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D2.5 – Technical market application report

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D2.5

Technical References

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Executive Summary

This document describes the mapping of application potential of bio-based solutions. It includes the technical evaluation of the properties of the preselected bio-based materials and compares them with standard thermal insulating reference materials. Further, it collects the essential information and analyses multiple aspects such as availability of the biomass feedstock, production capacities, logistics and transport possibilities, professional skills and all other relevant aspects enabling the TRL assessment.

Section 1 sets the context, describes the state of the art and provides detailed description of the objectives of the deliverable.

Section 2, the state of the art, provides the definition of bio-based product and offers an insight into history of use of the bio-based materials. Furthermore, few figures from the thermal insulation market are given, wide variety of materials are described including their properties.

Section 3 provides an overview of bio-based thermal insulation materials putting them into groups by origin. This section includes also pre-selected materials for BIO4EEB demonstration projects.

Section 4 presents the comparison of bio-based materials with common thermal insulation materials.

Section 5 outlines the framework for bio-based products. It is focused on the biomass feedstock and various aspects of the supply chain. Estimation of the application potential through typological approach (ref. EU project TABULA) is made.

Section 6 identifies the drivers and future trends for bio-based insulation materials.

Section 7 presents the policy framework on the bio-based materials.

Section 8 provides brief conclusions in few points.

Disclaimer

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Abbreviations and Acronyms

Abbreviation	Description
CED	Cumulative Energy Demand
EU	European Union
EN	EN: European Norm (used before a number to indicate a European standard, e.g., EN 16798-1)
EPD	Environmental Product Declaration
EPS	Expanded polystyrene
ETICS	External Thermal Insulating Composite Systems
GHG	Greenhouse Gases
GWP	Global Warming Potential
ISTAT	Italian National Institute of Statistics
INSEE	National Institute of Statistics and Economic Studies
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
FEDIOL	EU vegetable oil and protein meal industry association
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
LDF	Low Density Fiber
LECA	Light Expanded Clay Aggregate
MDF	Medium Density Fiber
MRL	Market Readiness Level(s)
PUR	Polyurethane
TRL	Technology Readiness Level(s)
VIP	Vacuum Insulation Panel
XPS	Extruded polystyrene

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1 Introduction

1.1 Background

This report is part of Work Package 2 (WP2) within the BIO4EEB project (101091967), funded by the European Commission under the new Horizon Europe programme. BIO4EEB aims to close the increasing gap of insulation material shortage caused by the regular growing demand and the mismatch caused by lacking production potential and the outcome of the current energy crisis by boosting the use of available bio-based qualified materials as alternative solutions. To do this, BIO4EEB focuses on mapping of the application potential of bio-based solutions. The mapping consists in several tasks, mainly the overview of the biomass feedstock in the EU countries, technical evaluation of the properties of the preselected bio-based materials and their comparison with standard thermal insulating materials, technology readiness, public awareness of the benefits of bio-based materials, the market readiness for the commercialization and co-operation between the stakeholders in the value chain. The expression “biobased material” in this report refers to bio-based thermal insulation materials. The application potential assessment is enabled through building typology approach. Each national typology consists of a classification scheme according to building size, age and further parameters and a set of exemplary buildings representing these building types. Building typologies seem to be a good means to combine communication about bio-based refurbishment measures for single buildings with the overall building stock scope. Finally, the task T2.4 identifies the drivers and future trends and overview of the policy framework across the EU countries.

1.2 Aims and objectives

Task 2.4 and the corresponding deliverable of D2.5 set out to deliver the following:

Table 1- Aims and objectives of Task 2.4

From an academic perspective:	From a practical perspective:
• Provide knowledge of the material properties and deliver technical data sheets that can be further used as a basis for testing and research activities • Provide inputs for product-based learning strategies in biobased materials education	• Provide inputs for T2.5 architectural definition of the digital BIO4EEB platform • Provide information to the bio-based product developers and manufacturers • Facilitate the decision-making process, finding optimized solutions and best renovation strategies for the demonstration cases

1.3 Target audience

- Scientific research organizations and researchers who can use these findings as a base for further investigations.
- Professionals in building materials industry.

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- Investors and developers going green and environmentally sustainable with their projects.
- Marketing and sales specialists.
- Energy specialists, architects and building contractors.
- Sustainable housing policy makers

2 State of the Art

2.1 Market context

2.1.1 Definition

According to the European commission (*2023*), the bio-based products are wholly or partly derived from materials of biological origin, excluding materials embedded in geological formations and/or fossilised. However, for the building materials descripted in this study, the definition is rather broad and some quantification is needed. Therefore, the materials, in which the biological component prevails (i.e. they contain more than 50% by volume of biological materials) are considered to be bio-based in this study.

2.1.2 History

Bio-based building materials have been used by the humankind from the very origin of human race. Locally accessible materials were used by first people. Wood usually served for the load-bearing structures, while other biological materials were used for the roofs (reed, straw), thermal insulations (cellulose fibres from different plants) or as addition to the inorganic (mainly gypsum) plasters (animal hairs, molasses). Remains of shelters, built from wood and animal skins 500 00 years ago were found in France [Jean Airvaux, Jackie Despriée, Alain Turq, et al., Premières présences humaines en France entre 1,2 et 0,5 million d'années, éd. Musée national de Préhistoire - Les Eyzies-de-Tayac, 2012]. Nevertheless, during the history, the bio-based materials were gradually replaced by man-made materials because of better properties as a mechanical strength, durability, price. However, the significance of bio-based materials increases nowadays because of the increasing demand for lower energy consumption and lower utilization of irreplaceable natural resources (minerals, petroleum). The biggest potential of bio-based products lies mainly in the field of thermal insulations.

2.1.3 Thermal insulation market

Thermal insulations play more and more important role in the construction industry, because the demand for energy efficiency of buildings is constantly increasing. While the global market size of building insulation materials achieved 28 billion U.S. dollars in 2021, it is expected to reach 33 billion U.S. dollars by 2026. (*Daedal Research, 2022*). According to the volume, the production of thermal insulating materials in Europe achieved more than 20 million tons in 2016.

About 30% of the global market belongs to Europe countries (8.5 billion US dollars in 2015). Market forecast for representative Eu countries is depicted in Figure 1. *(Pavel and Blagoeva, 2018)*

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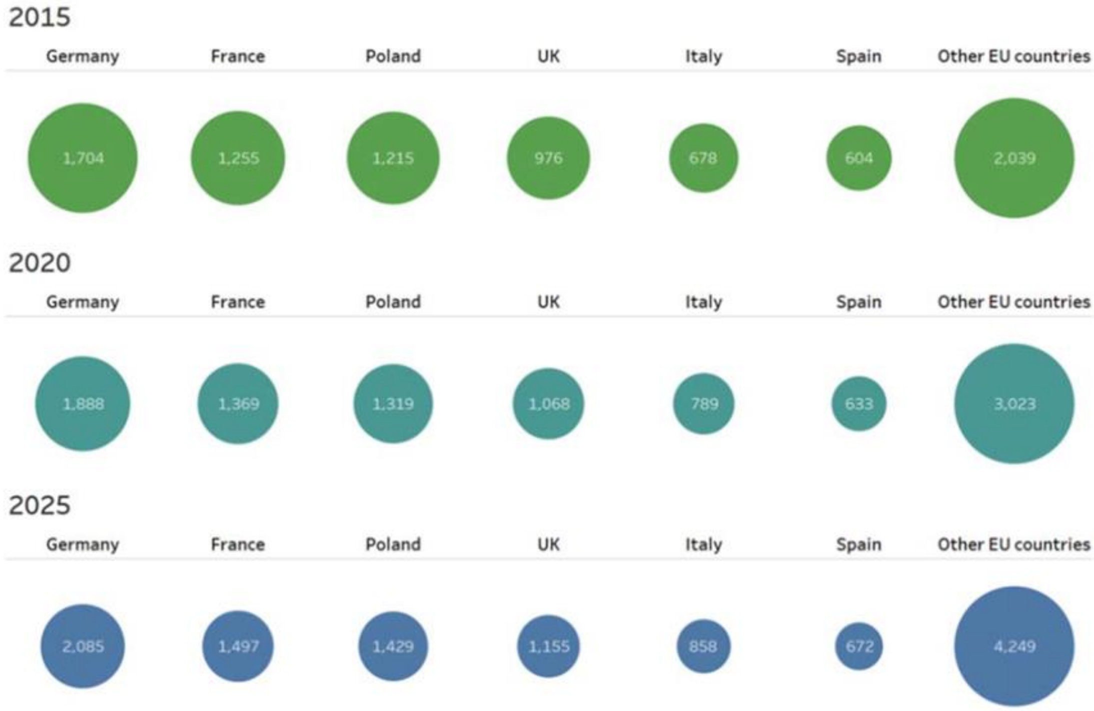

Figure 1- Market forecast of thermal insulation materials for representative EU countries in million US dollars *(retrieved from Pavel and Blagoeva, 2018)*

2.1.4 Properties of thermal insulating materials

The main thermal parameters of thermal insulations are thermal conductivity, specific heat capacity and thermal diffusivity. Thermal conductivity is ability of material to conduct heat and is expressed by the coefficient of thermal conductivity λ (W/m·K), which is defined as the quantity of heat conducted per second through a unit area of a slab of unit thickness when the temperature difference between its ends is 1K. Specific heat capacity C (J/kg·K) express the ability of material to store thermal energy and is defined as the heat which can increase one unit temperature of a mass unit of a substance. Thermal diffusivity a (m^2/s) describes the rate of temperature spread through a material and it is calculated as the ratio between thermal conductivity and the bulk density ρ and specific heat capacity. While the thermal conductivity is constant for the material, the insulating ability of product with defined thickness is described by the thermal resistance R-value (m^2·K/W), which is calculated as a ratio between the material thickness and thermal conductivity.

All the thermal properties are closely related to the bulk density, which is defined as a ratio between the mass of the material (kg) and volume of the material with all the pores and cavities in the material (m^3). For porous materials the bulk density gives better information about the behaviour of materials than specific density (i.e. ratio between the mass and volume of solid phase only). Air itself is very good thermal insulator (thermal conductivity 0.025 W/m·K at 25 °C), when dry and immobile, therefore the amount of dry air in the pores plays important insulation role.

Important parameter of thermal insulations is their reaction to fire. The European standard EN 13501-1 defines classes of reaction to fire (A1, A2, B, C, D, E, F), where the A1 is best one. It also defines the parameters, according which the materials are classified.

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The vapour permeability of materials is described most often by water vapor resistance factor μ-value (unitless) and it is a measure of the material's relative reluctance to let water vapour pass through. The higher the μ-value the lower the permeability. Also, the equivalent air layer thickness s_d (m) is sometimes used. It is a measure of how much resistance to moisture diffusion the material has, when compared to a meter of air. A material is considered as a vapor barrier if $s_d \geq 1000–1500$m and as a vapor retarder if $s_d \geq 10$ m.

Life cycle assessment (LCA) is usually used for the environmental characterization of materials. Cumulative energy demand (CED) and global warming potential (GWP) are usually used as an indicators of environmental burden. LCA can be performed using Cradle to grave approach or Cradle to gate approach. All the environmental impacts are normalized to a functional unit (f.u.), which, according to the Council for European Producers of Materials for Construction, in building thermal applications is defined as the mass in kg of material needed to have a value of thermal resistance equal to1m^2 K/W for a 1m^2 panel. Therefore, CED is expressed in terms of MJ/f.u. and GWP in kg $CO_{2,\ eq}$/f.u.

2.2 Conventional thermal insulating materials

Thermal insulating materials can be made from inorganic minerals, petroleum, plants or animals. The commercially available materials of each group are given in Table 2. The most common materials are mineral fibres (glass and stone wool) and expanded polystyrene, which made about 85% of the whole thermal insulations production in Europe. From the group of bio-based materials mainly products based on wood or other cellulose fibres are commonly used. The distribution of commercial thermal insulation products in Europe in 2018 can be seen in Figure 2.

Table 2- Types of commercial thermal insulating materials

<table>
<tr><td>Type</td><td>Inorganic</td><td colspan="3">Organic</td><td>Special</td></tr>
<tr><td>Feedstock</td><td>Minerals</td><td>Petroleum</td><td colspan="2">Bio-based (plants or animals)</td><td></td></tr>
<tr><td rowspan="7"></td><td>Stone wool</td><td>Expanded polystyrene (EPS)</td><td rowspan="5">Cellulose fibres</td><td>hemp,</td><td rowspan="3">Vacuum insulated panel (VIP)</td></tr>
<tr><td>Glass wool</td><td>Polyurethane foam (PU)</td><td>flax</td></tr>
<tr><td>Cellular glass</td><td>Polyisocyanurate foam (PIR)</td><td>wood fibres</td></tr>
<tr><td>Vermiculite</td><td>Extruded polystyrene (XPS)</td><td>straw</td><td>Aerogels</td></tr>
<tr><td>Expanded clay</td><td>Phenolic foam</td><td>cotton</td><td></td></tr>
<tr><td>Perlite</td><td>Rubber foam</td><td colspan="2">Cork</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Sheep wool</td><td></td></tr>
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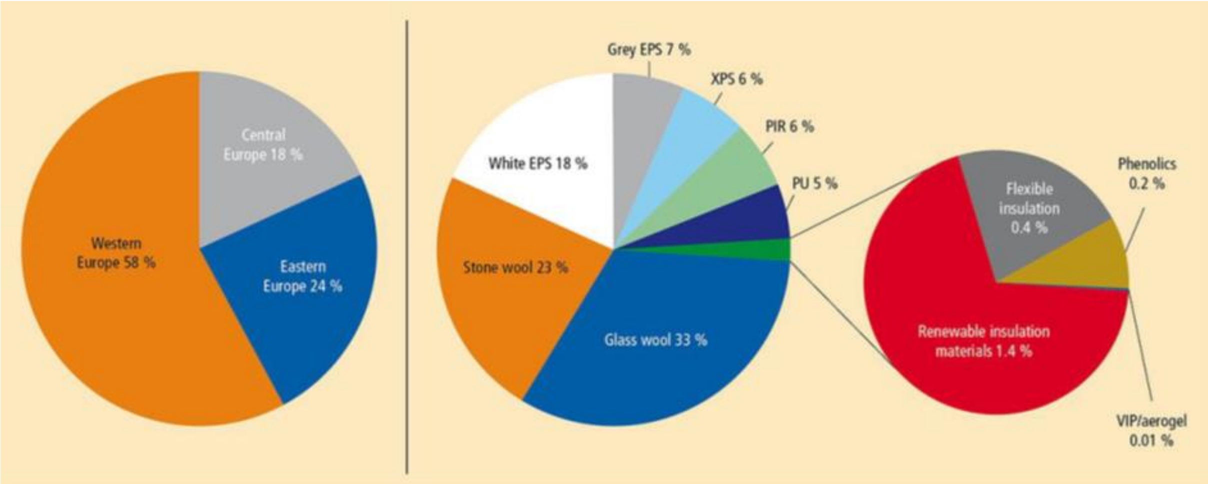

Figure 2- European thermal insulation market by region (left) and product (right) in 2018 (total = 270 million m^3) (*retrieved from Cardellini and Mijnendonckx, 2022*)

2.2.1 Inorganic thermal insulation materials

2.2.1.1 Mineral wool

Mineral wool is general term for fibrous materials, manufactured from different inorganic minerals (stone, glass, slag). Stone wool is made from basalt, diabase or similar rocks, glass wool from natural sand and recycled glass. Raw materials are melted at the temperatures between 1300 °C (glass wool) to 1600 °C (stone wool). The melted material is fiberized by centrifugation or blowing (Fig. 3). Binding agent is added to keep the fibres together and improve the physical and mechanical properties.

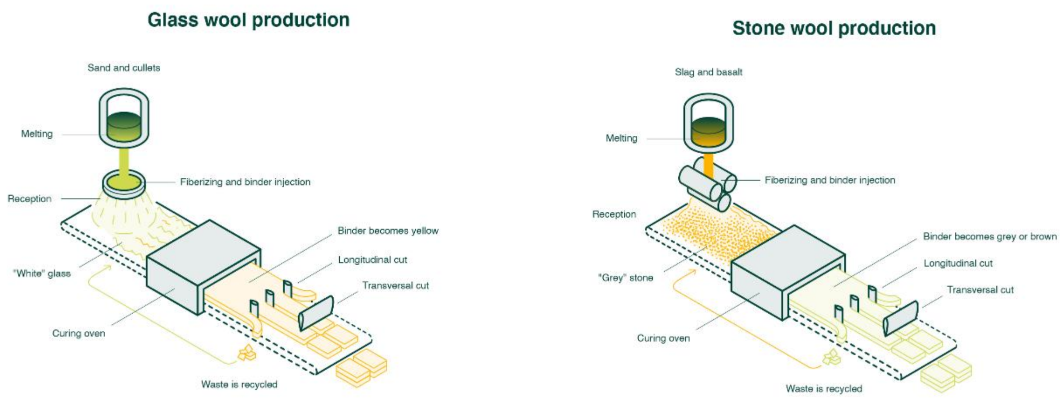

Figure 3- Technological route of glass wool (left) and stone wool (right) production (*retrieved from* [*www.eurima.org/how-is-mineral-wool-insulation-made*](www.eurima.org/how-is-mineral-wool-insulation-made))

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The fibres are than formatted into panels, felts, pipe sections or rolls or they can be used as a loose fibre for cavities filling (Fig. 4).

Figure 4 - Mineral wool products

The thermal conductivity of mineral wools ranges from 0.033 to 0.04 W/m·K, bulk density from 40 to 200 kg/m^3. Main advantage of this material is, besides very good thermal insulating properties, also good fire resistance (class A1 or A2) and good sound absorption. This material is open for water vapour diffusion, which can be advantage in the case of insulation of moist walls, but it can be disadvantageous in the passive houses.

2.2.1.2 Cellular glass

Cellular (or foamed) glass is rigid material, made mainly from recycled glass (cullet) and blowing agent (usually carbon). Glass is melted (at about 800 °C) and blowing agent releases a gas, forming closed pores. Typical thermal conductivity values for foam glass are between 0.038 and 0.055 W/m·K. Cellular glass has zero water vapour permeability, and it is non-flammable. It is used in the form of panels or as an aggregate for underground use (Fig. 5).

Figure 5 Cellular glass products (*retrieved from https://www.owenscorning.com/en-us/insulation/foamglas*)

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2.2.1.3 Expanded clay

Lightweight expanded clay aggregate (LECA) is produced from clay particles, heated to temperatures up to 1.150 °C in rotary kilns. This process transforms the clay into various sized lightweight aggregates with a hard-ceramic shell and a porous core. Its thermal conductivity is about 0.08 to 0.2 W/m·K, therefore it is not typical thermal insulating material, but its rather high density (290 – 750 kg/m^3) allows to obtain low thermal diffusivity levels. It is used also as an efficient sound absorber.

2.2.1.4 Expanded vermiculite

Vermiculite is hydrous phyllosilicate mineral which undergoes significant expansion when heated. The thermal conductivity of the expanded vermiculite is between 0.062 and 0.090W/mK and the density of the loose material is between 85 and 105kg/m^3.

2.2.1.5 Expanded perlite

Perlite is an amorphous volcanic glass with high water content. When calcined at 1000°C, the water molecules inside evaporate and material expands up to 20 times its original volume. Typical expanded perlite has a bulk density of about 30–150 kg/m^3 and the thermal conductivity between 0.040 and 0.052 W/m·K.

The expanded clay, vermiculite and perlite are examples of so-called lightweight aggregates. Lightweight aggregates are granular materials, which can be used loose or as a filler in the mortars and light-weight concretes.

2.2.2 Petroleum based thermal insulations

2.2.2.1 Expanded polystyrene (EPS)

Expanded polystyrene is produced from polystyrene beads, impregnated with the foaming agent (pentane). Beads are subjected to steam heating and they expand by around 40 times (Fig. 6). Expanded beads are then put into the moulds and reheated using steam. They expand by further 10% and stick together, forming the rigid foam. EPS has low thermal conductivity (0.031 – 0.037 W/m·K) and low density (15 – 75 kg/m^3). When used for building purposes, the fire-retardant agent has to be added, because pure polystyrene is easily flammable. EPS has rather high water vapor resistance. It is used mostly in the form of panels, which can be easily cut to the required dimensions. It can be bought also in the form of loose polystyrene beads, which can be used for filling of cavities or as a filler in the light weight concretes and mortars.

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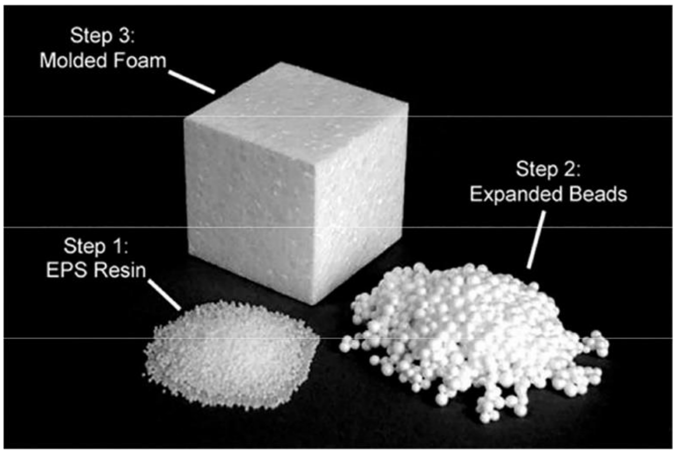

Figure 6- Polystyrene beads before (left)and after expansion (right) and final product (above). (retrieved from *Sulong et al, 2019*)

2.2.2.2 Extruded polystyrene (XPS)

XPS is chemically identical to the EPS, but its producing process and final structure are different. XPS is produced by melting the polystyrene beads in the extruder with the addition of blowing agent. Because its pores are mostly closed, it has lower water absorption and it has better mechanical properties then EPS. Its thermal properties are similar to EPS. Because XPS is about 10 - 30% more expensive than EPS, it is usually used for more demanding applications (floors, inverted flat roofs).

2.2.2.3 Polyurethane foam (PU)

Polyurethanes are rather large group of materials, formed by the exothermic reaction between di- or polyisocyanate with a polyether polyol. Polyurethanes can be used in different forms, but the principal consumption of PUs is in the form of foams (Fig. 7).

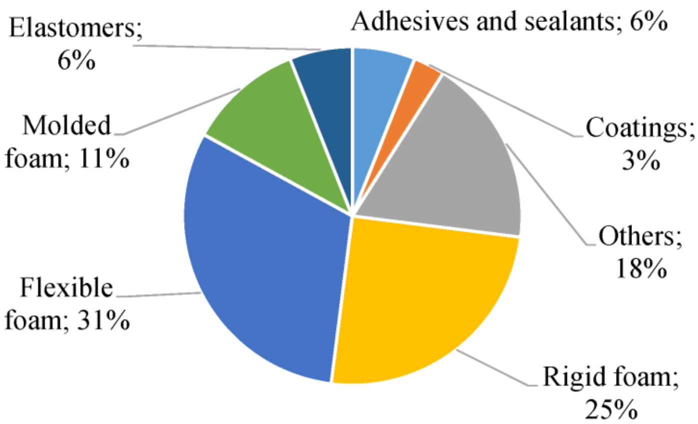

Figure 7- Global consumption of polyurethane (PU) in 2016 (retrieved from *Gama et al, 2018*)

PU foams has thermal conductivity in range from 0.025 to 0.040 W/m·.K. PU foam is often used as a sprayed insulation, where the two components are mixed in-situ in the special device and then sprayed on the substrate (wall or roof). The polymerization and expansion take place almost immediately. The rigid PU foams can be also used in the form of panels, similar to EPS panels.

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2.2.2.4 Phenolic foams

Phenolic foams are produced from phenolic resins by several foaming methods. Phenolic resins are synthetic polymers produced by polycondensation between phenol and formaldehyde. The foaming is made most often by volatilizing a solvent with a low boiling point (*Mougel et al, 2019*). Producers declare very low thermal conductivity (0.018 – 0.028 W/m·K) (*EPFA, 2023*) at bulk densities 60 -160 kg/m^3. Nevertheless, thermal conductivity of dry phenolic foam, measured in laboratory had 0,036 W/m·K and it was significantly affected by humidity (λ increased to 0,081 W/m·K at 100% humidity) (*Wang et al., 2023*). On the other hand, the phenolic foam has very good reaction to fire, compared to other polymer foams. Declared reaction to fire is B-s1-d0.

2.3 Special thermal insulation materials

2.3.1 Aerogels

Aerogels are an open-celled, mesoporous, solid foam that is composed of a network of interconnected nanostructures and that exhibits a porosity (non-solid volume) of no less than 50%. They are ultralight material derived from a gel, in which the liquid component for the gel has been replaced with a gas, without significant collapse of the gel structure. The most common is silica aerogel, prepared from silica gel (amorphous SiO_2) by drying the gel at supercritical temperature. The detailed production process is described in Dorcheh and Abbasi (*2008*). Silica aerogel porosity is between 85% and 99.8%. Its thermal conductivity ranges from 0.0131 to 0.0136 W/m·K at extremely low density (3 kg/m^3). However, the density of commercial aerogels for building applications is usually between 70 – 150 kg/m^3 and their thermal conductivity is about 0.015 W/m·K. It is rather fragile material and has to be protected well from moisture, because contact with water could demolish an aerogel structure because of the surface tension in the pores (*Baetens et al., 2011*). Aerogels are produced in the form of flexible blankets they can be used as a classical thermal insulation of buildings. Another form of aerogels are translucent granules, and in this form, they can be applied over large areas in new buildings for daylighting purposes (Fig. 8).

Figure 8- Examples of translucent aerogel insulation as a high performance thermal insulation solution for daylighting (retrieved from *Baetens et al., 2011*).

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2.3.2 Vacuum insulation panels (VIP)

Vacuum insulating panels consist of a gas-tight multilayer envelope surrounding a microporous rigid core, from which the air has been evacuated (Fig. 9). Open cell foams (silica foam, PU or EPS), powders (silica aerogels, expended perlite) or glass fibres are used as a core and metal foils, metalized polymer films or polymer foils are used for the envelope (*Alam et al., 2011*). Commercially available VIPs achieve a thermal conductivity of 0.004 W/(m·K) across the centre of the panel, or an overall value of 0.006 – 0.008 W/m·K after allowing for thermal bridging (caused by the envelope). The main problem of VIPs is their cost and the vulnerability to perforation.

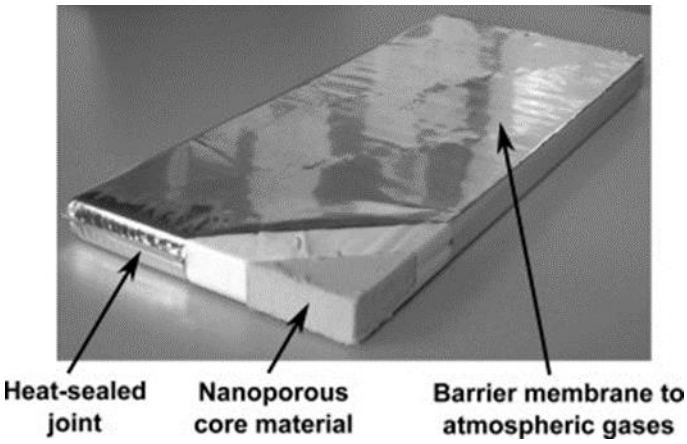

Figure 9- Composition of vacuum insulation panel [10.1016/j.enbuild.2012.07.034]

2.3.3 Bio-based materials

The types and properties of bio-based materials are described in the chapter 3 of this deliverable. They are not divided into commercial or unconventional groups, because for bio-based materials these groups overlap each other.

3 Overview of bio-based thermal insulation materials

3.1 Commercial bio-based materials

3.1.1 Materials based on plant fibers

The most common bio-based thermal insulating materials are based on the cellulose fibres, obtained from different plants (wood, hemp, flax). The production process is similar for all materials. The raw material is cut into small particles and fiberized by the help of steam and the loose particles are then bind together. The bonding is usually achieved by the added glue, which is activated chemically or by the heat. Mostly urea-formaldehyde (UF) or phenol formaldehyde resin (PF) are used, but sometimes the resin, naturally present in the material is used and no other glue is added. After mixing with resin the materials are compressed or hot pressed and the panels with required thickness and density are formed.

Thermo-insulating materials from cellulose fibres has usually the density from 50 to 250 kg/m^3 and their thermal conductivity value is between 0.038 W/m·K up to 0.042 W/m·K. These

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materials have usually high-water vapour permeability, good acoustic insulting properties and relatively high thermal capacity. The main problem of these materials is the vulnerability to the biological attack, rather high water absorption and the flammability (*Bianco et al., 2017*).

3.1.1.1 Wood-based materials

The wood-based boards are generally called fibreboards, even if also particle boards are usually put into this group. According their density, they are classified as low-density fibreboards (LDF), medium-density fibreboards (MDF), and hardboards (high-density fibreboard, HDF). HDF boards are not considered as a thermal insulating material because of their higher density (over 500 kg/m^3), while LDF and MDF boards can be used for thermal insulating purposes. UF resins are used in most of the commercial LDF and MDF boards, nevertheless the boards, bonded by thermo-mechanically treated re-polymerized lignin (naturally present in the wood) can be bought. The density of the fibre boards with natural resin is 140 – 300 kg/m^3 and thermal conductivity 0.037 – 0.07 W/m·K (*Natural Fibre Board, 2023*).

Wood particles can be also bonded by the cement, but the wood has to be mineralized (e.g. by sodium silicate), because fresh wood is incompatible with cement (polysaccharides in wood decelerate the setting time and decrease the mechanical properties of cement). The wood is used in the form of wood wool, chips or fibres. Wood cement composites are quite heavy (density between 320 and 600 kg/m^3) with the thermal conductivity between 0.060 and 0.107 W/m·K and the specific heat between 1.8 and 2.1kJ/kg·K (*Schiavoni et al., 2016*). They have better water resistance then fibreboards. The boards from wood wool (Fig. 10) have also very good acoustic properties.

Figure 10- Wood-wool cement board

3.1.1.2 Hemp

Hemp is a textile fibre produced from Cannabis sativa. The base fibres from hemp have a very high tensile strength and are often used as reinforcement in bio-composites. The industrial hemp binds large amounts of CO_2 plant during growth, faster than most other sources of biomass raw materials. Hemp fibres, used for building applications are usually mixed with polyester fibre and fire retardants. The thermal conductivity of the commercialized materials is between 0.038 and 0.060 W/m·K, the density between 20 and 90 kg/m^3 and the specific heat between1.6 and 1.7 kJ/kg·K (*Schiavoni et al., 2016*). The main problem is the flammability. Material, made from hemp fibres with the 21.75% addition of recycled jute fibres (from coffee and cocoa bean sacks), 9% of PET fibres and 4% of soda as fire retardant (Fig.11) can be bought at the European

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market (*Thermo Hanf, 2023*). This product has bulk density 37 kg/m^3, thermal conductivity 0.04 W/m·K, its reaction to fire is class E.

Another product utilizing hemp is hempcrete, material made from hemp fibres, lime or cement and sand. This material can be used in the form of precast blocks, sprayed or cast in-situ. The bulk density of hempcrete is about 300 kg/m^3 and thermal conductivity 0.06 W/m·K. Its strength is rather low (under 3 MPa), therefore it could not be used as a bearing material, but it can be used as a thermal insulation or timber frame infill.

Figure 11- Hemp thermal insulation (left) (retrieved from https://www.thermo-hanf.de) and hempcrete blocks (right) (retrieved from tecnocanapa-bioedilizia.it)

3.1.1.3 Flax

Flax fibres are produced from plant *Linum usitatissimum*. Flax fibres are usually mixed with polyester to improve mechanical resistance and with additives like boron salts to improve fire and moth resistance. Thermal insulation, using bicomponent fibre (PE and PET) as a binder and sodium carbonate as an impregnation against fire and pests has bulk density 32 kg/m^3 and thermal conductivity 0.039 W/m·K (*JUTA, 2023*). Reaction to fire is class E.

3.1.1.4 Cork

Cork is an outer bark of cork oak (*Quercus suber*) and it is used as a thermal insulation for a long time. Cork contains big amount of closed watertight pores, which cause the excellent thermal insulation properties of cork together with water impenetrability. For building purposes, the granules, obtained as a by-product of the stopper industry are used. For flooring and similar products usually, some binder is added (e.g. linseed oil), but for production of cork thermal insulation cork´s natural resin (suberin) is used. Cork granules are exposed to superheated steam in metal forms. The heating expands the cork granules and activates suberin, which binds the particles together.

Cork insulations are supplied in the form of panel, rolls or loose granules. Thermal conductivity of panels ranges between 0.037 and 0.050 W/m·K, bulk density between 100 -170 kg/m^3. Cork is also very good acoustic material and it is fully recyclable. In the countries, producing cork this material has the lowest value of carbon footprint from other common insulation materials (*Tartaro et al., 2017*).

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3.1.1.5 Straw

Straw is a by-product of cereal cultivation that is available in large quantities and at low cost in a great number of countries. Straw has been one of the first materials to be used in green buildings and there are plenty of buildings constructed using this technique all over the world (*Asdrubali et al., 2015*). Straw can be used in the form of straw bales, as they comes from the harvesting or they can be pressed into the straw panel or construction elements (Fig.12). The thermal conductivity of bales ranges from 0.04 to 0.07 W/m·K according to the bulk density, which is between 50 and 150 kg/m^3. The panels, made from straw, pressed at high pressure at high temperature without any binders and coated by recycled cardboard have rather high thermal insulation (about 0.9 W/m·K) and therefore they can be used as a partitions or cladding, but not as a thermal insulation. The structural wall element, composed from 30 mm clay plaster, 400 mm timber-straw panel and 60 mm wood fibre board has the U-value 0.123 w/m^2·K and its reaction to fire is excellent (B-s1, d0). The thermal conductivity of used straw is 0.0645 W/m·K and bulk density 110 kg/m^3 (*EcoCocon, 2023*).

Figure 12 - House built from straw bales (left) (retrieved from *https://www.veronica.cz/databaze-slamenych-domu?i=2119*) and straw-timber structural elements (right) (retrieved from *https://ecococon.eu/cz/panel*)

3.1.1.6 Reed

The most common types of reed in Europe is common reed (*Phragmites australis*) and another European types are giant reed (*Arundo donax*), reed canary-grass (*Phalaris arundinacea*) and reed sweet-grass (*Glyceria maxima*). Locally can be found also papyrus (*Cyperus papyrus*). Common reed can reach 3 m during 5 - 8 years. It has flat leaves, 10 - 30 cm long, 1-6 cm wide. Reed was used traditionally for roofing. Nowadays some panels can be found in the market, which can be used as internal or external insulation covered with plaster (Fig. 13). The reed stems are pressed together tightly under pressure and are bound with galvanized wire. The panels have the thermal conductivity 0.055 W/m·K at the bulk density 155 kg/m^3. Reed panels have good acoustic properties, if properly designed (*Asdrubali et al., 2015*). However, their use is not very widespread, even if the reed is rather common plant over the world.

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Figure 13 - Reed plant (left) and reed panel (right) (retrieved from https://www.britannica.com/plant/reed-plant and *https://www.hiss-reet.de/en/building-material/reed-panel*)

3.1.1.7 Cattail

Cattail are plants of genus Typha, which have long been used for various purposes, like cleaning wastewater at sewage treatment plants, for detoxifying soils, as raw material for handcrafted wickerwork, as means of nutrition and, in traditional medicine, as a healing plant for various illnesses. Cattail was never cultivated, but because it is highly prolific, there is redundant amount of this material. As one of nature's swamp plants, cattails are resistant to moulds and are very well equipped to deal with moisture.

Luamkanchanaphan et al. (*2012*) prepared insulation board, made from cattail fibres bonded by methylene diphenyl diisocyanate and obtained material had thermal conductivity between 0.044 to 0.061 W/m·K at bulk density 200 - 400 kg/m^3. The magnesite bound cattail insulating panel was made at Fraunhofer Institute, which had thermal conductivity 0.052 W/m·K (Fig. 15) (*Fraunhofer, 2013*).


Figure 14 - Cattail plant (left) and cattail insulating panel (right) (retrieved from https://www.britannica.com/plant/cattail and *Fraunhofer, 2013*)

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3.1.1.8 Corn

Corn plant (Zea mays] is produced worldwide and cobs (the remaining part of the corn ear after stripping the corn kernels) and corn stalks are considered as an agricultural waste. Corn cobs were used as a filling material in traditional Portuguese building called "tabique". In this case the reason for corn cobs use was the utilization of waste, not the insulating purposes (*Pinto et al., 2011*). Nowadays several materials using corn waste was studied. Particleboards made from ground cob particles and wood glue were tested by Paiva et al. (*2012*) (Fig. 16). The particleboards had thermal conductivity 0.101 W/m·K, therefore they were not considered as a proper thermal insulating material. Better results were achieved by Ramos et al. (*2021*). Particleboards bonded by polyvinyl acetate (PVA) and Fabricol AG222 (composition not provided) achieved the thermal conductivity 0.046 - 0.057 W/m·K and 0.076 - 0.097 W/m·K respectively. Composites, prepared from grounded corn particles, bound by epoxy resin achieved the thermal conductivity 0.075 -0.15 W/m·K at bulk densities 280 – 410 kg/m^3 (*Binici et al., 2016*). When gypsum was used instead of epoxy resin, the thermal conductivity increased to 0.11 – 0.20 W/m·K at 540 - 800 kg/m^3. Pinto et al. (*2012*) prepared the lightweight concrete with granulated corn cob particles as aggregates. Material had the thermal transmission coefficient (U-value) 1.99 W/m^2·K for the 5 cm thick panel and average bulk density of this material was 382 kg/m^3.

Interesting materials were prepared from corn cobs particles bonded by natural glue, obtained by alkali treatment of corn cobs or flax fines. But they had higher bulk densities (about 500 kg/m^3) and thermal conductivity (0.13 -0.15 W/m·K) than similar composites using hemp shives as an aggregates (0.067 - 0.079 W/m·K at bulk density 177 - 191 kg/m^3) (*Viel et al., 2019*).

Material made from corn pith (removed from corn stalks), bonded by sodium alginate achieved the thermal conductivity 0.042 - 0.048 W/m·K with the bulk density 60 - 100kg/m^3 (*Palumbo et al., 2018*).

Figure 15 - Corn cobs (left). Corn cob particles (middle) and corn cob particleboard (retrieved from *Paiva,* 2012)

3.1.1.9 Cotton

Because the cotton is the most widespread textile plant, there arises also high amount of plant residues (mainly stalks). Particleboard, made from cotton stalks without binder were tested. Cotton stalks were chipped, softened in steam, fiberized and then pressed in high-frequency hot press. Panels with bulk density 150 – 450 kg/m^3 had thermal conductivity 0.059 - 0.082 W/m·K (*Zhou et al., 2010*).

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Insulating panel made from 100% recycled cotton in polymer matric, obtained from PE/PP wastes achieved the thermal conductivity 0,04 - 0.11 W/m·K at bulk densities 270 – 173 kg/m^3 (*Sezgin et al, 2021*).

Figure 16 - Cotton plant (retrieved from *https://www.britannica.com/topic/cotton-fibre-and-plant*)

3.1.1.10 Rice

Rice is the third most produced commodity in the world (after sugar cane and corn). As a consequence, a large amount of residues is produced causing disposal concerns. Thermal insulation material made from rice straw was developed using high frequency hot pressing. Rice straw was chipped into the particles 10 -30 mm, then the particles were sprayed by methylene diphenyl diisocyanate resin diluted by acetone and material was hot-pressed into boards with bulk density 200 - 350 kg/m^3. Materials achieved the thermal conductivity 0.051 - 0.053 W/m·K (*Wei et al, 2015*). Rice straw was also tested in the form of bales. Rice straw bale with bulk densities 80 kg/m^3 and 100 kg/m^3 had very favourable thermal conductivity (from 0.039 W/m·K to 0.048 W/m·K according to the moisture content of the straw) (*Marques et al, 2020*).Panel from rise straw, bonded by polyester is commercially available (*FBT ISOLATION, 2023*). Panel has low bulk density (50 – 60 kg/m^3) and favourable thermal conductivity (0.039 W/m.K).

Figure 17 - Rice cropping (left) and commercial rice-straw MDF board (right) (retrieved from *Beamon, 2023*)

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3.1.1.11 Rapeseed

Rapeseed (*Brassica Napus*), also known as rape or colza, is an annual plant cultivated as a source of vegetable oil. It is the most prominent oily-seeds plant in Europe nowadays. Particleboards from rape straw are usually glued together by the adhesive. The hybrid pMDI/PF resin bonded boards achieved the thermal conductivity 0.064 to 0.088 W/m·K at bulk densities 450-650 kg/m^3 (*Dukarska et al., 2017*). Binderless board was pressed from rape straw particles, which passed through 4 mm sieve and then exposed to steam. Obtained material had the bulk density about 100 kg/m^3 and thermal conductivity in range of 0.045 – 0.052 W/m·K (*Jerman et al, 2022*).


Figure 18- Rapeseed plant (left) and sample of binderless rape straw board (right) (retrieved from https://www.britannica.com/plant/rapeseed-plant and Jerman et al, 2022).

3.1.1.12 Grapewine

Grapes are widely grown in the world for both fruit, grape juice and wine. Wine production generates a considerable amount of grape pomace. The grape pomace corresponds to all the solid parts that remain at the end of the pressing process. Grape pomace is constituted of the grape skins, stalk, and seeds (Fig. 20). The composites, made from whole pomace, grape skins, grape stalks and crushed stalks were bonded by 20% of potato starch. Composites had bulk density from 227 to 433 kg/m^3 and thermal conductivity from 0.069 to 0.079 W/m·K. Lowest values were achieved with crushed grape stalks, the highest by grape skins. Acoustic properties of the composites belong to class D or E and can be used in insulation in public buildings (*Badouard et al, 2021*).

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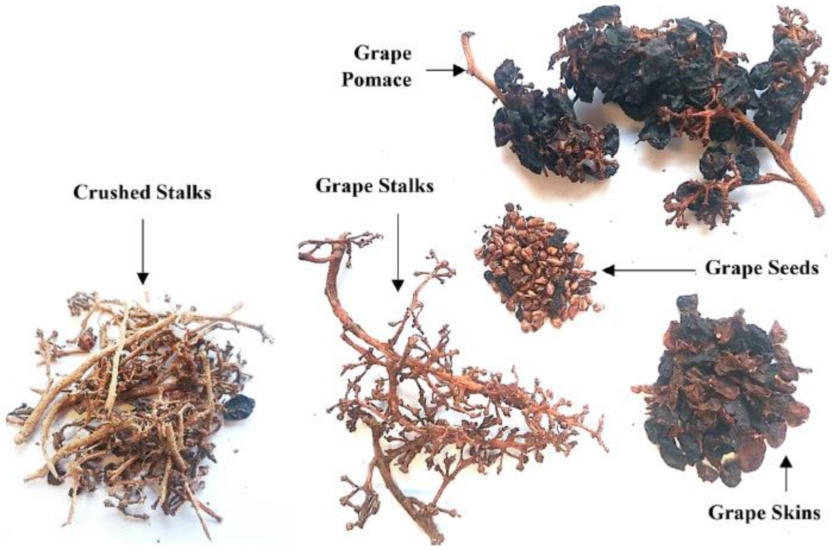

Figure 19 - The elements composing the grape pomace and crushed stalks (retrieved from *Badouard et al, 2021*)

3.1.1.13 Beet

Sugar beet (*Beta vulgaris var. saccharifera*) is widely grown all over the Europe and the process of producing beet sugar generates enormous quantities of by-products. One of these by-products is sugar beet pulp, which can be used as a feed for livestock or an important source of gelling pectin. An agro-composite based on sugar beet pulp and potato starch as a bio-sourced binder was tested by Karaky et al. (*2018*) (Fig. 20). Bulk density of composite ranged from 270 to 360 kg/m^3 according to the starch amount and thermal conductivity was 0.069 to 0.075 W/m·K.

Figure 20 - Sugar beet fruit (a), fresh sugar beet pulp (b), extruded pulp pellets (c) and dried extruded beet pulp (d) (retrieved from *Karaky et al., 2018*)

3.1.1.14 Sunflower

Sunflower (Helianthus annuus L) is cultivated for the high oil content of its seeds. Oil represents up to 80% of its economic value. The board made from sunflower pith without any binder was very light (60 - 80 kg/m^3) and its thermal conductivity was 0,041 – 0,043 W/m·K (*Vandenbossche et al., 2013*).

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The cake obtained after thermo-mechanical fractionation of whole plant and aqueous extraction of sunflower oil was used as a raw material for the production of fibreboards by hot-pressing. Plant proteins acted as an internal binder and they contributed to ensure cohesion of the material, in addition to the entanglement of lignocellulosic fibres also acting as reinforcement. Nevertheless, the most performing sample was quite fragile and characterized by a high thermal conductivity, 0.0885 W/m·K (*Evon, 2014*).

Sunflower stalks were often used together with other natural materials, as a flax (*Mahieu et al., 2019*), wheat straw (*Binici et al., 2020*) or rape straw (*Brouard et al., 2018*). Also material, composed from sunflower stalks, recycled cotton, bonded by gypsum or epoxy resin was studied (*Binici et al, 2014*).

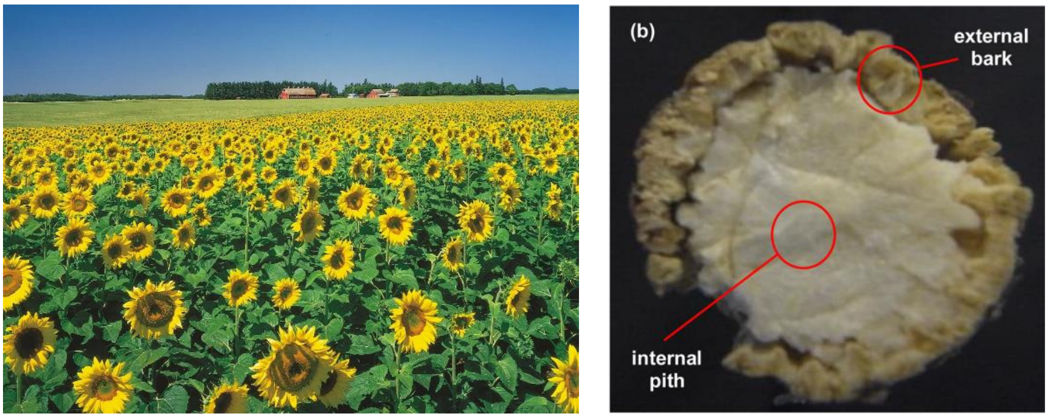

Figure 21 - Sunflower plant (left) and cross-section of sunflower stalk (right) (retrieved from *https://www.britannica.com/plant/sunflower-plant* and *Mahieu et al., 2019*)

3.1.2 Mycelium

Mycelium is the root structure of fungi, made up of interconnected cells called hyphae. This web-like structure spreads throughout its environment, breaking down food with enzymes and absorbing nutrients. Waste agricultural products (e.g. hemp, straw) are used as a nutrient and mycelium is mixed with it. The mycelium feeds itself and grows, binding all the fibres together. It takes place in the growth forms and when it has grown into the required shape, it is heated in an oven to stop the grow. Mycelium insulating panels are offered commercially. The bulk density of the commercialized mycelium material is 155.5 kg/m^3 and thermal conductivity 0.057 W/m·K. The fire resistance is class A according to the ASTM E84. Another commercial mycelium composite, made of locally sourced agricultural biomass like straw, miscanthus and flax with the mycelium growing on them and acting as a binder had the bulk density 97 kg/m^3 and thermal conductivity 0.05 W/m.K. Nevertheless, Mycelium is vulnerable to mould growth in a humid environment (*Koh et al, 2022*). The impact-resistant mycelium-based composites with agricultural waste straws (rice, wheat and corn) were studied by Cai et al. (*2023*) and they achieved the thermal conductivity 0.031 W/m·K at 250 kg/m^3 for composite with rice straw, 0.037 W/m·K at 270 kg/m^3 for wheat straw and 0.072 W/m·K at 370 kg/m^3 for corn straw.

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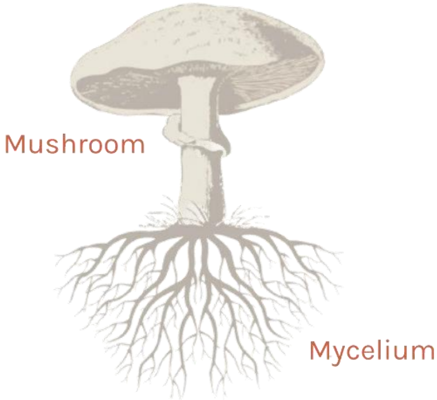

Figure 22 - Mushroom mycelium(left) and insulating panel from mycelium (right) (retrieved from *https://www.grown.bio*)

3.1.3 Bio-based polymeric foams

Large scale of polymeric foams, in which the petroleum-based components were partly or fully substituted by the components, obtained from agricultural, forestry and fishery products (cereal, oil, wood, algae, etc.). E.g. rigid polyester foam, prepared from citric acid, hydrochloric acid and crude glycerol (by-product from biodiesel production) had the thermal conductivity 0.058 W/m·K at bulk density 33 kg/m^3. The cellulose or glass fibres were added for better volume stability (*Auclair and Blanchet, 2020*).

Phenolic foams, using lignin, tannins or several bio-oils were studied by Sarika et al. (*2021*). Formaldehyde-free foam based on flavonoid tannins, extracted from some tree species, and on furfuryl alcohol, a residue from the hydrolysis of the sugars from several agricultural crops achieved low thermal conductivity (0.038 kg/m·K). The foam had an outstanding fire performance, compared to commercial phenolic foams (*Basso et al., 2011*).

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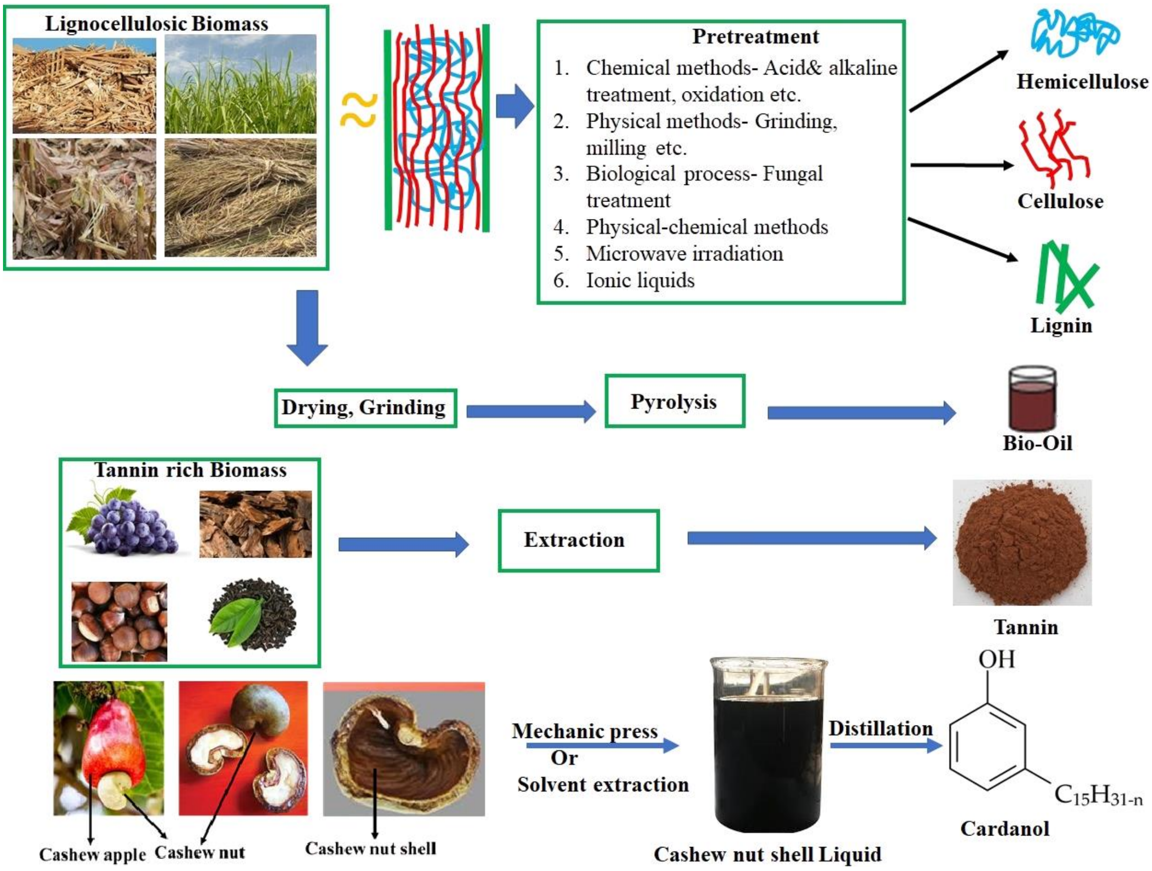

Figure 23 - Schematic demonstrating the conversion of biomass to the various phenolic foam precursors (retrieved from *Sarika et al., 2021*)

3.1.3.1 *Bio-based polyurethanes*

Bio-based polyurethanes are obtained by poly-addition reaction between polyols, isocyanates and suitable blowing agents, similarly to petrol-based polyurethanes. Polyols can be made e.g. by liquefaction of biomass materials. Polyols can be prepared from cellulose or lignocellulose (wheat, soya or rape straw, bagasse, coffee grounds waste, reed), vegetable oils (castor, soybean, rapeseed, sunflower, grapeseed), starch or polysacharides. Only a handful of bio-based polyisocyanates have been reported in literature, based mostly on vegetable oils, nevertheless some bio-based isocyanates are already commercially available. Thermal and mechanical properties of bio-based polyurethane foams are comparable with the petrol-based foams (their thermal conductivity is about 0.03 -0.04 W/m·K at bulk density 30-40 kg/m^3), nevertheless their long-term performance and durability has to be investigated yet (*Andersons et al., 2020, Vieira et al., 2023*).

3.1.3.2 *Graphite polystyrene (GPS)*

Graphite (grey) polystyrene (GPs) is expanded polystyrene with the graphite particles homogenously distributed in the polymer matrix. It is derived from renewable raw materials such as bio-naphtha or biogas extracted from kitchen waste, therefore it is partly bio-based. Graphite particles reflect radiant heat energy, increasing the material's resistance to the flow of heat, or R-value. Its bulk density is 12 - 20 kg/m^3, thermal conductivity about 0.031 W/m·K. Producer

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declares that GPS has about 20% higher thermal efficiency than normal EPS, nevertheless the price of the material is still high.

3.1.4 Sheep wool

Thermal insulations from sheep wool are made either from new or recycled wool fibres and sometimes they are mixed with the polymer fibres (e.g. recycled polyester). According to producer, the mixture with the polymer fibres has better properties. Wool insulations are in the form of batts, roles or loose fibres. The bulk density of sheep wool materials is comprised between 10 and 25 kg/m^3, the thermal conductivity between 0.038 and 0.054 W/m·K. Sheep wool has high hygroscopicity, therefore it can regulate the humidity in the interior. It is also excellent acoustic absorber. Sheep wool has to be treated against pets (especially moths) and fire (class E). Some users report, that wool insulation has a specific smell, when wet.

3.2 Pre-selected bio-based materials in BIO4EEB

3.2.1 Posidonia oceanica

Neptune grass or Mediterranean tapeweed (Posidonia oceanica) is a seagrass species that is endemic to the Mediterranean Sea. It grows in sandy channels around 35 m below sea level close to the beach and can grow up to 1.5 m tall. Dead leaves are washed on the shore in the form fibrous spherical shapes, called “Neptune balls” or as the layers of dead leaves (Fig. 22). They are usually considered to be a waste material and disposed of in open dumps or composted.

Figure 24 - Neptune balls (left) and layers of dead Neptune grass leaves (Photographer: Dimitris Poursanidis, retrieved from *https://www.grida.no/resources/13456*)

The balls can be separated into fine fibres, which were tested in several types of thermal insulating materials. Free fibres are already commercially available for a filling of cavities. The loose bulk density of fibres ranges from 17 kg/m^3 to 155 kg/m^3 (according the compaction level), thermal conductivity is between 0.043 and 0.070 W/m·K (*Hamdaoui et al., 2018*). Fibreboards made from 70% of fibres were hot pressed with partially bio-based epoxy resin as a binder. It

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was found out, that boards, made from untreated fibres had very low mechanical properties, therefore the authors recommended the chemical treatment (by NaOH and silanization) of fibres before their utilization (*Garcia-Garcia et al., 2018*). By addition of 20% of Posidonia fibres into the cement paste, the thermal conductivity of paste decreases about 20% (*Benjeddou et al., 2022*). Air laid panel were made from Posidonia fibres mixed by air flow with 10% of PET fibres. The fibres were then deposited on a moving-air permeable conveyor belt and heated. Panels with density 43 – 103 kg/m^3 had thermal conductivity 0,035 – 0,04 W/m·K (*Ayadi et al, 2022*).

The Posidonia leaves were studied less often. Dry leaves of Posidonia were used as a flat roof insulation in 14 housing units on the Balearic Island of Formentera. A layer of thermal insulation made from Posidonia at a density of 185 kg/m^3 had a thermal conductivity of λ = 0.044 W/m·K (*Carmona et al., 2018*). Dried Posidonia leaves, sprayed by pMDI (methylene diphenyl diisocyanate) resin were cold-pressed and hot-pressed, forming particleboards. They had thermal conductivity from 0.042 to 0.050 W/m·K and bulk density from 150 to 228 kg m^3 (*Kuqo et al, 2022*).

In the presented project, the particleboards, made from dry Posidonia leaves with vegetable resin are researched (Fig. 25). The bulk density of boards is between 159 to 289 kg/m^3. Thermal conductivity ranges from 0.054 to 0.076 W/m·K (Fig. 26). The thermal conductivity increases with the bulk density. Nevertheless, the increase of thermal conductivity is 42% at the increase of bulk density about 80%, which means that the thermal insulating ability can be maintained even at higher bulk densities. The water vapor resistance factor (μ-value) is 30 to 195 and flexural strength of boards is in range 0.33 to 1.34 MPa. All properties are related mainly to the bulk density. The boards were tested for ecotoxicity to algae, and it was found out, that the material is not ecotoxic to them.

Figure 25- Particleboard from Posidonia leaves

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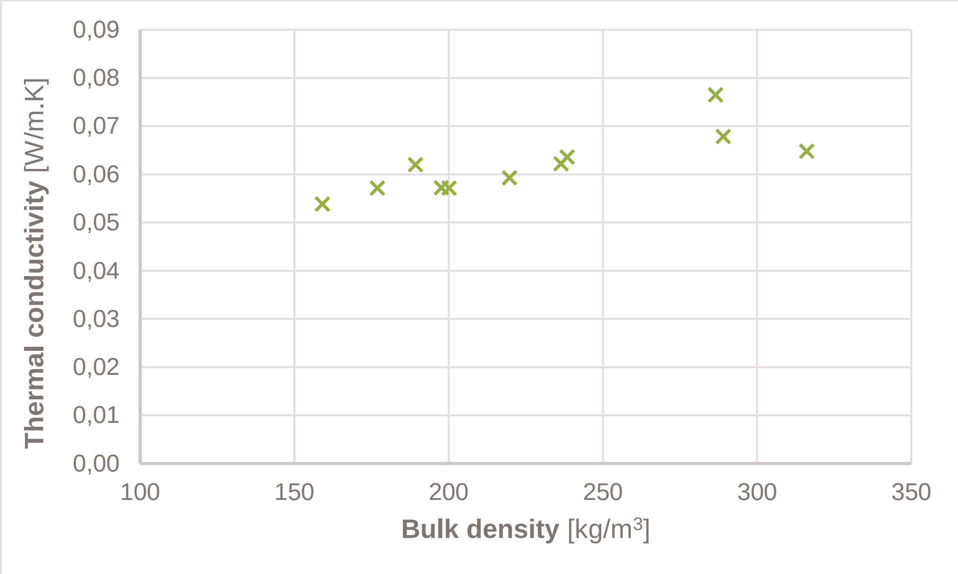

Figure 26 - Thermal conductivity of Posidonia particleboards

3.2.2 Biobased polyurethane foam

Bio-Polyurethane offers excellent insulation performance and high scalability as it can be sourced from multiple natural materials (natural oils, starch, sugar, lignin, proteins, CO2 fixation, etc). It also offers a high bio-based content (up to 75-80%) and a wide range of applications such as spray-foaming and injection-foaming for internal insulation, as well as insulation sheets and sandwich panels applications for external insulation. A circular approach for PUR including different end-of-life pathways is shown as follows:

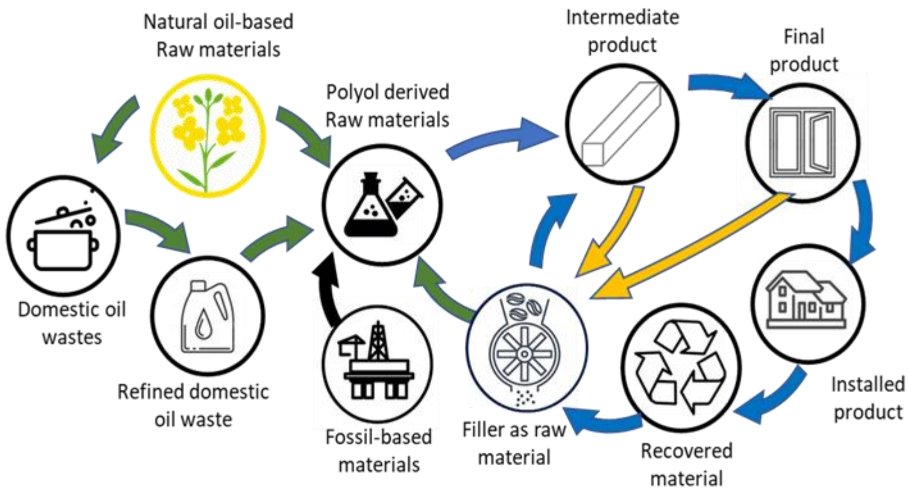

Figure 27- Value chain for Bio-polyurethane

The preferred bioPUR formulations include natural oil-derived polyols (Fig. 27) such as glycerol, dimerized fatty acids and epoxydized oils coming from soy, rapeseed and castor oil sources, as

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well as from lignin. These are commercially available polyols that enable an upscaled production, being this new development of interest for different market applications.

Figure 28- BioPUR formulations developed by INDRESMAT

4 Comparison of bio-based materials with common thermal insulation materials

4.1 Properties

The main properties of the thermal insulating materials (obtained from producers or sources, provided in the previous sections) are given in the Table 3 for non-bio-based materials and Table 4 for bio–based materials.

Table 3- Properties of non- bio-based thermal insulating materials

Material	Bulk density	Thermal conductivity	Specific heat	μ-value	Fire class.
	[kg/m^3]	[W/m·K]	[kJ/kg·K]	[-]	
Mineral wool	40 -200	0.033 – 0.049	0.8 – 1.0	1 - 2	A1 – A2
Cellular glass	80 - 170	0.038 – 0.055	0.84	≥ 40000	A1
Expanded polystyrene	15 – 75	0.031 – 0.037	1.25	20 - 100	E
Extruded polystyrene	32 - 40	0.028 - 0.035	1.3 - 1.7	80 - 150	E
Phenolic foam	60 - 160	0.018 – 0.028	1.3 – 1.4	35	B

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Polyurethane foam	15 - 45	0.025 - 0.040	1.3 – 1.45	30 - 170	E
Polyisocyanurate f.	30 - 45	0.022 – 0.028	1.5	55 - 150	E
Expanded clay	290 - 750	0.080 - 0.200	0.9 – 1.0	5 - 8	A1
Expanded vermiculite	85 - 105	0.062 - 0.090	0.8 - 1.1	2 - 3	A1
Expanded perlite	30 - 150	0.040 - 0.052	0.9 – 1.0	2 - 3	A1
Aerogel	70 – 150	0.013 - 0.014	1.0	4.7 – 5	C
VIP	160 - 230	0.004 – 0.008	0.8	≥ 340000	N.A.

Table 4- Properties of bio-based thermal insulating materials

Material		Bulk density	Thermal conductivity	Specific heat	μ-value	Fire class.
		[kg/m^3]	[W/m·K]	[kJ/kg·K]	[-]	
Wood	Fibreboard	50 - 300	0.036 – 0.07	1.9 - 2.1	1 - 5	E
	Free wood fibres	28 - 38	0.04	2.1	1 - 2	E
	Cement - wood wool	300 - 600	0.06 – 0.107	2.1	≥ 1,47	B
Hemp	Boards and blocks	20 - 330	0.038 - 0.070	1.3 – 1.7	1.5 – 4.5	E
	Hempcrete	200 - 300	0.053 – 0.07	1.3 – 1.5	2.8 – 4.5	A1
Flax		20 - 100	0.038 – 0.075	1.6	1 – 2	E
Cork		100 - 200	0.035 – 0.041	1.67	10 - 13	B
Sheep wool		10 - 25	0.038 - 0.054	1.3 – 1.8	1 – 3	E
Straw bales		85 – 115	0.049	2	2	F
Reed panels		155	0.055	1.2	2 – 6.5	B
Cattail		200 - 400	0.044 - 0.061	N.A.	N.A.	N.A.
Corn	Corn cob boards	280 – 410	0.046 – 0.15	N.A.	N.A.	N.A.
	Corn pith	60 – 100	0.042 - 0.048	N.A.	N.A.	N.A.
Cotton stalks		150 - 450	0.059 - 0.082	N.A.	N.A.	N.A.
Rice	Rice straw board	50 - 350	0.039 - 0.053	1.8	2.8	
	Rice straw bales	80 - 100	0.039	2.2 – 3.2	3.3 – 5.5	

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Mycelium			100 - 370	0.031 – 0.072	N.A.	N.A.	B
Rapeseed			450 - 650	0.064 - 0.088	1.4	4.3 – 5.6	
Grapevine pomace			227 - 433	0.069 - 0.079	N.A.	N.A.	
Beet pulp			270 - 360	0.069 - 0.075	1.4	22 - 29	
Sunflower pith			60 - 80	0,041 – 0,043	N.A.	N.A.	
Foams		PE	33	0.058	N.A.	N.A.	
		PUR	30 - 40	0.03 – 0.04	N.A.	N.A.	
		Bio-PUR (this study)	Same values as PUR expected		N.A.	N.A.	
		Phenolic	20 – 80	0.030–0.048	N.A.	N.A.	excellent
Neptune grass	Balls	Loose fibres	17 - 155	0.043 – 0.07	N.A.	N.A.	
		Panels	43 - 103	0,035 – 0,04	N.A.	1.8 – 2.3	
	Leaves	Loose	185	0.044	N.A.	N.A.	
		Panels	90 - 233	0.042 - 0.050	N.A.	N.A.	passed *
		Boards (this study)	159 - 289	0.054 – 0.076	0.9 – 1.2	30-195	

* Single flame test according to ISO 5660-1

The bulk density of thermal insulating materials can be seen in Fig.29 There can be seen that bio-based materials have generally slightly higher bulk densities (except for the expanded clay aggregates, which are not typical thermal insulating material). Nevertheless, some bio-based materials achieved the bulk density, comparable with the best non-biomaterials. The bulk density of bio-based materials, made from plant fibres strongly depends on the pressing intensity, therefore their range of bulk densities can be very large. Properties of bio-based foams are comparable with the petroleum based one.

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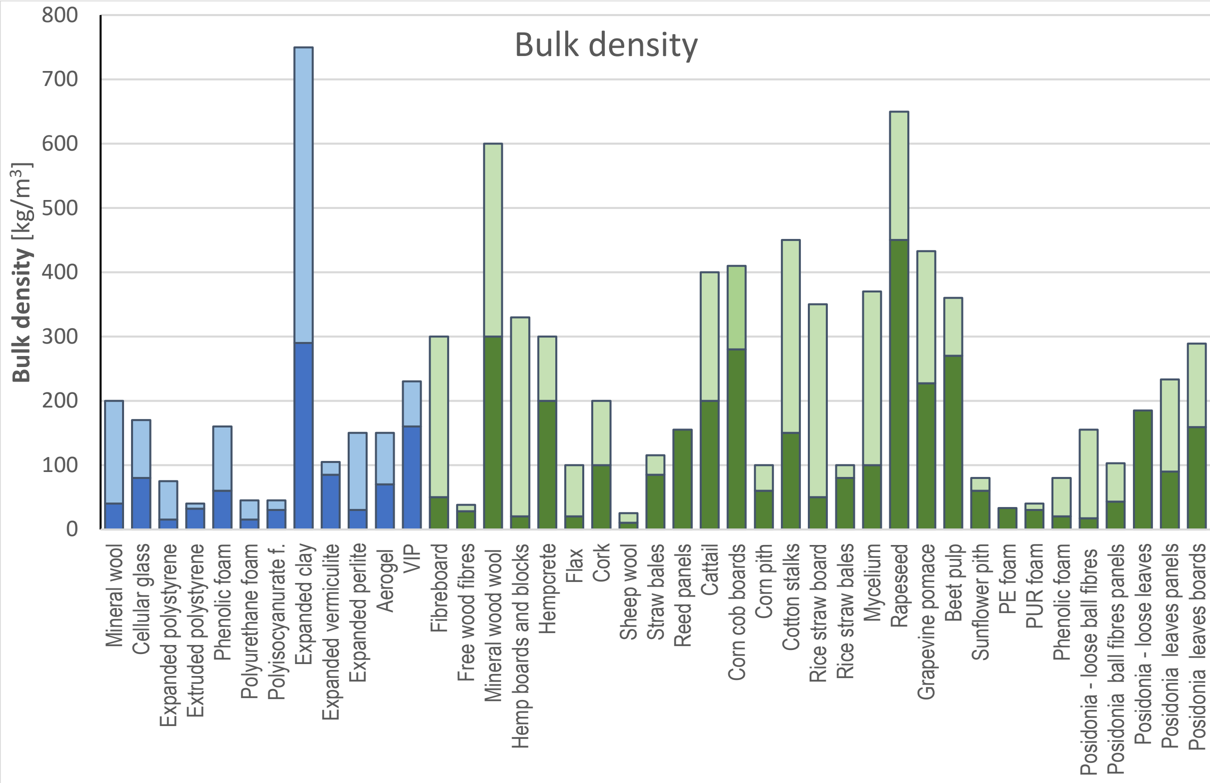

Figure 29 - Range of bulk densities of thermal insulating materials (dark colour are for minimal values, light colours for maximal values)

The thermal conductivity is considered as a most important property of thermal insulting material (Fig. 30). As can be seen, the thermal conductivity of the bio-based materials is also slightly higher than the thermal conductivity of non-bio materials. It is logical, because the thermal conductivity is strongly related to the bulk density. However, the thermal conductivity of bio-based materials is lower than 0.01 W/m·K, which is generally considered as a threshold value between the insulating and non-insulating materials. The only exception is the experimental board from corn cobs and even for that material the lower thermal conductivity was achieved.

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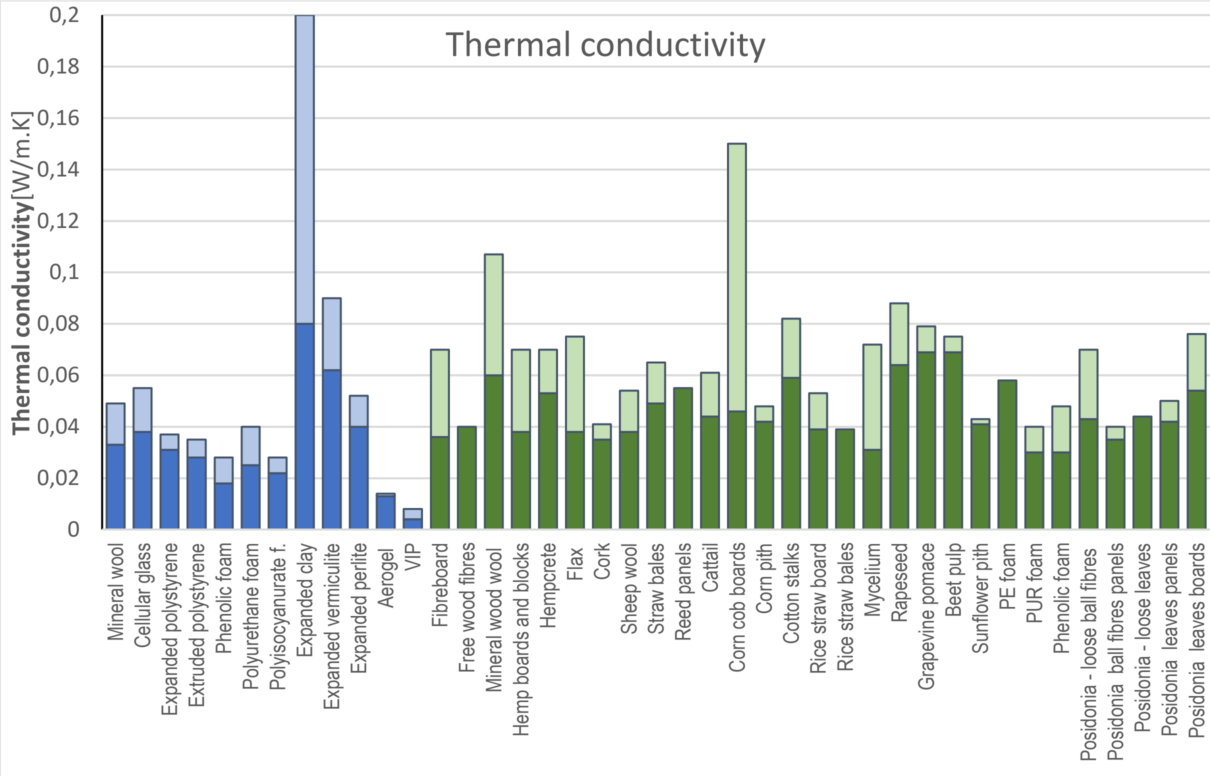

Figure 30 - Thermal conductivity range of thermal insulating materials

The main problem of the more lightweight materials are their mechanical properties, which are rather low for most of the experimental materials, nevertheless the commercial materials evince the satisfactory values of strength and modulus of elasticity.

The unknown durability and faster degradability can be regarded as the main problem of bio-based materials, used as a thermal insulation of building. Also, higher water absorptivity of these materials has to be taken into consideration. This can be solved by the addition of some hydrophobic admixtures or by the good protection of bio-based materials against water.

The big difference between non-bio and bio materials is in their water vapour permeability. As can be seen in Fig.31, the cellulose bio-based materials are diffusively open, while the most of non-bio materials are not permeable. The foamed glass and VIP panel are not comprised, because they are nearly fully impermeable. The information about the permeability of bio-based polymer foams is not known yet, but because their other properties are similar to the petroleum-based foams, it can be expected that their permeability is also rather low. The high permeability of materials can be successfully employed in the thermal insulation of older wet building, while for the passive houses some additional barrier would be necessary.

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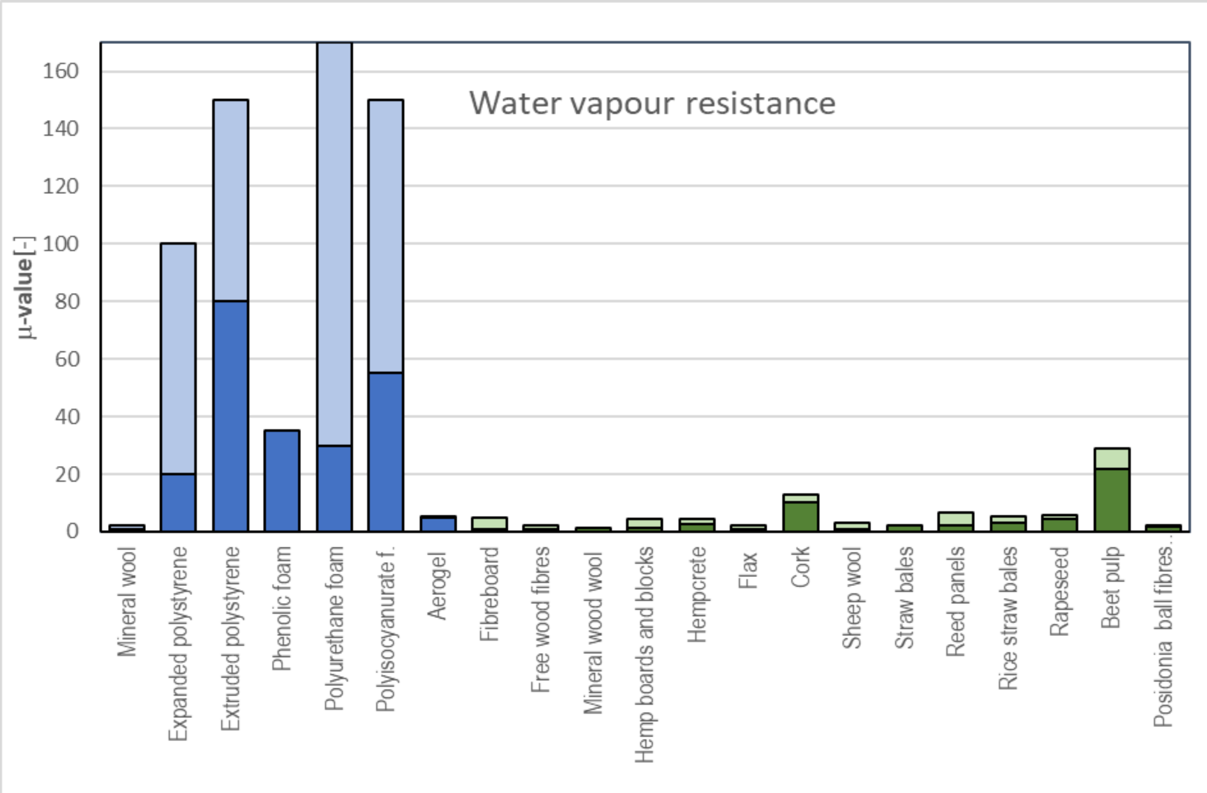

Figure 31 - Water vapour diffusivity factor of thermal insulating materials.

4.2 Environmental data

Basic environmental data are given in Table 5 for non-bio materials and in Table 6 for bio-based materials. The environmental data of commercially available materials were obtained mostly from Environmental Products Declarations (EPD), provided by producers or from EPD databases (ibu-epd.com, inies.fr, epd-norge.no, daphabitat.pt, environdec.com). Obtaining of the environmental data of non-conventional materials is difficult, because these materials are mostly in the research state yet and therefore their production is not established enough. Some data can be found in the scientific literature, nevertheless they are mostly incomparable to each other, because their approaches and boundaries differ substantially.

The global warming potential (GWP) in kg CO_{2eq} per functional unit and total energy consumption (use of primary energy resources) in MJ per functional unit were chosen as main environmental parameters. The approach “Cradle to gate” (phases A1 to A3 in EPDs) was used for better comparison, because the transport distances, assembling and handling of end-of-use materials can differ significantly in each country. For calculation of total energy consumption both renewable and non-renewable energy were summarized, because of different energy mix in individual countries and different situation of producers.

Data in tables are referred to a functional unit defined as the mass of material needed to obtain a thermal resistance of 1 m^2 K/W for a 1m^2 area, according to the suggestion of the Council for European Producers of Materials for Construction. Conversions were made if data were related to other functional unit of material.

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Table 5 - Environmental data for non-biomaterials

Material	f.u. weight	λ	Bulk density	Energy consumption	GWP	Source or producer/ product
	kg	W/m·K	kg/m^3	MJ_{eq}/f.u.	kg CO_{2eq}/ f.u.	
Stone wool	1.48	0.037	40	24.07	1.31	ROCKWOOL/ Stone wool insulation
Glass wool	0.49	0.039	12.5	12.44	0.56	Knauf Insulation/ Classic TI 140
Cellular glass	3.42	0.036	95	126.20	4.96	Pittsburgh Corning Europe NV/Foamglass
Expanded polystyrene	0.7	0,035	20	56.49	1.75	BEVI ASA / BEWi EPS 80
Extruded polystyrene	1.16	0.035	33	101.22	3.20	EXIBA/ XPS boards
Phenolic foam	0.74	0.021	35	50.09	1.62	Kingspan/ Kooltherm K5
PU foams (PUR/PIR)	0.87	0,028	31	61.3	2.52	PU Europe/ PUR or PIR boards
PIR foam	0.83	0.022	37.8	67.86	2.2	Recticel Insulation Oy/ IP PIR 022 board
Expanded clay	30.3	0.11	275	129.95	7.2	LECA Int. / LECA aggregate
Expanded perlite	3.57	0.042	85	12.8	0.79	Nordisk perlite/ Perlite Expand 0515 SC
Aerogel	2.25	0.015	150	384.9	18.45	Aspen Aerogels Inc./ Spaceloft® blanket
VIP	1.33	0.007	190	284.56	11.8	Porextherm Dämmstoffe / Vacupor®

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Table 6- Environmental data for bio-based materials

Material	f.u. weight	λ	Bulk density	Energy consumption	GWP	Source or producer/ product
	kg	W/m.K	kg/m^3	MJ$_{eq}$/f.u.	kg CO_{2eq}/ f.u.	
Wood fibres	5.99	0.038	157.5	150.55	-5.2	STEICO SE/ Steico flex
Mineral wood wool	40	0.08	500	412.8	9.92	Knauf Insulation / Heraklith board
Hemp block	23.1	0.07	330	273.03	1.86	SENINI / Blocco Ambiente
Hemp board	0.88	0.04	22	69.76	-0.84	TECHNICHANVRE/ Technilaine Panneau
Hempcrete	12.19	0.053	230	169.44	-3.30	SENINI/ BIO BETON JET
Flax	1.44	0.038	38	86.56	0.61	thinkstep AG/ Flax fibre fleece
Cork granules	2.8	0.04	70	185.96	-4.76	Amorim Isolamentos/ Exp. Cork Granules
Cork board	4.6	0.04	115	310.8	-7.92	Amorim Isolamentos/ Exp. insulation Corkboard
Sheep wool	0.7	0.039	18	35.1	0.05	Eden Renewable Innovations/Thermafleece CosyWool Roll
Straw bales	4.3	0.043	100	73.65	0.28	Fachverband Strohballen-bau Deutschland (FASBA)
Reed	8.52	0.055	155	N.A.	-12.30	*Gess et al, 2021*

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Seaweed	3.22	0.046	70	N.A.	-3.55	*Gess et al, 2021*
Meadow grass	2.13	0.044	48.5	N.A.	3.00	*Gess et al, 2021*
Grass	1.64	0.041	40	31.46	-1.25	GRAMITHERM EUROPE SA/ GRAMITHERM ® 100
Rice straw boards	1.95	0.039	50	66.81	-1.01	FBT ISOLATION/ Panneau Isolant FBT PR
Mycelium	6.8	0.04	170	N.A.	-0.88	Mykor Portugal/ MykoFoam
Bio-based PE foam	1.44	0.048	30	213.95	-0.79	Ubbink BV/ Aerfoam insulated ductwork
Graphite polystyrene	0.47	0.031	15	90.5	0.50	BASF/ Neopor® Plus BMB

The comparison of total consumption of primary energy resources (renewable and non-renewable) in Fig. 32 shows, that the energy consumption is comparable for both types of materials, for some bio-based materials it is even higher. The is probably given by the fact, that some conventional insulating materials are industrially produced for a long time and their production is already optimized.

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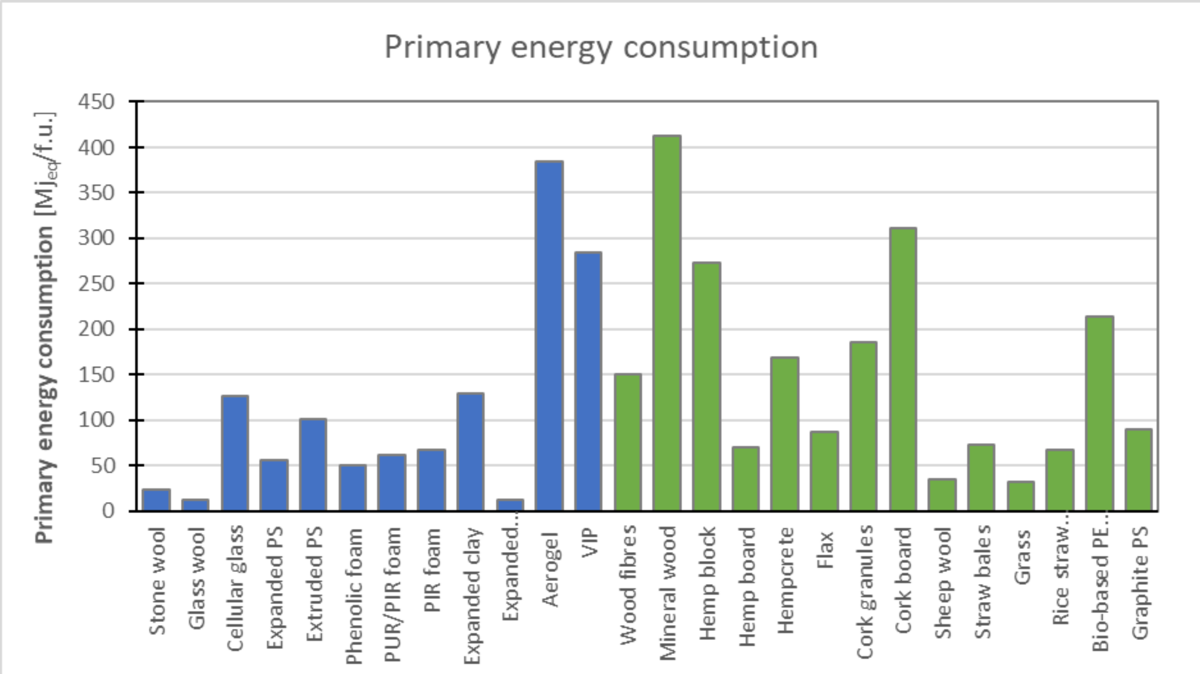

Figure 32 - Primary energy consumption of thermal insulating materials.

The big difference can be seen in the environmental impact data. The global warming potential of bio-based material (Fig. 33) is significantly lower than for other material. For most materials it is even negative. The exception is mineral-wood material, in which also inorganic binders (cement or magnesium binder) are used and they increase the environmental impact of this material. There is necessary to remind, that only production phase (Cradle to gate) is considered. It can be expected, that the end-of-life phase of bio-based materials would be more favourable too.

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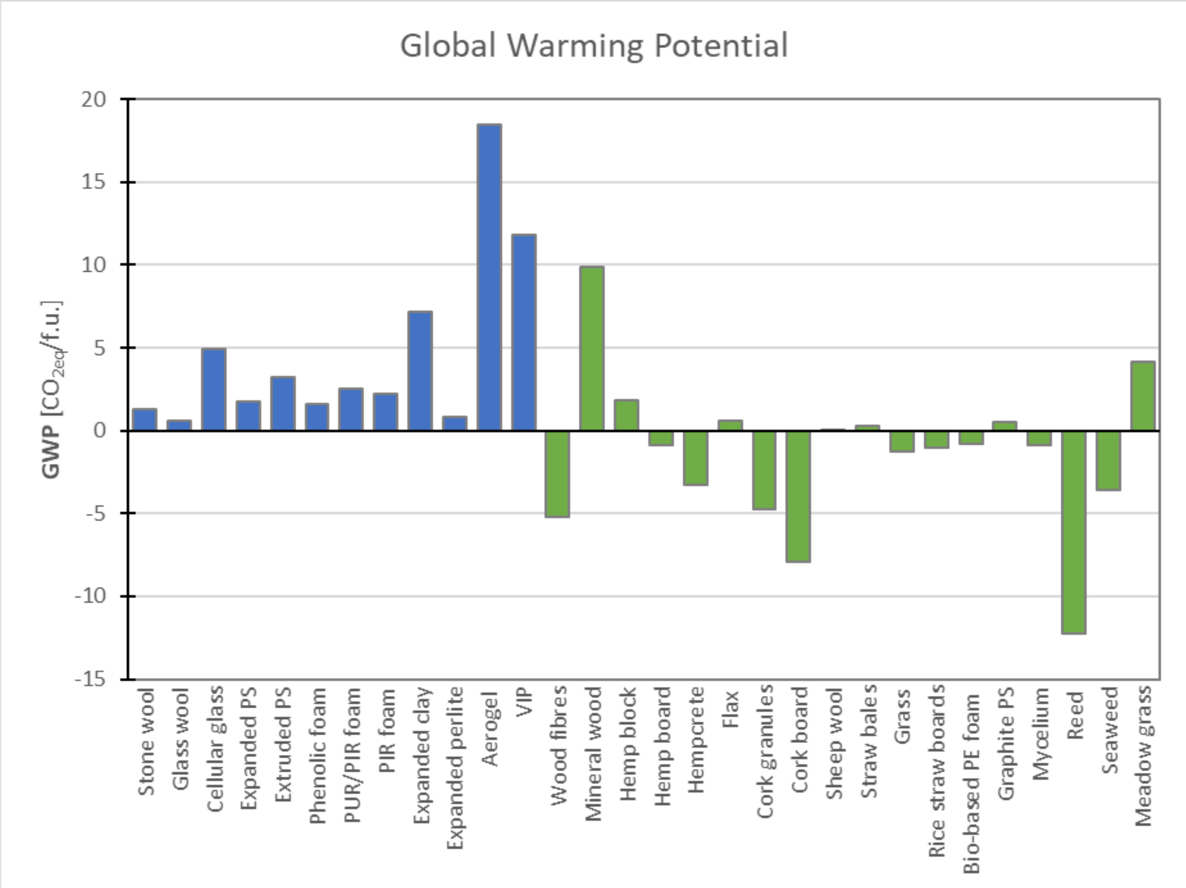

Figure 33 - Global warming potential of insulating materials

4.3 Advantages and drawbacks of bio-based materials

<u>Main advantages of the bio-based materials can be considered as follows:</u>

- The renewable, locally available and abundant feedstock
- Low carbon footprint
- Good thermal and acoustic properties
- Breathability
- Harmlessness
- Creation of local industries and jobs
- Form variability
- Easy installation
- Reusability/recyclability/compostable (if deprived of additives)

Main disadvantages of bio-based materials are:

- Usually lower effectivity (higher thickness)
- Lower strength
- Necessary chemical treatment (fire retardant, antifungal and hydrophobic additives …)
- Often content of non-biodegradable binders of fibers (PP, PE…)
- Low market share
- Still higher price (+ 10 to 15%)

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5 Framework for bio-based products

5.1 Biomass feedstock

5.1.1 Agricultural materials

Only the plants, which grow in the EU countries (either cultivated or natural) are taken into consideration. The values of agricultural crops production (in tons) were obtained from FAOSTAT (data from Food and Agriculture Organization of the United Nations) [https://www.fao.org/faostat] for year 2021.

From the total amount of crop the produced waste was calculated. For the calculation the ratio of residues to harvested crop according Tab. 7 was used. Values greater than 1 indicate that more residue is produced compared to the utilized part of the crop, and values less than 1 indicate that less residue is produced than the utilized part of the crop.

About two thirds of the produced waste are used for other purposes (e.g. as an animal bedding and fodder, mushroom cultivation, various horticultural uses or for soil fertilization), therefore one third of total amount is available for other purposes, in this case for production of bio-based building materials (*Searle and Malins, 2013*)

For flax and hemp availability, the data of whole fibres production are considered, because in this case the produced fibres, not waste, are used. For sheep wool the whole amount of produced coarse wool was taken into account for the same reason.

Table 7- Residue ratios for different crops (adopted from Searle and Malins, 2013)

Crop type	Field residue production ratio	Processing residue production ratio	Total residue production ratio
Barley	0.94	0.24	1.18
Rye	1.13	0.24	1.37
Wheat	0.94	0.24	1.18
Maize (corn)	0.80	0.47	1.27
Rapeseed (colza)	1.08		1.08
Sugar beet	0.27		0.27
Sunflower	1.77		1.77
Grapes*	0.18		0.18
Rice	1.32	0.27	1.59
*Value adopted from *Zhang and Hoadley, 2017*			

For the plants, which are not grown for agricultural purposes, but grow naturally the data about availability are unknown, only the regions and sometimes the covered areas were found at Natura 2000 (https://ec.europa.eu/environment/nature/natura2000).

Fig. 34 shows the total amount of waste agricultural materials and textile fibres, available for the production of bio-based building materials in the European Union in Mt. The values were calculated from data obtained for year 2021.

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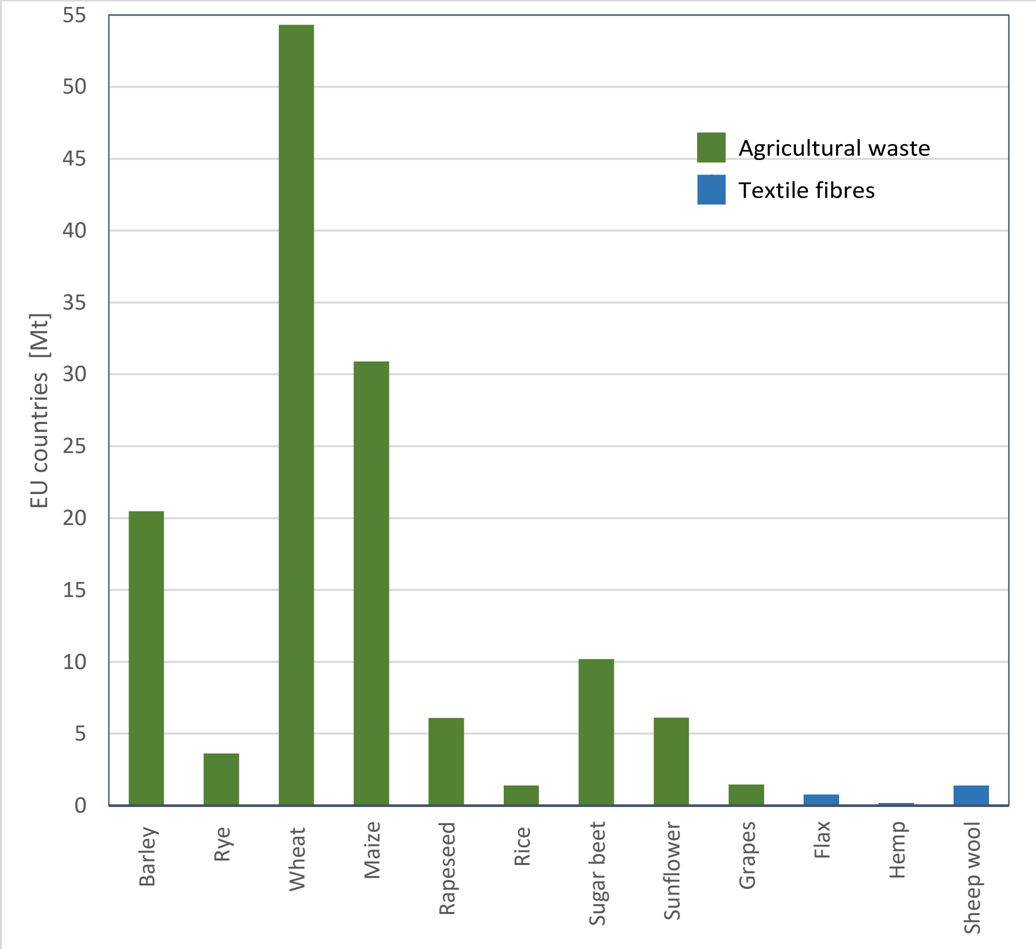

Figure 34 - Total amount of bio-based feedstock in EU in the 2021

The data for selected EU countries are given in Fig. 35, 36, 37 and 38. As can be seen, the largest amount of bio feedstock is available in France, followed by Germany for nearly all materials. Nevertheless, the feedstock in Italy, Poland, Romania and Spain are also rather substantial. In other countries the amount of feedstock is lower because of their small area (Cyprus, Malta, Luxembourg) or by their colder climate (Finland, Estonia, Latvia).

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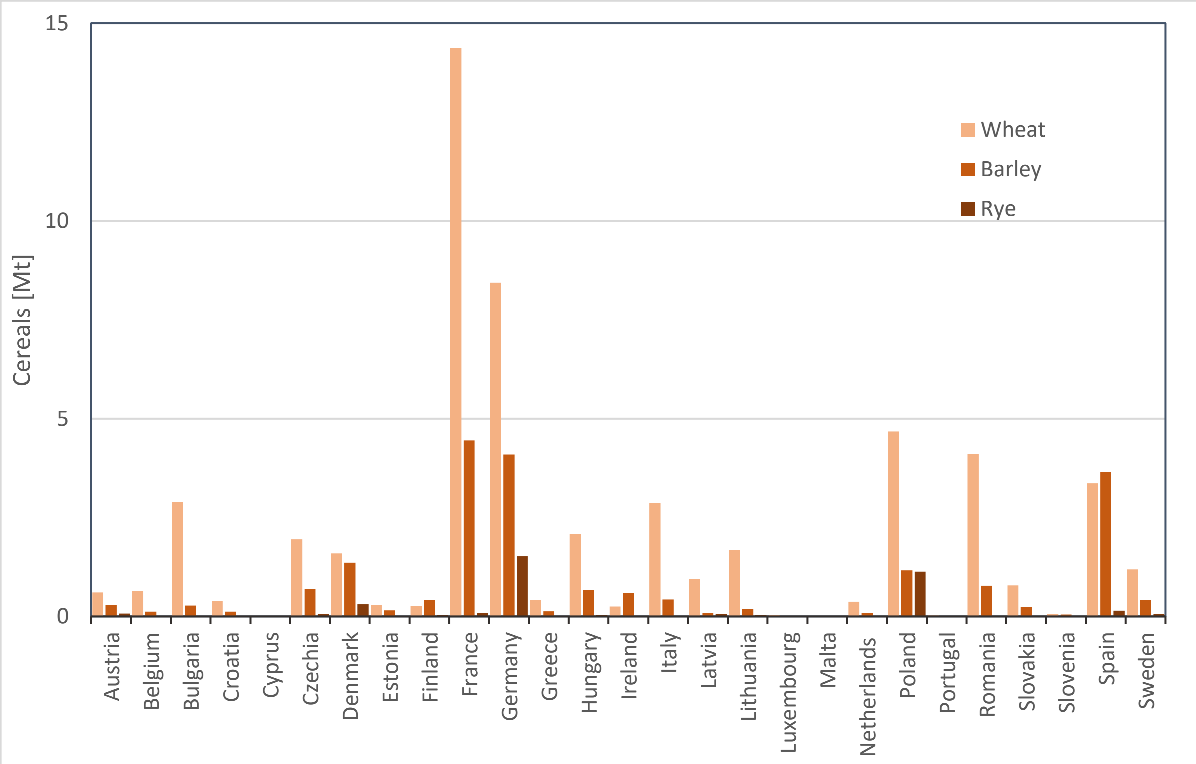

Figure 35 - Total amount of available different cereal waste in the EU countries, available in 2021

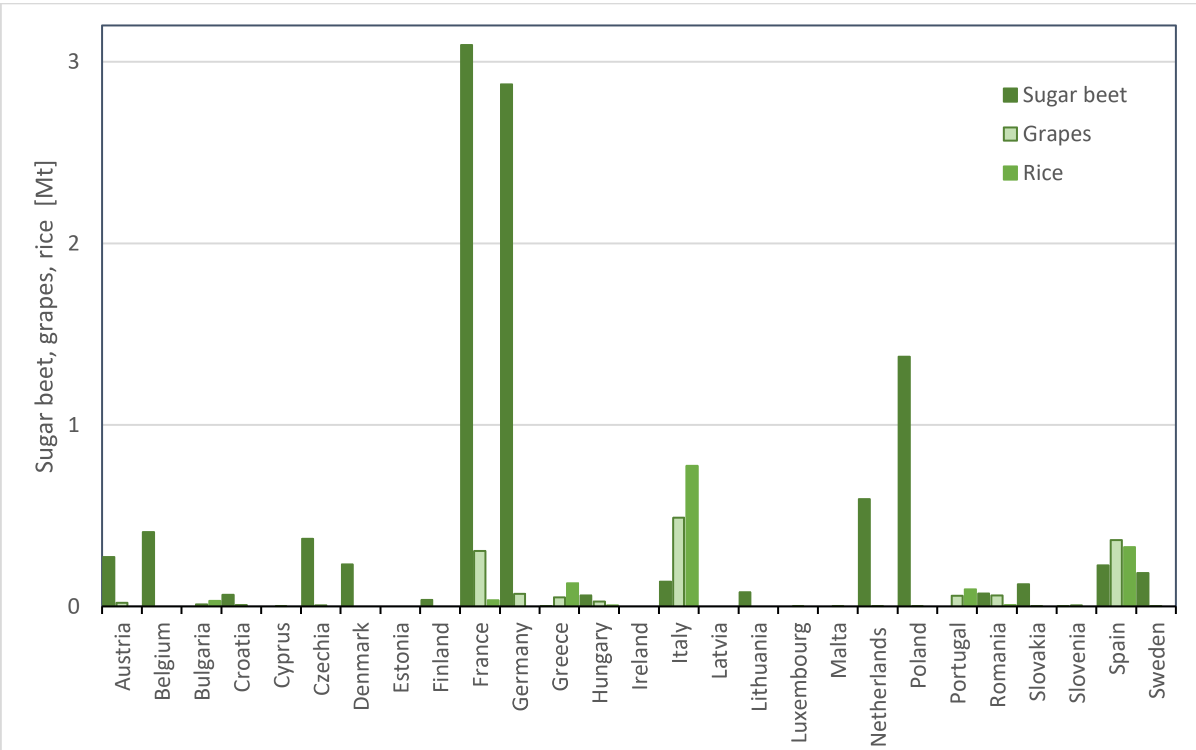

Figure 36 - Amount of sugar beet, grapes and rice waste in the EU countries, available in 2021

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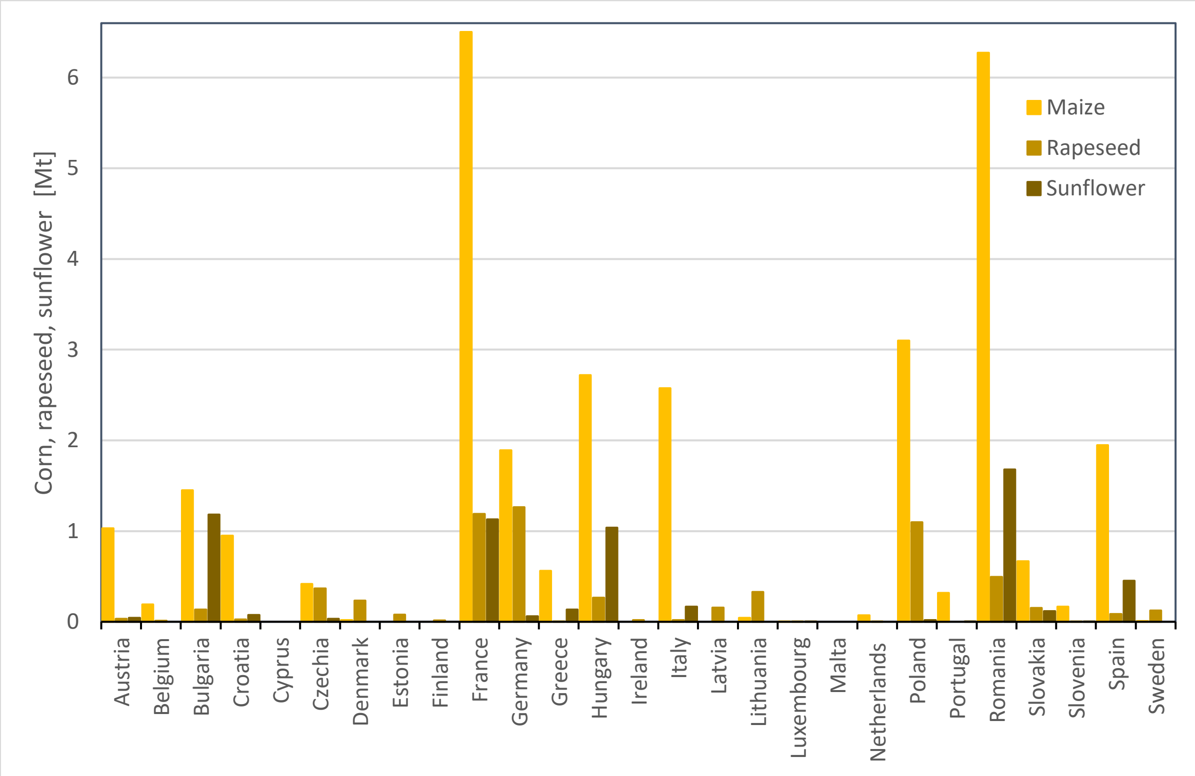

Figure 37 - Amount of maize, rapeseed and sunflower waste in the EU countries, available in 2021

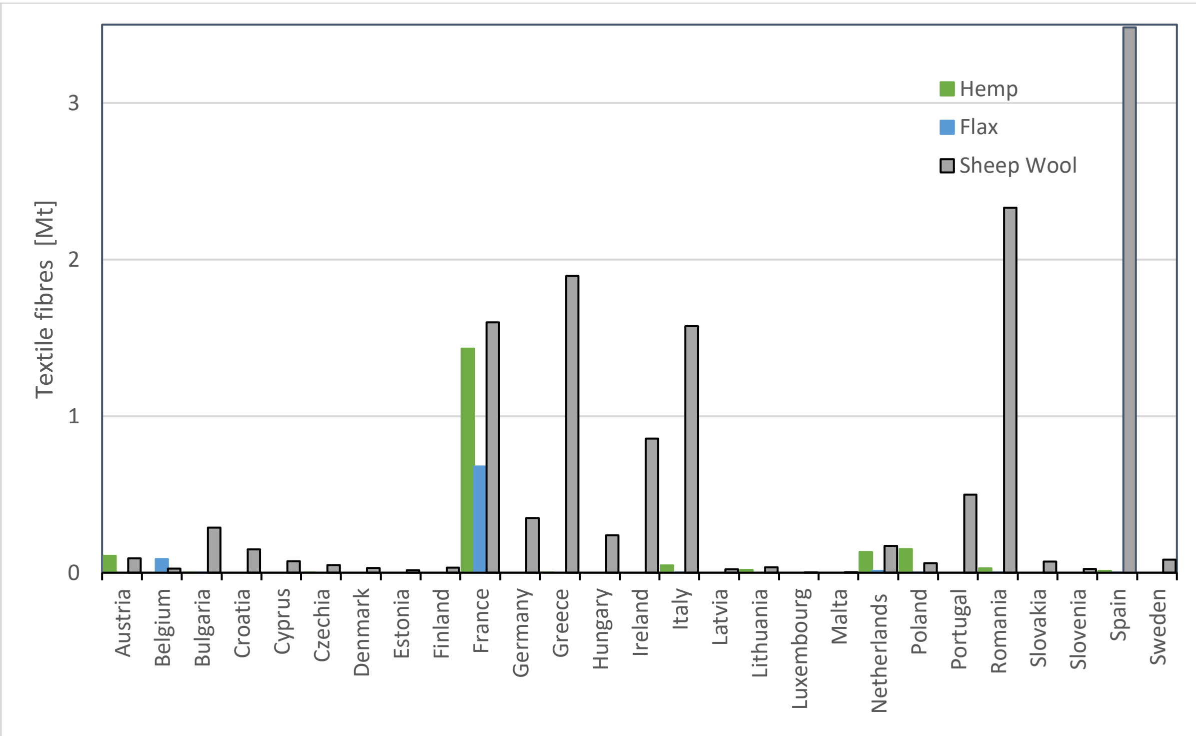

Figure 38 - Amount of textile fibres in the EU countries, available in 2021

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5.1.2 Wild plants

The data of quantity of wild plants (i.e., not grown for agricultural purposes) or about their utilizable mass are mostly inaccessible. The regions and the covered areas (if available) were found in these web pages:

Natura 2000 (https://ec.europa.eu/environment/nature/natura2000)
GBIF (Global Biodiversity Information Facility) (https://www.gbif.org/)
Land Use/Cover Area frame Survey (LUCAS) database of Eurostat (https://ec.europa.eu/eurostat/web/lucas/data/database)

5.1.2.1 Neptune grass (Posidonia Oceanica)

Posidonia Oceanica is endemic to the Mediterranean Sea, therefore it can be found only in the countries surrounding it (Fig. 39). Total area of Posidonia beds is about 60 812 km^2, the area in individual countries is in Table 8.

Table 8- Area of Posidonia Oceanica beds in EU countries (adopted from Natura 2000)

Country	Area km^2
Croatia	1167,61
Cyprus	419,54
France	7560,51
Greece	19987,11
Italy	20798,91
Malta	203,85
Slovenia	0,07
Spain	10681,59
Total	60819,18

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Figure 39 - European distribution of Posidonia Oceanica (from Natura 2000)

5.1.2.2 Common reed (Phragmite Australis)

The geographical distribution of Phragmites extends from cold temperate regions to the wetlands of hot and moist tropics although the transitional zones (ecotones) of rivers, big lakes and wetlands are its most preferred habitats. It is rather common species in all EU countries (Fig. 40).

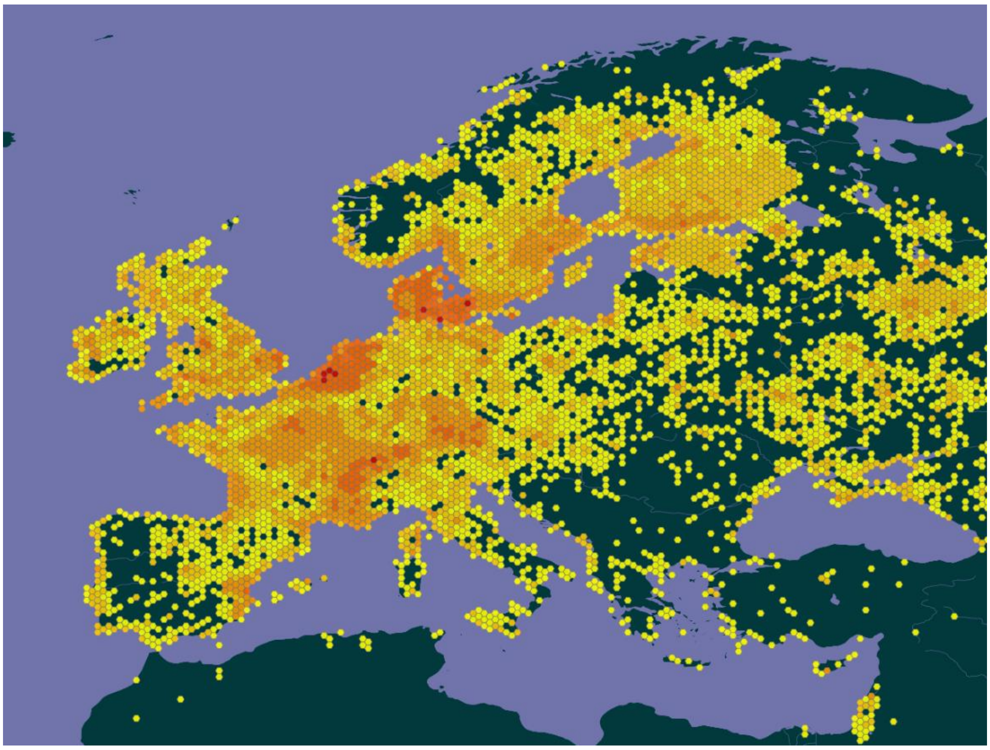

Figure 40 - European distribution of common reed (Phragmites Australis) (retrieved from GBIF)

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5.1.2.3 Cattail (Typha)

Typha is a genus of about 30 species of plants in the family Typhaceae. They are commonly named as cattail, bulrush or reedmace. They can be found mainly in temperate and cold regions of the Northern and Southern hemispheres (Fig. 41). The plants inhabit fresh to slightly brackish waters and are considered aquatic or semi-aquatic.

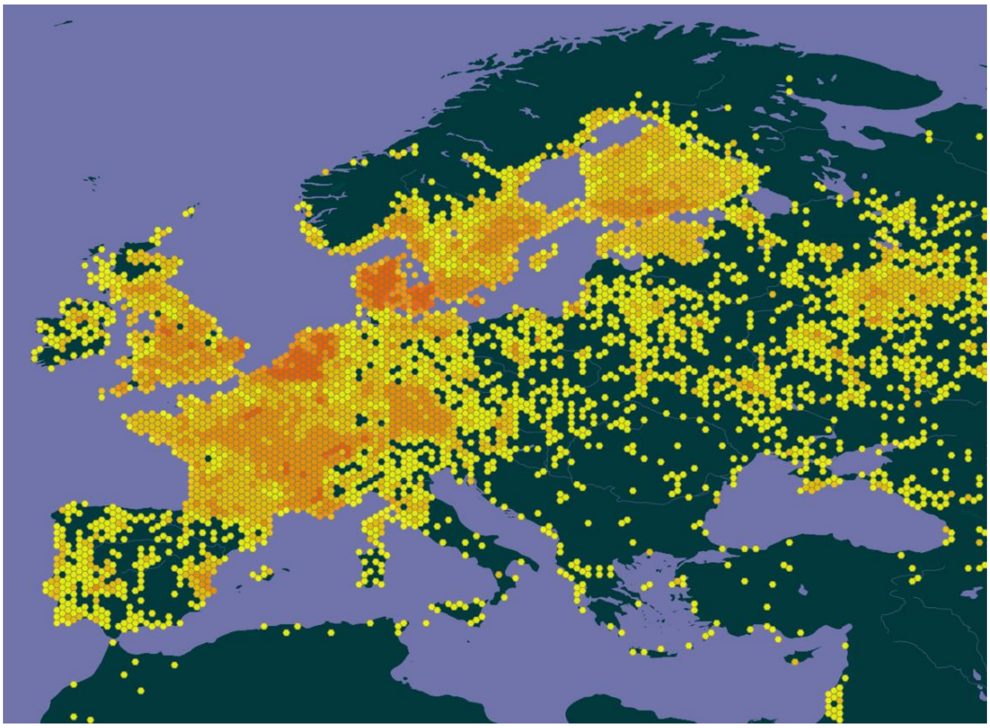

Figure 41 - European distribution of cattail (Typha) (retrieved from GBIF)

5.1.2.4 Grass

Grass is formed by a mixture of plenty of species and the grass composition differs significantly in particular regions according their climate and altitude. The area and percentage of the grasslands in EU countries were obtained from LUCAS database (Fig. 42 and Fig.43). The total area of grasslands in European Union in 2018 was about 717 135 km^2 and average percentage in all EU countries was 17.4%.

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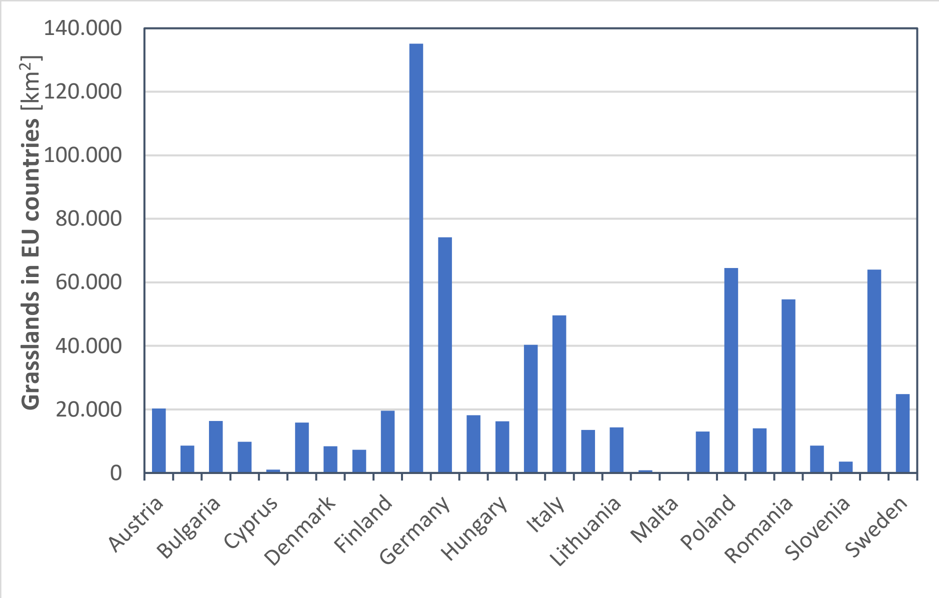

Figure 42 - Area of grasslands in EU countries in year 2018

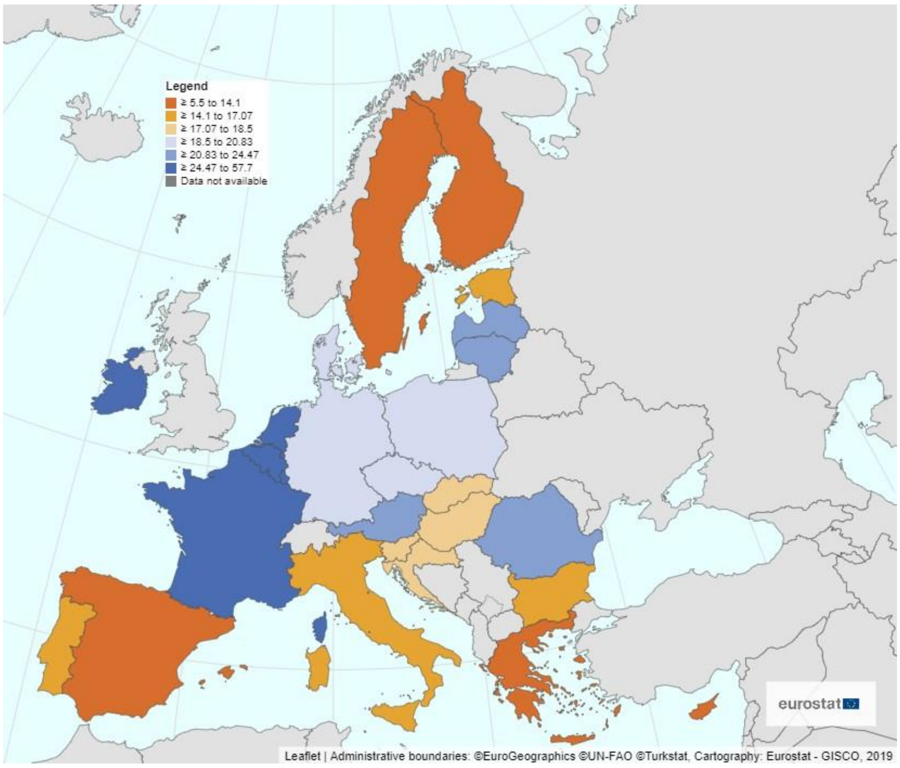

Figure 43 - Percentage of grasslands in EU countries in year 2018 (retrieved from LUCAS)

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5.1.2.5 Materials for components of bio-based polymeric foam

The main components of polymeric foams are polyol and polyisocyanates. Polyols can be prepared from cellulose or lignocellulose (e.g. wheat, soya or rape straw, reed or wooden pulp) or vegetable oils (castor, soybean, rapeseed, sunflower, grapeseed). Bio-based polyisocyanates are made less frequent and they are mostly based on vegetable oils. Because the amount of most cellulose materials is provided in the previous section, only the vegetable oils, produced in EU countries and wooden pulp (as main source of lignin) are considered in this section. Data were retrieved from FAOSTAT.

According FEDIOL (https://www.fediol.eu), 46% of vegetable oils was used for food, 39% for biodiesel, 6% for non-energy technical purposes, 4% for feed and 5% for energy in year 2019. Therefore, the estimated value of vegetable oils available for technical purposes (i.e. components of bio-based polymers) was considered to be 6% of total produced amount (Fig. 44).

Wood pulp is the biggest source of lignin, which can be also used for production of polymeric foams components. The main products made from pulp are tissue (45%), paper (30%), fluff (9%), special products (15%) (*STATISTA, 2022*). For other purposes remains 9%, which was used for calculation of amount available for production of bio-based components of polymeric foams. The total amount of available pulp in EU was 3,38 mil t in 2020. The production in EU countries is in Fig. 45.

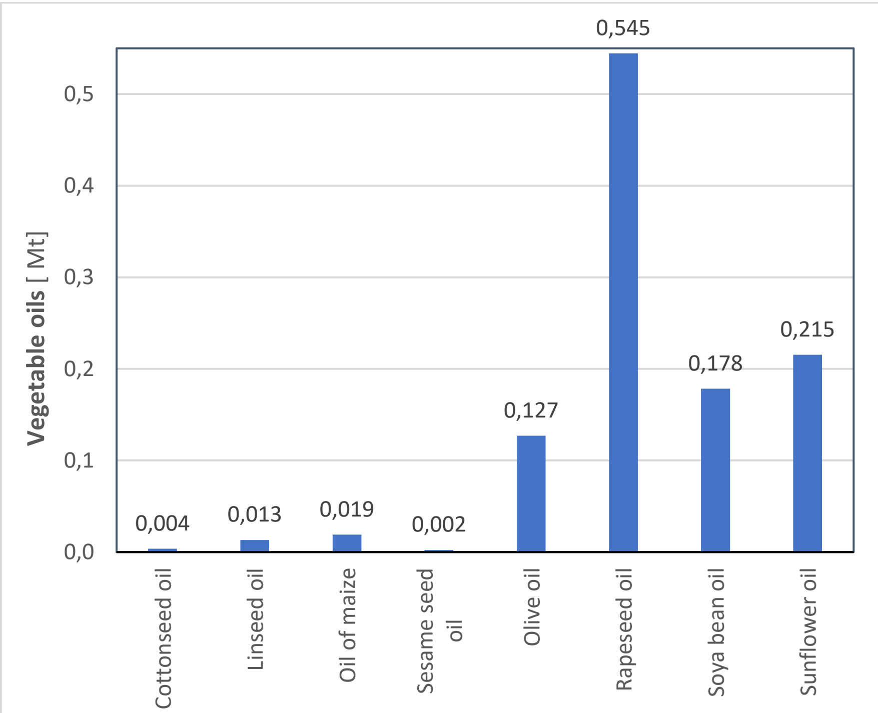

Figure 44 - Available amount of vegetable oils for components of polymeric foams in EU in 2021

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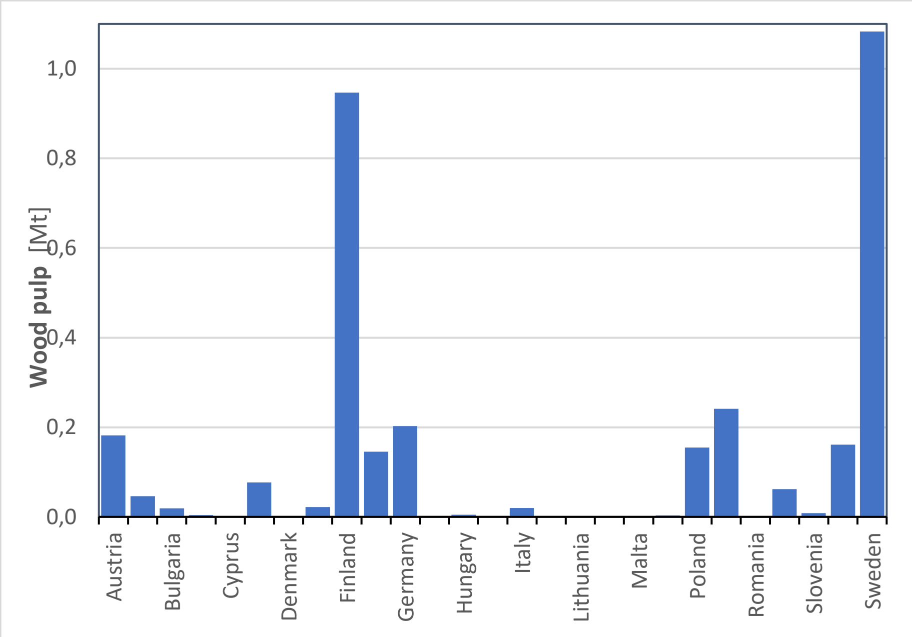

Figure 45 - Available amount of wood pulp for components of polymeric foams in EU countries in 2020

5.2 Manufacturing

Manufacture of all materials based on cellulose plant residues is similar. Plant particles, containing cellulose must be separated from the undesirable parts, dried and grounded, if necessary. The binder (when used) is added in the liquid or powder form. Sometimes the special polymeric fibers, which are melted during the hot pressing serve as a binder. For some material no binder is added and only their own resin (present already in the plant) is used. The plant particles (fibers, chips, grains) are then pressed together into desired form and if necessary, also heated. After pressing the products are cut and packed for distribution.

Process of making bio-based polymeric foam is different. The overview of manufacturing methods is shown below in the table Tab. 9.

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Table 9 - Overview of manufacturing methods. Modified from Liu et al. (2017)

Manufacturing methods	Explanation
Bonding	By help of at least one binder, such as glue, to make one or more kinds of loose/particle materials to form a whole body.
Natural form	Biomasses are packaged directly from raw type (e.g. straws bales with tight or loose structures).
Pressing	By help of high pressing at environmental temperature, to make one or more kinds of loose materials to form a whole body.
Hot-pressing	By help of high pressing at a relative higher temperature, to make one or more kinds of loose materials to form a whole body.
Others	Such as needle-punching, hydro-entanglement, aerosol processing. etc.
Injection	A magma is first produced, and then the solution is injected into a mold at a specified pressure.
Foaming	Generate a porous structure in solid materials by physical or chemical foaming methods.

At the present time, most of the bio-based products are in the initial development stage with a low MRL and TRL. The bio-based market and industry are growing but still it is difficult to get the benefit from economies of scale. The limited size of the bio-based market/industries makes it difficult to benefit from economies of scale and technological learning effects that would certainly help to increase the cost-efficiency of the products.

INDRESMAT is actively developing rigid bio-based polyurethane foams, with low density and medium to high density for different applications in the construction sector such as windows, insulation for walls, sandwich panels, and the newly introduced application is the ETICS system (External Thermal Insulation Composite System).

In the paragraphs below, the manufacturing of each of the chosen products to be developed for this project is described.

5.2.1 Bio polyurethane foam windows (density 450-550 kg/m3):

INDRESMAT has developed a Proof of Concept moulding technology that improves the productivity of the conventional Reaction Injection Moulding (RIM) *(Fig. below).*

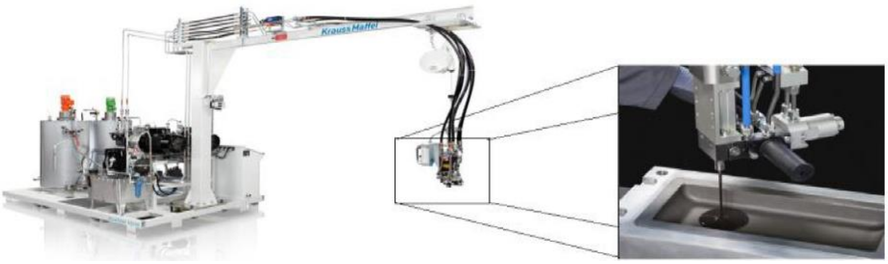

Figure 46- Conventional Reactive Injection Moulding (RIM) machine

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In the case of bio-polyurethane frames production, called KLIMA-PUR™, a large-scale production is achieved using multiple moulds placed in vertical position instead of typical horizontal position, allowing a serial injection of 6 moulds in a row within 1 min (18 m/min), using a novel property-owned moulding system (Fig.47).

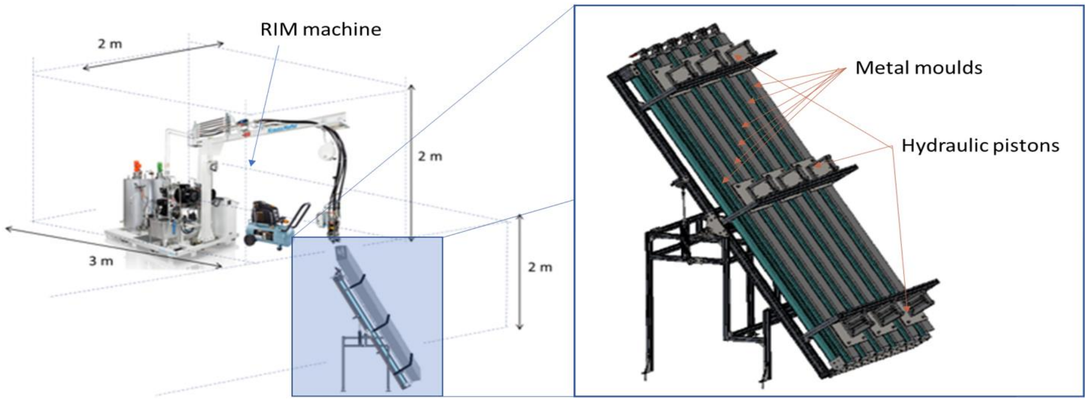

Figure 47- MVP of sRIM-PUR technology for KLIMA-PUR™ frames production

The main key point of INDRESMAT's serial injection-moulding process is the use of Aluminium moulds made from 2 extruded parts instead of CNC machined parts. The use of extruded aluminium moulding parts significantly decreases the manufacturing costs of sRIM (Structural Reaction Injection Molding)-PUR moulds. This enables the use of hundreds of moulds in a serial manufacturing process with larger productivity, representing a huge cost saving. However, as many moulds involved, a more automated technology is needed for the mould management.

5.2.2 Bio-polyurethane for ETICS (density 40-60 kg/m3):

ETICS, acronym for External Thermal Insulation Composite System, serves as an acronym for an innovative construction approach. This system contributes significantly to enhancing the sustainability and energy efficiency of structures, whether they are newly constructed or pre-existing. These kits are composed of specific pre-manufactured elements that are directly affixed to the building's exterior during on-site construction.

Typically, ETICS are predominantly employed on robust walls constructed from materials like masonry or concrete, and they incorporate a finishing rendering system. The figure 48 provides a visual representation of the key components of this system, including a layer of bio-based polyurethane manufactured by INDRESMAT.

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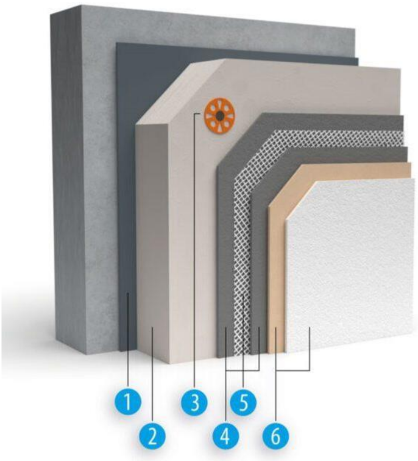

Figure 48- ETICS system composition (https://www.ea-etics.com/etics/about-etics/)

ETICS systems typically comprise of:

1. Adhesive
2. Thermal insulation board (bio-polyurethane produced by INDRESMAT)
3. Mechanical fixing devices
4. Base coat
5. Reinforcement
6. Finishing layer
7. Accessories, e.g. fabricated corner beads, connection and edge profiles, expansion joint profiles, base profiles, etc.

The bio-based polyurethane will be manufactured in-house by INDRESMAT using reaction injection moulding (RIM) machine which is the same used for conventional PUR described in paragraph 5.2.1. The difference of the manufacturing would be the density of the final product as well as minor changes in the formulation to adjust to the purpose of the application. Whereas the whole system of ETICS will be assembled by a third-party supplier.

5.2.3 Highly porous bio-polyurethane (density 40-100 kg/m3)

Highly porous bio-polyurethane is another product that possesses high thermal and acoustic insulation properties while maintaining a minimal carbon footprint.

The application in this case would be suitable for wall insulation and vegetation. This innovation not only reduces a building's energy consumption but also allows vertical gardening or arrangement of plants and vegetation that is grown on the surface of a wall or vertical structure thanks to the porous structure. These walls can be either indoors or outdoors and are designed to incorporate plants and they provide sustainability and circularity of the materials used, simultaneously mitigating air pollution in urban environments.

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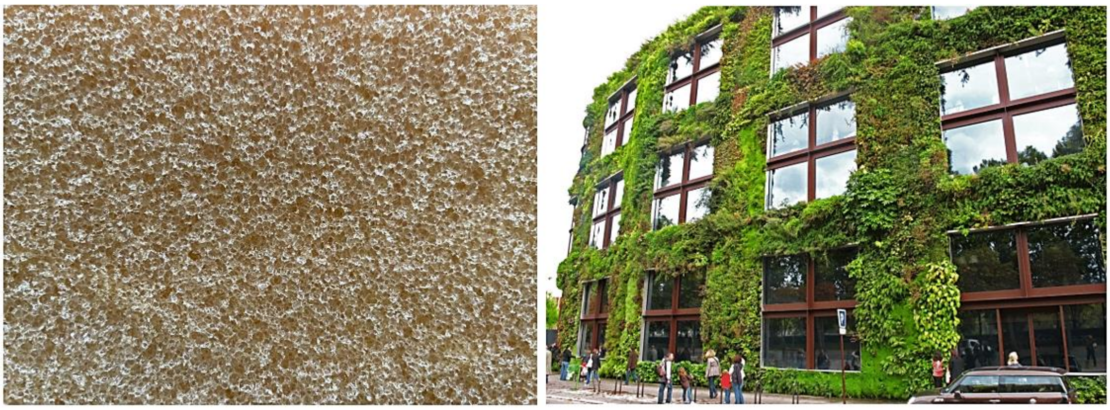

Figure 49- Porous structure of polyurethane suitable for vertical vegetation

Highly porous bio-polyurethane foams will have a very fast market development into the construction sector taking advantage of the fast & easy installation of spray foaming application. Spray foaming machines to be used and the application will remain almost the same than in conventional PUR foams.

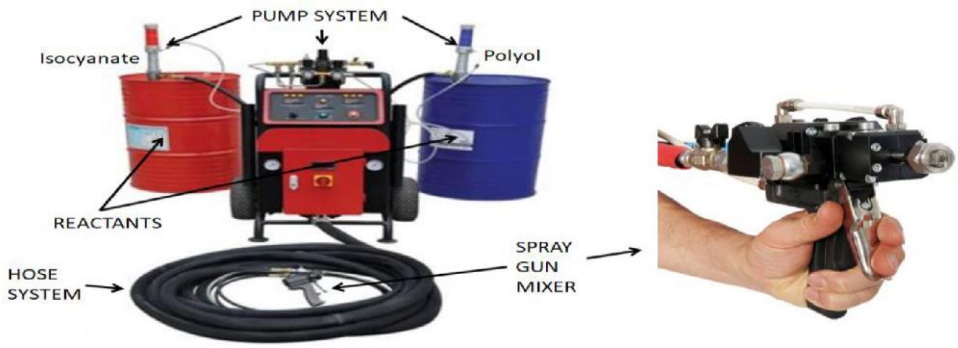

Figure 50- Conventional spray foaming PUR machine

5.3 Logistics and transport

The laboratory experiments have successfully demonstrated the feasibility of producing PU insulation using recycled cooking oil and bio-based polyols. Nevertheless, the ability to scale up this process for large-scale production is still uncertain and warrants additional research and investigation.

The existing supply chain in the EU is complex and divided, encompassing numerous intermediaries spanning various regions and nations. This complexity leads to elevated transportation expenses, greater carbon emissions, extended transit durations, and a heightened susceptibility to supply chain interruptions. Thus, there is a pressing requirement for a supply chain that is both environmentally sustainable and resource efficient. This entails leveraging locally accessible and renewable resources, like vegetable oil from the EU, for PU

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insulation production within the EU. The objective of optimizing the supply chain is to develop solutions that are not only more sustainable but also economically feasible.

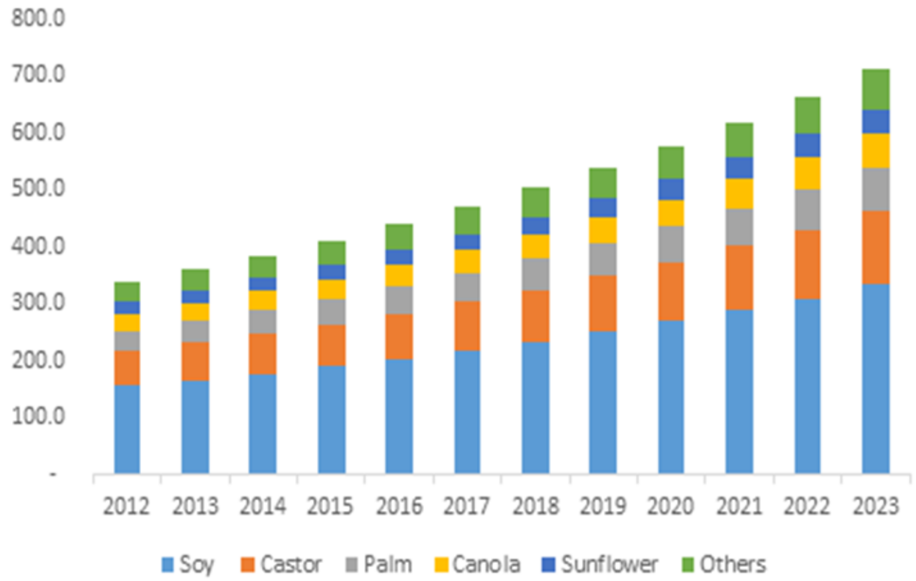

Figure 51 - European forecast production of natural oil-derived polyols REF.22

The primary approach for reducing reliance on petrochemical polyols in insulation manufacturing involves the utilization of vegetable oil. Nevertheless, it's crucial to recognize that certain oils cannot be cultivated in Europe due to their specific climate requirements. "Although, there are already several commercial production sites in Europe, there still is a lack of environmental assessment for natural oil-based polyols. There are few papers in regard to bio based polyol environmental assessment, but feedstock is limited to soybean and/or castor oil (Cargill, 2019; Helling and Russell, 2009) and palm oil (Zolkarnain et al., 2015). Towards the strengthening of the transition from a fossil to a bio-based economy, the sustainability of bio-based or green chemicals continues to be a topic of concern, as production of biobased feedstock may come at the cost of additional land use and related environmental impacts (Sheldon, 2014)."
[Life Cycle Assessment of vegetable oil-based polyols for polyurethane production Anda Fridrihsone, Francesco Romagnoli, Vladimirs Kirsanovs, Ugis Cabulis]

While the use of local European production locations and European suppliers reduces the need for long-distance transport from or to Asia, there is still room for further research and optimization to reduce the carbon footprint of transportation in our supply chain. For instance, depending on the main shipping method chosen, the travel time, cost, and carbon footprint can be further reduced. Additional measures, such as using more sustainable transport methods like rail or sea and implementing efficient logistics strategies like inbound logistics, and exploring renewable energy sources for transportation, could also be considered to minimize the environmental impact of transportation in the supply chain (McKinsey, 2021).
By continuously evaluating and fine-tuning the logistical aspect of the supply chain, INDRESMAT can further enhance its sustainability performance and contribute to the circular

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economy goals with the help of information provided from its bio-polyols and isocyanates suppliers regarding manufacturing, transport, packaging, disposal, etc.

5.4 Professional skills

Bio-based insulation materials are emerging as a promising alternative in both new constructions and renovations, aiming at improvement of building energy performance.

The application of bio-based materials and products can be successful only provided the professionals in the construction process have sufficient skills and knowledge of performance of these materials.

Bio-based materials still represent something unfamiliar to many construction engineers, architects, building contractors and other building consultants. This is often because their education and/or traditional practices are oriented towards the use of other, fossil-based, materials (Gustavsson et al., 2006).

Also, in the field of application there is a general lack of skilled workers and/or formal training programs along the value chain.

When compared to common insulation materials (rock and glass wool or petrol-based foams) bio-based materials show specific properties and behaviour. Many of bio-based materials have a distinct hygrothermal performance. The differences in the thermal performance are more noticeable when the bio-insulation materials are used as stand-alone than when these are used as a part of an ETICS. Some materials are suitable for outdoor applications and some can be used only in the interior in dry conditions. Some are prone to degradation and require special treatment with biocides, surface coatings and similar.

To satisfy the criteria of respective standards or user expectations the key performances must be considered in the design such as moisture performance, aesthetic performance, durability, thermal performance and fire performance. Thus, the service life of bio-based materials can be significantly prolongated with proper design and skilled labour in the construction process.

5.5 Application potential

EU market is expected to reach 2,64 Mt of expanded polystyrene and about 2,5 Mt of mineral wool in 2023. About 3 million tons of conventional thermal insulations can be replaced with bio-based insulations. This amount represents about 6,5 million tons of bio-based materials because the bulk density of bio-based materials is higher than in case of mineral wool or polystyrene.

The application potential in EU housing renovation projects was estimated through national building typologies. Residential building typologies were developed for 13 European countries During the IEE project TABULA. Each national typology consists of a classification scheme grouping buildings according to their size, age and further parameters and a set of exemplary buildings representing the building types. They have been published by the project partners in national "Building Typology Brochures", written in their respective languages. As a common element all brochures contain double page “Building Display Sheets” for all example buildings on which energy related features and the effects of refurbishment measures are illustrated graphically.

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Apart from the building typology brochures following project outputs were exploited:

- Country pages giving an overview of the typology and the statistics, including detailed brochures in the respective languages.
- TABULA web-based tool providing access to the respective building data and enabling an online calculation of typical values of the energy consumption.

Unique calculation model based on Excel sheet was created. This model was used for estimation of the areas of building envelopes such as roofs, walls, floors above basements and windows respectively (Tab.10). The areas were converted to cubic meters of insulation by assuming average thickness of insulation .

Table 10 – Application potential for bio-based materials in EU renovation projects

	Roofs	Walls	Floors	Windows
Mm³	1 379	2 176	847	
Mm²				3 228
Mt	124	196	76	

In reality the application potential is lower because some houses cannot be insulated due to technical or monument protection reasons. Fire safety restrictions and humid environment also reduce the volume of possible applications.

6 Identification of the drivers and future trends

6.1 Drivers for Bio-Based Insulation Materials

Regarding drivers for bio-based insulation materials, here follows a non-exhaustive list: environmental awareness in the European society and the construction sector; an increasing shortage of resources and disruptions in supply chains; application of circularity principles and good waste management methods; and the impact of ambitious European, national and local legislation.

6.1.1 Environmental concerns

The urgent need to mitigate climate change and reduce carbon emissions has directed attention towards more sustainable construction practices, even more so in the EU which aims at full decarbonisation of the continent by 2050. Materials sourced from renewable origins have a significantly lower carbon footprint compared to traditional materials. Their production requires fewer fossil fuels and generates fewer greenhouse gas emissions, making them a crucial component in achieving carbon neutrality in the construction sector.

6.1.2 Resource scarcity

Non-renewable resources, such as fossil fuels, are becoming scarcer and more expensive. This scarcity has motivated the exploration of alternative materials that do not deplete finite resources. Bio-based materials can utilize agricultural and forestry by-products, agricultural

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residues, and other renewable feedstocks, reducing the pressure on traditional resources and enhancing resource efficiency.

6.1.3 Circular economy and waste reduction

Bio-based insulation materials can be part of a circular economy model by utilizing waste streams from agriculture and forestry, in shorter and more local circuits for the supply of construction products. By diverting organic waste from landfills and repurposing it into insulation products, these materials contribute to waste reduction and promote a more sustainable waste management system.

6.1.4 Regulatory and policy frameworks

Stringent energy efficiency legislations, construction products regulations and building codes are creating a strong incentive for the adoption of energy-efficient building materials. Many regions have set ambitious targets for reducing energy consumption in buildings, prompting the construction industry to seek innovative solutions. Bio-based materials often fulfil the criteria set by these regulations, further driving their adoption.

6.2 Future trends for bio-based insulation materials

In terms of future trends for bio-based insulation materials, we have identified the following: the rapid pace of innovation in construction; the digital transition of buildings; holistic approaches for construction products; and potential in the market for bio-based solutions.

6.2.1 Technological advancements

Ongoing research and development efforts are continuously improving the performance and characteristics of bio-based insulation materials. Innovations in processing techniques, material composition, and fire resistance are enhancing their applicability and competitiveness compared to traditional insulation materials. As technology advances, these materials will likely become more cost-effective and versatile.

6.2.2 Integration of smart and sustainable design

The future of building design lies in smart and sustainable concepts that optimize energy consumption and occupant comfort. Bio-based insulation materials can be seamlessly integrated into such designs, offering thermal efficiency while promoting indoor air quality and thermal comfort. As buildings become more technologically advanced, bio-based materials will play a vital role in achieving holistic sustainability goals.

6.2.3 Multi-functional purposes construction materials

Bio-based insulation materials have the potential to serve multiple functions beyond insulation alone. Future trends may see the incorporation of functionalities such as acoustic insulation, moisture regulation, and even air purification. These multi-functional properties would enhance the overall building performance and occupants' well-being.

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6.2.4 Increased market adoption

As awareness of environmental issues grows in the EU society including the built environment sector, consumer demand for sustainable products is on the rise. The bio-based insulation market is expected to expand as consumers and industries increasingly seek or are pushed towards eco-friendly alternatives. This increased demand could likely lead to economies of scale, making bio-based insulation materials more affordable and accessible.

In a nutshell, bio-based insulation materials are poised to contribute to the digital and green transition of the construction sector towards more energy efficiency. Driven by environmental concerns, resource scarcity, circular economy principles, and regulatory frameworks, these materials offer a sustainable and effective solution for enhancing building energy performance. As technology advances and sustainable design concepts become more prevalent, bio-based insulation materials will play a pivotal role in creating greener, more energy-efficient buildings, setting the stage for a more sustainable building stock and future.

7 Policy framework on bio-based materials

Promoting the use of bio-based materials through supportive policies plays a key role in their adoption. Within the EU, this paradigm shift is driven by a range of motivations that shape such policies, including the imperative to reduce carbon emissions, foster circular economy principles and reduce waste. Indeed, recently, different policies and strategies, as well as a multitude of tools and standards to assess the sustainability of bio-based materials have emerged. This chapter provides an overview of the policy framework and instruments in support of the use of bio-based materials in construction.

7.1 Horizontal European policies

7.1.1 Circular Economy Action Plan

The Circular Economy Action Plan is a comprehensive policy framework that was launched by the EU in 2020 as one of the main building blocks of the European Green Deal. It aims to make sustainable products the norm and transform consumption patterns. Based on the principles of resource efficiency and waste reduction, the plan seeks to refit the lifecycle of products from design to disposal.

Specifically, regarding bio-based materials, the plan aims to ensure the sustainability of bio-based materials, including through actions following the Bioeconomy Strategy and Action plan. The plan recognises that biological resources are a key input to the EU economy and will play an even more important role in the future. Therefore, the plan proposes to take actions to ensure the sustainability of renewable bio-based materials.

Besides the development of a bioeconomy strategy, the plan advocates for the adoption of bio-based products in key sector such as construction, prioritising their circularity and sustainability. It also encompasses support for research and innovation, notably through Horizon Europe, and highlights sustainable production practices, emphasising reduced environmental impact and social responsibility. Finally, the plan promotes sustainable biomass utilisation and encourages the incorporation of bio-based products in public procurement, and the establishment of circular value chains through innovative business models and design principles.

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7.1.2 EU Bioeconomy Strategy

The Bioeconomy Strategy, which was adopted in 2018, aims to promote the sustainable production and use of renewable biological resources such as crops, forests, and marine resources, to support the transition to a more sustainable and circular economy. The Bioeconomy Strategy embraces multiple sectors and policies related to the bioeconomy, interlinks them, facilitates coherence and synergies, and provides a blueprint that will help the Union to develop the potential of bioeconomy and use it to effectively deliver on many of its policy objectives.

The strategy recognises the importance of bio-based products in construction, as products made from renewable biological resources or innovative biological processes and principles. Bio-based products can substitute fossil-based ones and can be identical to their fossil alternative ("drop-in") or novel products with entirely new functionalities. The strategy highlights the potential of bio-based products to contribute to a sustainable and circular economy and mentions examples of bio-based products made traditionally from biomass such as wood.

The strategy is accompanied by the Bioeconomy Action Plan, which encompasses 14 specific actions aimed at scaling up the bioeconomy an ensure its overall sustainability and circularity. The Action Plan applies a systems-approach, embraces multiple sectors and policies related to the bioeconomy, interlinks them, facilitates coherence and synergies, addresses trade-offs such as competing use of biomass, and provides a blueprint that will help develop the potential of bioeconomy and use it to effectively deliver on many of its policy objectives. Moreover, it includes a Guidance on how to facilitate the adoption of bio-based products in public procurement.

7.2 Sector-Specific policies

7.2.1 Renovation Wave

In 2020, the European Commission published a key strategy to drive energy efficiency in construction, named the "Renovation Wave". It highlights the importance of boosting building renovation for climate neutrality and recovery, and how it can improve energy efficiency, reduce greenhouse gas emissions, and create job opportunities. The strategy proposes a range of measures to support building renovation, including financial incentives, regulatory frameworks, and technical assistance.

The use of bio-based materials in building renovation projects is promoted in several ways. First, the strategy mentions the promotion of the development of standardised sustainable industrial solutions and the reuse of waste material, including biobased products. Additionally, it states the promotion of environmental sustainability of building solutions and materials, including wood and bio-based materials, on the basis of a comprehensive life-cycle assessment approach.

7.2.2 New European Bauhaus

The New European Bauhaus is an initiative launched by the European Commission in 2021, with the aim to promote long-term, life-cycle thinking in several industrial **ecosystems**, prioritising construction. It has three key principles: combination of global and local dimension, participation, and transdisciplinarity. To achieve its goals, the initiative supports and funds small-scale projects that demonstrate transformative initiatives.

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The use of bio-based products is promoted as a less-carbon-intensive and circular choice that supports the regeneration of nature and protects biodiversity. Moreover, the use of bio-based materials for improving the thermal insulation of old buildings is specifically encouraged as part of the circular solutions for rehabilitation and reinforcing the structural integrity of old buildings.

7.2.3 Roadmap for the reduction of whole life carbon emissions of buildings

In response to the above initiatives, the European Commission launched a study in 2023 to develop a roadmap for reducing the whole life carbon emissions of buildings. The study's objectives encompass establishing a baseline for embodied carbon emissions, projecting changes in embodied carbon by 2050, defining pathways for operational carbon emissions, and identifying solutions to reduce overall carbon emissions. It seeks to guide policy decisions and actions to advance sustainability in the construction sector.

The Commission aims to promote the use of bio-based materials as a way to reduce the whole life carbon of buildings. By establishing a baseline for embodied carbon emissions and projecting their evolution, the roadmap is expected to underscore the low-carbon attributes and environmental advantages of bio-based materials. By offering guidance, incentives, and potential regulations, the roadmap will encourage stakeholders to integrate bio-based materials into construction practices, fostering market awareness and demand. The study is expected to produce its results by the end of 2023.

7.3 Other tools

7.3.1 Normative mechanisms

Standards and European Assessment Documents (EADs) play crucial roles in supporting the integration of bio-based materials within the construction sector by establishing guidelines for quality, performance, and environmental impact. Although the current bio-based standards primarily focus on materials derived from wood, they serve as a basis for evaluating inherent characteristics. EADs complement these standards by delineating assessment methodologies and criteria, particularly for insulation products crafted from natural fibers of plant and animal origin. Furthermore, EADs emphasize the importance of integrating sustainability factors such as recyclability and compostability into technical documentation (Burgh et al., 2022). The upcoming revision of the Construction Products Regulation, which aims to address the sustainability performance od construction products, is expected to accelerate the development of more relevant standards.

On a broader scale, the Commission has recognized that a challenge with bio-based products lies in determining their bio-based content. To address this deficiency, the Commission has issued a series of mandates for standardization to the European Committee for Standardization (CEN). CEN has accepted the subsequent Mandates pertaining to bio-based products for standardization: M/429 for the formulation of a standardization plan for bio-based products, M/430 for bio-polymers and bio-lubricants, M/491 for bio-solvents and bio-surfactants, and M/492 for the establishment of overarching standards for bio-based products. Consequently, CEN has established both the CEN/TC 411 and CEN/BT/WG 209 to formulate the necessary standards.

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7.3.2 Level(s)

Level(s) is a voluntary framework which is used as a sustainability assessment tool for buildings, offering standardised indicators and metrics to measure their environmental performance across their life cycle. Structured with macro-objectives aligned to EU policies, core indicators for performance assessment, life cycle tools including scenario and data collection tools, and value and risk rating systems, Level(s) aims to establish a shared sustainability language for buildings, encouraging the adoption of Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) across Europe.

Bio-based materials generally are expected to score well when it comes to their environmental performance. This can be demonstrated by a LCA, which however is cost and time-intensive (Burgh et al., 2022). As such, Level(s) is proposed as a free tool which can calculate and showcase the benefits of bio-based construction products.

8 Conclusions

The major conclusions that can be drawn from this deliverable are the following:

1. Even though still marginal in the construction sector (about 1%), the bio-based products represent an important growing part of the construction market with tremendous potential.
2. Wood-based products and straw still dominate the market of bio-based construction products, however especially in the family of insulation materials, also other materials, such as flax, hemp or Posidonia grass have a good market potential.
3. The environmental performances of bio-based materials tend to be better than for example mineral fibre and polystyrene, although there is a relatively important variability that depends on the product under consideration and the feedstock used.
4. Local sourcing can be beneficial to the environment, as it uses less transportation and consequently causes less carbon emission.
5. At the present time the bio-based insulation materials are still more expensive compared to traditional products. This is one of the main bottlenecks in the future development but as the bio-based sector will most probably continue to grow it will be later possible to benefit from economies of scale and technological learning effects.
6. The potential of bio-based products and materials has two limiting factors, which is the finite resource of the raw material even though renewable and the range of use of the bio-based products due to their specific properties.

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