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Potential of bio-based insulation products for buildings

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Content

1 Introduction

In the past, thermal insulation relied solely on bio-based materials. In Europe, during the Bronze Age, walls made from wood wickerwork were filled with hay and roofs were covered by thick straw bundles. Other insulation materials included, sawdust, wood chives, seaweed, reed, cork, hemp and flax fibers as well as animal products such as sheep wool. Bio-based materials also served to keep the heat indoors by using them to achieve a certain degree of airtightness. Cellulose fibers represent a more recent type of insulation, because some decades ago old newspapers were mainly used as toilet paper or for food wrapping. Today the market share of bio-based insulation materials in the building sector is still below 10 % worldwide. In Germany, where the market share has increased by 2 % points in the past 10 years, the share of bio-based building insulation reached 9 % in 2020 which is among the highest in the EU. Almost 60% of these are wood fiber materials another 30 % are based on cellulose fibers and the last 10 % include all other bio-based insulation products.

The reasons why bio-based insulation materials have been replaced by organic foams and mineral fibers after World War II are manifold. Fire protection is the most common explanation; however, this does not explain why organic foams have the largest market share today. Moisture susceptibility may be another reason. Both problems can be alleviated by additives or better constructional measures. The main explanations for the low market share of bio-based insulation materials are availability, cost and bureaucratic hurdles. Organic foams contain more air and less solid matter than most other insulation materials. They are cheap, widely available, and easy to install. However, their flammability, and even more their disposal after deconstruction present problems, because of potentially hazardous chemical compounds in the matrix polymers. On the other hand, many bio-based materials are not completely harmless either. To reduce their flammability and moisture susceptibility as well as to protect them against insect attack, a variety of chemicals is often employed that may also pose some potential health risks. Sometimes, also polymeric glues or binding fibers are used which may impair recycling or composting.

However, there are also reasons why the application of bio-based insulation products should be encouraged. Buildings made of bio-based materials act as long-term carbon storage. Since buildings are meant to last, the CO_2 sequestrated during growth is removed from the air for a long time. Other reasons are the lucrative use of waste materials left over from food production or other industrial production processes. Equally important are environmental considerations and biodiversity aspects. In contrast to conventional insulation products, bio-based materials show an important hygroscopic storage capacity which helps to dampen humidity fluctuations. This so-called "moisture buffering" capacity stabilizes the microclimate in building envelope assemblies [1] and interior spaces [2], reducing the occurrence of potentially critical humidity peaks. This report focuses on different aspects and background information to develop criteria for the selection and evaluation of bio-based insulation materials corresponding to local conditions, natural resources as well as economic and ecological requirements.

2 Thermal properties of bio-based insulation materials

The most important characteristic of insulation materials is their resistance against heat flow through the building envelope assembly. Heat flow through porous materials is transferred by conduction, convection, radiation and latent heat flow. Convection should be excluded by a sufficient airflow resistance that prevents thermal buoyancy effects within the material (natural convection) under practical application conditions. Materials with coarse fibers such as straw bales may not always meet this requirement. The thermal conductivity of insulation materials is determined by the guarded hot plate method, measuring the heat flux through the sample and the surface temperatures on both sides at different temperature gradients. The thermal conductivity determined for a dry sample includes thermal conduction and thermal radiation effects within the porous material. Convection effects should be negligible, however, if in doubt the sample should be tested with alternating heat flow directions (up and down). Differences between the results indicate convection effects.

In practice, insulation materials are never completely dry. It is a well-known fact, that the presence of moisture increases the thermal conductivity of all insulation materials. Since bio-based insulation materials absorb more hygroscopic moisture than common conventional insulation products such es expanded polystyrene or mineral wool, the effect of moisture on the thermal conductivity may not be negligible. This includes materials that have been treated by silicones or equivalent compounds to render them water repellent because sorption moisture is largely unaffected by these treatments. While stationary moisture in the material can be included in the effective thermal conductivity value of the material, the influence of moving moisture on the heat-flow through the assembly must be treated separately.

The influence of moving moisture is called enthalpy flow or latent heat effect. It results from water evaporating at the warm side of the insulation layer and condensing at the cold side. This effect can double or even triple the heat flux through the insulation layer compared to the dry state. Even worse, not only the water in the insulation material but also in adjacent material layers may increase the heat-flow through the assembly (a more thorough explanation of the influence of vapor diffusion on the thermal resistance of building assemblies can be found in [3]). Therefore, care must be taken to determine the thermal conductivity of insulation materials in a way that excludes initial or reversible latent heat effects. Otherwise, bio-based products would be penalized by overly conservative values (unreasonably high thermal conductivity listings due to vapor transfer with evaporation and condensation) compared to conventional insulations.

The thermal conductivity of bio-based insulation materials depends mainly on bulk density, homogeneity and fiber thickness resp. pore size of the insulation.

The specific heat capacity in dry state is usually comparable to that of organic foams. Higher values found in literature are often due to sorption moisture which should be accounted for separately. The thermal conductivity of competitive bio-based insulation materials can reach similar levels as conventional mineral fiber or EPS insulation. However, bio-based materials are still not getting close to the low values achieved by modern high-performance insulation. Table 1 gives an overview of densities and design thermal conductivities of commonly used bio-based insulation batts and boards.

Table 1:
Density and German design values for thermal conductivity of different bio-based insulation materials listed in [4]

Insulation material	**Density (kg/m³)**	**Thermal conductivity ʎ [W/(m · K)]**
Flax batts	30–40	0.039
Hemp batts	50–60	0.043
Wood fiber batts	40–50	0.038
Wood fiber boards	110–270	0.040
Cellulose fiber boards	70–145	0.042
Wood wool cement boards	350–500	0.090
Expanded cork boards	120	0.040
Reed boards	150	0.065
Seaweed boards	65–75	0.045
Straw bales	85–115	0.052

The German design value ʎ is derived from the declared thermal conductivity $ʎ_D$ (90 % confidence interval) measured at 10 °C mean temperature on samples conditioned at 23 °C and 50 % RH according to the wood fiber products standard DIN EN 13,171. Compared to the dry thermal conductivity, the value at 50 % RH of wood fiber insulation calculated ranges between 1 and 2 % and is therefore almost negligible (< 0.001 W/(mK)).

3 Durability and health aspects of bio-based insulation materials

For insulation materials, health and durability aspects are at least as important as their thermal resistance. Since insulation layers are usually covered by an interior lining, humans are not directly exposed to the insulation material after enclosure. However, pressure gradients over the building envelope due to stack or wind may cause infiltration of air though the assembly into the interior spaces because perfect airtightness is rarely achieved. Therefore, the use of fungicides and insecticides as well as of potentially harmful fire protectives should be minimized or avoided altogether. Bio-based materials with high natural mold resistance should be preferred and the access of insects should be prevented by designing unvented building assemblies. Some flame retardants are also effective against mold growth and rot. However, they may provoke corrosion in contact with metals.

The following section summarizes different phenomena representing hazards to bio-based insulation materials.

3.1 Mold and rot

Mold and rot are caused by different species of fungi whose spores are ubiquitous. Mold will sporulate on any material if the hygrothermal conditions at the surface are favorable to growth. However, compared to conventional insulation materials, bio-based materials are usually more prone to mold growth on their surface because they contain nutrients that mold can feed on. In [5] building materials are divided into biodegradable und non-biodegradable materials. The risk of mold growth depends mainly on the temperature and humidity conditions but also on the surface material characteristics. Figure 1 shows the hygrothermal mold growth zones for wheat straw and untreated cellulose fibers determined for various hygrothermal conditions in a climate chamber [6]. The green zone stands for no risk, the yellow zone for low to medium risk and the red zone indicates a high risk of mold growth. The curve denoted as LIM 0 represents the Lowest Isopleth for Mold on an optimal growth medium such as agar. The distance between this curve and the upper border of the green zone in Fig. 1 indicates the quality of the substrate. The longer this distance, the better is the mold resistance of the material. The risk of mold growth on straw is therefore much higher than on cellulose fibers. This has also considerable implications for the application of both insulation materials. While there is a high risk of mold growth on straw at 80 % RH at 15 °C, there is no risk of growth on cellulose fibers even at 90 % RH.

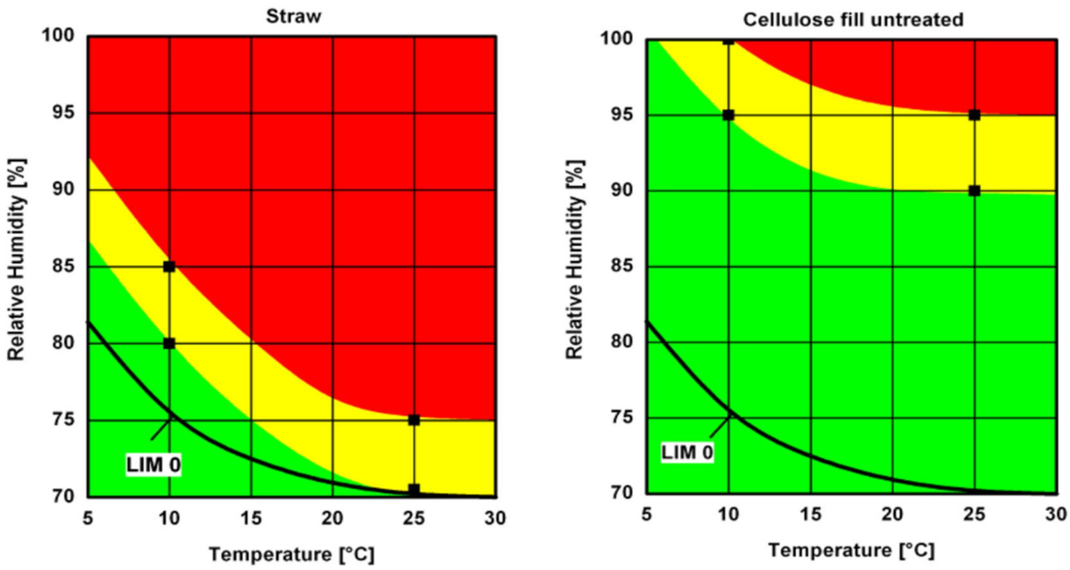

Figure 1:
Mold growth sensitivity of two building insulation materials illustrated by the RH-temperature zones of growth probability. Green indicates no growth risk, yellow low growth risk and red high growth risk [6].

This example demonstrates the large difference in natural mold growth resistance of bio-based insulation materials. Exposure test of straw bale walls at the Fraunhofer IBP field test site, lead to elevated material moisture conditions and resulted in mold being detected on some straw stalks. Likewise, insulation materials made from other plant fibers seem to be more moisture susceptible than wood fiber board. This means they need better moisture protection and may not be suitable for assemblies exposed to water from driving rain such as external thermal insulation composite systems (ETICS res. EIFS in the U.S.). On the other hand, there are alternatives to timber-based materials that show a comparatively high mold resistance because they grow in wetlands, such as bulrush also called cattail (Latin: Typha) [7] and reed. A survey inspecting reed insulation in practice showed no signs of mold growth despite long-term exposure of the assemblies to natural weather [8]. More information on the mold resistance of bio-based insulation materials can be found in [9].

Mold may be a health hazard for humans, but usually, it does not harm the function of the insulation layer. This is different if higher material moisture prevails. In this case decaying fungi may severely damage the insulation material. Investigations under high humidity loads of wood fiber board and timber samples infected with a cocktail of wood-decaying fungi have proven that wood fiber board is at least as resistant to rot as solid pine or spruce [10]. However, more research is necessary to prove that this is a general rule which may be transferred to other wood-based insulation products.

3.2 Further damage and degradation mechanisms

Compared to fossil polymers used to produce insulation foams or fibers, plant fibers are often more heat and UV resistant. However, if polymer binders are used for bio-based materials, the products may be subject to the same degradation mechanisms as their conventional peers. This includes thermal ageing effects and hydrolysis. Additionally mechanical stress and strain caused by hygrothermal dilatation (swelling and shrinkage) may accelerate setting and creep as well as cracking and possibly bulging or delamination. However, until now there is no indication that bio-based insulation materials are less durable than conventional materials as long as they are protected from excessive moisture. Currently, more research to evaluate the durability of wood-based insulation materials is ongoing.

4 Sustainability aspects concerning bio-based insulation materials

The energy and the expenses necessary to produce insulation materials are far less than the energy and cost savings enabled by insulating buildings. Hence, insulation materials are inherently sustainable independent of the raw materials they are made of. Since insulation materials have a low density, their carbon footprints per mass are also low especially compared to the values of structural building materials. An important share of the carbon footprint of all insulation materials represents the transport from the production to the building site. Therefore, insulation materials should be locally available, i.e., the raw materials of bio-based insulations should originate from local crops. Apart from the carbon footprint also the water footprint (amount of water required for manufacturing the insulation material) is becoming an important sustainability issue. In this respect, the most popular bio-based insulation material in Europe, wood fiber board ranks behind some conventional insulation systems.

As mentioned above, the carbon footprint of structural materials is not negligible and its importance, in relation to the carbon emissions for building operation, is rising with modern energy efficiency requirements. Limiting embodied energy of building materials and conserving natural resources implies careful selection of construction and finish materials and systems. Manufacturing and transport of these materials should be as energy efficient as possible. At the same time mining necessary raw materials must not deplete natural resources. Therefore, renewable (bio-based) or recycled materials should be preferred. Re-use of construction materials is also an excellent option which has widely been practiced in the pre-industrial times. Light-weight constructions have less mass per cubic meter than massive concrete or masonry structures. Generally, they contain less embodied energy and on top of that, timber and other bio-based materials sequester CO_2 during their growth which is subsequently stored over the lifetime of the building. Figure 2 shows the differences in global warming potential for various kinds of constructions, three of them considered to be massive and two light-weight building types.

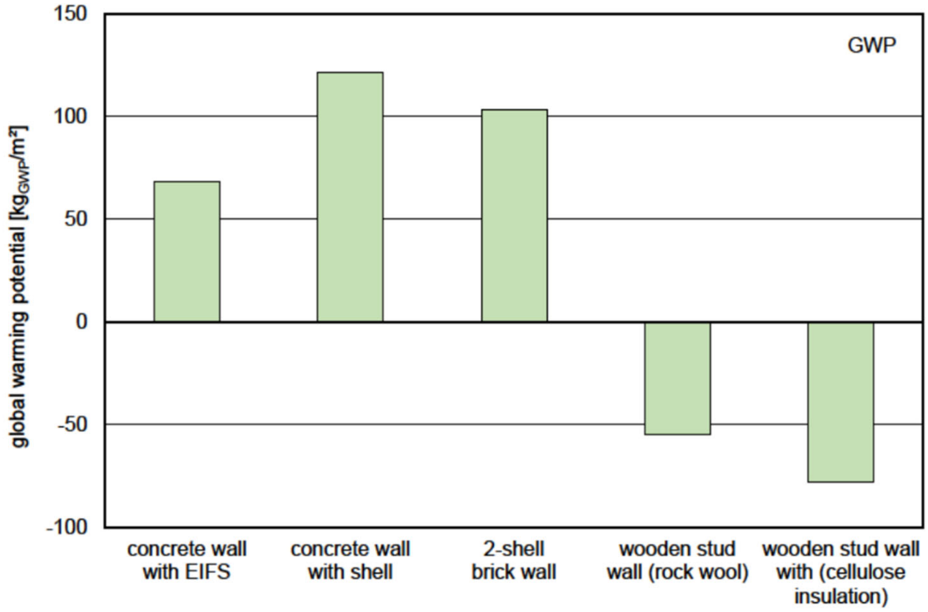

Figure 2:
Global warming potential for multi-family buildings having different structures and building envelopes determined by [11] based on established German calculation methods.

Does the carbon footprint of the structure have an impact on the selection of the insulation materials even if their carbon footprints are comparatively low? Yes, because people choosing to build a timber building often prefer to install bio-based insulation products. However, there is another, less emotional, reason why timber constructions and bio-based insulation materials are a good combination. Structural timber must be protected against water by an appropriate moisture control design which also helps to protect the insulation. On the other hand, the moisture buffering capacity of bio-based insulation materials dampens potentially critical humidity peaks within the whole envelope assembly.

5 Bio-based insulation materials on the market

Compilations of different bio-based insulation materials and their characteristics that are available on the market or under development can be found in [12] – [15]. These materials may be classified according to their origin and the additives such as binders. Natural resources for insulation products may come from:

- Forests: wood fiberboards, cellulose fibers (as loose fill or in board form).
- Aquaculture, wetlands, sea: cattail (Typha), reed, rice straw, seaweed.
- Agriculture: flax or hemp fibers, cotton, dried grass, straw, palm fibers
- Animals: wool, leather strips, dried insects.

In many cases these resources are waste materials from food or industrial production, respectively recycled products, such as cellulose fibers from paper or textile fibers from clothing. Exceptions are hemp fibers or chives and cattail leaves [7] which may be farmed just for the purpose to manufacture insulation products. However, farming cattail has also some environmental merits, e. g. stabilizing coastal marsh land or reducing carbon emissions from peat by rewetting drained fens as well as cleaning nutrient polluted surface water.

Fibers and particles from bio-based resources can be applied as loose fill or as insulation boards and batts. To keep the fibers together, high pressure is applied, or binders are employed. To manufacture medium density fiber board, wood fibers are mixed with water to form a homogeneous pulp which is dried under pressure. However, the majority of bio-based insulation materials is mixed with various glues to form rather rigid boards. To manufacture flexible insulation batts, natural fibers are mixed with polymer fibers. To achieve good bonding, the mixture is heated up close to the melting point of the polymer, thereby gluing natural and polymer fibers together. The following binders are used for bio-based insulation products:

- Mineral binders: lime, cement, magnesia, gypsum, geopolymers
- Polymer binders: synthetic resins, polyurethane
- Bio-based binders: biopolymers, casein, lignin, fungal mycelium
- Wires or strings to attach individual stalks to each other, e.g. reed

Laboratory tests performed on cattail insulation boards with different binders have shown that:

- Mineral binders such as magnesia and geopolymers offer good mechanical properties and low flammability but result in moderate thermal resistance of the boards
- Natural organic binders such as blood albumin or fungal mycelium provide thermal benefits but often have weak mechanical properties and low mold resistance

Recommended Solutions:

- Combination of mineral and organic binders
- Use of innovative bio-based polymers
- Optimization of production methods

Compared to conventional insulation materials, bio-based products have some advantages which are listed below:

- Carbon sequestration: bio-based materials (BBM) store CO_2 during their whole service life.

- Local Availability: BBMs are often locally available, reducing transport distances and costs.
- End-of-Life Options: BBMs can be recycled, reused, or composted.
- Moisture buffering: BBMs can absorb and desorb water vapor and dampen humidity peaks.
- Thermal storage: BBMs have a higher specific heat capacity than mineral building materials.
- Ecology: BBMs are renewable and don't exploit natural resources.

The challenges of BBMs include moisture sensitivity, mold resistance, and fire safety. Some materials can also suffer from insect attacks. Unprocessed products such as straw bales may be polluted by organic matter that increases the risk of insect or microbial infestation. Farming and processing of BBM products often consumes considerable water resources.

6 Evaluation criteria for bio-based insulation materials

Before investing in research and development and eventually in production facilities for a specific bio-based insulation products, the following evaluation criteria should be considered to perform a kind of SWOT analysis:

- Availability
  - Locally available in sufficient amounts [+]
  - Limited to specific local areas or climate zones [o]
  - Small natural resources [-]

- Thermal performance, i.e. thermal conductivity
  - < 0.04 W/(mK) [+]
  - $0.04 \leq \lambda \leq 0.06$ W/(mK) [o]
  - > 0.06 W/(mK) [-]

- Carbon Sequestration and Growth Rate
  - Fast growth or production waste [+]
  - Growth rate comparable to timber [o]
  - Growth risks due to unfavorable weather conditions or pests [-]

- Durability
  - Moisture resistance superior or similar to soft wood [+]
  - Limited resistance, requires biocides or special attention [o]
  - Low resistance to moisture or pests [-]

- Ecological Aspects
  - Low energy and water consumption for production [+]

  - Moderate resource consumption [o]
  - High energy and water consumption [-]

- End-of-Life Options
  - Easy to recycle or reuse [+]
  - Reasonable downcycling possibilities [o]
  - Only options are combustion or composting [-]

The above-mentioned criteria should be seen as an opportunity to scrutinize investment options. They are not meant to be rigid selection criteria and should be adapted to specific situations. There may be one important aspect overriding all other criteria, e. g. large amounts of waste materials that should be utilized. Most of the wood-based building products including wood fiber insulation boards have been developed to make use of wooden scrap and saw dust resulting from the high timber demand of the construction industry.

7 Conclusions

The study highlights the potential of bio-based materials for sustainable constructions. However, success depends on further development of binders as well as thermal and mechanical performance of bio-based insulation materials. Good moisture control design is essential to guarantee durability and to prevent adverse health effects. Therefore, future research should focus on analyzing different material types and complementing the material database of hygrothermal simulation tools.

Focusing on the climatic conditions in Vietnam and Germany and considering the existing sustainability challenges, the potential analysis of the project team resulted in the selection of two insulation material options for the application of bio-based materials in Vietnam. The first choice is rice straw due to its wide availability and because as water crop, it is assumed to be more moisture resistant than the European wheat straw products. Regarding the challenges of climate change ahead, the second choice has been cattail (Typha). It represents a viable solution against severe weather conditions, because it helps to manage flooding by retaining water. It also prevents excessive erosion by stabilizing land slopes and shorelines. Additionally, there are research result showing its capacity to purify surface water by absorbing pollutants that act as fertilizers. In contrast to the majority of insulation materials made from renewable raw materials, the Standard Typhaboard offers high compressive strength so that it can also be used for structural tasks.

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