EUROPEAN UNION

Interreg

France (Channel Manche) England

BIO-CIRC Project

European Regional Development Fund

BIO-CIRC Project

Bio(and)Circular Insulation for Resourceful Construction

Indoor air quality and health of workers and users:

Impact of natural and recycled fibre insulation

May 2021

EUROPEAN UNION
European Regional Development Fund
nomadéis ASBP The Alliance for Sustainable Building Products thermafleece Nature's finest insulation backtoearth

EUROPEAN UNION

Nomadéis Le Havre
120, boulevard Amiral Mouchez • 76600 Le Havre • France
Phone: +33 (0)1 45 24 31 44
www.nomadeis.com

The Alliance for Sustainable Building Products
The Foundry, 5 Baldwin Terrace • London N1 7RU • United Kingdom
Phone: +44 (0) 20 7704 3501
https://asbp.org.uk

Eden Renewable Innovations Limited
Soulands Gate, Soulby, Penrith • Cumbria, CA11 0JF • United Kingdom
Phone: +44 (0) 1768 486285
https://www.thermafleece.com

Back To Earth Limited
22 Tuns Lane, Silverton • Exeter, EX5 4HY • United Kingdom
Phone: +44 (0) 1392 861763
https://www.backtoearth.co.uk/

Interreg
France (Channel Manche) England
BIO-CIRC Project
European Regional Development Fund

Abstract of the project

The BIO-CIRC Project, Bio(and)Circular Insulation for Resourceful Construction, intends to tackle the building sector's high carbon, energy and resources dependencies while taking advantage of an unused waste resource: polyester from waste bedding.

The project aims to conceive, develop, and deploy 3 prototypes of innovative low-carbon thermal insulation material made from polyester and combined with natural fibres. It intends to promote the emergence of a bespoke waste polyester valorisation industry and the use of virtuous Natural and Recycled Fibre Insulation products.

This project is carried out by a cross-channel partnership of 4 key and complementary links in the building sector's value chain:

- Nomadéis (lead partner)
- Alliance for Sustainable Building Products
- Eden Renewable Innovations
- Back to Earth

Planned over 2 years, the BIO-CIRC project receives funding from the European Regional Development Fund (ERDF). The ERDF's contribution amounts to €399,600 for a total budget of €499,500.

Table of contents

Take-away points

The objective of this review is to study the impact of natural recycled fibre insulation (NRFI) on indoor air quality (IAQ) and the health of inhabitants and on-site workers. This activity responds to concerns that biomass and waste materials may not be safe in terms of particulate emissions, pest development, or pose risks to construction workers. **Based on a scientific review, this study summarises what is known about the impact of NRFI on indoor air quality and health (and especially of flax, hemp, cotton, sheep's wool, and recycled polyester).**

THE POLLUTANTS RESPONSIBLE FOR INDOOR AIR QUALITY DEGRADATION:

1. Over **2,700 potentially toxic substances** have been identified in the ambient air of the various types of indoor environments.

2. These toxic substances are classified into three categories:
   - **Chemical substances** (carbon monoxide - CO -, volatile organic compounds or sub-volatile organic compounds – VOC or SOVC – and radioactive substances like radon);
   - **Physical substances** (particulate matters, asbestos fibres, synthetic mineral fibres).
   - **Biological substances** (virus, bacteria, mould, allergens, acarids, etc).

3. When insulation is considered, three main types of pollutants are of concern: VOCs and SVOC, particulate matters (PM2.5 and PM10) and airborne fungal flora.

ASSESSMENT OF THE IMPACT OF NRFI ON INDOOR AIR QUALITY:

⇨ PARTICULATE MATTERS:

1. **No risk of mesothelioma, lung cancer, lung fibrosis or asthma has been associated with organic fibres**.

2. Impact assessment of PM by bio-based insulation is mostly inconclusive insofar studies mainly targeted the textile industry and not the insulation industry[1].

3. **No increased risk of mesothelioma, lung cancer or lung fibrosis have been identified for workers exposed to natural organic fibres** in contrast to workers exposed to inorganic crystalline fibres such as asbestos[1].

4. However, workers with a heavy exposure to organic dust seem to have an increased risk of obstructive lung disease and bronchitis. These effects have not been causally linked to the fibrous shape of the particles but rather to the dust, chemicals absorbed on the dust or microorganisms occurring together with the dust[1].

⇨ VOCS AND FORMALDEHYDE

1. **Biobased products do not present a health risk concerning TVOCs and formaldehyde**.

2. **90% of the insulation products on the French market have been classified A+**, the lowest indoor VOCs emission rating, by the Indoor Air Emission label.

3. Insufficient scientific examination of NRFI has been done. When undertaken, it has usually focused on raw materials rather than treated and finished products leading to unrepresentative or inconclusive data in most cases. More real-life measurements are needed to address this gap.

⇨ HUMIDITY AND MOULD GROWTH

1. **Hemp and polyester seem to be naturally resistant to mould growth**.

2. Similarly to rock and glass wool insulation, some NRFI (ex. flax, cotton, and wood) are sensitive to mould growth and need to be treated accordingly.

3. **Sheep's wool, hemp and wood show a very good capacity to regulate the humidity of the air.**

⇨ RODENTS, INSECTS, AND MITES[4]

1. **Flax, hemp, and polyester seem to be naturally resistant to rodents, insects and mites.**

2. In the same manner as rock and glass wool insulation, some NRFIs (ex. cotton, sheep's wool, and wood) needs to be treated against insects and rodents.

CONCLUSION

1. It appears that **NRFIs do not have a significant impact on indoor air quality in terms of particulate matters, VOCs and formaldehyde, and mould.**

2. Workers (manufacturers and installers) may have an increased risk of disease of the respiratory system in case of heavy exposure to dust and fibres (organic and inorganic). Therefore, **ensuring the strict respect of all protective measures (administrative, collective, and individual) is essential for the health of workers**.

3. **In the same manner as rock and glass wool insulation, some NRFIs (cotton, sheep's wool, and wood) need to be treated against insects and rodents.** On the contrary, flax, hemp and polyester seems to be naturally resistant to these disturbances.

4. **The lack of comparative research**, conducted under real conditions with insulation products does not allow strict conclusions on the precise impact of NRFIs and man-made vitreous and mineral fibres on indoor air quality.

5. **The French label Emissions within indoor air appears to be a good way to ensure insulation products meet European and national guidelines** for indoor air but is limited in its scope by excluding PM and mould growth.

1 Introduction

In the last few decades, Indoor Air Quality (IAQ) has received increasing attention from the international scientific community, political institutions, and governments striving to improve the wellbeing of occupants and building site workers. Indeed, several studies have shown it to be an issue of capital importance for public health, with health effects as varied as pollutants themselves.

The European population spends on average[1] 90% of its time in enclosed spaces: houses, offices, schools, and public transports; all of which are affected by IAQ issues. Faced with this new public health issue, the French Observatory on Indoor Air Quality (OQAI) was created in 2001 to improve knowledge of indoor air pollutants. In 2006, the observatory undertook a national survey of indoor air quality in French dwellings, studying around 600 dwellings[2]. In 2004, a similar survey had been commissioned by the British government on approximately 900 English households to learn more about the baseline of toxic substances and vectors responsible for potentially high concentration of pollutants[3].

These studies, and many others, highlighted the contamination of dwellings, schools, workplaces, and public transports with toxic airborne substances. The World Health Organisation (WHO) reported that, globally, 9 out 10 people breathe air containing high levels of pollutants (concentrations which exceed the WHO guidelines)[4]. The incriminated substances (which include chemical, physical and biological pollutants) may originate from the outdoor ambient air, surrounding environment, soil pollution linked to former industrial activities, components within a building's fabric or activities carried out by the occupants themselves.

Indoor air pollution has major public health consequences representing an estimated 19,900 deaths per year and lead cause of co-morbidity for an estimated 31,200 persons per year in France[5]. In the United Kingdom, air pollution has a burden on mortality equivalent to 40,000 deaths per year[6]. The sanitary consequences of indoor air pollution have also an economic cost: the OQAI valued its yearly impact in France to 19 billion of euros per year, including 195 million of euros related to public finances[7] (*Observatoire de la qualité de l'air intérieur*, 2014).

The objective of this review is to study the impact of natural recycled fibre insulation (NRFI) on indoor air quality and the health of inhabitants and on-site workers. This activity responds to concerns that biomass and waste materials may not be safe in terms of particulate emissions, pest development, or pose risks to construction workers. **Based on a scientific review, this study summarises what is known about the impact of NRFI on indoor air quality and health with a particular focus on flax, hemp, cotton, sheep's wool, and recycled polyester).**

---

[1] Ministère de la Transition écologique et solidaire, ministère des Solidarités et de la Santé, ministère de la Cohésion des territoires et des relations avec les collectivités territoriales. (2013). *Plan d'actions sur la Qualité de l'Air Intérieur.*

[2] Observatoire de la qualité de l'air intérieur. (2006) *Campagne nationale Logements, Etat de la qualité de l'air dans les logements français.* Centre Scientifique et Technique du Bâtiment (CSTB) et Agence Française de Sécurité Sanitaire de l'Environnement et du Travail (AFSSET).

[3] Raw, G., Coward, S., Brown, V., & Crump, D. (2004) Exposure to air pollutants in English homes. *Journal of Exposure Analysis and Environmental Epidemiology*.

[4] World Health Organisation. (2018). Ambient air pollution: A global assessment of exposure and burden of disease.

[5] Observatoire de la qualité de l'air intérieur. (2014) *Etude exploratoire du coût socio-économique des polluants de l'air intérieur.* CSTB, ANSES.

[6] The Royal College of Physicians and the Royal College of Paediatrics and Child Health. (2016) *Every Breath We Take: The Life Long Impact Of Air Pollution.*

[7] The impact on public finances involves expenditure on care and prevention, the cost of research, expertise and institutional communications relating to indoor pollution, and the "positive" impact on retirement pensions that will be paid, or not, in case of premature death.

2 Characterisation of the pollutants responsible for IAQ and health degradation

Over the last decades, indoor air quality has garnered increasing attention due to the adverse effects it may have on human health. In this report, the term "indoor" refers to a variety of enclosed environments including dwellings, workplaces or buildings used as offices or for recreational purposes. Some studies cited may also have been carried out within the confined atmosphere of commuting vehicles.

2.1 Review of the pollutants responsible for IAQ degradation

Indoor air pollution is a multi-factorial issue with pollutants originating from the outdoor ambient air, soil pollution caused by former or nearby industrial activities, components or materials within the building's structure, or activities carried out by the occupants themselves. These multiple factors all contribute to releasing an array of toxic substances that can be broadly classified into three categories[8]:

- **Chemical substances** such as carbon monoxide (CO), volatile organic compounds or sub-volatile organic compounds (VOC or SVOC) and radioactive substances like radon;
- **Physical substances** such as particles, asbestos fibre, synthetic mineral fibres, etc.;
- **Biological substances** such as viruses, bacteria, mould, domestic animal allergens, acarids, etc.

Nowadays, **over 2,700 potentially toxic substances have been identified** in indoor ambient air across the various types of indoor environments. The following table summarises these different substances and classifies them according to their characteristics and their origins (Table 1).

[8] ADEME (2019) Un air sain chez soi - Des conseils pour préserver votre santé.

Table 1 - Summary of toxic substances causing indoor air pollution

TYPE OF POLLUTANT		ORIGIN
CHEMICAL SUBSTANCES		
Carbon monoxide (CO)	Carbon monoxide is a deadly and toxic gas invisible and impossible to smell[9].	Faulty heating and hot water appliances, tobacco smoke, external urban pollution such as road traffic (Veolia Institute in partnership with Nomadéis, 2020).
Volatile organic compounds (VOC) (aldehydes, hydrocarbons, organochlorides, glycol ethers, etc.)	VOCs are a diverse group of gaseous compounds emitted by solid or liquid substances, some of which may have short- and long-term adverse health effects. A VOC is defined as an organic compound with an initial boiling point less than or equal to 250° C measured at a standard atmospheric pressure of 101.3 kPa. [10]	Emissions from building materials, air from outside the building, and human activities inside buildings[11].
Sub-volatile organic compounds (SVOC) (pesticides, fire retardants, etc.)	SVOCs are emitted by gas or particles by many daily chemical products and materials. Because of their physicochemical properties, these compounds are distributed in the air and the dust on the floor and the furnishings. A SVOC is any organic compound having an initial boiling point between 240 and 260°C and between 380 and 400 °C measured at a standard atmospheric pressure of 101.3 kPa (United States Environmental Protection Agency). Because of this higher boiling point, SVOCs are not as volatile as VOCs.	Emissions from building materials, air from outside the building, and human activities inside buildings (Tsakas, Siskos, & Siskos, 2011).
Radioactive substances (radon)	Radon is an odourless and colourless radioactive gas created by the natural disintegration of uranium located in the earth's crust. In risk areas (like Brittany in France[12]), high rates of radon can be measured inside a dwelling[13].	Construction materials, soil in potential radon zones (fissures, porosity, joints, pipeline paths) (Veolia Institute in partnership with Nomadéis, 2020).
PHYSICAL SUBSTANCES		

[9] Observatoire de la qualité de l'air intérieur : Pollutions : Le monoxyde de carbone

[10] The United States Environmental Protection Agency: Volatile Organic Compounds' Impact on Indoor Air Quality.

[11] Tsakas, M., Siskos, A., & Siskos, P. (2011) Indoor Air Pollutants and the Impact on Human Health. *Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality*.

[12] The Institute of radioprotection and nuclear safety mapped the radon potential of geological formation and classified municipalities in three risk categories. Link of the mapping. The same kind of mapping has been done in United Kingdom by the organisation Public Health England. Link of the mapping.

[13] Observatoire de la qualité de l'air intérieur : Pollutions : Le radon.

Particulate matter (smoke, dust, pollen, etc.)	Particulate matter is an airborne material that can be solid or liquid. It can be classified into two categories PM2.5 (size less than 2.5 µm) and PM10 (size less than 10 µm). The health consequences of particles will depend on their size: the finest having a higher sanitary impact. Moreover, bacteria and viruses responsible for infectious diseases can be spread by airborne particles[14].	Dirty or deteriorated ventilation systems, fuel burning, tobacco smoke, proximity to a construction site, external urban pollution including from road traffic, proximity to industrial sites, polluted outdoor air (including with pollen) (Veolia Institute in partnership with Nomadéis, 2020).
Synthetic mineral fibre	Synthetic mineral fibres are the components of the main insulant materials since asbestos has been forbidden in France, the United Kingdom, and many other countries. These fibres can be released into the indoor atmosphere during on-site installation or maintenance of the building insulation.	Glass wool, rock wool, refractory ceramic fibre, alumina fibre (Veolia Institute in partnership with Nomadéis, 2020).
BIOLOGICAL SUBSTANCES		
Viruses and bacteria (legionella)	Viruses and bacteria can be spread in the atmosphere by drops of water and airborne dust and cause diseases.	Effectiveness of air recirculation, cleanliness of the premises and ventilation/air conditioning systems.
Mould and airborne fungal flora	Moulds are microscopic fungi capable of colonising a variety of surfaces such as wood, paper, fabric, food, etc. In dwellings, mould can release spores in large quantities or odorous and toxic substances such as mycotoxin and VOCs[15].	Internal source of damp (water damage, leaks, condensation, poorly insulated walls, etc.) (Veolia Institute in partnership with Nomadéis, 2020).
Allergen	Allergens are foreign airborne substances that can be found in dwellings, capable of triggering an allergic reaction[16].	Domestic animals (dog, cat, cockroach), acarids, pollens, etc.

[14] Observatoire de la qualité de l'air intérieur : Pollutions : Les particules.

[15] Observatoire de la qualité de l'air intérieur : Pollutions, les moisissures.

[16] Observatoire de la qualité de l'air intérieur : Pollutions, les allergènes.

2.2 Factors influencing indoor air quality degradation

As shown in Table 1, a variety of pollutants have been identified in the indoor atmosphere. These pollutants came from four principal sources: human activities inside buildings (heating and cooking appliances, cleaning products, smoke, domestic animals, etc.), building materials, entrainment of air from outside the building, and the surrounding environment (green areas, soil characteristics, water, and ground pollution, etc.).

The types and quantities of pollutants found indoor vary temporally and spatially and may be very context specific. These pollutants' consequences on users and construction professionals' health are influenced by two main factors: duration of exposure and concentration in pollutants.

With respect to duration of exposure, the National Human Activity Pattern Survey (NHAPS), sponsored by the U.S. Environmental Protection Agency (EPA), reported that people spend an average of 87 % of their time in enclosed buildings and about 6 % of their time in enclosed vehicles[17]. This indicates that even mild concentration of pollutants within an indoor environment may have drastic health consequences.

Indoor air quality is notoriously difficult to predict at any geographic or temporal scale as it is determined by complex and dynamic relationships between the specific environmental context of a confined space, the occupants' activities, and variable structural characteristics. For instance, a building's interior-space design (space planning), envelope design (airflow), and materials' selection can contribute greatly to the accumulation, or the dissipation, of pollutants.

The objective of the following paragraphs is to examine the data surrounding the impact of some bio-based and waste-based insulation materials on indoor air quality and the global health of inhabitants.

[17] Klepeis, N. *et alii* (2001) The National Human Activity Pattern Survey: a resource for assessing exposure to environmental pollutants. *Journal of Exposure Science & Environmental Epidemiology*, pp. 231-252.

2.3 Regulations and labels

To assess potential hazards from bio- and waste-based insulation material, laws and regulations must first be consulted in order to estimate what levels are considered safe or unsafe.

2.3.1 European level

The main guidelines regarding IAQ have been developed by the WHO which sets target levels or concentration indoor air pollutants for which scientific knowledge has identified effects on human health. In **European legislation, there is no specific reference directive on IAQ**, although pre-legislative initiatives (studies, non-legislative standards, etc.) have increased over the years.

In addition, some EU Member States such as France, Portugal, Finland, Austria, Belgium, Germany, the Netherlands, and Lithuania have adopted specific guides or threshold values for different pollutants[18].

→ Focus on European guidelines on air quality:

The EU is equipped with two main pieces of legislation which set the guidelines for IAQ: the 2008 ambient air quality guideline and the guideline on arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air[19]. **However, no specific guideline on indoor air quality has been published to date.**

→ The European air quality label natureplus®:

The international association natureplus e.V. developed an eco-label to offer consumers and construction professionals in Europe guidance on building products. It attests compliance with high standards of quality in various sustainability measures and currently certifies over 600 building products.

The award of the natureplus® eco-label is made on following criteria:

1. **Clean and efficient production:** an environmentally friendly and energy efficient manufacturing that meet social responsibility standards. The end product must be functional and recyclable.
2. **Protection of the environment and health:** the end product does not adversely affect the environment or human health through harmful substances and ensure, in particular, healthy indoor living spaces.
3. **Sustainability of resources:** products must be made from renewable resources, abundant mineral raw materials, or secondary raw materials. In any case, raw materials must be sourced sustainably.

In addition, natureplus has established specific guidelines for each type of product. For example, the “Insulation materials from renewable raw materials” guidelines specify, for each type of resource (hemp, flax, sheep’s wool, etc.), requirements to follow in terms of composition,

[18] Dimitroulopoulou, S., & Shrubsole, C. (2020). *Indoor Air Quality Guidelines for selected VOCs in the UK.* ASBP - Healthy Buildings: Conference and Expo 2020 - Public Health England.

[19] Service de recherche du Parlement européen. (2018) Qualité de l'air : Sources de pollution et leurs effets, législation de l'Union européenne et accords internationaux.

ecological parameters, and emission of pollutants in indoor ambient air (TVOC, VOC, metals, and pesticides)[20].

The **certification procedure** mandates manufacturers to apply to the natureplus Institute SCE for certification and to provide exact data on the input components and a detailed description of the production process. Product eligibility to the eco-label is determined by the specific product category and an assessment plan is issued. The manufacturer must then commission the necessary assessments, which generally include:

- Inspection of the production site(s) with verification of the manufacturer's details and sampling;
- Life cycle assessment of the manufacturing process in compliance with guideline values, e.g., for primary energy consumption and CO_2 emissions;
- Product-specific laboratory tests, e.g., for VOC and formaldehyde emissions, heavy metals, biocides, and impurities with harmful substances;
- Analysis of the product life cycle regarding environmentally compatible resource extraction, social responsibility, and possible recycling.

If all requirements are met, the natureplus Institute SCE awards the natureplus® label and issues a temporary certificate. The tests must be renewed at fixed intervals[21] for the certificate to be upheld.

2.3.2 United Kingdom level

In the United Kingdom (UK), minimum requirements for indoor air quality are covered by Part F of the Building Regulations published by the Ministry of Housing, Communities & Local Government, with statutory guidance provided in Approved Document F[22]. Part F of the UK Building Regulations [23] is currently under revision with a new version expected to become statutory guidance in 2021.

Criteria for moisture and indoor air quality are covered in Appendix B of the Approved Document. This appendix specifies the threshold values for carbon monoxide, nitrogen dioxide (NO_2), formaldehyde and TVOC (Total VOC concentrations). Public Health England's Indoor Air Quality Guidelines for selected Volatile Organic Compounds (VOCs) in the UK should be used where individual VOC's are measured.

This document also suggested the limits for relative humidity and surface water: surface water activity[24] for moving average period 1 month (resp. 1 week and 1 day) should be 0.75 (resp. 0.85 and 0.95) and indoor air relative humidity should be 65 % (resp. 75 % and 95 %).

Whereas the Regulations change little with respect to VOC's and TVOC's, there is an acknowledgement that humidity and water activity play a vital role in the quality of indoor air, an ongoing theme in the Future Building Standard that is currently open for consultation.

[20] Natureplus: Award guidelines.

[21] The costs depend on the amount of testing required and can be found at www.natureplus-institute.eu . Licence fees are charged for the use of the natureplus label.

[22] Ministry of Housing, Communities & Local Government. (2010) *Statutory Guidance - Ventilation: Approved Document F.*

[23] Approved Document F – Ventilation. Consultation Version January 2021.

[24] Water Activity is the amount of unbound water in a sample. This unbound water can be used by microorganism. The more unbound water we have the more likelihood we have for microbial spoilage. Water Activity (aw) Metres measure the unbound water vapor pressures to determine microbial spoilage, chemical and physical stability.

2.3.3 France level

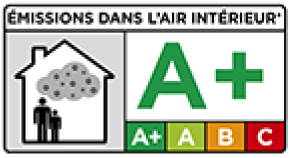
In France, the national ambient air quality monitoring system, an application of the European regulation, defines limit values, quality objectives, alert threshold, and critical levels for a selection of pollutants. These pollutants are nitrogen dioxide (NO_2), nitrogen oxides (NOx), sulphur dioxide (SO_2), lead (Pb), PM10 (particles with a diameter of 10 micrometres or less), carbon monoxide (CO), benzene, ozone (O_3), PM2.5, arsenic, cadmium, nickel, and benzo(a)pyrene[25].

To address the health issue of indoor air quality and provide public authorities with tools to manage this risk, the ANSES (National agency for food, environment and workplace health and safety) has developed the indoor air quality guidelines (IAQGs). These guidelines (edited in 2007 and updated in 2016) are based exclusively on health criteria and have led to the creation of a label intended for building and decoration materials. The aim here is to enable promotion of materials considered to emit less air pollutants.

For this purpose, the ANSES has identified and selected key chemicals emitted by these products. Of the 600 potentially emissive substances identified, only 31 were considered by the ANSES to be of primary importance. Finally, **ANSES experts assessed that a selection of 10 indoor air pollutants, all members of the category of volatile organic compounds (VOCs), whose harmful effects have been observed needed to be monitored as part of the label**. These pollutants are listed in Table 2 below. The label mandates that the cumulative sum of the concentration of all VOCs present in the air to be calculated (the following table show the different quality classes of the label). The label “Emission within indoor air” thus only evaluates VOCs concentration and excludes other pollutants as mould and physical particles.

Table 2 - Pollutant concentration of the different quality classes of the label Emission within indoor air[26]

VOCS	UNIT*	A+	A	B	C
Formaldehyde	$\mu g.m^{-3}$	< 10	< 60	< 120	> 120
Acetaldehyde	$\mu g.m^{-3}$	< 200	< 300	< 400	> 400
Toluene	$\mu g.m^{-3}$	< 300	< 450	< 600	> 600
Tetrachloroethylene	$\mu g.m^{-3}$	< 250	< 350	< 500	> 500
Xylenes	$\mu g.m^{-3}$	< 200	< 300	< 400	> 400
1,2,3-Trimethylbenzene	$\mu g.m^{-3}$	< 1000	< 1500	< 2000	> 2000
1,4-Dichlorobenzene	$\mu g.m^{-3}$	< 60	< 90	< 120	> 120
Ethylbenzene	$\mu g.m^{-3}$	< 750	< 1000	< 1500	> 1500
2-Butoxyethanol	$\mu g.m^{-3}$	< 1000	< 1500	< 2000	> 2000
Styrene	$\mu g.m^{-3}$	< 250	< 350	< 500	> 500
Total COV	$\mu g.m^{-3}$	< 1000	< 1500	< 2000	> 2000



* 28 days after incorporation or installation of the insulation.

The emission grade given to a product is based on the lowest mark achieved (from A+ to C) in any of the included pollutants[27].

[25] Ministère de la transition écologique. (2017) Les critères nationaux de qualité de l'air.

[26] ADEME. (2017) Comparaison des émissions de COV dans l’air intérieur par les produits biosourcés utilisés dans le bâtiment. Direction Productions et Energies Durables.

[27] ANSES. (2016) Labelling of building and decoration products with respect to VOC emissions.

Since the 1st of September 2013, every building material (including insulation)[28] has the obligation to hold this label. However, this label has an only informative and non-coercive vocation. Moreover, the regulation does not impose carrying out systematic tests to certify the class of VOCs emission but only to label the concerned products.

Criticism of the "Emission within indoor air" label:

A critical evaluation of the label undertaken by the ADEME (French agency for ecological transition) noted that[29] :

1. Compared to other European regulations, the ANSES protocol on indoor air quality is broadly the strictest.
2. It is not strict enough to distinguish between commonly marketed products as 90% of labelled products studied by the ADEME were classified as A+.
3. The current protocol is not strict enough to distinguish oil based, minerals or biobased products.

2.4 Global hazards of IAQ degradation on public health

There exist disparities in the knowledge of pollutants on human health risks. Indeed, knowledge of the health impact indoor air pollution (IAP) depends on the type of substance considered. Broadly speaking, the identified impacts of IAP on humans' health are the following (Tsakas, Siskos, & Siskos, 2011):

- **Respiratory health effects associated with exposure to IAP**: Several effects on the respiratory system have been associated with exposure to IAP. These include acute and chronic changes in pulmonary function, increased incidence and prevalence of respiratory symptoms, augmentation of pre-existing respiratory symptoms, and sensitisation of the airways to allergens present in the indoor environment. Also, respiratory infections may spread in indoor environments when specific sources of infectious agents are present, or simply because the smaller indoor mixing volumes allow infectious diseases to spread more easily from one person to the next.
- **Allergic diseases associated with exposure to IAP**: Allergic asthma and extrinsic allergic alveolitis (hypersensitivity pneumonitis) are the two most serious allergic diseases caused by allergens in indoor air. Allergic rhino-conjunctivitis and humidifier fever are other important diseases. Allergic asthma and extrinsic allergic alveolitis resolve with cessation of exposure to the allergen, but continued exposure in sensitised patients may result in permanent lung damage and death from pulmonary insufficiency.
- **Cancer and effects on reproduction associated with exposure to IAP**: Lung cancer is the major cancer which has been associated with exposure to IAP (radon or environmental tobacco smoke - ETS). Asbestos exposure has been linked to cancer in workers and in workers' family members, presumably due to asbestos fibres brought into the home on workers' clothing. However, there are no studies associating asbestos exposure in homes

[28] This regulation concerns every construction or wall covering products or soil and paints and varnishes. Décret n° 2011-321 du 23 mars 2011 relatif à l'étiquetage des produits de construction ou de revêtement de mur ou de sol et des peintures et vernis sur leurs émissions de polluants volatils.

[29] ADEME. (2017) Comparaison des émissions de COV dans l'air intérieur par les produits biosourcés utilisés dans le bâtiment. Direction Productions et Energies Durables.

or public buildings from asbestos used as a construction material to the development of cancer. Effects on human reproduction have been associated with exposure to chemicals in the environment, but it is yet unclear to what extent exposure to IAP is involved.

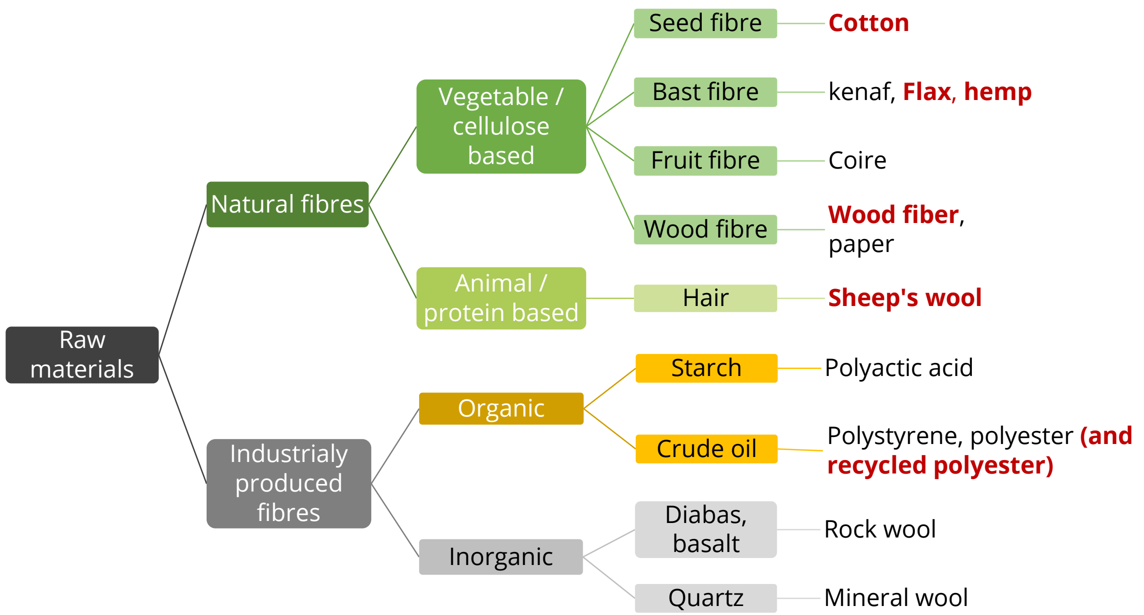
- **Sensory effects and other effects on the nervous system associated with IAP**: Sensory effects are defined as the perceptual response to environmental exposures. These effects are generated by the odorous or mucosal irritation properties of many chemical compounds found in the indoor air. Therefore, sensory effects are important parameters of control of indoor air quality: the olfactory system plays an important role as a warning system.
- **Cardiovascular effects associated with IAP**: Increased mortality due to cardiovascular diseases (CVD) has been associated with exposure to ETS in some groups of non-smoking women married to smokers.

3 Characteristics of NRFI

3.1 The different types of insulation materials

Thermal insulation, especially for the domestic sector, has been given importance since the push to insulate buildings and meet energy targets over 30 years ago[30]. Since then, the insulation sector has been dominated by synthetic inorganic fibrous insulation (glass wool and stone wool) and organic foams (expanded polystyrene, extruded polystyrene, polyurethane)[31].

Insulation materials may be categorised according to their main raw material as follows (Figure 1).



In red: Insulation materials studied in the following paragraphs.

Figure 1 : Categorisation of fibres used for insulation (source: Mansour, Loxton, Elias & Ormondroyd, 2014)

In the past decades, there has been a growing interest for insulation material with additional beneficial properties such as moisture buffering, durability, sustainability, and positive impact on human health. These new properties have increased the focus on natural biobased (cotton, flax, hemp, wood fibre and sheep's wool) and recycled (polyester) resources which have been historically used by the textile industry. Indeed, accumulating research has highlighted their attractive properties and benefits: efficient thermal resistivity, good structural strength, moisture buffering capacity and uptake of certain gasses (Mansour, Loxton, Elias, & Ormondroyd, 2014). In most cases, bio- and waste-based insulation materials have equivalent thermal properties and are thus fully comparable to their conventional counterparts (synthetic inorganic fibrous insulation)[32].

However, natural, and recycled fibre insulation products' impact on indoor air quality and human health remains unclear as the literature is sparse.

[30] Papadopoulos, A. (2004) State of the art in thermal insulation materials and. *Energy and buildings*, pp. 77-86.

[31] Mansour, E., Loxton, C., Elias, R., & Ormondroyd, G. (2014) Assessment of health implications related to processing and use of natural wool insulation products. *Environment International*, pp. 402-412.

[32] Korjenic, A., Petranek, V., Zach, J., & Hroudova, J. (2011) Development and performance evaluation of natural thermal-insulation materials composed of renewable resources. *Energy and Buildings*, pp. 2518-2523.

3.1.1 Wood fibre

© STEICOFLEX – Wood fibre

Wood fibre insulations are made by fiberising[33] dried chipped waste wood which is then either formed into rigid boards via a 'dry' or 'wet' process, or formed into a non-woven flexible batt type insulation:

- The dry process involves taking the dried fibres and mixing with approximately 4 % by mass of pMDI (Polymeric diphenylmethane diisocyanate) adhesive and 1.5 % by mass paraffin emulsion before being laid on a conveyor and compressed into a board of the appropriate thickness and density. This material is steam cured to react and set the adhesive and then cut to size[30].
- Wet process boards are made in a similar way to paper. The fiberised wood is further broken down by mixing it with heated water and chemicals to create a fibre slurry. This is laid on a sieve conveyor, compressed to the correct thickness and density and then steam cured and dried. This process links the lignin on the surface of fibres to adjacent fibres and so no synthetic glues are used at this point. However, this process typically produces 20 mm thick boards which are then PVA (polyvinyl acetate) glue laminated to create thicker boards.
- The non-woven batts use a similar process to other non-woven fibre insulations. The dried fibres are blown with a bi-component polyester fibre which loosely binds the fibres together to form densities of batts between 40 and 60 kg/m^3. Fire retardants in the form of ammonium sulphate are added to slow oxidation such that the product will only burn very slowly, without flame[31].

Both types of rigid insulation boards can be used for external insulation on roofs and timber framed walls, over solid masonry walling, and certain types can also be used for internal insulation, directly against masonry. The added paraffin gives them a degree of weather resistance and allows them to be left exposed to the elements for up to 3 months.

Wood fibre products generally have good thermal conductivity and twice the thermal capacity of mineral/glass fibres[29]. This high thermal capacity slows heat transfer, enhancing the overall energy performance of the material, especially in hot weather.

As a result of the pore structure and hydrophilic nature of wood fibres, they adsorb and desorb large quantities of moisture making them useful in managing both construction and in-use moisture without detriment to surrounding timber structures.

[33] Fiberising is a manufacturing process that is used to make objects such as insulation. It describes several processes that permit to form a fibrous mass.

3.1.2 Cotton

Cotton insulation comprises a blend of cotton fibres (75-90 %) and polyester (PET) bicomponent binder (10-25 %). The primary source of cotton comes from denim that has been reconstituted into loose fibres. Pre-consumer cotton waste is used extensively in bedding where it is mixed with polyester bi-component binder[34] to produce wadding that is used as a mattress component. Manufacturing cotton insulation utilises this technology and is a natural extension to conventional bedding applications of poly-cotton denim non-woven.

© BUILDDIRECT –Denim Insulation

Polyester has an ignition temperature in the region of 485 °C whereas the ignition temperature of cotton is 255 °C. A fire retardant must be applied to the cotton component of the insulation. Typical fire retardants include mixtures of inorganic sulphates, borates, nitrates, and phosphates.

Moreover, cotton is a breathable cellulose-based fibre although its fibre saturation point[35] is lower than other ligno-cellulosic materials such as wood or hemp[36].

3.1.3 Flax and hemp

The stem fibre of flax is durable and lightweight making it suitable for use in insulation. Flax fibres derive from flax straw once separated from the inner shive. The fine fibre is then blended with a binder (polyester fibres or corn polymers) to form insulation. A mineral fire retardant can be blend with the flax fibres to improve fire performance.

© Ecological Building Systems – Hemp and Jute fibres insulation

Hemp insulation is made in much the same way as flax. The technical hemp fibres[37] are separated from the shive in the hemp plant stems. The technical hemp fibres are then blended with binders and co-fibres (polyester fibres) to produce finished insulation.

Hemp fibres are also incorporated with lime and clay materials to form composite plasters and concrete substitutes.

[34] Bicomponent fibres are defined as "extruding two polymers from the same spinneret with both polymers contained within the same filament." The main objective of producing bicomponent fibres is to exploit capabilities not existing in either polymer alone.

[35] Fibre saturation point is a term used in wood mechanics and especially wood drying, to denote the point in the drying process at which only water bound in the cell walls remains - all other water, called free water, having been removed from the cell cavities.

[36] BondedLogic Inc.: UltraTouch Denim Insulation.

[37] Technical hemp fibres are the finer usable hemp fibres once woody material is removed.

3.1.4 Sheep's wool

Sheep's wool insulation uses coarse coloured sheep's wool combined with other fibres to create quilted thermal and acoustic insulation. Sheep's wool is not used to manufacture rigid of loose blown insulation. Coarse coloured wools are best suited to insulation owing to their low economic value and their natural high bulk properties.

© ArchiExpo – Sheep's wool insulation

The proportion of sheep's wool in the wool insulation should be greater than 50 % up to 100 % wool. Indeed, ISO 17749:2018 Thermal insulation products — Sheep wool mat and board — specification applies to insulation with a wool content greater than 50 %.[38]

Additional fibres are used in sheep's wool insulation to permanently bind fibres together eliminating the risk of fibre settlement and insulation slumping in service. PET bi-component binder is commonly used for this purpose as is the case with other types of recycled and natural quilted insulation. Recycled polyester (rPET) fibres are also added to provide more rebound to the insulation and to improve thermal performance allowing lower thermal conductivities or lower densities without losing thermal performance. Effective protection against insects is essential for wool insulation.

Wool is a structural protein and as such has different chemical properties to carbohydrates such as cellulose, hemi-cellulose or lignin. Wool is highly absorptive and is capable of binding approximately 30% of its own mass in water.

Moreover, keratin reacts with formaldehyde in a condensation reaction creating a methyl bridge within the protein and generating water as a by-product. This makes sheep's wool extremely efficient at reducing formaldehyde levels within the building fabric.

3.1.5 Recycled polyester

Recycled polyester insulation is composed of two types of polyester fibre: polyester staple fibre which forms the bulk of the insulation (80-90 %) and polyester bi-component binder (10-20 %). The polyester bi-component binder has an outer core that melts at 110 °C and binds the fibres together preventing them from slumping[39].

Recycled polyester insulation currently utilised rPET originating from waste packaging. The packaging is cleaned and re-spun into fine staple fibres. rPET is an inert material: it will not degrade in the presence of excess moisture and is not susceptible to biological attack.

Because the insulation is designed to last the life of the building, converting waste PET into insulation is an efficient way to remove waste PET from circulation for decades.

[38] ISO 17740. 1st Edition 2018-05Thermal insulation products — Sheep wool mat and board — Specification

[39] Eden renewable Innovations Ltd – Technical Specification

3.2 Man-made vitreous and mineral fibres' impact on IAQ and health

As for each type of insulation, it is complicated to assess the impact of fiberglass on indoor air quality and health. Assessment of this impact mainly concerns particle and formaldehyde emissions.

3.2.1 Carcinogenic hazard of man-made vitreous and mineral fibres

REGULATION (EC) No 1272/2008[40] on classification, labelling and packaging of substances and mixtures classifies man-made vitreous (silicate) fibres (MMVF's) or mineral fibres (MMMF's) (of which mineral wool insulation is a part of) as category 3 of carcinogens. The Refractory Ceramic Fibres and Special Purpose Fibres are classified as category 2 carcinogens.

These categories are as defined below:

- Category 1: Substances known to be carcinogenic to humans;
- Category 2: Substances which should be regarded as if they are carcinogenic to humans;
- Category 3: Substances which cause concerns for humans, owing to possible carcinogenic effects.

However, note Q of Regulations allows the classification not to apply if it can be shown that the substance fulfils one of the following conditions:

- A short-term bio-persistence test by inhalation has shown that the fibres longer than 20 μm have a weighted half-life less than 10 days;
- A short-term bio-persistence test by intra-tracheal instillation has shown that the fibres longer than 20 μm have a weighted half-life less than 40 days;
- An appropriate intra-peritoneal test has shown no evidence of excess carcinogenicity;
- Absence of relevant pathogenicity or neoplastic changes in a suitable long term inhalation test.

MMMF insulation with specific compositions can be shown to dissolve in the lungs ensuring their bio-persistence falls within the above criteria[41]. Organisations such as the EUCEB[42] verifies that composition of MMMF insulation falls within their published reference ranges and therefore falls within the Note Q exemption previously mentioned.

In the UK, the Health and Safety Executive in its latest guidance (operational circular OC267/2) in 2012 concluded that there is no cancer risk from disturbing existing loft insulation which includes insulation installed prior to 1998[43].

In 2007 and 2008, in France, the ANSES published two reports on man-made vitreous and mineral fibres evaluating the technical characteristics and uses of these fibres and assessing the exposure of the general and occupational populations. The reports concluded on the limited exposition of the population to theses fibres except for the on-site workers exposed to a higher concentration

[40] REGULATION (EC) No 1272/2008 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006. Annex VI 1.1.3.1 Note Q.

[41] EUCEB: The chemical range.

[42] European Certification Board for Mineral Wool Products: http://www.euceb.org

[43] Health and Safety Executive : Man-made mineral fibres (MMMF).

of fibres than recommended, 10 % of the time (for the cases followed by the study). The report also acknowledged a lack of data on the exposure of the general and occupational population and on its impact on human health[44].

3.2.2 Formaldehyde emissions of man-made vitreous and mineral fibres

A joint evaluation performed by the French MSCA (ANSES) and the Dutch MSCA (RIVM) evaluated formaldehyde in order to clarify concerns about CMR (carcinogenic, mutagenic, or toxic for reproduction) properties[45], exposure of workers, high (aggregated) tonnage, wide dispersive use, and consumer use. In their evaluation, mineral wools were identified as a permanent source of formaldehyde with a 95-P level of 31.9 µg/m^3. However, the evaluators concluded that mineral wools are always covered by other building materials. Therefore, it was not included as a relevant source for emitting formaldehyde.

The EU RAC (Committee for Risk Assessment) also identified mineral wool insulation as a source of formaldehyde emissions[46]. The report is based on an inter-laboratory comparison experiment on formaldehyde emitted from mineral wool board using small test chambers (Wiglusz et al.,2000)[47]. This experiment yielded a range between 44 µg/(m^{2}h) and 210 µg/(m^{2}h) with a P50 value of 57 µg/(m^{2}h).

Other experiments[48] have been carried out on the subject but they did not allow to conclude on the impact on human health of formaldehyde emissions from man-made vitreous and mineral fibres.

Thus, the question of the impact of man-made vitreous and mineral fibres on the health of on-site workers and populations is not yet solved and remains an important subject to study, as it is still a source of controversy.

[44] AFSSET. (2008) Les fibres minérales artificielles siliceuses - Evaluation de l'exposition de la population générale et des travailleurs.

[45] Substance Evaluation Conclusion document EC No 200-001-8. as required by REACH Article 48 and EVALUATION REPORT for Formaldehyde EC No 200-001-8 CAS No 50-00-0. 7th June 2019.

[46] Committee for Risk Assessment (RAC). Committee for Socio-economic Analysis (SEAC) Opinion on an Annex XV dossier proposing restrictions on Formaldehyde and formaldehyde releasers. ECHA/RAC/RES-O-0000006740-76-01/F. RAC opinion, adopted 13 March 2020.

[47] Wiglusz R, Jarnuszkiewicz I, Sitko E, Nikel G (2000) Interlaboratory comparison experiment on the determination of formaldehyde emitted from mineral wool board using small test chambers. Build Environ 35(1): 53-57.

[48] Unpublished WKI data from eight different samples of mineral wool (four glass wool, four stone wool) report for 96 h concentrations between 10 µg/m³ and 66 µg/m³ (GM 31.0 µg/m³, T 23 °C, RH 50 %, ACH 1 h-1, L =1 m²/m³)[48].

4 NRFI's impact on indoor air quality and health

4.1 Particulate matters

International and national health agencies have issued guidelines on particulate matters levels in indoor air (Table 3). These recommendations target particulate matters coming from man-made vitreous and mineral fibres but also organic fibres (such as sheep's wool, hemp or flax fibres).

Table 3 - Particulate matters guidance values

POLLUTANT	WHO GUIDELINES[49] (2005)	ANSES GUIDELINES - IAQGS[50]	UK AIR QUALITY LIMITS[51] (2004 - 2020)
$PM_{2.5}$	– 10 µg/m³ – annual mean – 25 µg/m³ - 24-hour mean	The ANSES agrees with the guidance values established by the WHO.	25 µg/m³ – annual mean
PM_{10}	– 20 µg/m³ – annual mean – 50 µg/m³ – 24-hour mean	The ANSES agrees with the guidance values established by the WHO.	– 40 µg/m³ – annual mean – 50 µg/m³ – 24-hour mean

An article[52] published in 2014 reviews the literature on the emission of particulate matter by natural fibres, in particular wood and sheep's wool fibre. It summarises dust exposure patterns, toxicological pathways and the hazards imposed by inhalation.

This study concludes that no risk of mesothelioma, lung cancer, lung fibrosis or asthma has been associated with organic fibres.

However, it seems difficult to conclude on the real impact of emission of particulate matters of bio-based insulation because the article mentioned above does not target insulation materials. Moreover, it put less focus on potential inhabitants than on installers and manufacturers, even though it is a crucial parameter.

Thus, more studies on the potential emission of particulate matters by NRFI are needed. In this spirit, the French centre for studies and expertise on risks, environment, mobility, and development (CEREMA) is now starting a study (called EmiBio – *Emissions des Matériaux biosourcés)* on the impact on indoor air quality of wood wool and cellulose wadding used as insulation[53].

---

[49] World Health Organization (WHO). (2005) WHO Air quality guidelines for particulate matter, ozone, nitrogen, dioxide and sulfur dioxide - Global update 2005.

[50] AFSSET. (2010). Valeurs guides de qualité d'air intérieur. Edition scientifique

[51] UK AIR - Air Information Resource: National air quality objectives and European Directive limit and target values for the protection of human health.

[52] Mansour, E., Loxton, C., Elias, R., & Ormondroyd, G. (2014) Assessment of health implications related to processing and use of natural wool insulation products. Environment International, pp. 402-412.

[53] CEREMA. (2020) Matériaux biosourcés et émissions de polluants en intérieur: deuxième campagne de mesures du projet EmiBio.

→ Focus on the impact of NRFI on onsite workers

Atmospheric wool dust is generated throughout the manufacturing process of sheep's wool insulation products.

The study on health implications related to processing and use of natural wool insulation products concluded **there was no increased risk of mesothelioma, lung cancer or lung fibrosis in workers exposed to natural organic fibres** in contrast to workers exposed to inorganic crystalline fibres such as asbestos.

However, workers with a heavy exposure to organic dust seem to have an increased risk of obstructive lung disease and bronchitis. These effects have not been causally linked to the fibrous shape of the particles but rather to the dust, chemicals absorbed on the dust or microorganisms occurring together with the dust.

Moreover, according to the article, there are no results on the manufacturing of bio-based wool insulation; all studies to date report on findings from the textile industry instead (Mansour, Loxton, Elias, & Ormondroyd, 2014).

4.2 VOCs and Formaldehyde

Materials used within the fabric of the buildings can frequently act as sources of indoor air pollutants such as formaldehyde and other VOCs. In consequence, the WHO but also United-Kingdom and French sanitary agencies published guidelines for different types of VOCs pollutants (including Formaldehyde) and total VOCs (TVOC) emissions. The Table 4 presents these guidelines and the limit values of the performance A+ of the label *Emission within the indoor air* (presented in the section above *Regulations and labels).*

The following experiments have been carried out by researchers and insulation producers to evaluate the impact of NRFI on indoor air quality and health (the results of these experiments are synthesized in the table 5):

- **Maskell, D., da Silva, C., Mower, et al. (2015). Properties of bio-based insulation materials and their potential impact on indoor air quality. ICBBM**

  This paper presents the results of an experiment which measured the emissions of TVOC and formaldehyde from biobased insulations as sheep's wool, hemp fibre, hemp lime, wood fibre and rigid wood fibre board. For this experiment, the products are installed in hermetic chambers. After 3 and 28 days, the air of these chambers were sampled.
- **The tests conducted in BS EN 16516:2017 for Carcinogenic compounds as defined in Annex VI to Regulation (EC) No.1272/2008.**

  The two technical studies concerned an insulation product composed at 75% of sheep's wool and at 25% of polyester, and another composed at 100 % of polyester.
- **Institut Bauen und Umwelt e.V., Environmental product statement, STEICO SE, 2016**

  This study is the environmental product declaration of a wood fibre compartment insulation produced by STEICO SE.
- **ADEME (2017), Comparison of VOC emissions to indoor air from bio-based products used in buildings**

  This study compared different biobased, mineral, and petroleum-based products currently on the French market, based on the assessments of the French label *Emission within the indoor air*.

Table 4 - VOCs guidance values for indoor air

POLLUTANTS	WHO GUIDELINES[54] (2010)	ANSES GUIDELINES - IAQGS[55] (UPDATE IN JULY 2018)	A + PERFORMANCE IN THE LABEL EMISSION WITHIN INDOOR AIR[56] (JUNE 2017)	APPENDIX B OF THE APPROVED DOCUMENT[57] UK GUIDANCE VALUES (2010)
Benzene	– No safe level of exposure can be recommended – The concentrations of airborne benzene associated with and excess lifetime risk of 10^{-4}, 10^{-5} and 10^{-6} are 17, 1.7 and 0.17 µg/m³	– Long-term exposure (> 1 year): 10 µg/m³ – Long-term exposure (>1 year) corresponding to a risk level of 10^{-5} are 2 µg/m³ – Long-term exposure (>1 year) corresponding to a risk level of 10^{-6} are 0,2 µg/m³		
1,2,4-Trimethylbenzene			< 1 000 µg/m³ after 28 days	
1,4-Dichlorobenzene			< 60 µg/m³ after 28 days	
Ethylbenzene		Long-term exposure >1 year: 1,500 µg/m³	< 750 µg/m³ after 28 days	
Formaldehyde	0,1 mg/m³ for 30-minute average	Short-term: 100 µg/m³	< 10 µg/m³ after 28 days	– 100 µg.m³ – 30-minute – 10 µg.m³ – 1-year
Naphthalene	0,01 mg/m³ – annual average	Long-term, for an exposure >1 year: 10 µg/m³		
Trichloroethylene	– Unit risk estimate of $4.3*10^{-7}$ per µg/m³	– Long-term, for an exposure from 14 days to 1 year: 800 µg/m³		

[54] World Health Organisation (WHO). (2010) Valeurs guides de l'OMS pour la qualité de l'air intérieur : le cas de plusieurs polluants.

[55] ANSES. (2018) ANSES's List of Indoor Air Quality Guideline Values.

[56] ADEME. (2017). Comparaison des émissions de COV dans l'air intérieur par les produits biosourcés utilisés dans le bâtiment. Direction Productions et Energies Durables.

[57] Ministry of Housing, Communities & Local Government. (2010). Statutory Guidance - Ventilation: Approved Document F.

	– The concentrations of airborne trichloroethylene associated with and excess lifetime cancer risk of 10^{-4}, 10^{-5} and 10^{-6} are 230, 23 and 2.3 µg/m³	– Long-term exposure (>1 year) corresponding to a risk level of 10^{-5} are 20 µg/m³ – Long-term exposure (>1 year) corresponding to a risk level of 10^{-6} are 2 µg/m³		
Tetrachloroethylene	0.25 mg.m³ – annual average	Long-term exposure >1 year: 250 µg/m³	< 250 µg/m³ after 28 days	
Acrolein		Long-term exposure >1 year: 0,8 µg/m³		
Acetaldehyde		Long-term exposure >1 year: 160 µg/m³	< 200 µg/m³ after 28 days	
Toluene		Short and long-term: 20 000 µg/m³	< 300 µg/m³ after 28 days	
Xylenes			< 200 µg/m³ after 28 days	
2-Butoxyethanol			< 1 000 µg/m³ after 28 days	
Styrene			< 250 µg/m³ after 28 days	
Total VOC (TVOC)			< 1 000 µg/m³ after 28 days	300 µg.m³ – 8-hour

Table 5 - Results of several studies measuring TVOC and Formaldehyde emissions in the indoor air of bio-based products and materials

PRODUCTS / INSULATION MATERIALS	SOURCES	FORMALDEHYDE	TVOC
75% sheep's wool 25% polyester insulation	Tests conducted in BS EN 16516:2017 for Carcinogenic compounds as defined in Annex VI to Regulation (EC) No.1272/2008	<2µg/m3 at 3 and 28 days	9µg/m^3 at 3 days and no VOC above the limit of detection at 28 days (5µg/m^3)
100% polyester insulation		2.8 µg/m3 at 3 days and 2.7 µg/m3 28 days	32µg/m3 at 3 days and no VOC above the limit of detection at 28 days (5µg/m3)
Wood fibre[58]	Institut Bauen und Umwelt e.V. (2016). Environmental Product Declaration. STEICO SE.	2 µg/m^3 at 28 days	80 µg/m^3 at 28 days
100 % Sheep's wool	Maskell, D., da Silva, C., Mower, K., Rana, C., Dengel, A., Ball, R., et al. (2015). Properties of bio-based insulation materials and their potential impact on indoor air quality. *ICBBM*.	100 µg/m^3 at 3 days and 107 µg/m^3 at 28 days	573 µg/m^3 at 3 days and < 1 µg/m^3 at 28 days
Hemp fibre		115 µg/m^3 at 3 days and 54 µg/m^3 at 28 days	659 µg/m^3 at 3 days and 158 µg/m^3 at 28 days
Hemp lime 330 kg/m^3 mix		77 µg/m^3 at 3 days	552 µg/m^3 at 3 days
Hemp lime 275 kg/m^3 mix		80 µg/m^3 at 3 days	682 µg/m^3 at 3 days
Wood fibre		134 µg/m^3 at 3 days and 121 µg/m^3 at 28 days	18,220 µg/m^3 at 3 days and 3,192 µg/m^3 at 28 days
Rigid wood fibre board		374 µg/m^3 at 3 days and 242 µg/m^3 at 28 days	280 µg/m^3 at 3 days and 181 µg/m^3 at 28 days
Unnamed biobased product	Agency for the Environment and Energy Management (ADEME) (2017), Comparison of VOC emissions to indoor air from bio-based products used in buildings		Median emission rates of 4 unnamed biobased products: 7,5 µg/m^3 after 28 days

The measured concentrations respect the guidelines — The measured concentrations do not respect the guidelines

Table 5 above allows us to make several conclusions:

1. Biobased products studied show emission rates of TVOCs and Formaldehyde far below the WHO, English, French, and even the A+ Performance of the label *Emission within the*

[58] Institut Bauen und Umwelt e.V. (2016) Déclaration environnementale de produit. STEICO SE.

indoor air, guidelines. **As concluded in the ADEME study, these biobased products do not present a health risk concerning TVOCs and Formaldehyde.**

Moreover, it had to be noted that NRFI are relatively new products on the market. There is therefore potential room for innovation for certain biobased products, to get as close as possible to "zero emission".

2. The materials studied in the paper *Properties of bio-based insulation materials and their potential impact on indoor air quality* show emission rates slightly higher than the listed guidelines (Table 4). This difference with the other studies seems to be related to the fact that **they are materials and not finalized insulating products**. Moreover, the materials are placed in **direct contact with the sampled air, which is not representative of the way insulations are installed**. In fact, they are always covered by other building materials. It is also important to keep in mind that natural and biobased products physical properties, and especially pollutants emissions, will change depending on the variety of plants used and the way insulation products are prepared.

3. To conclude, it is therefore necessary to evaluate VOCs emissions not from materials but from finished insulation products. These measurements must also be carried out in real conditions to be the most representative possible. Finally, it should be noted that **90% of the insulating products on the French market have been classified A+** (best label rating) in the Indoor Air Emission label.

Furthermore, the need for insulation to meet minimum fire performance requirements necessitates the use of flame retardants in many situations. Natural fibre insulation tends to contain inorganic phosphate, sulphate, and borate-based fire retardants. However, none of the fire retardants used in NRFI's are a source of VOC's.

→ Focus on insulation binders

Formaldehyde forms part of phenol formaldehyde binders commonly used in MMMF and MMVF insulation[59]. On the contrary, NRFI in commercial use do not require formaldehyde-based binders (Table 6).[60]

It remains important in most cases to incorporate a binder into insulation to ensure the bulk insulation fibres do not settle in service.

Flexible quilted insulation such as most sheep's wool, hemp and wood fibre use a polyester bi-component binder fibre. The

Table 6 - Binders for each type of insulation

TYPE OF INSULATION		BINDERS COMMONLY USED
MMVF insulation and MMMF insulation		Formaldehyde used as ingredient in the binder
NRFI	Sheep's wool, hemp, and some wood-fibre	Polyester bi-component binder fibre
	Dry formed wood-fibre	Methylene diphenyl diisocyanate (MDI)
	Some types of NRFI, and blown cellulose or wood-fibre	Binder free
	Wet formed wood-fibres	Natural binding properties of lignin

[59] Man-made vitreous (silicate) fibres (MMVF's) or mineral fibre (MMMF's).

[60] ASBP Natural Fibre Insulation Group Members.

binder fibre is composed of 100% polyester, the recycled content of which varying depending on the specification used.

Dry formed wood-fibre insulation is bonded using methylene diphenyl diisocyanate (MDI)[61].

Some types of NRFI are binder free, in particular loose blown cellulose or wood fibre. These insulations rely on compaction to a minimum density in order to ensure the insulation does not slump.

Wet formed wood-fibres relies on the natural binding properties of lignin within the wood fibres to hold the bulk insulation fibres together.

The use of binders that do not include formaldehyde can also represent a first way to prevent emissions of VOCs in indoor ambient air.

4.3 Humidity and mould growth

A frequent concern raised against natural and biobased insulation is their supposed weakness to degradation in humid conditions and susceptibility to mould growth. While no major study has been found on these topics, some knowledge is available on the sensitivity of these natural fibres and panels to mould growth. The following table gives a summary of this knowledge.

Table 7 - Sensitivity of NRFI to mould growth

TYPE OF MATERIALS	SENSITIVITY TO MOULD GROWTH [62]	TREATMENT AGAINST MOISTURE FORMATION
Sheep's wool	The resistance of sheep's wool to mould is controversial.	Yes (boron salt)
Wood	Wood could be susceptible to mould growth	Yes
Flax	Susceptible to mould growth.	Yes (boron salt)
Hemp	Very good humidity regulator. Hemp's is rot-proof, antifungal and antibacterial.	No
Cotton	Very good humidity regulator but susceptible to mould growth.	Yes (boron salt)
Recycled polyester	Polyester is resistant to mould growth. Therefore, there is no information on recycled polyester.	No

As shown by the table 7, hemp and recycled polyester seems to be naturally resistant to mould growth. On the contrary, some NRFI are sensitive to mould growth, especially flax, cotton and wood. In response, these materials are treated with boron salt, among others, that is safe for workers and indoor air quality.

Moreover, sheep's wool, hemp and wood show a very good capacity to regulate the humidity of the air. As an example, the Society for the Protection of Ancient Buildings (SPAB)

[61] Irritant and allergenic product but not very volatile. MDI therefore presents a risk to workers during the production and installation of the insulation.

[62] Université de Nantes : Propriétés et utilisation des fibres naturelles, artificielles et synthétiques,

Guide de la maison écologique : Comparatif des isolants naturels avec des matériaux biosourcés

ECOCO2, Eco-rénovation : les matériaux isolants écologiques.

building performance survey demonstrated a more stable humidity and moisture balance in real life system where wood fibre insulation was used within internal insulation wall treatments[63].

→ **Focus on the link between relative humidity, water activity and mould growth**

Relative humidity (RH) and water activity (a_w) levels within the building fabric greatly influence indoor air quality especially because it influences the growth of moisture. The sorptive properties of natural fibres enables NRFI to bind moisture which in turn has a bearing on relative humidity and water activity.

Water activity is a measure of the availability of water for deleterious reactions, metabolic activity, and growth of microorganisms. Different species of microorganisms have different minimum levels of a_w that permit growth. The growth of most bacteria and fungi occurs at a_w values above 0.90 and if a_w is below 0.8 then only xerophilic moulds and osmophilic yeasts are likely to grow. This is because the energy required to capture water from materials below 0.8 a_w is far too high for most organisms.[64]

In the same way, microbial growth begins to become significant in buildings when relative humidity (RH) rises above 90% with only xerophilic moulds and osmophilic yeasts growing below 80% RH. This is because the energy required to capture water from air below 80% RH is far too high for most organisms.[56]

It is possible to use a_w and RH in conjunction to predict microbial growth and to determine the microbial stability of a product or control the risks from microbial activity in buildings. Indeed, if the moisture content of breathable materials can vary considerably, maintaining water activity below 0.8 reduces the risk of microbial activity within the system.

Therefore, increases in relative humidity do not have a severe impact with "breathable materials" because they can equilibrate the water activity.

→ **Focus on the resistance of NRFI to development of rodents, insects, and mites**

It appears that some NRFI (cotton, sheep's wool, and wood) are susceptible to insects and rodents and should be treated accordingly. On the contrary hemp, flax and polyester are naturally seem naturally resistant to insects and rodents[65].

However, as for the growth of moulds, there is currently no major study on the subject to conclude on the strict sensitivity or resistance of NRFI to pests in different climatic conditions.

[63] Historic England. (2020) SPAB Building Performance Survey - Final report.

[64] Public Health England . (2017) Determination of water activity in food.

[65] Université de Nantes : Propriétés et utilisation des fibres naturelles, artificielles et synthétiques,

Guide de la maison écologique : Comparatif des isolants naturels avec des matériaux biosourcés

ECOCO2, Eco-rénovation : les matériaux isolants écologiques.

4.4 Impacts and benefits of a successful installation

Flexible fibre insulations are, by definition, flexible, and compressible which ensures that the cavities into which these products are installed are fully filled. This property, along with the hygroscopic nature[66] of the NRFI insulations allows the construction to cope with both 'built in' and in-use moisture in such a way as to prevent moisture induced damage[67].

Fully filling cavities is vital to the overall performance of a building as it ensures ventilation losses are eliminated, winter heating and summer cooling are minimised. This also prevents issues associated with condensation in walls and subsequent mould growth, which has an extremely deleterious effect on indoor air quality.

Finally, correctly installed insulation with an appropriate vapour control membrane prevents air passing through the fabric and entering the building. This air movement is not usually an issue in older properties but in new properties where treated/processed timber or plastics are used within the structure, any VOCs released by them can enter the internal space.

[66] The hygroscopic nature of the NRFI means that their moisture content and water activity adjust depending on the relative humidity of the surrounding environment. Hygroscopic materials are capable of adsorbing and desorbing molecular water.

[67] For timber frame construction

5 Conclusions

1. It appears that **NRFIs do not have a significant impact on indoor air quality in terms of particulate matters, VOCs and formaldehyde, and mould.**

2. Workers (manufacturers and installers) may have an increased risk of disease of the respiratory system in case of heavy exposure to dust and fibres (organic and inorganic). Therefore, **ensuring the strict respect of all protective measures (administrative, collective, and individual) is essential for the health of workers**.

3. **In the same manner as rock and glass wool insulation, some NRFIs (cotton, sheep's wool, and wood) needs to be treated against insects and rodents.** On the contrary, flax, hemp and polyester seems to be naturally resistant to these disturbances.

4. **The lack of comparative research**, conducted under real conditions with insulation products, and not under experimental conditions with materials, does not allow strict conclusions on the precise impact of NRFIs and man-made vitreous and mineral fibres on indoor air quality.

5. **The French label Emissions within indoor air appears to be a good way to ensure insulation products meet the national guidelines for indoor air.**

   However, this label has some limitations: 1. It does not include particulate matters and mould growth, and focuses on VOCs, 2. It is not strict enough to distinguish the insulation products currently on the market.

6 Recommendations

In order to provide quality and homogeneous information to users of indoor environments, building contractors and workers installing NRFI, it appears necessary to conduct further research. A systematic approach, inclusive of the diversity of materials available on the, seems a necessary measure to fill the identified data gaps.

In this respect, the BIO-CIRC project partners recommend that the following actions be carried out both in France and in England:

1. Creation of a working group bringing together thematic experts and private, public and academic organisations. The consortium could usefully bring together expertise in eco-construction, air quality measurement, occupational medicine, respiratory diseases and product regulation;
2. Precise mapping of missing, unreliable or non-representative data on all the pollutants identified, the risks incurred by workers and users of buildings;
3. Setting up an experimental plan to obtain systematic knowledge of the behaviour of the insulation materials deployed:
    a. Emphasis should be placed on the *in-situ* measurement (building in operation and on site during installation) of particle emissions;
    b. Similarly, the experimental design should include the notion of material durability and thus study pollutant emissions during material ageing (e.g.: measurement in installations >20 and >50 years);
4. Issuing recommendations to normative bodies, institutions in charge of construction practices, etc. in order to improve, if necessary, the deployment instructions, as well as the construction practices in order to prevent the exposure of workers and users to pollutants.

7 Bibliography

ADEME. (2017). *Comparaison des émissions de COV dans l'air intérieur par les produits biosourcés utilisés dans le bâtiment.* Direction Productions et Energies Durables.

Ademe. (2019). *Un air sain chez soi - des conseils pour préserver votre santé.*

AFSSET. (2008). *Les fibres minérales artificielles siliceuses - Evaluation de l'exposition de la population générale et des travailleurs.*

AFSSET. (2010). *Valeurs guides de qualité d'air intérieur.* Edition scientifique.

Agence française de sécurité sanitaire de l'environnement et du traval (AFSSET). (2010). *AVIS de l'Agence française de sécurité sanitaire de l'environnement et du travail relatif à la proposition de valeurs guides de qualité de l'air intérieur pour les particules.*

ANSES. (2016, 08 24). *Labelling of building and decoration products with respect to VOC emissions*. anses.fr: https://www.anses.fr/en/content/labelling-building-and-decoration-products-respect-voc-emissions

ANSES. (2018). *ANSES's List of Indoor Air Quality Guideline Values.* https://www.anses.fr/fr/system/files/Tableau_VGAI_Juillet2018EN.pdf

CEREMA. (2020). *Matériaux biosourcés et émissions de polluants en intérieur: deuxième campagne de mesures du projet EmiBio.* cerema.fr: https://www.cerema.fr/fr/actualites/materiaux-biosources-emissions-polluants-interieur-deuxieme

Dimitroulopoulou, S., & Shrubsole, C. (2020). *Indoor Air Quality Guidelines for selected VOCs in the UK.* ASBP - Healthy Buildings: Conference and Expo 2020 - Public Health England.

EPRS - Service de recherche du Parlement européen. (2018). *Qualité de l'air : Sources de pollution et leurs effets, législation de l'Union européenne et accords internationaux.* Parlement européen.

European Certification Board for Mineral Wool Products (EUCEB). . http://www.euceb.org/

Health and Safety Executive (HSE). (2011). *EH40/2005 Workplace exposure limits.* HSE Books.

Health and Safety Executive (HSE). . *Man-made mineral fibres (MMMF)*. hse.gov.uk: https://www.hse.gov.uk/foi/internalops/ocs/200-299/oc267_2.htm

Historic England. (2020). *SPAB Building Performance Survey - Final report.*

Institut Bauen und Umwelt e.V. (2016). *Déclaration environnementale de produit.* STEICO SE.

Klepeis, N., Nelson, W., Ott, W., Robinson, J., Tsang, A., Switzer , P., . . . Engelmann, W. (2001). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Science & Environmental Epidemiology*, pp. 231-252.

Korjenic, A., Petranek, V., Zach, J., & Hroudova, J. (2011). Development and performance evaluation of natural thermal-insulation materials composed of renewable resources. *Energy and Buildings*, pp. 2518-2523.

Mansour, E., Loxton, C., Elias, R., & Ormondroyd, G. (2014). Assessment of health implications related to processing and use of natural wool insulation products. *Environment International*, pp. 402-412.

Maskell, D., da Silva, C., Mower, K., Rana, C., Dengel, A., Ball, R., . . . Shea, A. (2015). Properties of bio-based insulation materials and their potentiel impact on indoor air quality.récupéré ré *ICBBM*.

Ministère de la transition écologique. (2017). *Les critères nationaux de qualité de l'air*. AirParif: https://www.airparif.asso.fr/reglementation/normes-francaises

ministère de la Transition écologique et solidaire, ministère des Solidarités et de la Santé, ministère de la Cohésion des territoires et des relations avec les collectivités territoriales. (2013). *Plan d'actions sur* *la Qualité de l'Air Intérieur.* https://www.ecologie.gouv.fr/sites/default/files/Plan_QAI__23_10_2013.pdf

Ministry of Housing, Communities & Local Government. (2010). *Statutory Guidance - Ventilation: Approved Document F.* gov.uk: https://www.gov.uk/government/publications/ventilation-approved-document-f

natureplus. . *Award guidelines.* natureplus.org: https://www.natureplus.org/index.php?id=43&L=2

Observatoire de la qualité de l'air intérieur . . *Pollutions : Les particules*. oqai.fr: https://www.oqai.fr/fr/pollutions/les-particules

Observatoire de la qualité de l'air intérieur. (2006). *Campagne nationale Logements, Etat de la qualité de l'air dans les logements français.* Centre Scientifique et Technique du Bâtiment (CSTB) et Agence Française de Sécurité Sanitaire de l'Environnement et du Travail (AFSSET).

Observatoire de la qualité de l'air intérieur. (2014). *Etude exploratoire du coût socio-économique des polluants de l'air intérieur.* CSTB, ANSES.

Observatoire de la qualité de l'air intérieur. . *Pollutions : Le monoxyde de carbone*. oqai.fr: https://www.oqai.fr/fr/pollutions/le-monoxyde-de-carbone

Observatoire de la qualité de l'air intérieur. . *Pollutions : Le radon*. oqai.fr: https://www.oqai.fr/fr/pollutions/le-radon

Observatoire de la qualité de l'air intérieur. . *Pollutions, les allergènes*. oqai.fr: https://www.oqai.fr/fr/pollutions/les-allergenes

Observatoire de la qualité de l'air intérieur. . *Pollutions, les moisissures*. oqai.fr: https://www.oqai.fr/fr/pollutions/les-moisissures

Papadopoulos, A. (2004). State of the art in thermal insulation materials and. *Energy and buildings*, pp. 77-86.

Public Health England . (2017). *Determination of water activity in food.*

Raw, G., Coward, S., Brown, V., & Crump, D. (2004). Exposure to air pollutants in English homes. *Journal of Exposure Analysis and Environmental Epidemiology*.

Royal College of Paediatrics and Child Health (RCPCH). (2020). *The inside story : Health effects of indoor air quality on children and young people.* Royal College of Physicians.

Settimo, G., Manigrasso, M., & Avino, P. (2020). Indoor Air Quality: A Focus on the European Legislation and State-of-the-Art Research in Italy. *Atmosphere*.

The Royal College of Physicians (RCP) and the Royal College of Paediatrics and Child Health. (2016). *Every Breath We Take: The Life Long Impact Of Air Pollution.*

Trades Union Congress (TUC). (2011). *Dust in the worplace, guidance for health and safety representatives.*

Tsakas, M., Siskos, A., & Siskos, P. (2011). Indoor Air Pollutants and the Impact on Human Health. *Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality*.

UK AIR - Air Information Resource. . *National air quality objectives and European Directive limit and target values for the protection of human health.*

United States Environmental Protection Agency (EPA). . *Volatile Organic Compounds' Impact on Indoor Air Quality*. epa.gov: https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality#:~:text=Additional%20Resources-,Introduction,ten%20times%20higher)%20than%20outdoors.

Veolia Institute in partnership with Nomadéis. (2020). Managing indoor air quality to protect occupant health. (T. V. Review, Éd.) *Indoor air quality: tackling the challenges of the invisible*, pp. 8-13.

World Health Organisation (WHO). (2010). *Valeurs guides de l'OMS pour la qualité de l'air intérieur : le cas de plusieurs polluants.*

World Health Organisation. (2018). *Ambient air pollution: A global assessment of exposure and burden of disease.*

World Health Organization (WHO). (2005). *WHO Air quality guidelines for particulate matter, ozone, nitrogen, dioxide and sulfur dioxide - Global update 2005.*

EUROPEAN UNION

Interreg

EUROPEAN UNION

France (Channel Manche) England

BIO-CIRC Project

European Regional Development Fund

The BIO-CIRC project is part of the cross-border European Territorial Cooperation (ETC) Programme Interreg VA France (Channel) England and benefits from financial support from the European Regional Development Fund

nomadéis

ASBP The Alliance for Sustainable Building Products

therma fleece® Nature's finest insulation

backtoearth