Health, comfort, energy use and sustainability issues related to the use of biobased building materials

To what extent are the effects supported by science and data? What are next steps to take?

Chris de Visser, Kees van Wijk, Marcel van der Voort, PPO-AGV

Praktijkonderzoek Plant en Omgeving, onderdeel van Wageningen UR

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For quality of life

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Business Unit arable farming, multifunctional agriculture and field production of vegetables

Address	:	Postbus 430, 8200 AK Lelystad
	:	Edelhertweg 1, 8219 PH Lelystad.
Tel.	:	+31 320 291111
Fax	:	+31 320 230479
E-mail	:	info.ppo@wur.nl
Internet	:	www.ppo.wur.nl

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Abstract

With the exception of wood, the use of natural (biobased) materials (based on hemp, flax, straw or other natural resources) is still limited. Nevertheless, many benefits are attributed to these materials in terms of a healthier and more comfortable indoor climate. Other potential benefits of natural insulation materials that are often mentioned are energy savings and reduced environmental impact. This report focuses on the empirical support for these claims, identifies research gaps and suggests, where appropriate, recommendations for next steps.

Healthy indoor
In practice, moisture problems in both new and older homes are currently associated with poor indoor climate management. This is partly related to the use of conventional insulation materials and related constructions that aim at preventing indoor and outdoor air exchange as much as possible. However, alternative natural insulation materials are available that could improve the indoor climate (and thereby create a more healthy living environment) and reduce the environmental impact. New products are tested for volatile organic compounds (VOCs) before they reach the market. However, combinations of products still could lead to high emission rates, even though many of the constituent products may be low emitting materials.

Hydration and comfort
Research has shown that low humidity in an indoor environment can be associated with a less oppressive experience. Materials that reduce and stabilise the humidity can contribute to a more comfortable and pleasant living or working environment.

Material properties
In the literature, it has been demonstrated that biobased insulation materials are equivalent to insulation materials of fossil or mineral origin in terms of heat insulation and acoustic or sound-reducing performance. The microbiological risks associated with biobased building materials are mitigated through the addition of natural anti-fungal agents. Likewise, fireproof salts reduce the flammability of these materials to the legally required level. Fire resistance performance and emissions of VOC from biobased insulating materials is tested by independent institutes. Labels on biobased insulation materials provide information about the level of certification.

Moisture buffering
Pilot-scale studies have shown that many natural insulation materials, such as those based on flax and hemp, provide good moisture buffering performance. Thus, they seem suitable for moisture regulation of interior spaces and vapour-permeable constructions, but further testing is needed in practical situations. However, the hygrothermal properties of biobased materials as such, or in combination with other materials, need to be mapped with specific reference to the prevailing North West European climate.

Heat buffering
Biobased materials combined with natural materials such as clay and limestone have a high heat absorbing effect (based on their specific heat capacity) and are therefore potentially able to buffer indoor temperature in winter (releasing heat) and summer (absorbing heat). This could save energy and improve comfort.

Indoor climate and ventilation
A major research question concerns the impact of the use of biobased materials on indoor climate and the associated need for ventilation. If biobased materials result in a significant decrease in VOC emissions, it would be possible to ventilate less intensively depending on other indoor activities that require ventilation (cooking activities, CO_2 production, sweating etc.). However, the contribution of building materials to total VOC level indoors is unclear, and also largely determined by local conditions, and thus the possible contribution of biobased building materials is also unclear. Adding to this uncertainty is the lack of knowledge on VOC emissions associated with the use of biobased materials themselves. This represents a large gap in

knowledge regarding biobased building materials.

Sustainability
Regarding the cradle to end-of-life period of buildings, the greenhouse gas emissions associated with the production and use of materials are largely dependent on the energy requirement during the use phase of the materials (living, working). This causes the beneficial effects of using biobased materials to be more or less pronounced within the total greenhouse gas emissions profile, depending on the effect they have on energy use in construction. Regarding the cradle to factory period, biobased materials have an advantage over mineral or fossil-based materials because they first sequester CO_2. However, with composite materials the potential sustainability advantages can be obscured. Thus uniform methodology to determine greenhouse gas emissions for biobased materials would be advisable.

Implementation of innovation: The role of markets
At the moment, the market for biobased products is restricted to the so-called early adopters. If the market wants to increase in size, producers need to convince consumers to base their supply decisions on a business-like approach, looking at advantages that materials would have for them personally. To enter this market successfully, the biobased materials value chain should focus on the advantages that the use of these materials brings for consumers personally. Potential advantages could refer to a healthier indoor environment, living and user comfort and maintenance. The price should also be taken into account. This should include not only the acquisition cost of these materials and the building, but also the cost during the use of the building. In the end, the integral cost per unit time (including acquisition, depreciation, maintenance and demolition) can be different from the acquisition cost alone. Finally, the success of the market increase lies with the capacity to guarantee a supply of the biobased materials at competitive prices.

Unique selling points
There are several Unique Selling Points (USPs) related to biobased materials that could support market expansion. One relates to the relative humidity (RH) of the indoor climate and the health benefits associated with lower and more stable RH (reductions in fungi, toxins and allergens). A more stable and moderate RH can also be associated with higher living comfort. As mentioned above, it is necessary to underpin this USP with reliable data collected in practical situations under ambient climate conditions. Heat buffering relating to energy use is another potential USP that requires underpinning in the same way as the USP of RH. A third USP could be sustainability, but standardisation of the methodology would be necessary to support this USP in practice. These USPs, especially those relating to RH (health and comfort) and energy use, can be used to support market enlargement because they can exert a market pull effect, provided end-users have a decisive influence on the materials used. At the same time, the supply chain needs to organise a reliable and guaranteed supply of high quality biobased building products to meet increasing demand.

Product valorisation and scaling
At present, most biobased building materials have higher purchase cost than their fossil-based or mineral competitors. This is why the unique selling points of the biobased materials should be made more explicit in terms of gains for consumers. Moreover, the higher purchase price of biobased insulation materials can be expressed as a limited share of total building price. Finally, increased market volume of biobased materials can be expected to result in lower prices. However, an increase in volume will demand more cooperation across the value chain to lower transaction costs.

Recommendations
Based on this report, the following recommendations can be made.

Technical recommendations:
Future applied research under local conditions into the moisture buffering performance of biobased insulation materials is necessary. Although these materials have the potential to buffer humidity, the question of how this potential can be exploited in construction remains unanswered. Future research should integrate this performance aspect with others such as energy use and living or working comfort.
Research has shown that energy can be saved with a combination of biobased insulation materials with

airproof and vapour-permeable foils, which at the same time increases comfort and hygiene. However, present day building contractors and constructors have doubts as to whether this research is relevant to everyday practical conditions, especially under the variability experienced in the climate of North West Europe. Independent applied research under practical conditions into these effects is required as a demonstrator for the value chain. This research should include the heat buffering performance of materials that have high specific heat capacity, such as hempcrete.
There seems to be some variation in definitions of properties such as airtightness, damp openness and damp conductivity. It is thus necessary to implement clear definitions, alongside uniform testing procedures.
In the cradle-to-factory phase, the sustainability of biobased building materials has been decisively proven. This is mainly due to carbon sequestration. However, for the cradle-to-end-of-life phase, the sustainability of natural building materials is less evident. Therefore, clear and uniform definitions on Life Cycle Assessments for natural building materials are required.
For many of the new building materials wholly or partly composed of natural materials, the life expectancy is not sufficiently known. Monitoring of this aspect in existing constructions is required to fill this knowledge gap.
A construction usually consists of a few wall layers which form an assembly to control rain, air, vapour and temperature. Such an assembly can easily rescind the effects of damp-open natural building materials when layers with low damp conductivity are included. An information source on the performance of compound constructions is advised.

Market recommendations
A number of natural building materials are missing in the Dutch National Environmental Database for construction materials composed by the Dutch SBK Foundation. As this database is a frequently used source for certificates, subsidy schemes and energy labels, inclusion of these materials in the database would be helpful in accessing markets. This requires collaboration within the value chain.
The large group of contractors and constructors are not familiar with natural or biobased building materials, their properties and how to handle them. Rectifying this requires an extensive information campaign, as well as embedding of these materials in education.
Consumers should be well informed about the availability and special properties of biobased building materials.
The biobased building material sector is made up of many small-scale businesses. They are in need of support to comply with tender rules and the associated administrative burden. Moreover, producers of these materials should be assisted with the high cost of certification procedures.
Market access by biobased building materials could be supported by giving these materials a better position in subsidy schemes on energy saving in the building environment, based on their improved sustainability.
On average, the purchase prices of biobased building materials are higher than those of their mineral or fossil-based counterparts, at least as long as volumes are relatively low. To overcome this, a value chain that supports these higher prices could be developed.

Many of the recommendations mentioned in this report require a collaborative approach within the value chain. There are already many partnerships operational that could possibly absorb and implement these recommendations.

1 Introduction

This report was produced within the framework of the North West Europe Interreg project Grow2Build. The aim of this project is to support the value chain of biobased building materials by collecting and supplying information and setting up pilot studies that promote the added value of these materials. These added values are specified and substantiated in this report, which also attempts to identify future areas for research and demonstration.

The most prominent biobased[1] material is wood, while the market for products based on other biobased materials (like hemp, flax, straw etc.) is still limited. This report focuses on the latter category.

Different advantages are associated with biobased materials:

- A positive effect on human health related to improvement of indoor air quality threatened by pollutants and contaminants.
- A positive effect on living comfort. Two aspects are said to be involved:
    - o The high moisture absorption capacity of biobased building materials can stabilise relative humidity indoors.
    - o The use of biobased materials in walls and ceilings can provide sound insulation and thus decrease noise nuisance, while improving acoustics.
- A positive effect on energy use. This would be associated with:
    - o The insulation value of biobased materials.
    - o Improved heat absorption capacity and thereby increased heat buffering, resulting in a decrease in energy use.
- A positive effect on the ecological sustainability of constructions related to carbon sequestration and less energy use during the production process.

This report aims at providing evidence for such claims and, where necessary, indicating knowledge gaps regarding these claims. The claims apply not only for new constructions but also for existing buildings where indoor air quality needs improvement, for example related to continuous moisture problems. This report addresses the claims relating to both types of buildings and seeks to provide scientific data and evidence to support the claims. Where applicable, the report identifies relevant areas for further research. It also addresses factors in innovation failure, examines existing implementation processes and applies these to the biobased building sector. Finally, an integrated approach for demonstrating the value of these products in construction is presented .

[1]The literature gives a number of definitions for biobased materials. The following definition, used by the Sustainable Biomaterials Collaborative, is rather comprehensive: “biobased materials are all materials made from living or recently living organisms (contrary to non-renewable fossil raw materials), including arable crops and harvest waste streams, trees and algae.”

2 Indoor air health risks

People are indoors for around 90% of their life, of which 70% is spent in their own home (RIVM, 2003)[2]. Thus, the indoor climate has a large impact on human well-being and health. Indoor air quality has been related to health issues in many studies, a review of which is presented by e.g. Berglund et al. (1991). The issues include respiratory health effects, influence on reproductive organs, effects on the immune system, effects on skin and mucous membranes in the eye, nose and throat, sensory effects, effects on the cardiovascular system and effects on the kidneys, liver and gastro-intestinal system. A review paper by Jones (1999) summed up the pollutants and contaminants associated with these issues, which include asbestos, carbon monoxide, formaldehyde, nitrogen dioxide, radon, respirable particles, tobacco smoke, volatile organic compounds (VOCs), allergens and microbes. The health situation associated with indoor air quality goes beyond the use of building materials only. Some polluting or toxic compounds in spaces enter from the outside air and accumulate indoors. Other sources of emissions relate to activities that are not linked with the use of building materials.

Textbox 1
Indoor environmental threats are critical for public health. Individually, these pollutants are known to pose a serious health threat. However, exposure is frequently to multiple pollutants. Current research has begun to look at the chemical reactions between pollutants and toxins, in order to determine their true comprehensive health impacts. Significant debate continues over the health impacts of different levels and lengths of exposure. There are three primary modes of exposure to indoor pollutants and toxins: breathing the air (inhalation) and physical contact either through ingestion or dermal absorption. While most exposures are low level, over time they may have significant health impacts due to bioaccumulation, build-up of the pollutant or toxin within an organism, and biomagnification, the increased concentrations of a pollutant or toxin along the food chain. *Source: http://www.sustainablejersey.com/fileadmin/media/Events_and_Trainings/Add_Event/2013/Sustainability_Summit/Sustainability_Briefs/Indoor_Health_FINAL_9_10_13_.pdf*

Insulation measures have caused the relative air humidity in many houses to be high, thus giving rise to growth of moulds. Allergens associated with growth of moulds and fungi can cause asthma problems (Van Ginkel et al., 2012). In many countries, including the USA,[3] indoor air quality is identified as being critical for human health (see Textbox 1). Improved insulation results in decreased energy use by consumers, which on its own can be judged as being a beneficial effect. The question remains as to whether this introduces unwanted side-effects. Well-functioning insulation may decrease ventilation and outdoor air exchange, and thus increase the level of allergens and other adverse and harmful compounds. The challenge is how to decrease energy use while at the same time improving indoor air quality. The question is to what extent biobased building materials can be of added value in this challenge.

Textbox 2
Balanced ventilation is a modern way of ventilating where fresh air enters the home and stale air is removed. A system unit balances the inlet air flow with the outlet flow. A heat exchanger is used to cool down the outlet flow and heat the inlet flow. *Source: http://www.groenegrondstoffen.nl/downloads/Boekjes/15Catalogusiobasedbouwmaterialen.pdf*

2.1 Humidity and mould problems

Thick insulation and insufficient ventilation can cause the relative air humidity in inhabited constructions to rise to high levels. A report by Van Ginkel et al. (2012) concluded that in the Netherlands, 9% of houses (0.5 million houses) have problems with moisture and moulds. According to Grün & Urlaub (2014), around 80

[2] http://www.rivm.nl/Documenten_en_publicaties/Wetenschappelijk/Rapporten/2003/juli/Ionising_radiation_exposure_in_the_Netherlands

[3] http://www.sustainablejersey.com/fileadmin/media/Events_and_Trainings/Add_Event/2013/Sustainability_Summit/Sustainability_Briefs/Indoor_Health_FINAL_9_10_13_.pdf

million people in the EU-28 live in dwellings with a leaking roof, damp walls, floors or foundations, or rot in window frames or floors.

The World Health Organisation (WHO) has issued guidelines on indoor air quality[4] where indoor air moisture and mould problems imply health risks (WHO, 2010). These guidelines are based on a comprehensive review of the scientific literature. The report concluded that the present day indoor air quality affects people with and without known allergies. Fisk et al. (2007) reported that the risk of respiratory complaints increases by 1.5 fold on staying indoors for prolonged periods. Van Dam & Van den Oever (2012) claim that the increasing demand for energy saving performance in houses (and associated levels of insulation), as well as the installation of mechanical ventilation and balanced ventilation systems (see Textbox 2), have resulted in a risk of accumulation of indoor air contaminants, microorganisms (bacteria, fungi, moulds) and moisture. Balanced ventilation systems can also create noise nuisance and occasionally suffer from capacity control problems. Finally, many homes where balanced ventilation systems are installed do not always meet all building requirements and this could give rise to health complaints, as demonstrated in a documentary by Zembla (2011)[5]. The Dutch Association for private house owners also reports doubts and worries about this technology[6]. Van Dam & van den Oever (2012) devised a solution to overcome the problems based on an adapted version of the technology where the heat of the outlet air only is used to heat the inlet air flow.

Textbox 3
According to the RIVM website, MDI enters the human body by skin contact or inhalation. It sensitises the respiratory system and skin. Health effects occur within minutes of exposure to MDI and include nose complaints (swollen mucous membrane, sneezing, runny nose), difficulty breathing, red eyes (conjunctivitis) and skin (heat, itch, eczema) and inflammation of the respiratory system). *Source*: *http://www.rivm.nl/Onderwerpen/B/Binnenmilieu/PUR_schuim.*

2.2 Release of volatiles and irritation caused by insulation materials

Polyurethane (PUR)
Frequently used insulation materials such as polyurethane, rock wool, glass wool and several construction adhesives and glues can emit volatile compounds that are a health threat to humans. In an open letter to the Dutch Minister of Housing, Dutch health professionals explicitly addressed the health concerns associated with the use of polyurethane (see Textbox 3). This open letter is supported by an extensive literature list.

The effects of polyurethane and emitted compounds such as isocyanates on the health of workers applying or removing the material, but also for inhabitants, are described by Verschoor & Verschoor (2013). These authors call for a ban on polyurethane in houses. On its website[7], the Dutch National Institute for Public Health and the Environment (RIVM) also issues a warning on the health risks involved in applying polyurethane (Textbox 4). In particular, the risks associated with methylene diphenyl diisocyanate (MDI) are pointed out. The Institute also points out that the level of exposure at which people can develop hypersensitivity to MDI is still unknown and may differ between individuals. Furthermore, the RIVM lists other compounds present in polyurethane foam, such as polyols, catalysts, blowing agents, stabilisers and flame retardants. Together, these are responsible for strong smells and can cause health complaints, according to the RIVM.

[4] http://www.euro.who.int/__data/assets/pdf_file/0009/128169/e94535.pdf
[5] https://effepuffe.wordpress.com/ventilatie-vocht-schimmels/
[6] http://www.woonhelpdesk.nl/index.php?wonen=6&artikel=285&onderwerp=Eigen%20Huis
[7] http://www.rivm.nl/Onderwerpen/B/Binnenmilieu/PUR_schuim

Textbox 4
Health professionals have written an open letter to the Dutch government on health aspects associated with polyurethane foam. When applying this material to insulate homes, a mixture of isocyanates (quite often methylene diphenyl diisocyanate, MDI), polyols and neurotoxic compounds is used. The recommended exposure limit of MDI is 0.05 mg/m^3 (*National Institute for Occupational Safety and Health, (NIOSH) USA*). This limit value is already reached in indoor spaces of 105 m^3 when using 5 kg of DMI, yet for insulation of such an indoor space many more kg of MDI are applied. Inhabitants present at the time of application are often unaware of the harmful effects on the respiratory system, eyes, skin and intestine. Sensitivity reactions are caused by skin contact and repeated contacts can lead to more heavy reactions at even lower amounts. The health professionals also addressed problems caused by glass and rock wool. Upon inhalation, these fibres can irreversibly accumulate in the human body, specifically in the lungs, where they can give rise to respiratory problems. The result can be chronic lung diseases like asthma and lung fibrosis. The latter disease can even lead to severe disability for which no effective medical treatment exists at present. Skin irritation can result from living in spaces where these fibres are present in the air or from working with these materials without using protection. *Source*: *http://demonitor.ncrv.nl/data/files/uploads/brief%20Woonakkoord%202013%20Minister%20Blok.pdf*

Rock wool and glass wool
In the aforementioned open letter by Dutch health professionals (see Textbox 4), the unwanted side-effects of insulation materials such as rock wool and glass wool are mentioned.

2.3 Volatile organic compounds

The term volatile organic compounds (VOCs) refers to a diverse group of organic molecules that occur in paints, coatings and resins. The compound MDI also belongs to this group of contaminants. Sources emitting these VOCs are present not only within houses and buildings, but also outdoors (for example busy motorways), from where the VOCs enter buildings to accumulate. Since people spend a large part of their lives indoors, VOCs can contribute to so-called sick building syndrome (Wang et al., 2007). The standard advice for preventing VOCs from accumulating to unacceptable levels is to use ventilation. The use of insulation materials of natural origin could also assist in creating a more healthy indoor environment.

To conclude: The use of building and insulation materials is associated with VOC release and also with humidity problems occurring indoors. Insulation materials in particular are associated with VOCs, while also contributing to humidity accumulation indoors in present day buildings. However, it is important to note that VOCs in indoor air are emitted from a wide variety of indoor and outdoor sources.

3 Insulation and indoor climate

This chapter provides an overview of the claimed beneficial characteristics of insulation building materials of natural origins as regards the indoor climate. It then aims to underpin these characteristics with empirical evidence by referring to research and monitoring studies.

3.1 Overview of characteristics

The website of the magazine *Gezond Bouwen & Wonen*[8] (*Healthy Building and Living*) provides information on insulation and environmental impact. The magazine focuses on the sustainable construction industry and offers applied knowledge to professionals and entrepreneurs. Its website also provides an overview of the characteristics of materials of mineral and fossil origin and of natural origin (Table 1). Qualitative and semi-quantitative indications of the functionalities of the materials listed are also included. One of these functionalities is the ability to contribute to so-called vapour diffusion or vapour-open construction. The background to this construction concept is presented in section 4.3.3.

Table 1 also provides information on the contribution of the materials to the so-called Trias Ecologica[9], a footprint reduction strategy. This strategy comprises three distinct steps: (1) Prevent unnecessary use, (2) use sustainable, renewable materials and (3) use non-renewable materials efficiently and without further pollution.

According to Table 1, materials such as cellulose, glass wool, hemp, shells, cork, cotton, sheep's wool, flax wool, wood fibres and softboard are suitable for vapour-open constructions. Materials such as hemp, cork, sheep wool, shells, flax wool, wood fibres and soft board are indicated in Table 1 as having a positive effect on health (indoor air quality) and moisture regulation (and thereby on a comfortable indoor climate). Of these materials, hemp, cork, sheep's wool and flax wool are characterised as being environmental friendly.

Textbox 5
Flax wool has the ability to buffer both heat and moisture, resulting in regulatory functionality for indoor spaces. In winter this material can release accumulated heat, while in summer it can help cool indoor spaces. It is also known for its good sound absorption properties. Flax wool is treated with a flame retardant for fireproofing purposes. It is also treated to prevent mould. The material is flexible, so can easily be used in construction. During processing, it causes less irritation than mineral wool. *Source: https://www.eigenhuis.nl/downloads/inhoud/Eigenschappenvanisolatiematerialen.pdf*

To conclude: According to Table 1, biobased building materials such as hemp, cork, sheep's wool and flax wool show the best combined properties regarding insulation, health and moisture control of indoor climates and environmental impact. These properties of flax wool and sheep's wool are also pointed out by the independent society of house owners in the Netherlands (*Vereniging Eigen Huis* - VEH) on its website[10] (see Textbox 5 and 6 on flax wool and sheep's wool, respectively).

8 http://www.vwg.net/gbw/bouwdata/isolatie.html
9 http://www.bouwlogie.nl/trias-ecologica/
10 https://www.eigenhuis.nl/downloads/inhoud/Eigenschappenvanisolatiematerialen.pdf

Table 1. **Overview of beneficial construction properties of building materials**[11]

Material	H*	R*	M*	C*	Health	Environment [1]	Vapour-open	Moisture regulating	Trias Ecologica		
Cellulose	x	x			0	1	+		x	x	x
Foam glass		x	x		0	3	-	-	x		x
Glass wool		x	x		-	1	+	-	x		x
Hemp	x				+	+	+	+		x	x
Wood fibre	x	x			+	2	+	+	x	x	x
Cotton	x				0	4	+	+		x	x
Coconut	x				0	3	+	+		x	x
Cork	x				+	1	+	+		x	x
Perlite			x		0	0	+/-	-			x
Polyester Aluminium				x	0	+	-	-	x		x
Polystyrene				x	0	2	-	-			x
Polyurethane				x	-	3	-	-			x
Sheep's wool	x				+	1	+	+		x	x
Shells	x				+	-	+	+		x	x
Rock wool (wall)			x		-	2	+	-			x
Rock wool (floor)					0	4	+	-			x
Flax wool	x				+	+	+	+		x	x
Soft board	x	x			+	0	+	+	x	x	x

** H: renewable resource, R: residue, M: mineral, C: chemically manufactured [1], rated according to environmental classification NIBE (www.nibe.info); the higher the number, the greater the environmental impact: 1 = best, 2 = good, 3 = acceptable, 4 = less good, 5 = not recommended, 6 = poor, 7 = unacceptable.*

Additional quantitative information on a number of insulation materials is provided by Van Dam & Van den Oever (2012) in their "*Catalogue of Biobased Building Materials*" (Table 2). Dorsch et al. (2014) also provide data on the functionalities of insulation materials (Table 3), as does the German NGO BUND in their 2013 annual "*Ökologisch Bauen & Renovieren*"[12] (*Ecobuilding and renovating*) (Table 4). Tables 2-4 provide data on natural insulation materials and on their mineral benchmarks. i.e. rock wool, glass wool, polyurethane and polystyrene.

Textbox 6
Sheep's wool has a similar insulation value to mineral wool and the ability to buffer both heat and moisture. Like flax wool, it also provides good sound insulation. Sheep's wool is a vapour-open material, allowing vapour through easily. In some buildings this property is beneficial to the indoor climate (low relative humidity). Sheep's wool insulation is treated to repress moulds and insects. It is a renewable raw material, a by-product of meat production. *Source: https://www.eigenhuis.nl/downloads/inhoud/Eigenschappenvanisolatiematerialen.pdf*

Van Dam & Van den Oever (2012) point out that the technical performance of several renewable insulation materials, such as cellulose and fibres from hemp, flax, kenaf and cotton, is comparable to that of the mineral benchmarks. According to those authors, renewable insulation materials could therefore easily replace traditional materials without loss of performance. This is underpinned by their thermal conductivity (usually denoted λ and expressed as W per m per degree Kelvin (W/m·K): see Table 5), which often lies at or below 0.045, the value associated with good thermal insulation performance.
Suppliers of natural insulation materials report a positive moisture regulating influence of these material to indoor climate conditions. The water vapour diffusion resistance factor (μ) expresses this property. The μ values for natural insulation materials are comparable to those of their rock wool and glass wool benchmarks, but are much lower than those of polyurethane, polystyrene and poly-isocyanurate. The actual performance of

[11]http://www.vwg.net/gbw/bouwdata/isolatie.html
[12]http://www.bauinfo24.de/thema~folder~1~letter~~branche~150~news~15642~print~on.asp

all insulation materials, regardless of their origin, depends strongly on the building in which they are applied (Van Dam & Van den Oever, 2012). Other technical performance indicators of insulation materials are the density (ρ; kg/m^3), the specific heat capacity (c; expressed as J/kg·K) and the fire classification. These aspects are discussed later in this report.

Table 2. **Technical characteristics of insulation materials based on natural fibres compared with standard insulation**

Insulation material	Lambda, λ W / m·K	Thickness (needed for R = 2.5)	Density kg / m^3	Vapour diffusion resistance factor μ	Energy content (R=2.5) MJ / m^2
Straw	0.12	30			
Reed	0.06	15			
Coconut	0.045	11			
Flax	0.040-0.055	014	50		
Cotton	0.040				
Sheep's wool	0.040	10			
Cork	0.045	11	250		
Wood wool	0.050	13			
Wood fibre	0.100	25			
Cellulose	0.040	10	30-70	1.5	3
PUR / PIR 244	0.025-0.027		50	23-185	
PS (Styrofoam)	0.035-0.038		15	23-150	158
Glass wool	0.038		35	1-2	53
Clay pellets	0.11				

Source: Van Dam et al., 2012.

Table 3. **Insulation at a glance**

Insulation material	λ (W/(m·K)	ρ (kg/m^3)	μ	c (J/kg·K)	Fire class (DIN 4102)
Flax mats	0.036–0.040	30–60	1–2	1.600	B2
Hemp mats	0.040–0.050	30–42	1–2	1.600–1.700	B2
Hemp (loose)	0.048	40–80	1–2	1.600–2.200	B2
Wood shavings	0.045	75	1–2	2.100	B2
Wood fibre insulation board	0.040–0.052	140–180	2–5	2.100	B2
Wood fibre insulation board (flexible)	0.040–0.052	40–55	2–5	2.100	B2
Wood fibre (loose)	0.040	30–40	1–2	2.100	B2
Wood wool boards[1]	0.090	330–500	2–5	2.100	B1
Cork scrap	0.050	160	1–5	1.800	B2
Cork board	0.040	100–220	5–15	1.800	B2
Sheep's wool	0.0326–0.040	30–90	1–5	1.720	B2
Reed (rush)	0.055	190	6.5	*	B2
Straw bale construction	0.052–0.080	90–110	2	2.000	B2
Meadow grass	0.040	25–65	1–2	2.200	B2
Cellulose flakes	0.040	30–55	1–2	2.100	B2
Cellulose sheets	0.040	70	2–3	2.000	B2
Seagrass	0.037–0.0428	70–130	1–2	*	B2
Conventional insulation materials for comparison:					
Polystyrol PS (Styrofoam)	0.035–0.040	11–30	30–100	1.400	B1
Rock wool	0.033–0.040	33–130	1	840–1.000	A1

[1] Only used as plaster base.
Source: Fachagentur Nachwachsende Rohstoffe (FNR), composition based on estimates from suppliers.

Table 4. **Performance indicators of different insulation materials, including primary energy consumption and energy payback time.**

Building material	λ_R	ρ	μ	c	Fire classification	Primary Energy consumption	Energy payback time	Cost U-value of 0.3
	W/m·K	kg/m^3		J/kg·K		kWh/m^3	Months	Euro/m^3
Cellulose plates	0.040	70-100	2-3	2000	B2	400	5	21
Cellulose flakes	0.039-0.045	35-60	1-1.5	2200	B2	85	3-4	8-10
Recycled cotton[1]	0.037	27	1-2	~ 1700	B2	72	2-3	13
Drywall	0.045-0.065	100-150	3	1000	A1,A2	3600	n\a[5]	90
Grass	0.042	53-68	1-2	2200	B2	low	2-3	6-8
Hemp	0.040-0.048	24-60	1-2	1800	B2	40-80	3-4	14-19
Wood fibre boards	0.039-0.052	40-60	1-2	2100	B2	620	6-8	15-21
Wood fibre board fixed[2]	0.040-0.055	160-250	5-10	2100	B2	600-900	10-16	27-33
Wood fibre, separate	0.040-0.055	70-140	5-6	2100	B2	92	3-5	11-15
Wood wool, LBP[3]	0.075-0.150	400-500	5-6	2000	B1,B2	200-300	18-24	(38-49)[3]
Clay pellets	0,100-0,160	300-800	2-8	800	A1	290-420	12-48	36-76
Coir [4]	0.045	80-120	1	1300	B2	1050	n\a	(26-30)[4]
Cork plate	0.040-0.045	70-140	2-10	1800	B2	50-250	12-16	30-36
Mineral foam sheets	0.045	115	5	1000	A1	250	n\a	20-28
Reed[1]	0.038-0.055	190-225	2	1300	B2	low	6-10	18-22
Sheep's wool	0.035-0.040	18-30	1-2	1700	B2	70-95	3-4	14-18
Foam, glass	0.040-0.090	105-165	closed	830	A1	500-1600	15-25	38-57
Straw bales	0.052-0.080	~400	2	2000	B2	low	2-3	5
Flax	0.038-0.050	15-60	1-2	1600	B2	50-80	3-4	17-19
EPS	0.032-0.040	15-30	20-100	~ 1200	B1,B2	800-900	3-6	7-11
Glass wool	0.032-0.040	20-140	1	840	A1-B1	250-700	4-8	7-21
PUR/PIR	0.020-0.040	15-80	30-200	~ 1400	B1,B2	800-1400	6-10	14-18
Rock wool	0.032-0.050	25-400	1-2	840	A1-B1	160-800	4-10	7-23
XPS	0.030-0.040	20-60	80-300	~ 1200	B1,B2	810-1100	4-8	20-25

[1]So far no general construction approval in Germany. [2]Mainly used as roof insulation. [3]Primarily used as plaster support. [4]Mainly used for soundproofing. [5]n/a= not applicable.
Source: BUND-Jahrbuch 2013[13]

[13]http://www.bauinfo24.de/thema~folder~1~letter~~branche~150~news~15642~print~on.asp

Table 5. **Symbols, explanations and units used to indicate the performance of insulation materials**

Symbol	Explanation	Units
U - Overall heat transfer coefficient	Rate of transfer of heat through 1 m^2 of a structure divided by the difference in temperature across the structure.	$W/m^2 \cdot K$
µ - Vapour diffusion resistance factor	Ratio of the water vapour diffusion coefficient (δ) of the air to the δ value of the building material in question	-
λ - Thermal conductivity	Indicates the transport of energy through a body of mass as the result of a temperature gradient	W/m·K
c - Specific heat capacity	The heat energy needed to raise the temperature of 1 kg of material by 1 K.	J/kg·K
ρ - Density	Mass per unit volume	kg/m^3
R - Thermal resistance	The ratio of the temperature difference across an insulator and the heat flux through it.	m·K/W
δ - Water vapour diffusion coefficient	The amount of water vapour [kg] which diffuses through a layer of material 1 m thick and with an area of 1 m^2 at a partial water vapour pressure difference of 1 Pa in 1 hour.	kg/m·h·Pa
Fire classification	European fire class system according to DIN4102	-
Primary energy consumption	Energy required to produce a standard volume of a material	kWh/m^3
Energy payback time	Period required to compensate for energy use to produce the material by savings during its use	Months

The next paragraphs address the most important performance indicators in more detail.

3.2 Insulation and heat buffering

Tables 2-4 give different values for the thermal conductivity of a particular material, but these are of the same order of magnitude. Based on these indicators, the insulation performance of natural insulation materials can compete with that of materials of mineral or fossil origin, such as rock wool, glass wool and polystyrene. Using these values, Van Dam & van den Oever (2012) concluded that natural insulation materials could well replace those of mineral or fossil origin. Another important performance indicator for insulation materials is the specific heat capacity (Table 5). This parameter indicates the amount of heat that a certain material can accumulate. A higher number indicates a higher heat storage capacity and a corresponding capacity to release heat to a cooler environment. This property can be beneficial in buffering indoor temperature. As Tables 3 and 4 show, natural insulation materials can be superior to traditional fossil or mineral-based materials when it comes to heat buffering. The heat buffering capacity of hempcrete has been demonstrated by Shea et al. (2012), who over 11 days in May measured indoor and outdoor temperatures of a hempcrete building in the UK and calculated the indoor buffering capacity of this material. With outdoor temperatures fluctuating between 10 and 20 °C, the indoor temperature varied only from 1 to 3 °C. This represented buffering of 86% of the outdoor temperature fluctuation. This effect can be of value in summer to reduce the need for cooling.

Of course, the question remains as to whether these material properties will be expressed sufficiently in actual buildings. The research reported by Shea et al. (2012) is promising, but the data only represent a limited period of 11 days in an experimental building. Measurements throughout the year in an actual building fit for habitation are needed.

To conclude: The claims that natural insulation materials have good insulating properties are reliably substantiated and do not need further research. However, the actual performance in practice could be influenced by the construction and could require a different building concept. The specific heat capacity of natural buildings and insulation materials is higher than that of materials of fossil or mineral origin and this could be helpful in creating a more comfortable indoor climate and in saving energy.

3.3 Vapour control and indoor comfort

Suppliers claim that renewable insulation materials have vapour-regulating effects on the indoor climate and this claim is supported by the data in Tables 2-4. A low vapour diffusion resistant factor could allow better humidity control. In other words, high indoor relative humidity could be levelled out or decreased more quickly at a lower outdoor relative humidity level. The water is conducted outside, requiring less ventilation capacity. This leads to less energy loss during the ventilation process and at the same time buffers the relative humidity indoors. As indicated earlier, this potential effect needs to be proven in actual constructions.

3.3.1 Comfort and air humidity

Boerstra et al. (2008)[14] carried out a review of the indoor climate in offices and schools. They also considered the phenomenon of thermal comfort (see Textbox 7), which has an influence on human functioning and thus a significant impact. It goes without saying that the actual temperature is highly determining for this comfort indicator, but air humidity also contributes significantly. The French platform Constructions et Bioressources (C&B)[15] issued a technical document in February 2013 in which temperature and air humidity standards for indoor comfort are given. In general, that document also relates high indoor comfort to low relative air humidity. It shows different combinations of indoor air temperature and relative humidity that could result in a comfortable indoor climate. It should be noted that these standards may differ between countries (Table 6).

To conclude: Low relative humidity is usually associated with improved indoor climate comfort. Building materials that could help stabilise indoor relative air humidity could thus support a more agreeable indoor climate.

Textbox 7
Thermal comfort relates to the perceived temperature. This perception is not only influenced by the actual air temperature, but also by air speed, solar radiation, air humidity, the level of activity and the insulation properties of clothing. Thermal comfort also applies to outdoor temperature and expectations on the perceived ability to influence indoor climate play a role. In buildings without air conditioning and with windows that can be opened, people accept higher temperatures than in air-conditioned buildings. *Source: http://www.arbokennisnet.nl/images/dynamic/Dossiers/Klimaat_verlichting/D_Thermisch_binnenklimaat.pdf*

Table 6. **Temperature and humidity standards for indoor comfort**

Origin	Season	Temperature °C	Relative humidity (%)
CSA Z412-FOO	Winter	20-35	50
(Canada)	Summer	23-26	50
	Winter	20.5-25.5	30
55-2004 of ASRHAE	Winter	20-24	60
(USA)	Summer	24.5-28	30
	Summer	23-25.5	60
NF ISO 730	Winter	20-24	30-60
(Afnor NF 35 121)	Summer	23-26	30-60

Source: C&B

3.3.2 Vapour control and vapour buffering

Based on their ability to conduct water vapour and regulate relative humidity indoors, insulation materials of natural origin are often associated with vapour-open constructions. The vapour regulating potential of natural fibres has been studied by Kymäläinen (2004), Kymäläinen & Sjöberg (2008), Zach et al. (2011) and Freivalde & Kukle (2011). Woloszyn et al. (2009) report that the use of vapour buffering materials is an efficient way of reducing the daily amplitude in relative humidity. In their study, vapour-conducting and vapour-accumulating

[14] http://www.arbokennisnet.nl/images/dynamic/Dossiers/Klimaat_verlichting/D_Thermisch_binnenklimaat.pdf
[15] http://www.constructions-bioressources.org/wp-content/uploads/2013/05/Download-English-Version.pdf

materials created a stable level of relative humidity between 43 and 59%. Even in combination with a relative humidity sensitive ventilation system, an added value of moisture buffering materials was found. According to the German Fachagentur Nachwachsende Rohstoffe (FNR)[16], insulation materials of natural origin can accumulate moisture to up to 30% of their weight and then release it again. Insulation materials of fossil or mineral origin only show a fraction of this moisture accumulating ability. Bruijn et al. (2013) describe the building material hempcrete as having good heat insulating properties with significant moisture buffering potential and a unique porosity based on macro-, meso- and micro-pores. They point out that at high relative humidity values, hempcrete can show a strong increase in moisture uptake, based on its ability to expand its moisture accumulating potential at high levels of humidity. Holcroft & Shea (2013) and Barclay, Holcroft & Shea (2014) compared the moisture accumulating potential of three building materials of natural origin (hempcrete, hemp fibre and sheep's wool) with that of glass wool, either in combination with or without plaster. The materials were exposed to increasing and decreasing relative humidity over periods of 12 hours. The relative humidity varied between 53 and 75%. Hempcrete appeared to show the largest moisture buffering capacity, twice as large as that of hemp fibre and sheep's wool. However, the use of plaster significantly reduced the moisture accumulating potential, by 50-60% (Figure 1). Based on this result, the authors emphasised the importance of using plaster with good moisture accumulating and/or conducting potential (Holcroft & Shea, 2013).

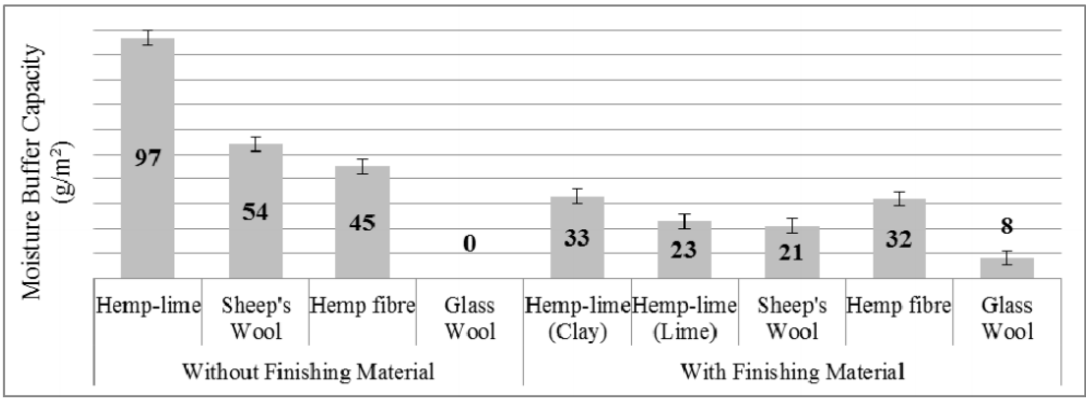

Figure 1. **Moisture absorption capacity of natural insulation materials, with and without finishing material (plaster), compared with that of glass wool (Holcroft & Shea, 2013).**

The moisture buffering properties of hempcrete were also demonstrated in the study by Shea et al. (2012) based on measurements in an experimental hempcrete building. These showed that the relative humidity indoors scarcely varied (around 55%), while outdoor values oscillated between 30 and 90%.

Research by Brandhorst et al. (2012) showed that the flax-based insulation material Isovlas can handle high moisture exposure without influencing the insulation value of the product. Relative to traditional insulation materials, the flax-based material showed good moisture buffering and regulating properties. Those authors mention positive practical experiences with vapour-open construction when using moisture buffering insulation materials.

In their market review on insulation materials, Dorsch et al. (2014) point out the moisture buffering capacity of hemp and flax. Based on its moisture conducting ability, hemp has good moisture buffering capacity and contributes to a comfortable indoor climate, good insulation performance and an insulating effect under summer heat conditions (Dasch et al., 2014). Those authors also point out that based on its low protein content, hemp would not need protective treatment against insects. Besides the fact that flax has moisture regulating properties, contributes to vapour-open constructions and has good insulation potential, the product is also regarded as being environmentally friendly and having good resistance against decay by insects and

[16]http://baustoffe.fnr.de/daemmstoffe/bauphysik/behaglichkeit/

moulds (Dorsch et al., 2014). Insulation materials based on sheep's wool, cellulose and wood fibres appear to have good moisture accumulating and regulating properties. Cork and reed can conduct moisture, but have low moisture accumulating potential. Finally, according to Dasch et al. (2014), straw bales have good insulating properties but at humidity contents of 15% or higher, decay will occur.

Research carried out in Nancy, France, under winter conditions showed that the use of hempcrete resulted in an energy saving of 12% compared with a classical ventilation system (Tran Le et al., 2010). Those authors attributed this to its moisture regulating and buffering properties. They developed a simulation model with good predictive value for indoor air moisture conditions and showed the added value of the moisture regulating property of hempcrete. Rahim et al. (2015) published research results on two building materials of natural origin (hempcrete and flax-based limecrete) and their behaviour under stable and fluctuating moisture conditions. Those results demonstrate the moisture regulating properties of these materials.

Given the ability of natural building materials like hempcrete to accumulate and conduct moisture to the extent that indoor relative air humidity is stabilised, these materials could also have potential in storage rooms for agricultural and horticultural products such as onions and potatoes. These products must be stored at constant, moderate relative humidity and the use of materials such as hempcrete could lower the energy cost of storage.

To conclude: Scientific research has shown that most natural insulation materials can accumulate and conduct moisture, resulting in a regulating effect. These materials can thereby contribute to improving indoor climate comfort. They also appear to have good potential for vapour-open constructions, but this needs to be confirmed in commercial constructions and under local conditions. Furthermore, the potential of hempcrete in agricultural storage facilities (potatoes and onions) should be tested.

Textbox 8
Damp-proof: In conventional construction, the inner insulation layer is almost always a damp-proof sheet that prevents moisture condensing between layers. This results in accumulation of moisture within buildings and thus leads to a less healthy indoor climate. Moreover, completely damp-proof construction is not possible, as small openings occur around cables, nails etc., allowing moisture to enter the insulation layers. In damp-proof systems this moisture is trapped, causing mould growth.
Vapour-open: The use of vapour-open insulation materials and no damp-proof layer will result in sufficient moisture being conducted to the outside air, so the building is able to breathe. This suggests that the vapour-open construction works as a ventilation system, but this is incorrect. The amount of vapour actually passing through the construction is 50-100 times smaller than with normal ventilation. Vapour-open construction means that excess moisture indoors is drained through the construction and then released to the outside air. For this, it is important for the construction to be fully vapour-open. *Source: http://www.eco-logisch.nl/kennisbank-Damp-open-isoleren-139*

3.3.3 Moisture regulating properties in vapour-open construction

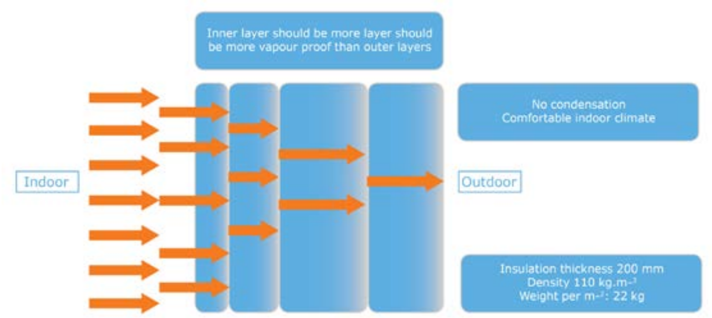

Figure 2. **Schematic representation of vapour-open insulation layers (Vandenbussche, 2011).**

Regulating indoor moisture conditions using insulation materials only can function if the accumulated moisture is also conducted outwards. This means that no damp-proof layer can be applied, as it would interrupt the flow of moisture and thus nullify the vapour-open potential of these materials. Figure 2 shows a schematic cross-section of layers in a vapour-open construction (Vandenbussche, 2011). The most vapour-open materials should be placed as the outer insulation layer. The inner side should be more damp-proof than the outer layers. The knowledge database for vapour-open constructions created by the company ECO-LOGISCH[17] provides comprehensive information on the concepts of vapour-open and damp-proof properties and on the application of these materials. The essential information is provided in Textbox 8.

Vandenbussche (2011) describes a vapour-open construction concept in which only the outer layer of the multi-layer insulation is of a vapour-open nature, while a damp-proof inner layer results in moisture being trapped between layers. This concept does not regulate relative humidity indoors and is not considered in this report.

Textbox 9
Vapour-open construction can be compared to breathing fabrics (like GoreTex). It keeps rain out but conducts transpiration vapour to the outside air. Vapour-open constructions do the same based on the right choice of layers and their order within the multi-layer system. In order to construct e.g. a vapour-open roof, it is first important to apply an outer layer that allows moisture to be released to the outdoor air. This layer must protect against rain while being vapour-open for the roof system moisture. Next, an insulation layer is required that is able to conduct moisture from the warmer and humid indoor environment to the outdoor air. This should be an insulation material based on natural fibres such as cotton. A multi-layer system should ideally be composed of vapour-open plasterboard or drywall, a vapour-control foil sheet or membrane, insulation material, vapour-open but water-resistant foil sheet and roof tiles. Moisture present in the inside air environment passes through the foil sheet, after which the insulation material fibres accumulate moisture and transport this to the outside air. This results in more constant internal relative air humidity. Furthermore, the natural fibres of the insulation material can store heat, resulting in a cooler indoor climate in summer. The peak temperature outdoors usually occurs at around 2 pm, but with a 20 cm thick insulation layer, the indoor temperature peak can shift to 8 pm, at which time the outdoor air has cooled down and ventilation and cooling can be achieved by opening windows. This also is a unique property of insulation material of natural origin. *Source: http://www.duurzaamthuis.nl/duurzaam-wonen/isolatiemateriaal*

3.3.4 Airtight and vapour-open

The website *Sustainable Home*[18], run by an architect's bureau, advises use of a combination of airtightness (preventing convection, but allowing diffusion of air) and vapour-open insulation using natural fibres (see Textbox 9). The airtightness is required to prevent heat loss (and thus save energy). The vapour openness allows transport of excess moisture, while the natural fibre insulation material has the functionality of heat absorption and storage (thus contributing to lower cooling cost). The most classic example of an airtight, but vapour-open layer is newspaper, but nowadays more advanced materials have been developed that are both airtight and vapour-open.

To conclude: According to the information available, a combination of natural fibre insulation materials and airtight, vapour-open foils or membranes placed in the right order within a multi-layer construction could save energy, prevent moisture problems and improve living or working comfort. Data confirming this in practical situations are not available.

Textbox 10
A quote from the forum discussion: "Is this risk (moisture accumulation) also applicable to rock wool and other insulation materials from non-renewable origin? Many natural raw materials, like hemp and flax have the property of buffering much moisture which makes a vapour proof layer redundant. These materials will cede this moisture again as soon as the indoor air is capable of containing more water vapour. At the same time the moisture transport to the outdoor air is an ongoing process"*Source: http://bouwprofsnederland.nl/forum/topics/is-luchtdicht-en-dampopen-bouwen-onmogelijk-in-nederland)*

3.3.5 Discussion on vapour-open construction and the need for research

There is still much discussion on the application of the vapour-open building concept.[19] This discussion seems to be supported by lack of clear definitions of airproof, vapour-open and vapour control functionalities of foils, membranes and other materials. In particular, the combination of airtight and vapour-open functionalities is debated as regards use in the cool, moist climates prevailing in North West Europe. Many participants in this

[17]http://www.eco-logisch.nl/kennisbank-Damp-open-isoleren-139
[18]http://www.duurzaamthuis.nl
[19]http://bouwprofsnederland.nl/forum/topics/is-luchtdicht-en-dampopen-bouwen-onmogelijk-in-nederland

discussion cite the risks of moisture accumulating and condensing within the building envelope insulation layers. This would lead to mould growth and associated problems. Others dismiss this problem, as the quote in Textbox 10 illustrates. Data from monitoring in practice would be helpful in resolving the discussion. The Dutch Maskerade pilot project could possibly help supply much information. It involves construction of two biobased apartment buildings in which two different biobased facade constructions are applied according to the vapour-open concept. The functionality of these facades will be monitored during use of the buildings and, from 2015 onwards, will result in much useful information on the properties of biobased insulation constructions. The results will also be used to validate a construction physics simulation model. The project is expected to result in much useful information to guide the discussion on vapour-open constructions.

To conclude: The functionalities of vapour-open building concepts is not in widespread use and commonly accepted. Additional practical research and demonstration projects are required to yield unassailable proof of the reported advantages of this building concept and the associated use of renewable materials.

3.4 Microbiological risks

In their report on industrial hemp, Snauwaert & Ghekiere (2011) address the possibility of microorganisms with potential allergenic properties being present in hemp fibres. Kymäläinen et al. (2008) concluded that flax and hemp are suitable for insulation applications, but that the risk of microbiological contamination should not be overlooked. Their advice was to monitor these fibre materials frequently for microbial populations. Furthermore, they concluded that the products need adequate treatment to prevent impacts on indoor air quality. Baudoin (2004) pointed out the possibility of disinfecting with peroxide to eliminate possible microbial contamination. The German Wikipedia site[20] reports that treatment of wood wool panels and wood sawdust with boron salts and soda can prevent contamination with vermin or mould growth and increase fire resistance. However, the Wikipedia entry makes an exception for Neptune grass, which does not need treatment as it has natural resistance to moulds, free from vermin and non-flammable (code B2). This is said to be associated with the high titre of silicic acid in this material. Research reported by Herrera (2005) shows that sodium polyborate prevents the growth of fungi present in cellulose and that the effect is prolonged because the borate can also eliminate fungal spores. According to the information brochure "*Duurzame Gebouwenschil*" ("*Sustainable Building Envelope")* issued by the East Flanders Development Agency (www.pomov.be), boron salt or ammonium phosphate are usually applied to insulation materials based on flax, cellulose or wood fibres to decrease inflammability and increase mould resistance. These additions would not be harmful to public health. The brochure also points out that hemp would have natural mould-preventing and anti-bacterial properties and thus would not need this treatment. The background to this effect is not mentioned. The Dutch National Institute for Public Health and the Environment[21] (RIVM) reports that proper use of borates (acids as well as sodium borate) to prevent mould growth in insulation materials of renewable origin will not endanger public health. It is important to mention that borates are not volatile and that skin exposure or inhalation is not likely to occur. The RIVM report also mentions that airborne bacterial populations are difficult to measure, which prevents the establishment of a reliable correlation between exposure to bacteria and health effects.

All building materials, including renewables, require certification according to standards, among which DIN IEC 68 and ISO 846 both refer to mould growth on materials. Certificates such as the NaturePlus label use these standards.

To conclude: There are microbial risks associated with materials of natural origin. Appropriate treatment can lower these risks substantially. Standards and certificates cover such risks.

[20]www.de.wikipedia.org/wiki/Naturd%C3%A4mmstoff
[21]https://www.athene-noctua.nl/wp1/wp-content/uploads/2013/05/HB_Binnenmilieu_2007.pdf

3.5 Volatile Organic Compounds (VOCs)

Volatile organic compounds (including semi-volatile organic compounds (SVOC) and very volatile compounds (VVOC)) are organic molecules that have high vapour pressure at room temperature and thus can evaporate or sublimate from liquid or solid form into the volatile phase. These molecules can negatively influence health. The question within the context of this report is to what extent building materials emit these compounds and thus contribute to public health issues. Jones (1999) provides an overview of VOC compounds that can contaminate indoor air quality.

VOC emissions can originate from building materials themselves but also, or particularly, from compounds added to the material to improve product properties: adhesives or solvents, paints, compounds to lower inflammability or to prevent growth of fungi etc. These additives can be an important source of VOCs. The scale of the emissions varies from one material to another and also depending the amount of the VOC-emitting chemical present in the product.

A study by Scherer (2011) on VOC emissions from insulation materials showed that insulation materials of natural origin, but with quality improving additives, were more variable in the production of VOCs than materials of mineral origin. This was attributed to the larger variation in origin of natural insulation materials (growth, harvesting and drying conditions). However, that study was based on uncovered materials and thus does not necessarily reflect practical situations. Nevertheless, the results showed that the VOC problem is also associated with biobased building materials. They also showed that hemp products with soda addition met standards for fungal presence and emissions, but not for odour (Scherer, 2011). Flax products with additives such as boron, phosphate and polyester (added for reinforcement) satisfied all three criteria: free from fungi, free from emissions and free from odours. Products based on wood fibres with additives such as phosphate and polyolefin (or polyalkene) fibres remained free from fungal growth and were low in emissions, but not free from odours. Cellulose panels and cellulose granules with polyolefin fibres, boron and boric acid satisfied all three criteria studied by Scherer (2011).

Since 2010, building products in Germany are tested and proofed on emissions according to the so-called AgBB[22] specification (German Task Force of Public Health Authorities), based on the EU Construction Products Regulation. The AgBB procedure is carried out by several government authorities and independent institutes. According to this testing procedure, building products need to satisfy strict emission levels for trade authorisation. The testing procedure can be used on VOC in critical construction materials including renewable insulation materials. The EU is working on harmonising the regulations on volatile compounds in construction materials, in which work the German AgBB procedure is playing a model role. Assays and regulations such as this are important in minimising the level of volatile compounds in indoor air to acceptable standards. However, in practice combinations of different construction materials can together raise emission levels to unacceptable levels in spite of the assay results on individual construction materials.

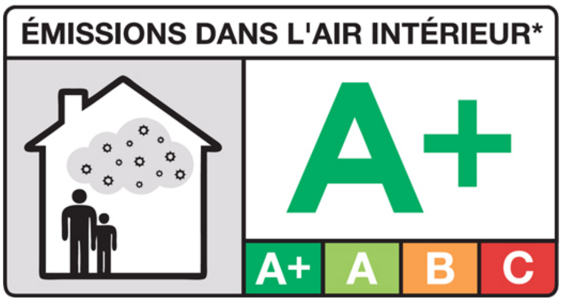

Figure 3. **Qualification designation for emissions of volatile organic compounds**. *Source: www.biofib-isolation.com/biofib-ouate.php*

In Germany, biobased insulation materials can be tested and proofed for fungal growth, emissions and odours amongst others by the Fraunhofer Institut für Bauphysik (IBP)[23]. The company Eurofins is also certified to carry out these tests. For example, the company has tested insulation materials from the French company Biofib, which produces hemp insulation materials and compound

[22]http://www.wecobis.de/service/lexikon/agbb-lex.html
[23]http:// http://www.fnr-server.de/cms35/fileadmin/allgemein/pdf/veranstaltungen/10symposium/vortrag/F_Mayerfuerslnet.pdf

materials based on hemp, flax and cellulose (Figure 3)[24].

According to research by Wang (2014)[25], insulation materials with sheep's wool or products from sheep's wool have an air purification effect in combination with hemp and flax. The keratin in sheep's wool has the unique property of absorbing and neutralising a large variety of VOCs (e.g. formaldehyde, nitrogen oxides and Radon), a property that the company Fermacell is using in advertising for its building board products.

To conclude: VOCs can originate from a number of sources, amongst which are building materials of mineral, fossil or natural origin. Testing procedures and standards are available to prove and certify the VOC properties of construction materials. The extent to which these procedures and standards certify good indoor air quality depends on other VOC sources present and on the combination of construction materials used and their combined effect on VOC levels.

3.6 Sound insulation and acoustics

Sound insulation and acoustics are two concepts that are closely connected. Acoustics is the interdisciplinary science that deals with the study of all mechanical waves in gases, liquids and solids including topics such as vibration, sound, ultrasound and infrasound. Thus, acoustics deals with phenomena such as diffraction, absorption and reflection of sounds. Sound insulation is the ability of building elements or structures to reduce sound transmission. A schematic diagram of sound reflection absorption and transmission through a wall is shown in Figure 4. This section of the report presents knowledge referring to the sound functionalities of construction and insulation materials.

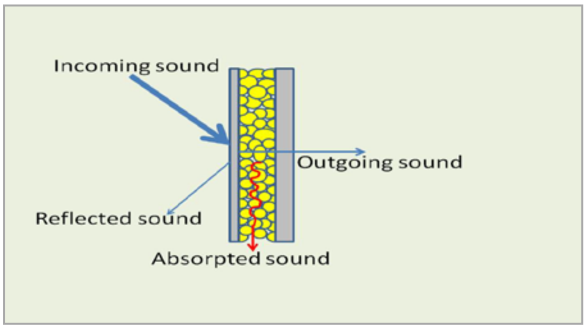

Figure 4. **Schematic sound insulation, reflection and absorbed sound**

3.6.1 Sound transmission

Sound transmission levels in public spaces are regulated depending on the moment of day or night and thus the demand for sound absorption and reflection properties of building elements and facades. The lower the reflection and sound absorption, the more sound is likely to be transmitted, causing noise pollution. The Brussels Environment Institute (BIM, www.leefmilieu.brussels) has issued an information brochure entitled "*Akoestische Isolatie: gezonde materialen met een gunstige milieubalans*"[26] ("*Acoustic insulation: Healthy materials with a beneficial environmental balance*"). This publication discriminates between different types of sound that could have different implications for constructions: airborne sound, contact sound and technical sound. Airborne sound is the sound directly associated with a sound source. Contact sound is sound that travels through constructions and within elements such as girders, pillars, walls and floors. Technical sound is vibrating sound caused by all kinds of instruments and machines that are transferred to building elements such as walls and floors. The BIM information brochure points out different performance indicators concerning sounds, such as the weighted sound reduction index, R_w, and the weighted standardised impact sound pressure level based on field measurements. $L'_{n,t,w}$. Both of these are related to sound attenuation. The BIM brochure also indicates the absorbent or attenuation coefficient α_w as being an important performance indicator. This coefficient represents the ability of a material to convert sound energy into heat (next paragraph). In addition, the brochure provides an overview of the performance of different materials regarding R_w. This indicator represents the difference between the measured sound level on both sides of a material. This value is determined on laboratory scale and is expressed in decibels (dB). The higher its value, the lower the sound

[24]http://www.biofib-isolation.com/biofib-ouate.php?L=EN
[25]http://repositories.lib.utexas.edu/bitstream/handle/2152/25838/WANG-THESIS-2014.pdf?sequence=1
[26]http://app.leefmilieubrussel.be/handleiding_duurzaam_gebouw/(S(lfknwla5raq0y44550wpf2zg))/docs_NL/MAT11_NL.pdf

transmission of the material. The R_w index is indicated by producers of the materials. The ultimate effect that a material has in practice depends also on the construction in which the material is applied. The indicator $L'_{n,t,w}$ represents the sound level caused in a receiving room by a standardised sound source produced in an adjacent room separated by a material construction. Materials are often labelled with an index that represents an improvement to the value of this parameter, called ΔL_w.

Asdrubali et al. (2012) conducted a review on the acoustic properties of natural insulation materials. Their main conclusion was that biobased insulation materials such as flax and cellulose have good sound insulating properties and that other materials have good sound absorption properties. However, their review of the acoustic properties of insulation materials of both natural and fossil or mineral origin revealed some lack of knowledge. This indicates a need for more research in which a wide spectrum of insulation materials is involved.

Oldham et al. (2011) studied the sound absorption properties of insulation materials, comparing renewable materials with standard materials such as glass wool and rock wool. The results showed that natural fibres such as wool are as effective in sound reduction as the standard mineral materials. Cotton fibres, but also the shorter and more compact fibres of flax and ramie (*Boehmeria nivea*) proved to be effective sound reducers. Wool was less effective than cotton, because the longer wool fibres are less compactable. Jute has long fibres as well, but these are not easy to compress. Reed species and straw also appeared to have sound reducing properties, with straw being especially effective above levels of 1 KHz. The sound reduction of these materials was most effective when the open ends of reed and straw stalks were exposed directly to the sound source (Oldham et al., 2011).

The company Biofib claims superior sound insulation and very good acoustic values of their hemp and recycled cellulose insulation materials. The company underpins this claim with measurements performed by the French FCBA Institute which show that this material applied on standard wall systems reaches a noise reduction level beyond standard regulatory requirements[27].

To conclude: There appears to be ample evidence showing that biobased insulation materials have good sound insulation or sound reducing properties that are comparable to those of standard materials of mineral origin. However, the actual application of the materials in buildings will determine the sound insulation levels achieved.

3.6.2 Absorption and reverberation of sound

An important aspect of acoustics is the reverberation of sound (echo) within a room. The echo depends on sound absorption of materials in floors, walls and ceilings. For instance, the speech intelligibility of a sound must be of high quality and the reverberation time should not exceed 0.6 seconds[28]. In many rooms and spaces speech intelligibility should be very good, for obvious reasons. A larger reverberation time reduces the perception capacity of the human ear for sound details. The intensity of the sound reverberation depends on the speed of sound in combination with the size of the room and the number of sound reflections (echoes) within the room. With each reflection, the intensity (and energy level) of a sound wave decreases owing to absorption and transmission of sound by a wall or floor. The absorption coefficient of a space can be determined experimentally or analytically. The sound absorption value varies from one material to another and also from one frequency to another, as shown in Table 7. The higher the value, the better the absorption and the lower the reflection. The maximum value is 1, representing 100% sound absorption (or transmission).

[27] http://www.biofib-isolation.com/files/en/BIOFIB-Ouate.pdf
[28] http://www.cisca.org/files/public/Acoustics%20in%20Schools_CISCA.pdf

Table 7. **Sound absorption coefficients of some materials at various frequencies**

Material Frequency >>	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
Marble	0.01	0.01	0.01	0.01	0.02	0.02
Brick wall	0.01	0.01	0.02	0.02	0.02	0.03
Wooden floor	0.15	0.11	0.10	0.07	0.06	0.07
Plywood panels on batten grid	0.6	0.3	0.1	0.09	0.09	0.09
Plaster	0.3	0.15	0.1	0.05	0.04	0.05
Carpet on a layer of felt	0.08	0.27	0.39	0.34	0.48	0.63
Thick curtains against the wall	0.14	0.35	0.55	0.72	0.7	0.66
Reed fibre tiles on concrete	0.22	0.47	0.7	0.77	0.7	0.48

Source: www.logosfoundation.org/kursus/4400.html

Asdrubali et al. (2012) reviewed different renewable and non-renewable materials in terms of their sound absorption coefficient and the index of reduction of impact noise

Table 8. **Acoustic properties of various natural (1-8) and traditional (9-11) insulation materials**

Material	Absorption coefficient a_s at 500 Hz (-)	Index of reduction of impact noise, ΔL_w (dB)
Hemp	0.6 (30 cm)	-
Kenaf	0.74 (5 cm)	-
Coir	0.42	23
Sheep's wool	0.38 (6 cm)	18
Wood wool	0.32	21
Cork	0.39	17
Cellulose	1 (6 cm)	22
Flax	-	-
Glass wool	1 (5 cm)	-
Rock wool	0.9 (5 cm)	-
EPS = Expanded polystyrene	0.5	30

Source: Asdrubali et al., 2012.

No values for flax are included in Table 8. However, Thormark (2007) presented test results from two flax fibre samples of different lengths (2 and 10 mm). The 10 mm sample had a sound absorption coefficient of more than 0.5 at frequencies over 500 Hz. The 2 mm sample displayed a lower absorption coefficient, but both types were considered to be useful for sound insulation in sandwich panels.

To conclude: Research shows that flax and cellulose are comparable to glass wool and rock wool in terms of sound absorption properties. Other natural materials have sound absorption properties, but at lower levels.

3.7 Fire safety

Fire safety is an important characteristic of construction materials. Therefore, all materials are classified according to the European fire classification system. The Euro classes A1-F symbolise the contribution of these materials in the event of fire (Lehner, 2006). Class A1 is less contributing to fire, while class E symbolises a high contribution and class F is used for all materials for which the fire classification is not yet determined (Table 9). The seven fire classes are specified in standard EN-13501-1. This includes the SBI test procedures to determine the fire classification for insulation materials. This test determines the potential contribution of a construction product to a developing fire, which is assessed in a fire scenario that simulates a single burning item in a room corner close to this construction product. The tests can be carried out by certified institutions or organisations. Finally, all building materials require a CE label.

Table 9. **The seven Euro fire classes for classification of construction materials**

Euro class	Contribution to fire	Euro class	Contribution to fire
Class A1	No contribution	Class D	High contribution
Class A2	Hardly any contribution	Class E	Very high contribution
Class B	Very limited contribution	Class F	Undetermined
Class C	Major contribution		

Source: www.topteam.nl/uploads/preventie/Brandgedrag%20isolatiematerialen.pdf

Table 10 shows the fire classification for a number of natural and mineral insulation materials according to the older DIN-4102 system[29]. In this classification system, A1 represents "100% non-combustible", B1 "difficult to ignite" and B2 "normally combustible". Insulation materials based on hemp, flax, wood fibres and cellulose appear to be more easily combustible than glass and rock wool.

To increase the fire safety of natural insulation materials, borax, ammonium sulphate or soda is added[30]. To insulation materials based on cellulose, 10-20% borax is added to decrease inflammability. Borax is also used against insects or fungal growth[31]. The aforementioned BIM institute lists borax as a natural alternative to chemical fire retardants[32]. Although borax is not classified as being harmful to people, it does affect plants upon direct contact. Therefore, there has to be protection against emissions to the environment and especially to groundwater, according to Van den Dobbelsteen & Albert (2001). To improve the fire resistance of wood shavings and slivers, these materials are sometimes dipped in whey end then dried back. The claim for sheep's wool is that the material is fire resistant and will not melt even at high temperatures of 570-600 ^{o}C. It also needs more oxygen than cotton to support a fire[33,34].

Table 10. **Summary of the fire safety of insulation materials including the sensitivity to fire (fire class)**

Insulation material		Fire class (DIN4102)	Available as:
Mineral wool	Glass wool	++ (A1/A2/B1)	Mat, felt
	Rock wool	++ (A,B1)	Mat, felt
Polystyrene	EPS	O (B2)	Panels
	XPS	O(B2)	Panels
PUR foam		O (B2)	Panels
Wood fibre		O (B2)	Mat, felt
Wood wool		+(B1)	Panels
Cork		O (B2)	Panels
Cellulose	Panels	O(B2)	Panels
	Flakes	O (B2)	Flakes
Flax		0 (B2)	Mat, felt
Hemp		O (B2)	Mat, felt
Coir		O (B2)	Mat, felt
Cotton		+O (B2)	Mat, felt, flakes

Source: www.waermedaemmstoffe.com/htm/uebersicht.htm

To conclude: Most biobased insulation materials are combustible and treatment with fire resistant compounds is required to make these materials satisfy fire standards. Test procedures are standardised and make no distinction based on the origin of the material.

[29]http://www.waermedaemmstoffe.com/htm/uebersicht.htm
[30]Van Dam 2012, Bouwcenter, 2011
[31]www.waermedaemmstoffe.com, 2010: Vergleich der wichtigsten Dämmstoffe.
[32]http://www.leefmilieu.brussels/uploadedfiles/Contenu_du_site/Professionnels/Formations_et_s%C3%A9minaires/B%C3%A2timent_durable_formation_g%C3%A9n%C3%A9rale/DUR_GEB_4_130312_1_GEZ_COM_NL.pdf
[33]www. eco2profit.eu/assets/files/brochure-duurzame-gebouwschil1.pdf
[34]wp.digischool.nl/scheikunde/files/2008/11/textiel.pdf

4 Biobased constructions and sustainability

4.1 Background information on sustainability of construction materials

Sustainability is a concept integrating many aspects that influence the environment and climate. The Life Cycle Assessment (LCA) approach is a method for revealing the environmental impact of products and their production processes across the value chain. A distinction can be made between "cradle-to-factory" and "cradle-to-grave" analyses. The first covers all direct and indirect energy use attributable to the product until use in construction. The second includes not only this process, but also the use of the product within the building and demolition at the end of life. This is schematically illustrated in Figure 5. For construction materials, the cradle-to-factory period is much shorter than the cradle-to-grave period, as most buildings have a long life. Wood can be an exception, as it takes much time for this raw material to be ready for commercial use. For most construction materials, biobased or fossil-based, the cradle-to-grave period includes the energy consumption during the use period. Thus the energy savings of insulation materials, for instance, can contribute positively to their LCA performance. This effect can obscure other sustainability advantages of natural insulation materials, such as CO_2 sequestration or less energy use in the production process. Shea et al. (2012) presented data showing that almost half of the total CO_2 emissions from buildings are attributable to the use phase and only 9% to the production of materials.

Figure 5. **Global timeline of the production, application and breakdown of insulation material in a building**.

The unique sustainability advantage of biobased materials is that they sequester CO_2. Furthermore, these materials can potentially have new applications after the end of life of buildings, which is mostly not the case with fossil or mineral-based materials.

4.2 Benchmarking insulation materials

According to Goverse (2003), the construction sector in Western Europe is responsible for 30% of total CO_2 emissions. The production of 1 ton of cement from limestone causes 0.8 ton CO_2 to enter the atmosphere (Worrell et al., 2001). The production of other materials such as cement blocks, lime and soda, iron and aluminium results in 0.4-0.5 ton CO_2 emissions per ton of material (Anonymous, 2010). When using construction materials based on organic materials, the CO_2 that is embedded in the material is sequestered for a long period. Wood sequesters 0.9 CO_2 per m^3 (EPA, 2010). However, use of renewable materials based on flax, straw or grass also leads to long-lasting CO_2 sequestration and can thus contribute to lowering greenhouse gas (GHG) emissions (Table 11). The energy use during the production of biobased construction materials contributes to GHG emissions, but is lower than the energy use in the production of fossil or mineral-based alternatives (Table 11). Moreover, the biobased materials have the potential to be re-used after the building's life time or to be recycled for energy production and soil fertilisation. All this can result in less energy use for materials of natural origin compared with their fossil or mineral-based counterparts. The sulphur emissions from most natural building materials are lower than those from mineral standards (Table 11). An exception is coco fibre, while rock wool also shows low sulphur emissions. One important material, hemp, is not included in Table 11 but section 4.3 of this report addresses the environmental performance of hemp-based materials.

Table 11. **Comparison of environmental impacts of natural and conventional insulating materials.**

Material	Density **(kg/m^3)**	Not renewable energy use **(MJ/kg)**	Potential GHG emissions **(kg CO_2 eq)**	Acidification potential **(kg SO_2)**
Natural rubber	6.4 (kg/m^2)	40	2.4	0.0086
Coir	50	42	0	0.0250
Flax fibres	25	4.4	0	0
Sheep's wool	30	12.3	- 0.3	0.0046
Cellulose flakes	35-70	4.2	0.2	0.0025
Polystyrene (EPS)	30	95	2.3	0.0201
Foam glass	130	67	3.7	0.0229
Glass fibre (wool)	34	43	2.1	0.0156
Rock wool	50-60	17	1.2	0.0052

Source: Ecoinvent database at www.ecoinvent.org

To conclude: The use of renewable construction materials such as flax, straw or grass results in CO_2 sequestration and thus leads to GHG emissions reductions. The energy required in their production is also lower.

4.3 Environmental impacts of hemp fibre

Haufe & Carus (2011) analysed five LCA studies regarding hemp base insulation materials. The studies used both cradle-to-factory and cradle-to-grave LCA approaches. The cradle-to-factory LCAs accounted for CO_2 sequestration, while the cradle-to-grave LCAs did not as the CO_2 was assumed to be released again to the atmosphere at the end of life. The cradle-to-factory analyses showed a GHG emissions reduction of 66-159%, whereas the reduction calculated with the cradle-to-grave approach varied between -174 and +8%, meaning an increase to neutral GHG emissions. The negative results for hemp-based materials were associated with the energy use in the production process for glass wool, which was used as the benchmark material. The level of energy use of glass wool assumed in the LCA studies was too low, according to Haufe & Carus (2011), who report that it varies between 500 and 800 MJ/m^3 with associated GHG emissions of 35 to 75 kg CO_2 eq/m^3 (Haufe & Carus, 2011). However, Pless (2001) assumed energy use of 460 MJ/m^3, with 28 kg CO_2 eq/m^3. Another explanation for the observed GHG emissions reduction of hemp insulation products could be that hemp fibres have a much higher density than glass wool, which requires more energy use during the production process per m^3 of material. However, this property could result in better energy saving performance of hemp and could counteract the energy use in production effect. Murphy and Norton (2008) also suggest using a thinner hemp-based insulation layer to improve the LCA performance, without reducing the energy saving performance compared with non-renewable benchmarks. A study by Zampori et al. (2013) showed that when accounting for CO_2 sequestration in hemp plants, building materials based on hemp can increase the GHG emissions reduction. According to Boutin et al. (2005), a hempcrete and wood combination wall would result in a 12% energy saving and a decrease in GHG emissions of 6% compared with a cement and EPS combination wall.

The average life expectancy of insulation material is around 50 years, according to Pless (2001) and Murphy & Norton (2008). For the benchmark cement it would be 100 years (Boutin et al., 2005). Based on this difference in life expectancy, there is discussion on whether this should be accounted for in LCA studies. However, in cradle-to-factory analyses, CO_2 sequestration based on CO_2 uptake by the plant during its growth in the field results in a substantial GHG emissions reduction. Haufe & Carus (2011) noted that the polyester fibres used in hemp-based insulation materials for reinforcement account for half the energy use associated with the product. Replacement of this plastic material with functional renewable materials could lead to substantial improvements in the environmental performance. Alternative renewable reinforcement materials could be polylactic acids (PLA), which are already developed and have good prospects of showing the desired functionalities.

Haufe & Carus (2011) refer to a study by Murphy (2008) that compared a number of natural fibre materials such as Thermafleece (sheep's wool) and Isonat (hemp and cotton) with Rockwool (rock wool) and Crown Loft (glass wool). The study showed that Isonat had lower environmental performance than Thermafleece based on the greater density of Isonat, its longer transportation route and treatment to increase fire safety.

In a study on a hempcrete wall, Pretot et al. (2014) calculated that GHG emissions were lower than for a standard cement wall, which was mainly attributable to CO_2 sequestration by the hemp material. Those authors also addressed the issue of life expectancy and its influence on LCA studies and environmental performance, based on a life expectancy variation of 30-100 years. They refer to studies showing that the operational phase of construction materials largely determines the environmental performance. Furthermore, the authors show that the limestone in hempcrete makes the largest contribution to the LCA performance of the product.

The literature cited above shows that the LCA performance of hemp-based material is obscured by a number of factors:

- Addition of polyester reinforcement fibres to hemp-based insulation materials.
- Differences in the density of products and insulation performance.
- Disagreement on the energy requirement to manufacture glass wool
- The transportation routes of raw materials.

To conclude: Whether or not hemp-based insulation materials reduce GHG emissions depends on many factors and assumptions. It is important to standardise the LCA calculations for insulation materials in order to reach sound conclusions. Some technical improvements are also required to improve the environmental performance.

4.4 Recycling and re-use policy

Biobased construction and insulation materials can potentially be re-used in various ways after demolition of the building. Ultimately, the minerals taken up by the plants during growth can again become available as fertiliser to close the cycle. Recycling of mineral wool is highly possible, but not standard practice. Potentially, these materials could be collected after demolition and then used again in the production of new wool or other products. However, there is no national policy in the Netherlands for recovering mineral wool after use, although a few municipalities require separate collection[35]. Construction materials based on flax and hemp can potentially also be re-used for other purposes or recycled at the end of life. Examples are producing compost or renewable energy. Zampori et al. (2013) report the amount of energy stored in hemp that can be re-used after its life. However, if polyester reinforcement fibres are used, the only processing option is to incinerate the material (Duijve et al., 2012).

General conclusions on sustainability: Most biobased materials have better environmental performance than their mineral counterparts. This is mainly associated with CO_2 sequestration. Hemp-based insulation materials give GHG emissions reductions in cradle-to-factory studies, but not in cradle-to-grave studies. For hempcrete, CO_2 sequestration by hemp plants contributes to positive environmental performance. In the end, the use phase of construction materials largely determines the environmental footprint. This leads to the conclusion that energy saving profiles are very important to lower the environmental impact.

[35]http://www.mineralewol.net/vaak-gestelde-vragen.

5 Biobased construction: Factors in implementation failure

5.1 Inventory by the biobased construction industry

Inclusion of biobased building materials in the current construction industry requires a complete transition, as described by Van Dam & Van den Oever (2012). The construction industry is highly competitive and price is an important instrument in competition. A reliable supply of large volumes of well-defined material is highly important. Biobased building materials are often only available in small quantities and thus lack the cost price benefits associated with large-scale production. Furthermore, the investment needed to obtain the required CE label is substantial. The small volumes available also make these products less attractive for use in large construction projects. Finally, the construction industry is not familiar with biobased materials, their special characteristics and benefits and how to apply them (for example scepticism still prevails on the vapour-open construction concept and the special properties of these materials). The use of biobased building materials can require adaptation in the procedures currently applied in the construction industry. In a price competitive market this is a disadvantage. To put this in a wider context, the market situation described above for biobased products in general is not uncommon and slows down the transition from a fossil-based economy to a biobased system.

In the Netherlands, several companies have combined forces in the Innovatie centrum Duurzaam Bouwen (Innovation Center for Sustainable Construction) (www.icdubo.nl). This platform organises interactions with customers and public institutions while exploring the market for biobased building products. This shows that large public organisations have a growing interest in renewable building materials. If applicable, they even give extra credit to use of these materials in issuing construction tenders. Nevertheless, the use of renewable building materials remains a marginal market. According to the Innovation Center, this situation is associated with the absence of a level playing field for biobased and conventional materials in the construction industry, caused by:

a) Existing regulations in the construction industry being tailored towards conventional materials, so they do not suit renewable materials.
b) Large-scale construction tenders being less suitable for the current biobased material supply chain, which is in its infancy.
c) Lack of familiarity among the construction industry with the technical properties of biobased building materials and how to apply them.
d) Poor communication of the green character of biobased building materials.
e) The higher price of biobased building materials associated with their small-scale production.

To conclude: The market introduction of biobased materials is experiencing the typical problems of an alternative in a price-competitive market.

5.2 Unique selling points of biobased building materials

As this report shows, the most distinctive characteristic of biobased building materials is associated with its hygrothermal properties. This can lead to improved indoor air climate and energy use, while also contributing to a more comfortable living and working indoor climate. In particular, insulation materials of natural origin are effective alternatives to mineral insulation materials, which are increasingly being associated with health risks to builders and users of buildings. These advantages of using biobased building materials are not sufficiently underpinned by practical, independent and conclusive data and experiences and, moreover, are not sufficiently communicated to the general public. Biobased building materials are mainly associated with improved sustainability, but this report showed that not all the scientific evidence points in the same direction. Furthermore, the cradle-to-factory product phase is of limited value compared with the cradle-to-grave product phase, where the use phase and the associated energy saving potential is of decisive importance for lifetime sustainability.

In a price-competitive market, introduction of alternatives is dependent more on technology push than on market pull. Klein Woolthuis et al. (2005) show that technological improvements alone are insufficient for successful implementation of innovations and that aspects such as market, regulations, cooperation, beliefs, standards and values also play a decisive role. These factors in innovation failure need to receive proper attention when implementing an innovation in practice.

To conclude: Independent applied research into the advantages of natural building materials in prevailing climate conditions, especially in the variable weather conditions of North West Europe, is required. This should not only seek to demonstrate the technological advantages of biobased building materials, but also to mitigate the factors in innovation failure.

5.3 Innovation and adoption process for biobased building materials

For many conventional building materials, biobased alternatives are available. These alternatives or their concepts are often produced by small innovative companies. Developing a product in a niche market is not easy, let alone the scaling up to mainstream production. Innovations are often confronted with a 'valley of death', which refers to financial risks that start-up companies and innovations face as they struggle to grow from small businesses to going ventures. The need for investments is substantial, with an uncertain payback time. Therefore, in the commercialisation process it is necessary to focus on a small group of customers and markets and temporarily ignore the large majority of customers and the associated large market.

The theory by Rogers (1995) is useful for distinguishing between the needs of early adopters and market trend followers. He divided users of technology into five categories: innovators, early adopters, early majority, late majority and laggards. These categories are plotted over scale and time in Figure 6. At first, the innovators determine the market scale. These are the enthusiasts of technology. Products need to be tailor-made for this group. Later, the market is enlarged by pragmatists and the more conservative users with different needs. The innovators and adopters represent a limited market. The larger markets lie with the early majority pragmatists and the late majority conservatives. According to Moore (1991), the first two groups are driven by technological innovation and are looking for technical solutions with improved performance. Higher prices and practical discomforts are taken for granted by these groups. The larger majority base their purchasing behaviour on a beneficial cost-benefit analysis and do not take technology risks. They will only become paying customers when the technology is proven, easily applicable and affordable.

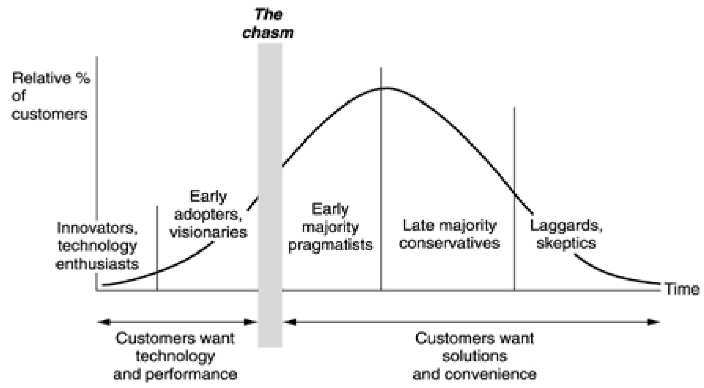

Figure 6. **Classification of adopters and the gap between the innovators and the majority (Norman, 1998)**

Norman (1998) identified a gap between the early adopters and the early majority and called this the 'chasm' (see Figure 6). To bridge this gap, product development must account for the different user types and the diverging needs of these groups.

It seems reasonable that the theory of Rogers (1995) and the research by Norman (1998) into the motives for technology adoption by customers are applicable to the technology of biobased materials. The challenge seems to be to bridge the gap between the smaller group of early adopters and the larger group of the majority. The former group seems to be sustainability driven and for them natural materials are a starting point. They are curious about the latest developments and invest time and energy in making purchase decisions. Many of the young companies active in construction innovations are themselves part of the innovator and early adopter culture. They have adopted sustainability as a major motive, are highly technology- and product-driven, but insufficiently account for the economic motives of early majority pragmatists. This latter group of customers is waiting until the advantage and comfort are proven based on well-defined and underpinned concepts.

To conclude: To bridge the gap between early adopters and the large majority of customers, it is especially important to account for the needs of the latter group. For biobased building materials, this could be translate into proven added value on health, living comfort and easy use and maintenance. The large majority requires a cost-benefit analysis not only for the purchase cost, but also for the use of the building and assumes availability through the mainstream supply channels.

5.4 Implementation

As soon as the advantages of biobased building materials and associated construction concepts are proven, the facts and figures on the advantages need to be promoted to the value chain in the conventional construction industry and to public and private customers. A transition period aiming at an increase in the use of these materials should account for the factors in innovation failure. The health and well-being of users of building can be a powerful motive. Private customers rather than public customers in the construction value chain can be a good stepping stone for implementation. This calls for active support by municipalities and other public government bodies.

The use of natural building materials with their hygrothermal properties could also play a role in the agricultural storage sector for products that require low relative humidity and regulation of temperature. In this sector, the use of biobased materials can result in energy savings, for instance in potato and onion storage.

The importance of education in the process of building up and professionalising this value chain should not be underestimated. If professionals within the construction industry are familiar with biobased building products and their hygrothermal properties, this could greatly support market growth for these products. Therefore, schools at different levels of education should be involved in the innovation process.

Together with increasing demand for biobased building products, the supply chain needs to grow and be professionalised (logistics, processing and distribution). It is an advantage that a (limited) number of Europe-based private companies already exist, especially in the flax and hemp business, that can support value chain build-up. Regarding the adaption of regulations, financial support to the value chain, research and promotion, cooperation between stakeholders could be improved.

To conclude: The process of implementation requires cooperation and an integrated approach including varying aspects that can influence the success and speed of innovation. A stepwise growth strategy can be helpful. On the supply side, cooperation among stakeholders on regulations, financial support, research and promotion is required to adequately cope with the challenges of this potential growth market.

5.5 Purchase price of biobased insulation materials

The existing construction industry is a large sector, with many suppliers, subcontractors and main contractors in a complicated and changing value chain regarding logistics and distribution. The sector is also highly price-competitive and highly regulated. Based on the nature of their application, building materials should prove themselves over a period of 30-40 years. New materials and their applications lack this practical quality experience. This is why added values for these materials, such as health, energy use profile and comfort, are so important. Purchase price is not one of these added values, owing to their small scale and low market volume. Table 12 presents a price comparison by VIBE[36] based on a standard insulation value of 0.3 W/m^{2}K. The layer thickness of the material associated with this value is also given.

Table 12. **Cost of insulation materials at 0.3 W m^2·K**

Insulating materials of:	Thickness (cm) per 0.3 W/m^2·K	cost per m^2 at 0.3 W/m^2·K
- ***natural origin***		
Flax wool	12	€ 14.04
Hemp	12	€ 16.30
Cellulose flakes		€ 15.00
Wood, fibre	12	€ 15.45
Cork	12	€ 31.10
Sheep's wool	12	€ 20.35
Straw	12	€ 6.45
- ***mineral origin***		
Perlite	15	€ 22.87
Vermiculite	15	€ 19.29
Foam or cellular glass	12	€ 44.04
Silicate foam pellets	12	€ 39.00
Glass wool	12	€ 9.60
Rock wool	12	€ 6.10
- ***petrochemical raw materials***		
Expanded polystyrene (EPS)	11	€ 19.74
Polyurethane (PUR)	8	€ 15.91

Source: www.vibe.be/downloads/4.Jeugdwerkinfrastructuur/Technische_fiches/TF_jeugd_Isolatie.pdf

More recent price information is presented in Table 4. Both tables show that biobased insulation materials based on flax wool, hemp, cellulose flakes and wood fibres are more expensive than mineral alternatives such as rock wool and glass wool. However, the price differences appear to have decreased over time.

Straw has the same price level as rock wool and is cheaper than glass wool, but requires extra work in its application. More expensive biobased insulation materials are sheep's wool and cork, but these materials come with added (hygrothermal) value, as explained in section 3.3.2 of this report. Insulation panels also seem to be more expensive. Scale effects can contribute substantially to cost price reduction. With a growing market, it can be expected that the observed price differences will level out and make biobased materials more competitive.

To conclude: At present, insulation materials of natural origin are more expensive than the fossil or mineral-based alternatives. That is why the added value of biobased materials needs to be promoted. It also should be noted that the share of insulation materials in the total construction costs is very small and so a higher purchase price of this category of products has only a small influence on the cost of a building.

6 Discussion and conclusions

Indoor air quality: Indoor air quality in today's buildings still requires improvement. Building materials, especially insulation materials, contribute to poor indoor air quality, based on moisture and VOC-associated health risks. This effect is stressed by, amongst others, Dutch health professionals in an open letter to the Dutch Wonen en Rijksdienst (Ministry of Housing and Government). Despite the strong argument they put

[36] http://www.vibe.be/downloads/4.Jeugdwerkinfrastructuur/Technische_fiches/TF_jeugd_Isolatie.pdf

forward, the relationship between the living and working indoor air environment and the health risk for occupants is not straightforward or direct. The effect is obscured by other causal agents of poor indoor air quality and by the large time lag between exposure and actual health concerns. Nevertheless, poor indoor air quality in not a recent issue. From the perspective of preventive healthcare, there is reason to replace conventional insulation materials with biobased materials.

Biobased building materials: Wood is the most widely applied biobased building material. Less commonly used materials are paper (cellulose), hemp, cotton, coir, cork, sheep's wool, shells, flax, wood fibre products and combinations of these materials. This report focused on the opportunities and constraints in applying biobased building materials. Their properties should be not only comparable to those of conventional materials, but they should have proven and accepted added values. This report listed many of the hygrothermal and other properties that biobased building materials are required to display and compared them against those of the conventional materials.

Insulation value: The thermal properties of natural insulation materials (thermal conductivity) are satisfactory and in most cases comparable to those of conventional materials. The claims of suppliers are underpinned by research and do not require further investigation. This report emphasises that the ultimate insulating or other effects are to a large extent associated with the actual construction of which insulation materials form part.

Comfort and relative air humidity: The report cites a source stating that lower relative air humidity is experienced as more comfortable by building inhabitants. International standards also point in this direction. Materials that contribute to lower and more stable indoor air relative humidity also increase living and working comfort.

Humidity control and buffering: Renewable building materials have specific hygrothermal properties that allow them to regulate indoor air moisture by buffering capabilities. Their vapour diffusion resistance factor has a magnitude comparable to that of rock wool and glass wool and greater than of polyurethane, polyisocyanurate and polystyrene. Recent research also indicates greater moisture absorption capacity of natural building materials such as hemp, flax, cellulose and combined materials. However, such research is often carried out on laboratory scale and does not always reflect the varying climate conditions in North West Europe. For this reason, practical demonstration projects under local conditions are advised. Furthermore, this report points out a possible area of application for these products that seems to have been overlooked so far, namely the agricultural storage sector, where low, constant relative humidity and low energy use are needed. This still needs research to explore the practical potential.

Humidity control in vapour-open constructions: Experimental set-ups in different climates have shown the added value of the hygrothermal properties of natural building materials in regulating indoor air relative humidity and temperature in vapour-open constructions. These added values can result in a more healthy and comfortable indoor climate. They can also result in lower energy use based on the heat storage capacity of these materials. All these added values still need to be proven in practical situations in different climate conditions.

Discussions on the value of vapour-open constructions: Vapour-open constructions are not widely accepted in North West European conditions. The relationship to humidity and humidity-related problems is debated. Professionals in the construction industry have cast doubt on whether vapour-open constructions can eliminate the use of damp-proof layers in building envelopes. There is concern that this might lead to moisture and associated mould and health problems in humid climates. This results in a need for independent research into the functionalities of vapour-open constructions with airtight but vapour-open foils. Such research should cover indoor climate measurements, as well as macroclimate measurements within the envelope construction. The comfort of the indoor climate should also be investigated, as well as the overall energy use.

Airtight, vapour-open and vapour controlling materials: Within the construction sector there does not seem to be complete agreement on the definitions of airtight, vapour-open and vapour controlling materials or characteristics. The development of uniform definitions to facilitate discussion and the interpretation of research results is recommended.

Microbiological risks: A number of renewable building materials appear to pose microbiological risks. Treatments with e.g. boron are required to eliminate these risks. This area does not require additional research.

Volatile organic compounds: The presence of VOCs presents a health risk and they have a large variety of sources, one of which may be building materials. The level of emissions can be tested according to standard procedures carried out by certified institutions. Biobased building materials as well as conventional materials can emit VOCs and all materials must be tested accordingly.

Noise pollution: Research has shown that biobased insulation materials are comparable to standard materials regarding noise pollution and sound insulation. The ultimate effect is determined by their application in actual building constructions, but there seems to be no reason to prefer conventional sound insulation materials over natural materials.

Acoustics: Flax and cellulose have good acoustic properties that are comparable to those of glass wool and rock wool. Other biobased materials can also improve the acoustics of spaces, but at a lower level than mineral insulation materials. No additional research into this property seems necessary, but the application in actual constructions determines the ultimate effect.

Fire safety: Most biobased insulation materials are inflammable and treatment with a fire retardant is required. All materials must satisfy regulations and standard testing procedures, for which certified institutions are available.

Sustainability: A number of studies have shown that renewable insulation materials have better sustainability scores than conventional materials. This is largely associated with the fact that renewable materials sequester CO_2 and require less energy in their production process. The re-use or recycling of renewable materials after their life in buildings also contributes to a better environmental profile. However, the environmental profile of hemp-based insulation materials is unclear. LCA studies show a large difference between cradle-to-factory and cradle-to-grave analyses. The thickness and density of the materials compared in such studies also result in varying outcomes. Therefore, it is advised to set up common calculation rules for the LCAs of building materials in order to facilitate discussion and decision making.

Constraints related to the use of biobased building materials: A range of different constraints identified by the biobased building sector itself can influence the future development of the Dutch biobased building industry:

a) There are a number of gaps in the current regulations. For example, not all biobased building materials are included in the Dutch national environment database[37]. This database is often used as a source in calculations determining the environmental effects of materials relevant for certificates and subsidies. This is associated with the fact that filling these gaps requires product certification, which can be too expensive for new materials and the small companies producing them[38]. Moreover, the energy saving potential of biobased building materials is not embedded in regulations and so the advantages cannot be fully exploited.
b) Existing public tenders for construction projects have many administrative demands that cannot easily be satisfied by the small companies often active in the biobased building industry[39].
c) Many main contractors and subcontractors in the building industry are not familiar with the technical properties and the application of biobased building materials.
d) The sustainability image of biobased building materials is not sufficiently promoted at consumer

[37]https://www.milieudatabase.nl/viewNMD/
[38]https://www.linkedin.com/groups/Belemmeringen-Biobased-bouwen-7414799.S.5912918059844149251
[39]http://www.duurzaamgeproduceerd.nl/nieuws/20141124-biobased-bouwmaterialen-vergroten-kans-op-succesvolle-aanbesteding

level.

e) Biobased building materials have a higher cost level, associated with their lower market volume and scale.
f) With relatively new materials, it is unclear how they will perform within a lifetime of 30-40 years in the absence of adequate experience.

The sector also presents some solutions to this situation: More technical information among all stakeholders in the construction sector; better consumer promotion; and a margin-sharing concept across the value chain. However, the sector has also asked for additional steps to be taken regarding certification and access to the national environmental database. Finally, closer cooperation along the value chain is recommended by the biobased building sector.

This report pointed out that the green image of biobased building materials might not suffice for a market increase. The associated health and energy properties should be demonstrated decisively at customer or user level, while environmental performance requires aligning of the calculation procedures. The socio-economic constraints identified by the sector are also summarised in this report.

Adoption of innovations: Innovations are often confronted with a 'valley of death' associated with the requirement for substantial financial investment and the gap ('chasm') between early adopters and the larger majority with economic motives. It is important that product development accounts for the different demands of these different adoption groups, especially the majority of users. For biobased building materials, this could involve:

a) Clear added value regarding health, comfort and energy use.
b) Solid underpinning of the cost:benefit ratio during the life of the building, which goes beyond the purchase price.
c) Availability and supply of biobased materials through the conventional supply chain.

Unique selling points: This report shows that the most important unique selling points of biobased building materials relate to their hygrothermal properties and their associated effects on comfort, energy use and health. Their use in replacing conventional insulation materials that pose health risks to the people applying the material or active in demolition should also be considered. These advantages are not sufficiently underpinned by independent demonstration and monitoring. Suitable demonstrations under different climate conditions should be set up to support the predictive value in practice. These demonstrations require an integrated approach with different experts and stakeholders.

Knowledge dissemination and cooperation: Knowledge on the unique selling points of biobased building materials should be shared across the value chain, including customers and occupants of buildings. A special role could be played by education institutions. Cooperation across the value chain is also important. This includes not only the private partners, but also the government (regulations), research and education. The value chain partners have the challenge of organising the supply of biobased materials to a level that could match increasing demands. This is a prerequisite for aligning the cost price of biobased building materials. However, this report emphasises that the cost price should not be based solely on the actual construction, but should also include the use phase.

7 Proposition

This report shows that much research has been conducted on the properties of biobased building materials and much is known about their added value. It is clear that their special hygrothermal properties play a key role, with the potential to promote health, energy savings and living comfort. Moreover, the health risks associated with conventional insulation materials make replacing these materials with good alternatives a matter of urgency.

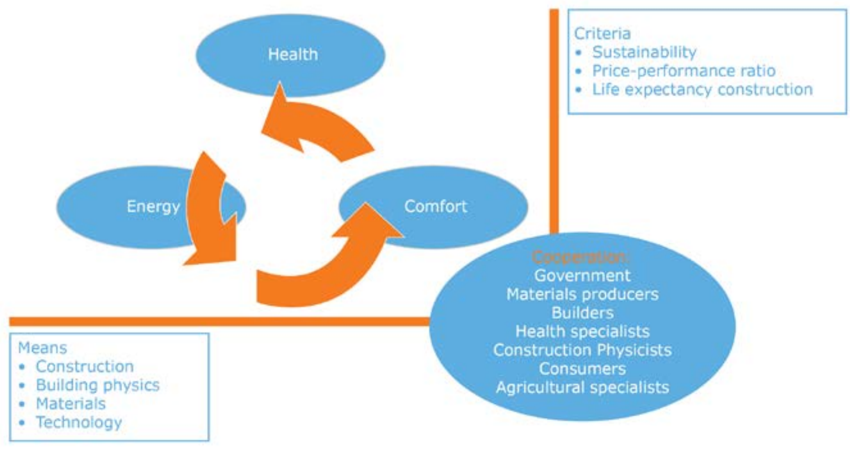

Figure 7. **Proposition for biobased building materials.**

The theory of innovation failure factors during implementation and the valley of death, as well the chasm between early adopters and the majority of customers, show that innovations based on biobased building materials require special attention. Practice is proving the truth of this.

Therefore, innovation demands an integrated approach in which the building and health sectors work together with customers and users and in which health, energy and comfort are assessed simultaneously.

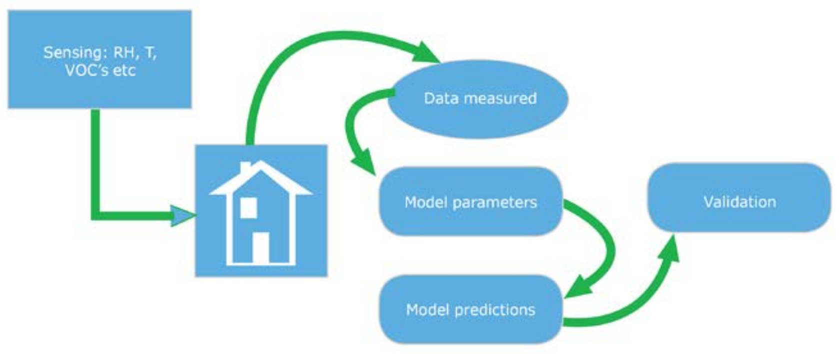

Figure 8. **Building climate measurement and substantiation.**

A proposition for an innovative approach that could satisfy the above, is schematically illustrated in Figure 7. Central to this proposal is an integrated approach to the added values regarding health, energy and comfort. These three values should not be studied separately. The approach should also integrate expertise from different fields and should include a range of partners. The cooperation between these partners should reflect the different interests involved and should ensure that these are all accounted for. This can realised by addressing a range of criteria. The proposition makes clear that experts on technology, materials science, building and construction physics are to be included to reach the final goal (Figure 7). This approach will support the innovation process of biobased building materials.

The proposition will have an important demonstration function, indicated as necessary in this report. That is why an actual construction should be part of the proposition. Measurements in this building will be required to support the possible outcome (Figure 8). The monitoring data will allow model parameters to be determined so that predictions are possible regarding the indoor climate and energy use of other constructions. The model will require subsequent validation by measurements in other existing buildings, which will allow general conclusions to be drawn. This demonstration can be expected to boost the biobased building sector and thus promote a more healthy and comfortable indoor environment and larger energy savings.

This report was discussed with stakeholders across the value chain on 21 March 2015. A summary of that discussion can be found in Appendix 1.

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Appendix 1: Group Decision Room session: Buildings & Health

Background
People spend an increasing proportion of their lives indoors, in climate-controlled and insulated offices or houses. For example, in Northern Europe people spent around 90% of their time indoors (RIVM, 2003). Research indicates that in most countries the quality of indoor air is worse than that of outdoor air, even in the most polluted cities in the world (NCEH)[40]. However, there is limited national and EU legislation and regulations on the health aspects of building products and construction methods, apart from bans on asbestos, volatile organic solvents and formaldehyde emissions. Most health-related legislation in the building industry is derived from labour conditions (e.g. occupational disease, skin disease, allergies and respiratory disease) and is not linked to the performance of building materials. The question is whether it is possible to add the element of health and well-being to building and construction principles. It might be feasible to design buildings in such a way that the health of residents is a starting point and the integral costs for construction plus healthcare may be decreased.
A specific factor in this relates to the trends of using bio-based building materials (for example, on the basis of hemp, flax, straw). These kinds of natural building materials are often associated with damp-open constructions and indoor climate control. This in turn is related to improved regulation of humidity and indoor air quality, with an expected positive effect on health conditions and reduced respiratory problems. Underpinning these presumptions with scientific research data is currently difficult and scattered information is spread over several applicants and experts.
For these reasons, the company HempFlax (producer of products from ecologically grown fibre hemp and flax), Biobrug (a knowledge valorisation organisation of University of Groningen focusing on SMEs) and the Interreg IVb project Grow2Build (focusing on stimulating the supply chain of biobased building materials) decided to hold an open brainstorming session on 31 March 2015.

Goal of the session
The open brainstorming session with an interdisciplinary team focused on:
- Sharing knowledge and identification of knowledge gaps in the field of biobased building and health.
- Formulation of (parts of) a road map with suggestions to fill knowledge gaps.
- Ideas for communicating to society the established health benefits of biobased building materials.

Approach
The brainstorming was facilitated by a Group Decision Room (GDR) approach. The use of a set of laptops and accommodating software in this GDR session resulted in anonymous brainstorming and direct collection of answers. Central questions raised during the session were:
- Is there a sufficient scientific basis for making a distinction between biobased building materials and building materials of fossil origin in the field of mould growth, toxins and VOCs, in terms of comfort and in the field of health for builders and demolition workers?
- If not, what are the knowledge gaps and what will it take to achieve clarity in these areas?
- How can you convince private housing clients of the advantages of biobased building materials?
- What is the role of different stakeholders from the supply chain, education, research and government in stimulating the use of these materials?
- What are elements of the roadmap for healthy biobased materials?

Participants
The GDR session was held at Applied Plant Research, Wageningen UR, Valthermond. Among the 22 participants were private companies active across the supply chain of biobased building materials, research

[40] http://www.cdc.gov/NCEH/

organisations (Wageningen UR, RIVM, RUG), higher education organisations (Saxion, NHL), housing associations and advisors. The composition of the group resulted in both fundamental and practical inputs and insights from different disciplines.

Results

The full results, with all answers collected during the GDR session, are available in a report in Dutch with unedited inputs (herman.schoorlemmer@wur.nl).
For the road map, suggestions were given on several topics, as summarised below.

1. Research & development:
    - Start with a multidisciplinary research programme on biobased building materials and their effects on health, energy use and comfort. Focus on:
    - Definition of performance indicators, parameters and norms on indoor air quality, health and comfort
    - Measurements in practice (reference houses) of VOCs, moulds and allergens
    - Model studies (scenarios) on performance of applied building materials in terms of health, energy use and comfort during development, use and demolition
    - Effects of single (biobased) building materials in performance of building constructions
    - Scientific research related to healthy aging and healthy biobased buildings (preventive health care)
    - Development of a certificate for healthy buildings and building materials in relation to the EU energy performance labels (EPBD).
2. Demonstration & Best Practices:
    - Pilot projects by institutional builders (housing), governments, insurance companies. Viable business cases with the best compromise for health, comfort and energy use. Pilot studies in combination with applied research
    - Stimulate innovation by bringing together several disciplines (builders, designers, health care specialists, etc.), creativity, scientific and tacit knowledge in a challenging 'iconic' project, like developing the healthiest baby room or nursery school
    - Develop biobased test houses and encourage interested consumers to reside there for a certain period (test living).
3. Education & promotion:
    - Introduce training on the use of biobased materials in professional schools, including health effects for consumers and builders & demolition
    - Further development of the knowledge database on biobased building materials (www.biobasedbouwen.nl) in relation to health effects.
4. Legislation & regulation:
    - Explore effects of liability and precautionary principles in the production chain of healthy biobased building materials. Liabilities of producers of biobased materials are not passed on to contractors and prevent interest in risks to healthy living
    - Explore the effects of increased insulation and energy labelling on the indoor climate.
5. Stakeholders & networks:
    - Join forces, connect with or start with a foundation, NGO or lobby group with the focus on the social interests of healthy living, resulting in a taskforce that puts healthy (biobased) building in motion
    - Use of media (social media, TV, radio) to boost the sense of urgency and stimulate the setting of an agenda on healthy building.

To explore the potential of nature to improve the quality of life

Praktijkonderzoek Plant & Omgeving,
onderdeel van Wageningen UR
Edelhertweg 1
Postbus 430
8200 AK Lelystad
T (+31)320 29 11 11
www.wageningenUR.nl/ppo

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De missie van Wageningen UR (University & Research centre) is 'To explore the potential of nature to improve the quality of life'. Binnen Wageningen UR bundelen 9 gespecialiseerde onderzoeksinstituten van stichting DLO en Wageningen University hun krachten om bij te dragen aan de oplossing van belangrijke vragen in het domein van gezonde voeding en leefomgeving. Met ongeveer 30 vestigingen, 6.000 medewerkers en 9.000 studenten behoort Wageningen UR wereldwijd tot de aansprekende kennisinstellingen binnen haar domein. De integrale benadering van de vraagstukken en de samenwerking tussen verschillende disciplines vormen het hart van de unieke Wageningen aanpak.

GROW 2 BUILD

Investing in Opportunities
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