature of crop-based building materials during this phase is their ability to be produced from locally available materials, thereby eliminating significant emissions associated with long-distance transportation. The necessity of natural binders such as mycelium will be pivotal in agricultural communities, which in turn leads to the circular usage of materials and wastes and a substantial reduction of the emissions related to the usage of non-locally produced materials. In Canada and France as the preferred cases for this study, we are seeing such arrangements. In France, a new environmental regulation (RE2020) is issued, which provides a regulatory basis for the use of crop-based alternative building materials for future sustainable construction. In an article in www.architectural-review.com (accessed on 29 April 2023) [43] there are interesting statistics reflected in the growth of crop-based construction in France. The main point is the abundance of straw as a bi-product of wheat cultivation in France, which produces up to 25 million tons per year, of which only 10 percent is reported to be enough for the insulation of 500,000 dwellings per year. In addition to that, France is also the leading producer of hemp in Europe, another substrate for crop-based materials [43].

3.3. Use Stage

Regarding the use phase, this stage of the lifecycle, in terms of environmental impacts, dominates all other stages throughout the cradle-to-grave boundaries. That is mainly rooted in the magnitude of energy consumption in this phase, which is consumed to satisfy the heating, air conditioning, electricity, and hot water needs of the residents. The role of crop-based materials in this phase is their considerable insulation capacity, which substantially decreases the building's energy loss and consequent environmental impacts in some cases by 50% [44]. However, there are also drawbacks, which cause adverse impacts. Gérardin [45] mentions the potential leaching process caused by preservatives in this type of material, as well as the release of chemicals into terrestrial and aquatic environments. Furthermore, the emission of volatile organic compounds (VOCs) in both indoor and outdoor conditions, is another part of the studies given particular adhesives and coatings, used in these materials [2,11].

3.4. End-of-Life Stage

In this phase, since crop-based materials do not have a long history, end-of-life scenarios are not yet assessed in practice [46]. Therefore, studies are based on assumptions and consider different end-of-life scenarios. Two distinctive processes and scenarios are mainly covered in the literature, including recycling and disposal. One of the most examined disposal processes surveyed in the literature is incineration, which has a significant environmental impact. The reason lies in the fact that most crop-based materials are combustible, and incineration could provide efficient energy recovery solutions [47].

Beigbeder et al. [48] conducted an assessment of the biocomposites' end-of-life scenarios. Their approach was based on examining four scenarios: landfilling, incineration, compositing, and recycling. Recycling scores best among other alternatives in terms of environmental impacts, except for crop-based plastic polymers wherein recycling is costly to be performed. In the case of incineration, resulting combustion gases may cause hazardous phenomena such as soil ecotoxicity and climate change if not properly carried out. Utilization of municipal incineration is suggested as an efficient approach. It results in saving fossil fuels for heat and electricity generation, especially when systematic exploitation of them happens within the framework of CHP systems in integrated neighborhoods [2].

Pittau et al. [49] investigated the effect of storing carbon in biogenic materials and lime-based products when they are used as construction materials, particularly in exterior walls. The novelty of this research is considering the time frame of emission and carbon sequestration. This in turn leads to different results compared to those assuming emitted and sequestered carbon as net zero. The results show that storing carbon in fast-growing biogenic materials is more efficient than in timber elements. The carbon accumulated in fast-growing biogenic materials is fully captured by crop regrowth only one year after construction; whereas a longer time is expected for forest products due to the long rotation period required for forest regrowth. The capacity for storing carbon increases when straw and hemp are used as thick insulation for exterior walls due to the rapid CO2 uptake in plantations. As for other compostable crop-based materials, the most commonly reported end-of-life scenario in the literature is landfilling. Its major consequences are categorized as land use pertaining issues, climate change, and eco-toxicity [50]. Furthermore, the anaerobic decay of this type of material (esp. wood, cork, and paper) is incomplete; and leads to long-term storage of carbon in landfills.

3.5. Partial Conclusion

The discussions presented in this section demonstrate that crop-based materials could have a positive impact at all stages of the life cycle of a building construction project.

In the production stage, the cultivation of perennial plants for the production of crop-based materials is found to be a critical issue due to its potential impact on increasing soil organic carbon (SOC) sequestration. The LCA review of this stage illuminates the critical issues related to crop-based materials such as acidification, eutrophication, land-use, etc. Water resource depletion, threats to biodiversity, and ecosystem quality are also factors to account for in this part of the complete analysis. Finally, the embodied energy difference between classical concrete-based structures and bio-based ones, are demonstrating that at the manufacturing phase, bio-based material manufacturing resulted in climate impact reductions in almost every studied scenario.

In the construction stage, the ability of crop-based building materials to be produced from locally available materials is found to eliminate significant GHG and other pollutant emissions associated with long-distance transportation.

In the most impacting use stage, the excellent insulation properties of crop-based materials at low cost are found to be a significant factor for their use. Despite these performances, care should be taken when comes to additives and related emissions of volatile organic compounds, for instance.

In the end-of-life stage, efficient energy recovery solutions are suggested as suitable ways to treat crop-based materials. In this case, ecotoxicity should be evaluated. For several compostable crop-based materials, the most commonly reported end-of-life scenario in the literature is landfilling.

4. Applications and Performance

Some of the most recurring investigated properties in the literature include hygric and thermal conductivity coefficients, moisture uptake capacity and moisture buffer, moisture retention curves, and hysteresis effect on recurring wetting and drying cycles. Analysis of their hygrothermal capacity leads to other attributes such as occupant comfort, indoor air quality, hygienic conditions, etc. As a whole, the hygrothermal performance of the building envelope can be evaluated via thermal and hygroscopic characteristics, namely conductivity, heat capacity, and thermal diffusivity as thermal properties, alongside moisture buffer, moisture diffusion efficiency, porosity, and water permeability as hygric behaviors.

Jones and Brischke [2] reviewed many of the key properties of crop-based materials and how these materials are chosen within modern construction methods and during their service life. The authors divided crop-based materials into non-wood (plant-based) and wooden substances. Wooden crop-based materials are enumerated as solid wood, cross-laminated timber, panels, wood plastic composites, cellulose, pulp and paper, and finally bark and cork. Non-wood crop-based materials, on the other hand, involve flax, hemp, straw, bamboo, rattan reed, wool, peat, grass, and vegetal pith. Hence based on the mentioned study's benchmarks, the following review will be conducted for each of these categories distinctly.

Plant-based materials have a wider variety of species, compared to wood-based materials, especially for insulation applications. These materials are implemented either as insulation infills or as crop-based blocks used in the building walls and floors. Based on the utilized plant type in the crop-based materials, their subsequent properties can vary widely, which are reviewed as follows.

One of the most popular crop-based materials in both academic studies and the construction market is the combination of lime and hemp, known as Lime Hemp Concrete (LHC) or hempcrete. Evrard and De Herde [51] reviewed the hygrothermal properties of Lime Hemp (LH) wall assemblies and compared their transient performance, as per five traditional assemblies using WUFI Pro 4.1 simulation. The results depicted the ability of LH for fast liquid transfer combined with high vapor permeability and high moisture retention level. These properties play a key role in the hygrothermal dynamic both inside the material and in the indoor environment. This capacity is enabled by lime hemp, especially when used in the inner layer of insulation and capillary active materials. Hence, it avoids condensation-related issues that lead to increasing comfort levels, enhanced hygienic indoor environments, etc. In addition, this study also considers parameters to analyze components' responses under sudden changes in exterior temperature (cold nights, intense solar radiation, and scorching days). Authors concluded that LH walls provide better results to dampen the effect of fast weather changes, more than other assemblies. Along with its hygroscopic capacity, its strength is examined by de Bruijn et al. [52], in which both fibers and shives of this plant are agglomerated using a lime-binding agent. Although its results showed that the mechanical strength did not differ in comparison with merely using fibers, it asserted that LHC could be used in load-bearing structures. Haik et al. [53] expanded this material's thermal characteristics by replacing lime agents with other materials and identified its thermal and hygric performance as to temperature fluctuation, relative humidity balance, and moisture buffer. Although alternative binders demonstrated the same thermal performance as the lime-based binder, they are shown to perform better, in terms of embodied carbon and energy in this study.

Rahim et al. [54] discuss the moisture properties of two crop-based materials, flax lime concrete (FLC), and hemp lime concrete (HLC). Hygric properties (sorption isotherm, water vapor permeability, moisture diffusivity, and moisture buffer capacity) are quantified by the Moisture Buffer Value (MBV). Materials' responses are analyzed under different equilibrium and dynamic conditions. Both crop-based materials exhibited an "excellent" moisture buffer capacity according to the classification proposed by the Nordtest project [55]. The sorption process is very slow, particularly under high relative humidity levels. The sorption isotherms of the two materials display a similar pattern, which is justifiable since they have similar microstructures. HLC absorbs lower moisture content than FLC since the width of flax's pores is smaller than that of hemp, and thus promotes more capillary condensation which results in more moisture adsorption [54].

In addition to more common crop-based materials including flax, hemp and straw based concretes, there are other non-wood materials (e.g., reed, wool, vegetal pith, grass, peat, etc.), all of which are capable of being developed into viable building materials, that are partly reflected in the literature.

Despite the lack of studies on the reed, Brischke and Hanske [56] investigated the viability of its usage as a thatching material. They recognized decay in the material as a result of its use in roofing applications. They also studied the moisture absorption and durability of this material. Hofmann et al. [57] studied the adverse effects of a specific fungus on the mentioned decay in the roof thatching. Wöhler-Geske et al. [58] measured the water absorption of this material and analyzed the subsequent quality changes in the material.

Wool is studied as to its hygric and thermal performance as a construction material. Joshi et al. [59] compared this substance's environmental aspects with reinforced glass fiber composites. It concludes that due to lower environmental impact, a diminished amount of pollutant polymers facilitated transportation due to their light weight, and lower embodied energy and carbon footprint caused by their capacity of being incinerated at their end-of-life scenario, this category of insulation material plays a pivotal role in the construction of green buildings. Abdou and Budaiwi [60] examined wool's hygric performance at different moisture content levels. They concluded that increasing moisture content at a specific temperature would result in higher changes in conductivity, according to the relationship between k-value and thermal resistance. Patnaik et al. [61] studied the acoustic and thermal insulation properties of this material. They asserted that the thermal conductivity of the waste wool fibers is considerably low compared to chemical counterparts, although the conductivity increases with the rise of temperature. In addition, the samples tested in this report demonstrated a good acoustic absorption over the whole sound frequency test range (50–5700 Hz).

Vegetal pith, as the innermost layer of many plants, has been studied by a few researchers in recent years, as the construction materials. There are many crop-based sources to extract this material. Korjenic et al. [62] offered a hygroscopicity analysis of this material throughout their study on natural insulation materials. Given its porous inner structure, this material is highly capable of absorbing and releasing moisture, thereby maintaining a hygric balance in the environment. Georgiev et al. [63] performed an analysis of the relationship between aggregate density and the product's conductivity and derived a linear connection between these two parameters. Palumbo et al. [64] studied the pith extracted from corn aggregates. It compared the material's thermal conductivity to straw fibers and concluded that it is 10% more resistant to heat flow than straw fibers.

5. Challenges

Recent attention to passive technologies in renewable energies led to many studies on the embodied energy of materials. Crop-based materials as the zero-emission alternatives, despite significant scientific efforts, have not been widely implemented as a best-practice in building industries. This section discusses some of the scientific and practical challenges that are crucial to the scalable promotion of crop-based building materials.

5.1. Sorption Isotherms and Hysteresis

Due to the hygroscopicity of this type of insulation material, physical properties such as moisture uptake, retention, and consecutive wetting-drying cycles play a preponderant role in their application in building. IUPAC classified different sorption isotherms of porous materials in the technical report of Sing [65]. Based on adsorbent-adsorbate characteristics and interactions, six types (I, II, . . . , VI) are identified in Figure 2. Type II of this chart (in the upper left corner) is reported to be related to non-porous or macro-porous materials, as opposed to other charts relevant to meso, micro, and nano-porous materials. However, in this report building materials are not specifically mentioned. Based on Hansen [66], all the porous building materials exhibit an S-shaped sorption curve same as that of Type II. The sorption curves are called isotherms because temperature influences the curves, in that with increasing temperature the corresponding curves lie under the colder isotherms.

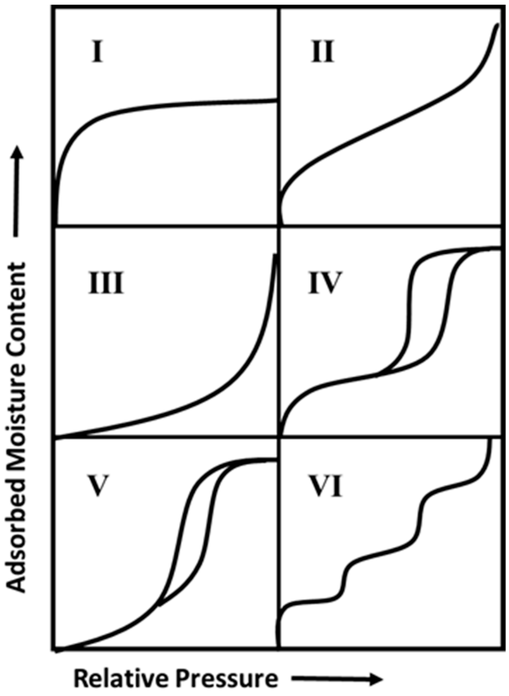


Figure 2. Sorption isotherm classification, adapted from [65].

Based on Sing [65], capillary condensation is a phenomenon accompanied by hysteresis. In a more recent update of the IUPAC report, Thommes et al. [67] offered a detailed explanation of hysteresis and its demonstration in sorption curves. The authors propose five different hysteresis types (H1 to H5), with a variation H2a and H2b for the second type (Figure 3). Due to the demonstration of the hysteresis effect in wetting-drying cycles as well as having a point corresponding to mono-layer and multi-layer adsorption, H3 is the hysteresis loop that is mostly used in building materials.

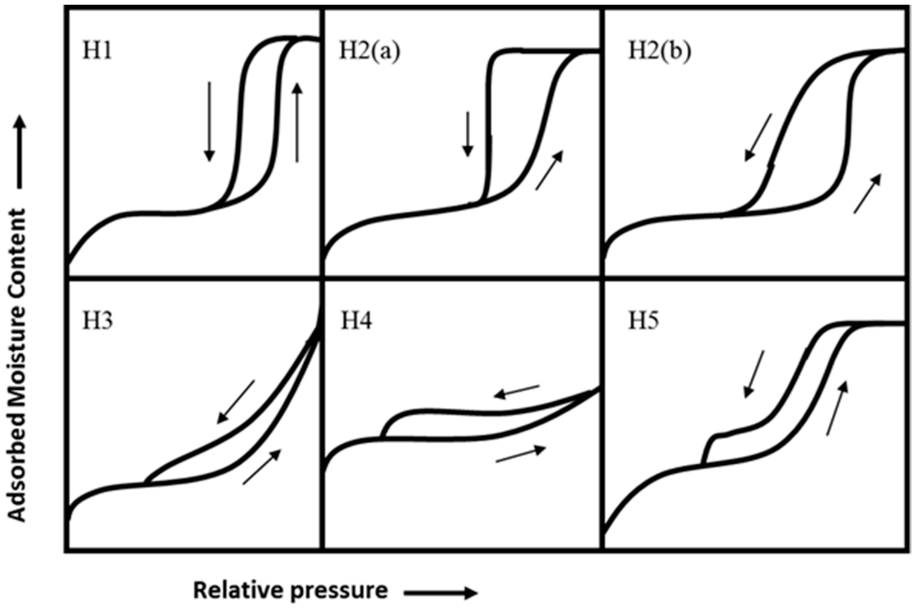


Figure 3. Classification of hysteresis loops into five general types, adapted from [67].

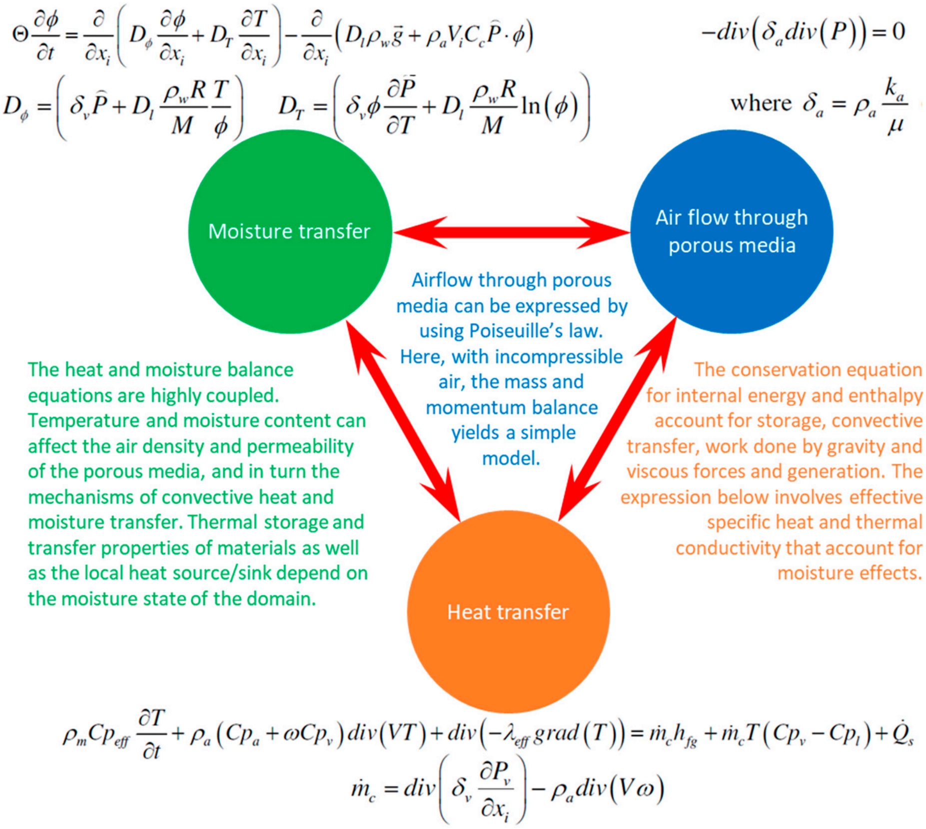
One of the dominant phenomena in crop-based materials is hysteresis. Due to their hygroscopicity and fluctuations in temperature and humidity of ambient conditions, a recurring wetting-drying cycle occurs. In order to take into account the hysteresis loop and sorption history, Zhang et al. [68] utilized a finite volume-based Fickian model for vapor flow and storage, as well as Frandsen's hysteresis model, to simulate temperature-dependent hysteresis. Promis et al. [69] analyzed hysteresis in hemp and rape straw using the Muallem II model, instead of Frandensen's. The aim was to demonstrate the influence of this phenomenon on wetting-drying cycles. The simulations yield the same outcome between hysteresis and non-hysteresis models in a steady state, whereas there is a considerable discrepancy in transient conditions. In another study, the effect of varying temperature through imposing non-isothermal models is examined by Promis et al. [70]. After applying mechanical, thermal, and hygric loads, they applied four non-isothermal models and detailed their accuracy. Out of the analyzed models, modified GAB is identified as the incorporated model in this study. They used monolayer and multilayer enthalpies to extend the sorption curve to different temperature, and simulate subsequent non-isothermal conditions in an entire range of 0 to 100% relative humidity.

5.2. Interconnected Heat, Air, and Moisture Transfer

The interdependency of the moisture content of the material to the airflow is not a very dated numerical trend in the analysis of porous building material. The complexity of nonlinear heat, air, and moisture (HAM) coupled analysis cause numerous challenges, some of which are addressed in the literature. Since airtightness criteria are met in many building envelopes, the majority of studies merely include heat and moisture coupling and ignore airflow in their analyses. Nonetheless, the inclusion of airflow and convection in the moisture flow proved to be a game-changer in the real-scale analysis of moisture in porous materials.

Teasdale-St-Hilaire and Derome [71] simulated statistical fluctuation of temperature and humidity in a large-scale building envelope in Montreal, during springtime. The paper argues that convection does not occur as a direct result of wind effects on exterior walls, but rather as a result of air circulation in cavity insulations. Moreover, they focus on experimental modeling of wind and rain infiltration in assemblies of sheathing and vapor retarder materials. Although this study does not consider the wind convection effect, it mainly focuses on the subsequent wetting process of rain infiltration. Another advantage of this study is to derive the convection effect in insulation parts.

Tariku et al. [72] defined and optimized building parameters, based on three factors: durability, indoor humidity level, and energy performance; all of which are tied to the thermal and moisture dynamic response of a building. They chose relative humidity as the main parameter to have a continuous domain for solving the corresponding equation. In addition to introducing the air permeability equation and defining its interdependency with moisture diffusion-capillary and energy equations, this study also incorporates it into calculations of convection terms. In this study air velocity and pressure field equations are solved independently to be embedded in convective terms of moisture and energy equations as demonstrated in Figure 4. This figure presents the relationships between heat, air, and moisture transfers along with their governing equations and short descriptions of their relationship.



$$\Theta\frac{\partial\phi}{\partial t}=\frac{\partial}{\partial x_i}\left(D_\phi\frac{\partial\phi}{\partial x_i}+D_T\frac{\partial T}{\partial x_i}\right)-\frac{\partial}{\partial x_i}\left(D_l\rho_w\vec{g}+\rho_a V_i C_c\bar{P}\cdot\phi\right)$$

$$D_\phi=\left(\delta_v\bar{P}+D_l\frac{\rho_w R}{M}\frac{T}{\phi}\right)\quad D_T=\left(\delta_v\phi\frac{\partial\bar{P}}{\partial T}+D_l\frac{\rho_w R}{M}\ln(\phi)\right)$$

$$-div\left(\delta_a div(P)\right)=0$$

$$\text{where }\delta_a=\rho_a\frac{k_a}{\mu}$$

Airflow through porous media can be expressed by using Poiseuille's law. Here, with incompressible air, the mass and momentum balance yields a simple model.

The heat and moisture balance equations are highly coupled. Temperature and moisture content can affect the air density and permeability of the porous media, and in turn the mechanisms of convective heat and moisture transfer. Thermal storage and transfer properties of materials as well as the local heat source/sink depend on the moisture state of the domain.

The conservation equation for internal energy and enthalpy account for storage, convective transfer, work done by gravity and viscous forces and generation. The expression below involves effective specific heat and thermal conductivity that account for moisture effects.

$$\rho_m Cp_{eff}\frac{\partial T}{\partial t}+\rho_a\left(Cp_a+\omega Cp_v\right)div(VT)+div\left(-\lambda_{eff}grad(T)\right)=\dot{m}_c h_{fg}+\dot{m}_c T\left(Cp_v-Cp_l\right)+\dot{Q}_s$$

$$\dot{m}_c=div\left(\delta_v\frac{\partial P_v}{\partial x_i}\right)-\rho_a div(V\omega)$$

Figure 4. Interdependency of heat, air, and moisture, adapted from [72].

Saber et al. [73] used a numerical 3D model that coupled the air leakage in conjugation with heat transfer to analyze two different types of walls, namely opaque walls (without penetration) and walls including windows (with penetration). They analyzed the effect of air leakage in different pressure differences on the apparent R-value and subsequent temperature distribution in the fabricated walls, numerically and experimentally. Unlike many of the studies, windows are incorporated in this analysis and modeling of the windows in the numerical simulation. The corresponding boundary conditions are cited by Elmahdy et al. [74].

Rahim et al. [75] investigated the hygrothermal balance of concretes made of hemp and rape straw from an experimental point of view by imposing alternating temperature and relative humidity in outdoor conditions. This was carried out in terms of static and dynamic modes. This study also characterized the homogeneity of the fabricated walls. They concluded that temperature and moisture are strongly interconnected to each other under hygrothermal loads. In addition, there is an identified heterogeneity between the top and bottom layers due to the compaction of layers and heterogeneous binder distribution. This affects temperature and moisture distribution profiles in the wall.

Demonstrating the effect of latent heat on total heat transfer, Slimani et al. [76] used two diffusive models for HM simulation including the "non-linear heat transfer model, purely diffusive" and "fully coupled heat and moisture transfer model". Since the former is based on measuring wall conductivity as a result of water content, they merely consider diffusion phenomena. Thus, the comparison between the two models quantified the latent heat of sorption effect on the heat transfer magnitude.

Kessentini et al. [77] introduced an analytical model, based on concentration gradient as a motive source and time evolution of concentration gradient while evaluating imposed mechanical loads caused by hygrothermal fluctuations. A state-of-the-art concept that is illustrated by this research is the coupling factors between dimensional parameters, which take into consideration edge effects. Finally, a coupling between material capacity for maximum moisture adsorption, boundary temperature difference, and external tensile stresses is extracted.

In addition to the mentioned forced convection effects, Langmans et al. [78] examined the possible effect of utilizing exterior vapor retarders on moisture distribution within insulation parts of the wall. The novelty of this study is to account for the natural convection effect as depicted in Figure 5. Therefore, moisture entering the building enclosure through discontinuities is considered the main source. This simulation has been conducted through DELPHIN 5 quasi-steady state airflow model enabled to capture natural convection.

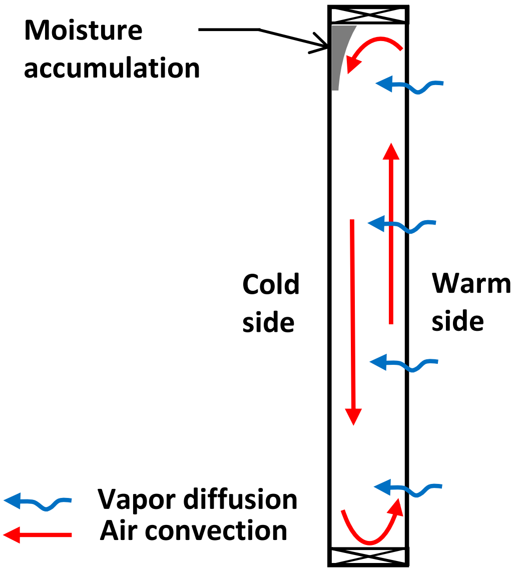


Figure 5. Potential moisture redistribution as a result of internal natural convection, adapted from [78].

Belleudy et al. [79] described a novel approach to coupling air leakage (infiltration/exfiltration) with heat and moisture transport and conservation equations in a wooden-frame building envelope. Using the analysis of porous media and air channels separately, they developed multiple governing equations for heat, air, and moisture. In some cases due to the problem's physics, these two approaches are unified and in some cases, the governing equations are developed separately. The benchmark of this study is the HAMSTAD project.

5.3. Whole Building Hygrothermal Analysis

The last milestone in the hygrothermal characterization of buildings is to extend the analysis of the building envelope to the whole building's inner spaces. This includes indoor air, the interaction of the building's different spaces, and the interconnected balance of indoor air with the building envelope. This analysis level especially in numerical approaches requires complicated numerical effort, in which the number of conditions, high non-linearity, and complex sets of equation makes it difficult to obtain accurate results.

Plathner and Woloszyn [80] conducted an experimental and numerical study on inter-zonal air and moisture transport through different rooms and spaces of a test house and explored airborne moisture in multi-zone models. Holm et al. [81] discussed the combination of the building envelope and the building's indoor space, in terms of the applicable hygrothermal models. They introduced the WUFI+ model [82] as an extension of WUFI [83], which was merely for the hygrothermal analysis of the building envelope. Rode and Sørensen [84] developed a transient model for hourly simulation of thermal conditions in multizone buildings. As part of this model, moisture buffer analysis is applied to all layers of the building envelope and indoor conditions, taking into account the activities and furniture of the residents.

One of the most comprehensive references on whole building HAM analysis was presented in IEA-ECBCS Annex 41 (Whole building heat, air, and moisture response) [85]. This annex follows the previous annexes, namely Annex 14 (Condensation and Energy) [86], Annex 24 (Heat, Air and Moisture Transport in Insulated Envelope Parts) [87], and Annex 32 (Integral Building Envelope Performance Assessment) [88]. This annex provides a detailed explanation of the complex physical phenomena occurring in the whole building's heat, air, and moisture response in four subtasks. The state-of-the-art is that almost all the models take the indoor conditions as the known parameters, whereas in real-scale solutions, indoor conditions should be a part of the analysis and this is the novelty of the whole building simulation in numerical approaches [89,90].

5.4. Available Benchmarks

As advanced hygrothermal models continue to be introduced, benchmarking their results is one of the challenges, and many studies and investments are focused on this area. In order to give an idea of the benchmarking projects in the case studies of this article, a few examples are enumerated.

The NORDTEST project is a benchmarking method developed by Rode et al. [55], in which a standardized figure to characterize the moisture buffering ability of materials is proposed. It has been the objective of a Nordic project to develop a definition and to declare it in the form of a NORDTEST method. In addition to the definition of the Moisture Buffer Value, the project also entails a test protocol, which expresses how materials should be tested.

One of the most referenced benchmarks is the European Union's initiative to standardize HAM calculation models, called HAMSTAD WP2. The main objective of this project is said to be "to reach consensus on standard methodologies to determine moisture transfer properties with acceptable precision and repeatability; to propose a reference HAM-document, including the basic equations, conditional requirements and benchmarks with performance criteria". Five different benchmarks including insulated roof, analytical benchmark, lightweight wall, response analysis, and capillary active inside insulation are characterized, formulated, and validated in this project.

Another reference benchmark is the sets of publications of the National Research Center of Canada (NRC). NRC-IRC is the institute for research in construction. In addition to the national codes issued by this institute, there are numerous publications on the hygrothermal assessment of buildings that serve as benchmarks to guide and validate scientific works. There are full-scale facilities constructed by this institution such as a two-story house for wall and ventilation studies, a facility for the study of ventilation and air quality, a flanking noise facility, etc. [91]. Out of thousands of practical offered benchmarks, three relevant examples to the scope of this review are mentioned as follows. Lacasse et al. [92] is a benchmark of one of the advanced models developed at NRC-IRC. They present a comparison of a computer model called hygIRC with experimental data for predicting heat and moisture transfer in building materials. Elmahdy et al. [74], another study of this institute from which, energy performance benchmarks related to different sections of walls can be extracted. Elmahdy [93] is another benchmarking practice that examined the heat transfer and R-value of various fenestration systems.

Needless to mention that there are other renowned benchmarks and standards, such as many studies conducted in ASHRAE. However, since the scope of this study was limited to Canada and Europe, two examples of these regions were mentioned here.

6. Discussion

6.1. Bottlenecks in LCAs Frameworks, Standards and Regulations

The most observed bottleneck in the literature is twofold: (1) the ability to determine the appropriate or complete boundaries of systems and (2) their multiple overlaps, in which case environmental impacts cannot be separately quantified and calculated. As reviewed before, there could be many approaches in crop-based LCAs. From a technical point of view, most of the cited variations among LCA methods originate from distinct system boundaries (such as cradle-to-gate, cradle-to-grave, or gate-to-gate). Diverse functional units and dissimilar life cycle inventory data (either primary or secondary data [94]) are another source of differences based on the reviewed investigations.

Specifically in clay-based construction materials, the uncertain percentage of each material in the final product and their variable compositions make it difficult to assess the overall input. Furthermore, the time-consuming and complicated processes of recycling or landfilling these materials generate a burden on the analysis of end-of-life scenarios [95]. Studies covered in this review that cite boundaries and overlaps as major challenges in LCA are listed in Table 2. Column 1 contains the citation to the reference, column 2 indicates the dominant aspect of the study and the last column proposes the type of method or application used during the analysis.

Table 2. Studies on the LCA methods.

Author	Field of Study	Method or Application
Bilec et al. [96]	LCA	Process & Input-Output methods
Säynäjoki et al. [97]	LCA	Hybrid method
Treloar et al. [98]	LCA	A hybrid method in the construction industry
Bowick [32]	LCA	Canadian residential dwellings LCA database
Lokesh et al. [99]	LCA	Non-aggregated hybrid LCA of circular crop-based building material
Sherwood et al. [100]	LCA	Techno-economic approach for using LCA

There are also existential trade-offs in the life cycle assessment of sustainability-oriented technologies that cause further differences in their approaches. In this context, active and passive technologies should be treated differently.

- In active technologies, the trade-off is mostly between energy-and-carbon-intensive manufacturing processes of the equipment (e.g., wind turbines, etc.) and zero carbon emission by their green power generation on the other hand, which is an ongoing source of debate and varies from case to case.
- In passive technologies (such as sustainable building materials), the argument is not focused on a particular life cycle stage and is extended to the entire life cycle. That said, in passive technologies, the trade-offs can be articulated as embodied vs. operational carbon emission, which is not limited to the manufacturing and use stage merely, compared to active technologies.

There are also differences in the goal and scope definition of LCA approaches related to different climates. For instance, although the UN's Sustainable Development Goals (SDGs) prioritize water resources depletion, in the local studies in Scandinavian countries water is not of utmost importance. On the contrary, land use change is a debatable subject in this area, and therefore set as the goal of relevant LCA studies.

Finally, the most important factor that causes discrepancies between LCA studies of crop-based materials, in particular, is the lack of a database in their life cycle assessment. Therefore, building a comprehensive database on the environmental impacts of crop-based materials is crucial in promoting their sustainable development and adoption. Discussed studies on the life cycle assessment of crop-based materials in this review are listed in Table 3. Here also, column 1 contains the citation to the reference, column 2 indicates the dominant aspect of the study while the last column indicates here the type of application used in the study.

Table 3. Studies on the LCA of crop-based building materials.

Author	Field of Study	Application
Hollberg and Ruth [101]	LCA	LCA in architectural design
Escobar and laibach [18]	Sustainability review	Circular and sustainable utilization of crop-based materials
Van dam and Bos [12]	Environmental impacts	Fiber crops usage in industrial applications
Schulte et al. [14]	LCA comparative assessment	Crop-based insulation materials
Berndes et al. [16]	Crop-based energy	LUC (land use change)
Escobar et al. [24]	Environmental impacts of bio-plastics	LUC-rooted GHG emissions
Escobar et al. [21]	Consequential LCA	Bio-fuels
Martin et al. [15]	LCA	LCA in crop-based value chains
Florentino et al. [26]	Landfilling	Biogenic carbon measurement
Silva et al. [27]	LCA	Environmental tradeoffs in agglomerates of wood-based and crop-based residues
Fieschi and Pretato [28]	LCA	Waste management
Sahoo et al. [102]	LCA	LCA of wood-based products
Peñaloza et al. [33]	LCA	Effect of increasing crop-based content in building materials
Ding et al. [35]	LCA	Closed loop LCA on recycled aggregate concrete
Gorse et al. [9]	LCA	Building sustainability
Potrč et al. [17]	LCA	Insulation environmental footprints
Giergiczny et al. [36]	LCA	Low CO2 emission concretes
Bumanis et al. [37]	LCA	LCA and review of alternative binders for crop-based concretes
Correa et al. [103]	Carbon footprint	Bio-composite materials
Elmasoudi et al. [42]	Environmental impact assessment	Environmental assessment of construction activities
Pittau et al. [49]	Embodied carbon assessment	Carbon sequestration effect in fast-growing crop-based material
Asif et al. [31]	LCA	Emission of different constructing building materials
www.architectural-review.com [43]		Current status of regulation and crop-based material production in France
Wojnowska-Baryła et al. [47]	Waste management	End-of-life scenarios: Effect of crop-based materials on the waste management
Beigbeder et al. [48]	End of life	End-of-life scenarios of crop-based composites
Fouquet et al. [50]	LCA	Biogenic carbon in low-energy buildings
Lecompte et al. [46]	LCA	GHG emission and uptake of lime hemp concrete

Given the available standards, models, and frameworks, an ongoing challenge in the promotion of crop-based building is the horizontal definition of ISO and EN sets of standards. In some cases, they fail to address the criteria, which are needed to conduct environmental measurements for construction products. Therefore, the need for more comprehensive vertical EPDs defined under these standards seems vital. In this regard, there are recurrent emerging crop-based products that should be environmentally assessed and published as specific EPDs.

Furthermore, environmental considerations should be reconciled with social and economic impacts as well. Criteria such as affordability, and adaptability in different cultures (e.g., in terms of farming-based or industry-based or service-based societies) are of the utmost importance in the development of these EPDs. Furthermore, the customization of the already developed studies to different urban or rural communities is another critical factor in evolving frameworks such as EPDs. This in turn could lead to increasing the technology readiness level (TRL) of crop-based materials.

Above the standards and frameworks, one of the most complicated barriers to the widespread use of crop-based building materials is regulation. In different building codes, from Canada and US to Europe, crop-based materials are vaguely discussed. For instance, in the US hempcrete is recently begun to be suggested by the US hemp building foundation to the International Code Council [104]. In Canada, hemp-based construction projects are permissible under Section 9 of Ontario's building code as an alternative material. However, according to Canada's building code, CSA must approve it, in order to be viable as a commercially available technology for the building sector. According to Northern Alberta Development Council [105], the first CSA-approved hempcrete prefab home is currently in production in British Columbia. In the European Union, and in particular in France as another case study of this research, building codes are clearer. This leads to not only allowing but also emphasizing the utilization of materials extracted from living organisms such as hemp and straw. In one of the most recent regulatory actions, from 2022 all public buildings financed by the French state are built from at least 50% timber or other natural materials [106].

In regard to the assessment of circularity, in some of the studies it is shown that due to the burning of crop-based materials in the manufacturing cycles, produced materials become carbon neutral. Thereby, to conclude the impacts of these materials, the energy source for different processes (esp. drying and gluing) needs to be considered. The gluing part in manufacturing-oriented studies is rarely seen, and there are not many offered alternatives for traditional energy-intensive binders. This issue could be critical when there is a constant need for the development of agents and binders adaptable to emerging crop-based substances.

Moreover, using agricultural products as the base material in building material's agglomerates could cause environmental downsides of acidification, eutrophication, etc. If this emerging industry becomes more prone to using agricultural waste as the base material, rather than the main products, and replaces chemical agents with natural binders such as mycelium, long-term mentioned environmental burdens would be highly compromised.

Some of the considerations in the assessment of environmental impacts pertaining to different crop-based materials were out of the scope of this study, so are not mentioned in detail in each study separately. Electricity consumption is a tricky parameter included in the assessment of GWP, in that depending on the type of fuel used for electricity generation, the consequent impact will vary considerably (as mentioned in the previous paragraph). Releasing stored biogenic carbon, as a result of burning biogas for electricity generation significantly influences environmental impacts, compared to burning fossil fuels.

Another point is the upscaling process in manufacturing and its details leading to decreasing environmental burdens, for example diminishing the consumption of plastic bags, decreasing the emissions of the sterilization process, etc. Finally, although there are comparisons between different produced crop-based materials, some of which are presented in this study, due to the varying applications and accordingly different functional units it is complicated to reflect an accurate comparison between their impacts.

6.2. Application and Performance

Although the potential for crop-based materials in building construction is promising, significant technical development is still needed to fully realize the benefits of these materials in building envelopes. The research has shown that analyzing the hygrothermal performance of these materials can lead to better building conditions and occupant comfort. While wood-based materials have been extensively studied, the viability of plant-based materials such as hempcrete and mycelium-based composites remains a matter of concern. Further critical examination of different materials, including their properties and potential uses in different building elements, can help drive further research and development in the field. Ultimately, a better understanding of the potential and limitations of crop-based materials will be critical to their successful application in building construction.

Some of the alternative practices such as the usage of bamboo in construction, although well-developed a long time ago, were somehow deemed outdated in the industry and not commercialized extensively. Compared to load-bearing structural developments, non-load-bearing applications demonstrate an acceptable prospect for the future of crop-based buildings, given their proven outstanding thermo-hygric performance. However, in terms of technical feasibility, even non-load-bearing technologies are not yet widely adopted by the construction industry. The case studies in most of the research are small-scale buildings. Load-bearing applications have a lower technology readiness level (TRL) and are still in the preliminary stages of research and development. Although there were successful studies on the development of crop-based concretes, except for a few case studies that are presented in this survey for one-story houses, there is no evidence of using a monolithic crop-based load-bearing building structure.

The cited studies that discuss the technical feasibility of wood-based and plant-based materials, in terms of their thermo-hygric and mechanical properties, are listed in Tables 4 and 5 respectively for wood-based and plant-based materials.

Table 4. Studies on the hygrothermal and mechanical properties of wood-based products.

Author	Field of Study	Application and Details
Jones and Brischke [2]	Crop-based building material	A comprehensive review of crop-based materials, their environmental impacts, and corresponding hygrothermal properties
Heinrich [38]	Gluing	Bio-based adhesives
Pizzi [39]	Gluing	Bio-based wood-binders
Segovia et al. [40]	Gluing	Bio-based wood-binders
Gérardin [45]	Wood preservation	Chemical modification of wood preservatives
Rode et al. [55]	Hygrothermal properties	Moisture buffer of building materials
[51]	Hygrothermal properties	Transient hygrothermal performance of lime hemp walls

Table 5. Studies on the hygrothermal and mechanical properties of plant-based products.

Author	Material	Field of Study	Application and Details
Evrard and Herde [51]	LHC	Hygrothermal properties	Transient hygrothermal performance of lime hemp walls
De Bruijn et al. [52]	LHC	Mechanical properties	Mechanical strength of lime hemp walls
Haik et al. [53]	LHC	Thermal performance	The effect of alternative binders on the thermal performance of LHC
Rahim et al. [54]	FLC & LHC	Hygric Properties	FLC and LHC characterization
Brischke and Hanske [56]	Reed	Hygromechanical properties	Moisture absorption and durability of thermally modified reed

Table 5. *Cont.*

Author	Material	Field of Study	Application and Details
Hofmann et al. [57]	Reed	Durability	Growth of fungi on reed decay in roof thatching
Wöhler-Geske et al. [58]	Reed	Hygric properties and durability	Water absorption and durability of thatching reed
Joshi et al. [59]	Wool	Environmental performance	Comparison between wool and glass fiber in terms of environmental performance
Abdou et al. [60]	Wool	Hygrothermal properties	Thermal and hygric properties co-dependence in wool
Putnaik et al. [61]	Wool	Acoustic and thermal properties	Acoustic and thermal insulation of wool
Korjenic et al. [62]	Vegetal pith	Hygric properties	Hygroscopicity analysis of vegetal pith as insulation material
Palumbo et al. [64]	pith	Thermal properties and durability	Thermal property of the pith extracted from corn aggregate

6.3. Challenges

Hygroscopicity of crop-based building materials causes several physical phenomena inside these materials, all of which are yet to be analyzed and not fully understood. The development path of crop-based materials so far, as well as their roadmap for further progress highly depends on the analysis of these phenomena. Porous structures of these materials cause complex interactions of heat, air, and moisture (HAM) within their structure.

Although heat and moisture interaction used to be recognized as the dominant physical phenomenon, recent advances in the recognition of physical interaction led to the inclusion of air transfer and its effect on the creation of advection, along with diffusion and this modifies the governing equations. The interaction of leaked air in different spots of the porous walls with moisture is still an unknown phenomenon in the literature. Developed air leakage models in the simulation are limited to the models such as orifice, or pre-designed air paths, and air infiltration from various spots of the walls such as window assemblies are not modeled as observed.

Finally, hysteresis is mentioned as a dominant phenomenon in crop-based building materials due to their hygroscopicity and fluctuations in temperature and humidity. Determining scanning curves in sorption isotherms as a result of hysteresis are important for understanding the moisture uptake, retention, and wetting-drying cycles of these materials. Overall, understanding hysteresis is important for predicting the behavior of crop-based materials in building applications. Studies on the numerical and experimental approaches and their development which are discussed in this study are listed in Table 6. Here again, column 1 contains the citation to the reference, column 2 indicates the field of the study and the last column proposes the type of application and related details.

The trade-off between moisture buffers' beneficial effects and the detrimental consequences of damp walls is another uncertain issue in the literature. On the one hand, the moisture buffer of porous crop-based materials is a significant property, which helps to regulate the humidity level in the environment and decrease the latent heat of the AC units. On the other hand, structural dampness and its consequent problems in weakening the structure and biological growth of detrimental species such as fungi, is a crucial problem in buildings. With the utilization of hydrophobic porous materials, it becomes a major design factor, which needs to have a design threshold for the balance of moisture in different parts of the wall. To the best knowledge of the authors, there is not yet a consensus on defining a balance for the humidity and moisture uptake in different sections of the wall from coating and plaster to insulation and base wooden layers. Benchmarking the moisture condition of the building envelope and the indoor condition of the building is very important to validate complex hygrothermal simulations. Out of many benchmarks offered in the literature three of them are discussed in this study and are listed in Table 7.

Table 6. Covered studies on the numerical and experimental developments and challenges.

Author	Field of Study	Application and Details
Sing [65]	Hygroscopicity	Classification of sorption isotherms
Hansen [66]	Hygroscopicity	A catalogue containing sorption and desorption isotherm equations for different building materials
Zhang et al. [68]	HM simulation	Modeling temperature-dependent hysteresis phenomena in
Promis et al. [69]	HM simulation	Moisture hysteresis analysis in hemp and rape straw
Promis et al. [70]	Hygrothermal and mechanical simulation	Simultaneous mechanical and hygrothermal loading and its analysis
Teasdale-St-Hilaire and Derome [71]	HAM simulation	Analyzing the Convection effect in insulation materials as well as the wetting process of rain infiltration
Tariku et al. [72]	HAM simulation	Heat air and moisture non-linear formulation and analysis
Saber et al. [73]	HAM simulation	Inclusion of windows in the wall models and further analysis of air leakage in the wall
Elmahdy et al. [74]	Energy rating experimentation	Benchmarking energy rating in different sets of wall assemblies
Rahim et al. [75]	HM experimentation	Experimental characterization of a hygrothermal balance of hemp and rape straw
Slimani et al. [76]	HM simulation	Developing two diffusive models for heat and moisture transfer
Kessentini et al. [77]	Hygrothermal and mechanical simulation	Evaluation of simultaneous mechanical load and concentration gradient
Langmans et al. [78]	HAM simulation	Inclusion of natural convection in the HAM simulation
Belleudy et al. [79]	HAM simulation	Describing different physics and solutions for the inclusion of air channels in wall assembly models
Plathner and Woloszyn [80]	Whole building simulation	Air-borne moisture transfer analysis in a multi-zone model of a test house
Holm et al. [82]	Whole building HM simulation	Introduction of the WUFI+ model
Holm et al. [81]	Whole building HM simulation	Combining thermal building simulation and hygrothermal envelope calculation
Rode and Sørensen [84]	Whole building HM simulation	Thermal and hygric transient model accounting for building envelope and indoor condition
Hens [86]	IEA Annex 24	Heat, air, and moisture transport in insulated envelope parts
Hens [87] (1996)	IEA Annex 32	Integral building performance assessment
Hens [85] (2009)	IEA Annex 41	Whole building heat air and moisture transport model

Table 7. Developed benchmarks for HAM transport in the building envelope and indoor condition.

Author or Project	Coordinator	Field of Study	Application and Details
NORDTEST project	Rode et al. [55]	Standardizing document	Standardizing moisture buffer of building materials
Lacasse et al. [92]	NRC-IRC	Benchmarking	Benchmarking of the hygIRC model
Elmahdy [93]	NRC-IRC	Benchmarking	Benchmarking the heat transfer of the fenestration system

The whole building simulation is an unsolved issue, which is still under development. The major bottleneck lies in the complexity of the non-linear analysis of simultaneous heat, air, and moisture interaction. The observed scale of analysis in the literature is from a single-layer material to multi-layer porous materials in the walls. As mentioned, the inclusion of windows in the models and its effect on air leakage is not observed. Moreover, despite many available commercial packages and models to simulate whole building hygrothermal conditions, extending the HAM models from a single wall to the room and the whole building's accurate simulation still seems far-fetched.

Finally, regarding the current state of both materials, solutions, and plant-based technologies, we are faced with a trend towards rapid evolution. This trend is not limited only to plant-based materials, which were mainly covered by this study. However, from phase change materials to hydrogels and algae-based technologies, and in other perspectives, from bio 3D printers to self-sufficient robotics and foam-based manufacturing, there are many solutions under development to neutralize the intrinsic carbon emissions of the materials.

As noted by the authors, this evolution is not limited to buildings but also extends to a wide range of industries, such as FMCGs, automotive, and aerospace. The works of MIT Media Lab [107–109] is a great example of cutting-edge research in this area, some of which is constructed as proof of concept [110]. Another example is the technology of mycelium-based bio-composites. However, what is seemingly occurring is that merely traditional solutions such as hempcrete began to scale in the construction industry and TRL of other technologies are still at prototype demonstration level.

7. Conclusions

As the use of crop-based building materials should become a growing trend in the construction industry, and as little is known about their potential, there is a need to understand their applications, their performance, and their current challenges. This paper, which mostly excludes a review of wood-based load-bearing biomaterials, investigates these three aspects of crop-based materials, beginning with a discussion of the four stages of their life cycle. It then looks at the applications, performance, and main challenges they face. The former section then presents summary discussions structured around compilation tables.

Research conducted in the field of Life Cycle Assessment (LCA) in the building sector has consistently demonstrated that crop-based building solutions and materials offer low environmental impacts, in all stages of their life cycle. Moreover, they are easy to manufacture, moisture resistant, potentially durable, locally available and they involve comparable thermo-physical properties for similar thicknesses, low toxicity, low embodied energy, high circularity potential, and low ultimate wastes.

However, despite this potential, the adoption of crop-based building materials remains relatively untapped in comparison to conventional methods. According to the surveyed literature, this could be caused to the scarcity of data and a limited number of studies across different research categories. As they have been, for most of them, recently incorporated into the built environment, long-term performance with respect to moisture and leaching issues is questionable. Moreover, several crop-based materials are still in the research phase, particularly in terms of their composition with other crop-based agents.

Consequently, the continuous assessment of emerging materials in the construction industry is necessary. Based upon the covered material in the current review, to effectively incorporate the most sustainable and feasible crop-bases substances in buildings for different climate conditions, it seems essential to:

- increase production of diverse crop-based materials, including sustainable binders such as mycelium;
- upgrade from lab-scale to full-scale benches;
- ensure long-term performance measurements;
- categorize crop-based building materials with respect to their potential use;
- assess more completely and thoroughly their environmental impacts;
- improve their thermo-hygro-mechanical characteristics;
- define new standards and regulations;
- more complete databases and inventories, and hence characterizations are needed in the use of hybrid LCA to estimate the environmental impacts of modern crop-based building materials (see Appendix C).
- life cycle costing and social life cycle analysis have to be combined into a stand-alone more complete Life Cycle Sustainability Assessment (LCSA) (see Appendix B).

Pursuing along these paths could pave the way for a future where buildings have minimal negative impacts on the environment, thereby fostering a more sustainable and resilient built environment.

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Appendix A. Bio-Based Materials

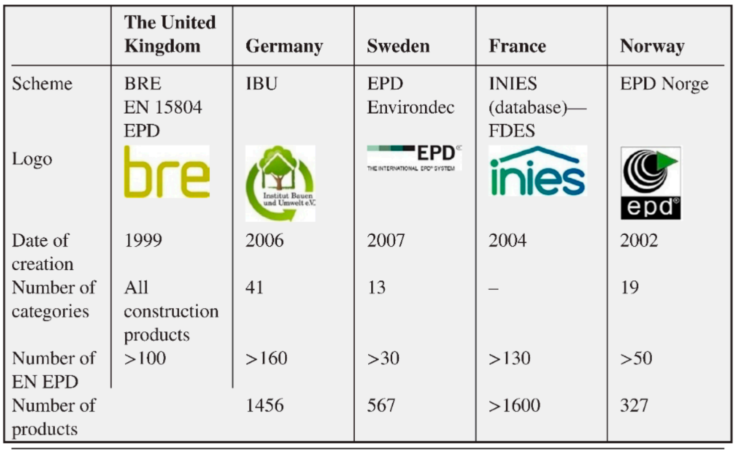
Bio-based materials could be broadly divided into two main categories regarding their characteristic types: forest/wood-based products and agriculture/crop-based products. Among the two main types, crop-based substances, such as sugar cane, corn, hemp, straw, and flax offer a viable supply source for building materials due to their fast growth and resulting short cultivation periods. These materials have the potential to be used in the construction of buildings in both load-bearing and non-load-bearing applications. They are renewable, almost globally distributed in a variety of forms, easily sourced, readily adapted to the needs and use, hygroscopic, recyclable, versatile, porous, and nonabrasive [2]. They have positive outcomes on global warming potentials (GWP), fossil fuel demand, acidification of soil, and eutrophication of water bodies [103].

Appendix B. Environmental Impacts Assessment

Appendix B.1. Standards, Frameworks, and Ecolabels

In order to assess the environmental impacts, there are several certifications and standards. This appendix briefly introduces standards, frameworks, and ecolabels. Ecolabels governed by ISO 14020 [111] series, namely ISO 14024 [112], ISO 14021 [113], and ISO 14025 [114] standards, are the most relevant to crop-based materials. The Ecolabels are defined under three categories of Type I, II, and III. Type III is the detailed environmental characteristics of any particular product, which are reflected in EPDs (Environmental Product Declarations). An EPD is an independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of a particular product, which is applied and verified, and thereby useful in benchmarking practices. The role of EPDs is the aggregation of data, as well as methods and assumptions, advocated in the framework of ISO standard 14025 [115]. Some examples of EPDs employed in different countries are mentioned in Table 1 for the reader who wants to start his research on the subject.

Eco-label III is governed by international and European standards mainly EN 15804. Furthermore, some of the LCA studies in these EPDs are conducted under ISO 14040 [116] (in the management framework) and ISO 14044 [117] (in the engineering and practitioner framework) criteria. Moreover, LCA studies adhere to the standards established in the 14000 series of environmental management standards of the International Organization for Standardization (ISO). Typically, ISO 14040 and 14044 are referred to as determining standards in this area. In addition, European Union developed its own standards which provides core product category rules (PCR) as the frameworks of EPDs. This, in turn, ensures that all EPDs are meticulously elaborated and verified in all construction categories.



	The United Kingdom	Germany	Sweden	France	Norway
Scheme	BRE EN 15804 EPD	IBU	EPD Environdec	INIES (database)— FDES	EPD Norge
Logo	bre	Institut Bauen und Umwelt e.V.	EPD THE INTERNATIONAL EPD SYSTEM	inies	epd
Date of creation	1999	2006	2007	2004	2002
Number of categories	All construction products	41	13	–	19
Number of EN EPD	>100	>160	>30	>130	>50
Number of products		1456	567	>1600	327

Figure A1. Examples of environmental product declaration in Europe [2].

Appendix B.2. Life-Cycle Assessment Related Methods

Life Cycle Assessment (LCA) is typically used for the analysis of material's environmental impacts. However, it is also important to evaluate other impacts, including economic and social issues. As a result, along with the standard LCA, other complementary evaluations began to be employed in the literature. Concerning the economic assessment, complementary methods include Life Cycle Costing (LCC) or Techno-Economic Analysis (TEA). Although these two methods are adequate for the assessment of crop-based building materials, they have mostly been used in the production of biofuels through the simultaneous consideration of process conditions and feedstock characteristics [18,118,119]. The social analysis method is referred to as Social LCA (SLCA). This Social Life Cycle Assessment (SLCA) is not a well-developed framework yet [18]. It needs to include many attributes of impacts namely environmental, and economic implications and their corresponding social implications, which in turn, leads to many multi-functions in overlapping boundaries, and makes it complicated to be explicated, assessed, and quantified. Based on the literature, there is no comprehensive method yet to consider all of the social footprints of crop-based technologies [120]. The combination of the aforementioned LCA, LCC, and SLCA into a stand-alone framework is known as Life Cycle Sustainability Assessment (LCSA) [18].

There are many reported constraints in the literature to combine and reconcile the outputs of these analyses together. The major bottleneck lies in the lack of integrated parameters and indicators between analyzed systems, most of which are reported to involve different boundary conditions [18,121–123].

Appendix C. Life-Cycle Assessment Methods

The main issue addressed in the analysis of the life cycle, is the quantification of environmental impacts of harvesting, transportation, manufacturing, operating, and disposal procedures, specifically when it is narrowed down to GHG emissions. Bilec et al. [96] explained one of the customized approaches for assessing the environmental impact of the construction sector based on two principal methods for conducting LCA: Process Method, and Input-Output (I/O) method. The process method defines the life cycle assessment as a process flow diagram, and sets an indicator, at which the flow between process and emissions are negligible, at the ending point of the process. I/O Method tackles the issue, from an operational perspective, in that this method uses a matrix accounting for each stage of the life cycle change's impact on the overall life cycle of a product or service. In other words, it uses the input and output of the cycle to conclude the emissions. As a result, the interdependencies will be calculated and quantified.

Since each of these two approaches have their own advantages and disadvantages, most of the literature suggested a hybrid model, which combines both of them. Accordingly, Säynäjoki et al. [97] introduced a hybrid method, which combines the two aforementioned approaches. This hybrid model relies on the inclusion of selected amounts of process and I/O extracted data, depending on the specific purpose of the project. Treloar et al. [98] proposed a hybrid model in the construction industry. It is formulated with respect to different practices, depending on the proportion, in which both I/O and process methods are incorporated. It divides hybrid models into four primary approaches: tiered, I/O based, integrated, and augmented. The tiered model uses I/O iterations in each step, whereas the details are considered in the process framework rather than I/O. The energy burden of products is measured via process methods, while the boundaries of a system, and the energy crossing them is accounted for by the I/O method.

Nevertheless, the use of hybrid LCA to estimate the environmental impacts of modern crop-based building materials may fall short of practical crop-based solutions assessment. In this regard, the approach of creating more complete databases and inventories is discussed in some of the literature. Bowick [32] in his master's thesis at Ryerson University outlines the methodology used to create an LCA database of brand-new Canadian constructions for the purpose of building stock modeling and benchmarking national construction practices, both of which are the key tools for higher-level decision-making. This study covers many materials and process models and complies with ISO standards 14040/44. Lokesh et al. [99] explored the circular life cycle of crop-based material in manufacturing via an I/O-based hybrid method. This method defines non-aggregated (non-combined) sectors, as opposed to aggregation in current LCAs, in which each part has to be recognized by its inputs and environmental burdens to be realized as one of the sectors of the whole system. Sherwood et al. [100] elaborate a distinct third method, with a strong mathematical framework, in which process data is included as technology matrices with physical units per capita, and the I/O model is embedded as an economic approach, defined by monetary units. This study introduces a techno-economic perspective toward using LCA hybrid method. In sum, it is based on three principles: incorporation of a detailed process framework (process method), specifying whole economy as boundary (I/O method), and accounting missing process by process method [96,100].

From an architectural perspective, there are parametric LCA methods, which focus on helping architects provide a better understanding of the environmental effects of their designed building. These models use the geometry of the building as input and produce the same outputs as conventional LCA methods Optimization is a key component of these approaches, where a range of design variants are considered, including changes to geometry or material, and the design process is modified iteratively [101].

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