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Recycling of organic residues to produce insulation composites: A review

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ABSTRACT

The building sector accounts for high energy consumption, and increasing the energy efficiency of buildings is considered a key measure to meet the climate goals worldwide. Even though there are various residual biomass streams available that show good thermal insulation properties, most applied thermal insulation materials are of mineral or synthetic polymer basis and non-biodegradable. To foster the application of bio-based thermal insulation materials, the aim of this study was an investigation of bio-composite- and mycelium-based boards and mats currently available or under research and their thermal insulation properties. The focus was laid on the treatment of various biomasses using fungi to enhance their application in the building sector as well as their thermal insulation properties. The different materials were compared regarding density, thermal conductivity, specific heat capacity, water vapour resistance, water absorption, fire performance, and mechanical properties. This work provides the basis for selecting residual biomass streams to produce case-specific thermal insulation materials.

1. Introduction

The energy transition is of great urgency to achieve the climate protection goals and strongly depends on realizing energy-saving potentials. The building sector accounts for 40% of the total energy consumption in Germany and increasing the energy efficiency of buildings is considered by the German government as a key measure. To reduce the energy consumption of buildings, the German government focuses on energy-efficient renovation by the application or modernization of thermal insulation envelopes. The overall objective is to reduce the primary energy demand until 2050 by 80% compared to 1990. To achieve this goal, the rate of annual energetic modernization should be doubled from approximately 1–2% (BWE, 2010), which is expected to result in a strong increase in the demand for thermal insulation materials.

In agriculture and forestry, as well as in garden and landscape maintenance, enormous quantities of lignocellulosic materials such as wood residues, straw, and green cuts accumulate, which are frequently incinerated. In 2009, 250 Mio. tons of straw were burned in China alone (Grimm and Wösten, 2018). Even though there are some bio-based insulation materials available, the use of synthetic and non-biodegradable additives as binders, flame retardants, or hydrophobic agents (Table 1) (Ökobaudat, 2020; Pfundstein et al., 2013) makes it non-biodegradable and non-eco-friendly, and new materials are needed to address these issues (Rafiee et al., 2021). In 2019, the German thermal insulation market was dominated by polymeric foams (48%), like polystyrene and polyurethane, followed by mineral wools (43%), which are not biodegradable and have to be disposed of or incinerated at their end-of-life. Bio-based materials had a market share of 9%. Among the bio-based materials, wood fibres had the largest share (58%), followed by cellulose (32%). The total estimated volume of sold insulation materials was 38.5 Mio. m^3 (FNR, 2021), an increase of 37.5% compared to 28 Mio. m^3 in 2010 (Sprengard et al., 2013).

Mycelium-based materials are a relatively new research subject with growing interest in recent years. The idea of producing mycelium-based building materials was patented in the early nineties by Yamanaka and Kikuchi 1991; however, peer-reviewed studies on the subject remain limited, especially concerning their potential for thermal insulation. The fundamental principle of producing mycelium-based materials is using the mycelial ability to bind loose particles with its fibrous network by growing into a nutritive substrate. The materials can be grown in different shapes by filling or pressing inoculated substrate into a negative mould. After a certain growth period, the fungi must be inactivated by drying or heating to stop the mycelial growth and obtain the desired ratio of mycelial mass to the substrate or prevent primordia development. Various parameters in the fabrication process influence the material properties, starting with selecting a fungal species or, more specifically, a fungal strain, where strains are subtypes of a species with genetic variations. Further, the substrate composition, growth conditions, and period, as well as potential post-processing, were shown to

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Table 1
Bio-composite-based thermal insulation material.

Raw Material	Type of insulation	Binder	Density [kg m^{-3}]	Thermal conductivity [W m^{-1} K^{-1}]	Specific heat capacity [J kg^{-1} K^{-1}]	A.1) Compressive strength A.2) Compressive stress at 10% strain B) Internal bonding C) Flexural D) Tensile strength [MPa]	A) Water absorption [%] after 24 h or saturation B) Water vapour resistance [-]	References
Bagasse	Loose	No binders	70–120	0.046–0.053	–	–	–	(Manohar, 2012; Manohar et al., 2006; Panyakaew and Fotios, 2011)
	Boards	Hot pressing	250–350	0.049–0.055	–	C) 0.43–4.16	–	(Panyakaew and Fotios, 2011)
Bagasse and coconut coir granulate	Boards	Gum Arabic (33%)	245–276	0.015	1141	A.1) 0.48–0.88	A) 410–449	(Ndagi et al., 2021)
Banana fibres	Loose	No binders	20–120	0.041–0.076	–	–	–	(Manohar and Adeyanju, 2016)
Banana fibre powder	Boards	Polystyrene (10–40%)	–	0.018–0.037	–	–	–	(Mohamed et al., 2021)
Coconut fibres	Loose	No binders	40–90	0.049–0.058	–	–	–	(Manohar, 2012; Panyakaew and Fotios, 2011)
	Boards	Hot pressing	250–350	0.046–0.068	–	C) 0.12–1.94	–	(Panyakaew and Fotios, 2011)
Coconut coir	Boards	Urea formaldehyde, phenol formaldehyde or isocyanate plus paraffin wax emulsion (1%)	329–380	0.054–0.077	–	–	A) 63–186	(Khedari et al., 2003)
		Phenol formaldehyde resin (10%)	360–1000	0.046–0.062	–	B) 0.15–0.74 C) 1.76–15.47	–	(Hasan et al., 2021b)
Coffee husks	Boards	Polypropylene (10–30%)	500–1000	0.052–0.105	–	C) ca. 8–21.5 D) ca. 13–24.2	A) 21–38	(Ilangovan et al., 2019)
Cork granules (expended)	Loose	No binders	65	0.041	1063–2152	–	B) 3	(Marques et al., 2020)
	Boards	Acrylic resin (10–20%)	119–133	0.050–0.054	–	C) 0.10–0.21	–	(Maderuelo-Sanz et al., 2022)
Cork granules (expanded) and rice husks	Boards	Toluene diisocyanate-based polyurethane (20%)	199–390	0.045–0.080	1329–1793	A.2) 0.07–0.51 B) 0.04–0.20	B) 10–114	(Marques et al., 2020)
Corn pith	Boards	Sodium alginate (3–5%)	60–100	0.042–0.048	–	–	–	(Palumbo et al., 2018)
Cotton stalk fibres	Boards	No binders	150–450	0.059–0.082	–	B) 0.08–0.17 C) 0.15–0.58	–	(Zhou et al., 2010)
Durian peel	Boards	Urea formaldehyde, phenol formaldehyde or isocyanate plus paraffin wax emulsion (1%)	357–442	0.063–0.064	–	–	A) 151–189	(Khedari et al., 2003)
Fique fibres	Mats	Superficial polymer cover	–	0.037–0.078	–	–	–	(Navacerrada Saturio et al., 2014)
Flax fibres and shives	Mats	Bicomponent fibres (20%)	32	0.043	–	A.2) 0.0004 B) 0.008	B) 3	(Korjenic et al., 2011)
Flax shives	Boards	Sodium silicate	230	0.054	–	A.2) 0.48 C) 0.62	–	(Bakatovich et al., 2018)
Flax tow	Mats	No binders	170–225	0.065–0.100	–	C) 0.15–0.30	330–700	(Hajj et al., 2011)
Hemp fibres and shives	Mats	Bicomponent fibres (15–20%)	30–82	0.039–0.049	–	A.2) 0.0005–0.0112 B) 0.016–0.023	B) 2–4	(Korjenic et al., 2011; Zach et al., 2013)

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Table 1 (*continued*)

Raw Material	Type of insulation	Binder	Density [kg m^{-3}]	Thermal conductivity [W m^{-1} K^{-1}]	Specific heat capacity [J kg^{-1} K^{-1}]	A.1) Compressive strength A.2) Compressive stress at 10% strain B) Internal bonding C) Flexural D) Tensile strength [MPa]	A) Water absorption [%] after 24 h or saturation B) Water vapour resistance [-]	References
Hemp shives	Boards	Potato starch (7–17%) or Corn starch (ca. 9%)	165–406	0.059–0.068	1240–1270	A.1) 3.00–3.50 A.2) 0.47–1.50 B) 0.39–0.45 C) 6.30–6.90	A) 150–190	(Kremensas et al., 2021; Pundiene et al., 2022)
		Gypsum or Phosphogypsum (45%)	190–210	0.058–0.070	–	A.1) 0.10–0.57	–	(Bumanis et al., 2021)
		Corn con extract, flax fine extract, black liquor, lignin, molasses, or PLA (15%)	167–267	0.067–0.078	–	A.1) 0.23–0.42	–	(Viel et al., 2019)
Jute fabric, sunflower stalk	Boards	Gypsum (20–22%)	–	0.049–0.064	–	–	–	(da Rosa et al., 2015)
Jute fibres	Mats	Bicomponent fibres (20%)	26	0.046	–	A.2) 0.0010 B) 0.008	B) 2–4	(Korjenic et al., 2011)
Kenaf	Boards	Hot pressing	100–260	0.040–0.065	–	B) 0.15 (for 260 kg m^{-3}) C) 1.1 (for 200 kg m^{-3})	–	(Xu et al., 2004)
Moss	Boards	Sodium silicate	120–300	0.034–0.075	–	A.2) 0.05–0.21	–	(Bakatovich and Gaspar, 2019)
Oil palm fibres	Loose	No binders	20–120	0.056–0.098	–	–	–	(Manohar, 2012)
Reed	Loose	No binders	110–150	0.052–0.066	–	–	–	(Asdrubali et al., 2016)
Rice Husks	Loose	No binders	100	0.063	1138–1599	–	B) 4	(Bakatovich et al., 2018; Marques et al., 2020)
	Boards	Toluene diisocyanate-based polyurethane (20%); Sodium silicate	223–390	0.053–0.075	1411–1470	A.2) 0.06–0.50 B) 0.02–0.06 C) 0.08–0.28	B) 7–16	(Bakatovich et al., 2018)
Rice straw, rice husks	Boards	Sodium silicate, latex, polyvinyl alcohol	225–235	0.058–0.069	–	A.2) 0.43–0.47 C) 0.68–0.72	–	(Bakatovich et al., 2018)
Rice straw	Boards	Phenol formaldehyde resin (10%)	714	0.061	–	B) 0.25 C) 11.18	A) 62	(Hasan et al., 2021a)
Rye straw, flax shives	Boards	Sodium silicate, latex, polyvinyl alcohol	225–230	0.049–0.058	–	A.2) 0.60–0.65 C) 0.95–1.00	–	(Bakatovich et al., 2018)
Sheep wool	Mats	No binders	20–40	0.036–0.044	–	–	–	(Bosia et al., 2015; Zach et al., 2012)
	Boards	No binders	76–130	0.034–0.040	–	–	–	(Bosia et al., 2015)
		Polypropylene fibres (10–20%)	–	0.058–0.083	–	C) 38.5–55.6 D) 7.8–10.3	A) 21–34	(Guna et al., 2021)
Straw (barley, oats, rice, rye, wheat)	Boards	Sodium silicate, methylene diphenyl diisocyanate-acetone	200–250	0.048–0.063	–	A.2) 0.23–0.35 B) 0.011–0.013 C) 0.40–0.82	–	(Bakatovich et al., 2018; Wei et al., 2015)
Straw bale	Loose/ pressed bales	No binders	56–123	0.040–0.194	–	–	–	(Goodhew and Griffiths, 2005; Sabapathy and Gedupudi, 2019)
Wood particles (Oil Palm), Ramie fibre	Boards	Tapioca starch (30%)	660–790	0.067–0.148	–	–	A) 55–65	(Mawardi et al., 2021)

have an impact. The literature on fungal cultivation conditions shows the effect of temperature, moisture content, pH, and nutrient availability, often monitored in terms of C/N-ratios, on mycelial growth rate and densities (Jayasinghe et al., 2008; Jo et al., 2010; Park et al., 1989). However, not all these parameters are systematically evaluated in the literature on mycelium-based materials, which impedes results' reproducibility, comparability, and conclusiveness. Furthermore, there is a multitude of possible combinations of influencing factors, resulting in a variety of materials with different properties.

The high number of already available bio-composites and mycelium-based composites challenges selecting proper materials for certain purposes. Thus, this study aimed to investigate the properties of materials made from different raw materials and a mixture of them and to path the way to its application in thermal insulation. Different materials were compared regarding density, thermal conductivity, specific heat capacity, water vapour resistance, water absorption, fire performance, and mechanical properties to provide a sound basis for the future development of thermal insulation materials.

2. Thermal insulation materials

In Germany, the overall production of thermal insulation materials increased continuously from 24.5 Mio. m^3 in 2005 (Pfundstein et al., 2013) to 28 Mio. m^3 in 2010 (Sprengard et al., 2013) and 38.5 Mio. m^3 in 2019 (FNR, 2021). In 2005, mineral fibres still had the largest market share at 54.6%, followed by expanded polystyrene (EPS) at 30.5%, extruded polystyrene foam (XPS) at 5.8%, and rigid polyurethane foam (PUR) at 4.9% (Pfundstein et al., 2013). By 2019, polymeric foams (48%), like polystyrene and polyurethane, had become dominant, while mineral fibres (43%) declined (FNR, 2021). In 2005, thermal insulation made of renewable resources represented only a low market share. The statistics show that other materials, which are not further specified, including bio-based materials, had a share of 4.2% (Pfundstein et al., 2013). The share of bio-based insulation materials increased to 9% by 2019. Here, wood fibres accounted for the largest share (58%), followed by cellulose (32%). All other bio-based materials together accounted for just 10% (FNR, 2021).

A great number of materials from various renewable resources are commercially available or under development, yet renewable insulation materials remain niche products. Wood wool, wood fibres, cork boards, cellulose fibres, hemp, sheep's wool, cotton, flax, cereal granulate, reeds, coconut fibres, seagrass, wood chippings, giant Chinese silver grass, peat, and straw bales have been listed as potential raw material (Pfundstein et al., 2013). Asdrubali et al. reviewed unconventional sustainable insulation materials. They described thirteen additional renewable materials produced from bagasse, cattail, corn cob, cotton stalks, date palm, durian fruit peal, oil palm fibre, pineapple leaves, rice hulls, rice straw, sansevieria fibre, sunflower pith, and recycled cotton and denim (Asdrubali et al., 2015). Furthermore, mycelium-based composites with promising low thermal conductivities have been described (Elsacker et al., 2019; Holt et al., 2012; Schritt et al., 2021; Wimmers et al., 2019; Xing et al., 2018; Yang et al., 2017). An overview of the different composites described can be seen in Table 2.

2.1. Heat transfer in thermal insulation

The primary purpose of thermal insulation is to increase energy efficiency by retarding the heat transfer through the envelope of buildings. There are three modes of heat transfer, namely conduction, convection, and radiation. Conduction occurs by the interactions of particles in a substance (gas, liquid or solid) that results from particle movements. Thereby, heat is transported from more energetic particles to less energetic ones. Convection is the heat transfer between a solid surface and a fluid in motion. In this case, heat is transferred by a combination of conduction from the solid to the fluid and the bulk movement of fluid particles. Convection sustains the temperature difference and the heat transfer by carrying away the heated particles and replacing them with cooler ones. Thermal radiation is heat transfer by electromagnetic waves and does not require a medium. Every gas, liquid or solid, having nonzero absolute temperature, emits thermal radiation (Cengel, 2003).

The high thermal resistance, the ability to retard the heat flow, of thermal insulation results mostly from gases entrapped in the porous material structure. The materials prevent gas movements and suppress convection due to small-sized gas-filled cells (Al-Homoud, 2005). For fibrous insulation materials with densities > 20 kg m^{-3} (Daryabeigi, 2003; Stark and Fricke, 1993) or porous materials with pore sizes < 4 mm (Collishaw and Evans, 1994) convection is considered negligible. Heat transfer through these materials remains a combination of the two modes: Conduction and radiation.

According to Fourier's law of heat conduction, the rate of one-dimensional steady heat conduction $\dot{Q}_{Cond}$ is proportional to the thermal conductivity of the medium λ, the temperature gradient dT/dx and the heat transfer surface area A normal to the direction of heat transfer (Çengel, 2003):

$$\dot{Q}_{Cond} = -\lambda A \frac{dT}{dx}\ [\mathrm{W}] \tag{1}$$

In low-density thermal insulation, thermal radiation can account for a large percentage of the total heat transfer. For instance, in polymeric foams, the radiative component can account for up to 40% of the combined heat flux (Kaemmerlen et al., 2010b). Exact radiative heat transfer equations are computationally demanding to solve. The diffusion approximation can be used for highly absorbing porous materials. If the convective heat flux is negligible, the total heat flux $\dot{Q}_{tot}$ can be approximated by the sum of the radiative heat flux $\dot{Q}_{rad}$, the conductive heat flux in the solid $\dot{Q}_{sol}$ and the conductive heat flux in the gaseous phase of the pores $\dot{Q}_{gas}$ (Ferkl et al., 2013):

$$\dot{Q}_{tot} = \dot{Q}_{rad} + \dot{Q}_{sol} + \dot{Q}_{gas} \tag{2}$$

Under the diffusion approximation, all partial heat fluxes are proportional to the temperature gradient, and therefore, the total thermal conductivity can be expressed as (Ferkl et al., 2013)

$$\lambda_{tot} = \lambda_{rad} + \lambda_{sol} + \lambda_{gas} \tag{3}$$

where λ_{sol} is the thermal conductivity of the solid, λ_{gas} is the thermal conductivity of the gas filled pores, and λ_{rad} is the radiative conductivity, which is given by (Ferkl et al., 2013)

$$\lambda_{rad} = \frac{16\sigma {T_m}^3}{3\kappa_R} \tag{4}$$

where σ is the Stefan-Boltzmann constant, κ_R is the mean Rosseland absorption coefficient, and T_m is the mean temperature.

For optically thick fibreboards and a temperature of 20 °C, the contribution of the radiative conductivity to the total thermal conductivity is relatively small. Kaemmerlen et al. estimated that the radiative conductivity of wood fibreboards accounts for 4% of the total thermal conductivity (Kaemmerlen et al., 2010a).

2.2. Thermal insulation properties

A low thermal conductivity is the primary characteristic of thermal insulation materials. However, additional criteria such as density, specific heat capacity, water vapour diffusion resistance, water absorption, fire performance, and mechanical properties are important depending on the type of application and were evaluated for various bio-based composites. The specific heat capacity is an essential parameter for summer thermal insulation, and beyond the material properties, the environmental impact needs to be considered for the sustainable development of the building sector.

Table 2
Comparison of fungal species and substrate composition used for mycelium-based materials formation as well as their structure and moisture content.

Species	Substrate	Supplements	Inoculum	Particle size	Moisture content [w w^{-1}]	Dry density [kg m^{-3}]	Thermal conductivity [W m^{-1} K^{-1}]	Reference
Pleurotus ostreatus, Hypsizygus ulmarius, Ganoderma lucidum, Trametes versicolor	a) Pinewood sawdust b) mixed sawdust c) coffee grounds	potato dextrose broth and potato dextrose agar	–	–	–	–	–	(Escaleira et al., 2021)
Ganoderma lucidum, Trametes versicolor	Beech sawdust, spent *Pleurotus eryngii* substrate	a) No supplements b) 5% wheat bran, 5% wheat meal, 3% oil seed press cake	10% grain spawn	93% of spent substrate and 100% of sawdust were < 2 mm	61.4%	178–211	0.061–0.072	(Schritt et al., 2021)
Fomitopsis pinicola, Gloeophyllum sepiarium, Laetiporus sulphurus, Phaolus schweinitzii, Piptoporus betulinus, Pleurotus ostreatus, Polyporus arcularius, Trametes pubescens, Trametes suaveolens Trichaptum abietinum	Sawdust of birch, aspen, Spruce, pine, fir	Nutrient solution of peptone, malt extract and yeast extract	18 agar plugs with preincubated mycelium per 240–500 g substrate	10% of ca. 1 mm 60% of 2–10 mm 30% of 5–30 mm	45% (samples dried out) 65%	–	0.051–0.055	(Wimmers et al., 2019)
Trametes versicolor	Hemp, flax, wheat straw	No supplements	10% grain spawn	< 5 mm	70%	94–135	0.040–0.058	(Elsacker et al., 2019)
Pycnoporus sanguineus, Pleurotus albidus, Lentinus velutinus	94% pine sawdust	5% wheat bran, 1% calcium carbonate	5% grain spawn	–	66%	300–350	–	(Bruscato et al., 2019)
Trametes multicolor, Pleurotus ostreatus	Beech sawdust, rapeseed straw, cotton fibres	Bran (except for cotton fibre samples)	Grain spawn	–	65–70% (beech sawdust and rapeseed straw) 55% cotton fibres	non-pressed: 100–170, cold-pressed: 240, heat-pressed: 350–390	–	(Appels et al., 2019)
Pleurotus ostreatus	Wheat straw, sawdust	a) no supplements b) 10% wheat bran	2.7% spawn	–	67.5%	Straw-based: 192–277 Sawdust-based: 493–552	–	(Ghazvinian et al., 2019)
Oxyporus latermarginatus, Megasporoporia minor, Ganoderma resinaceum	Wheat straw	No supplements	6–8 grains of grain spawn per 60 g wet substrate	30–40 mm	67%	51–62	0.074–0.087	(Xing et al., 2018)
Trametes versicolor	Rice hulls, wheat grains	Glass fine additives to modify flammability	25% grain spawn	–	–	193–359 (589 with glass fibres)	–	(Jones et al., 2018)
Pleurotus pulmonarius, Pleurotus ostreatus, Pleurotus salmoneostramineus, Aaegerita agrocibe	Eucalyptus, oak, pine, apple and vine woodchips	–	One agar plug of preincubated mycelium per petri dish	5 mm × 15 mm	50% (w/v)	–	–	(Attias et al., 2017)
Irpex lacteus	Sawdust pulp of Alaska birch, natural fibres	Millet grain, wheat bran, calcium sulphate	–	< 5 mm	–	ca. 160–240 (sawdust + plant fibres) ca. 185–280 (sawdust)	0.050–0.070	(Yang et al., 2017)
–	Sandwich composite of cotton waste or	–	–	–	–	–	–	(Ziegler et al., 2016)

(*continued on next page*)

Table 2 (*continued*)

Species	Substrate	Supplements	Inoculum	Particle size	Moisture content [w w^{-1}]	Dry density [kg m^{-3}]	Thermal conductivity [W m^{-1} K^{-1}]	Reference
	hemp pith between fibre fabric							
Ceriporia lacerata	79% soybean straw	20% wheat bran 1% gypsum	37.5% (v/w) liquid culture	< 2 mm; 2–8 mm; < 2 and 2–8 mm ratio 1:1; 3–8 mm	65%	150–170	0.054	(Shao et al., 2016)
Ganoderma sp.	Cotton carpel, cotton seed hulls	Starch, gypsum	Grain spawn and liquid culture	28–51 mm; 12–28 mm; 0.1–12 mm; 12–51 mm; 0.1–12 and 28–51 mm; 0.1–51 mm	–	67–224	0.100–0.180	(Holt et al., 2012)

2.2.1. Density and porosity

Density is the quotient of a material's mass to its volume. Thermal insulation materials usually have low densities, which implies a high porosity. The insulation effect is partly based on the low thermal conductivity of still gases trapped within the small-sized voids of porous materials. Pores can be classified into two types: Open pores are interconnected and are characteristic of granular and fibrous materials, whereas closed pores are separated by a solid matrix and are typical for insulation foams like extruded polystyrene. The solid phase usually has a higher thermal conductivity compared to the gaseous phase. On the contrary, lower densities increase the heat transfer by radiation. However, the total thermal conductivity is not a simple function of the component's thermal conductivities and porosity. Further porosity characteristics that affect the thermal conductivity are the pore geometrics, the microstructure of pore networks and the tortuosity, which is the ratio of the average geometrical length of the heat transfer path throughout a porous material to the thickness of the material layer (Xu et al., 2018).

2.2.2. Thermal conductivity

A low thermal conductivity *(λ)* is the essential property of insulating materials. It is measured in W m^{-1} K^{-1} and defined as the heat flow through a 1 × 1 × 1 m cube of homogenous material for a temperature difference of 1 K across the sample. Bio-based insulation materials should perform similarly to conventional materials in terms of thermal conductivity, e.g., expanded polystyrene (0.031 W m^{-1} K^{-1}), extruded polystyrene (0.025–0.028 W m^{-1} K^{-1}), rigid polyurethane foam (0.020–0.023 W m^{-1} K^{-1}), and glass wool (0.034–0.037 W m^{-1} K^{-1}) (Wi et al., 2021) to achieve a broader use of these materials. The primary factors influencing thermal conductivity are raw materials, density/porosity, moisture content and temperature. Further factors are airflow velocity, material thickness, pressure, and material ageing (Hung Anh and Pásztory, 2021). Therefore, the measured thermal conductivity is strongly dependent on the measurement temperature and the relative humidity of the material at the time of measurement. Due to inconsistent measurement conditions, the thermal conductivities in Tables 1 and 2 are only comparable to a limited extent. For instance, Manohar showed that the thermal conductivity of bagasse fibres increases by 4.0% on average when the temperature increases from 18 °C to 32 °C and the thermal conductivity of coconut fibres increases by 1.2% on average when the measuring temperature increases from 15.6 °C to 21.8 °C (Manohar, 2012). Korjenic et al. investigated the moisture dependence of the thermal conductivity of jute, flax, and hemp fibres by testing moisture contents between 0% and 14%. Their results show a sharp increase in thermal conductivity as the moisture content increases above 6%. When the moisture content increased from 0 to approximately 5%, the thermal conductivities were relatively stable (Korjenic et al., 2011).

2.2.3. Specific heat capacity

Structural heat protection of buildings is necessary to prevent overheating in summer and the need for energy-intensive air conditioning. One method of protecting against overheating is installing materials with a high heat storage capacity in contact with the indoor air. The greater the heat capacity of these materials, the more heat energy can be buffered. This ability enables materials in contact with indoor air to compensate for peaks in room temperature (DIN 4108–2). The specific heat capacity *(c)* describes a material's ability to absorb heat about its mass (*m*). It is defined by Eq. 5 as the heat quantity (*Q*) necessary to raise a material's temperature (*T*) with a mass of 1 kg by 1 K (Pfundstein et al., 2013).

$$c = \frac{Q}{m \times \Delta T} \quad \left[\frac{\text{J}}{\text{kg} \times \text{K}}\right] \tag{5}$$

The total heat capacity increases with higher densities because of an increased mass per volume. Materials with higher heat capacities can store more thermal energy and have a greater ability to buffer heat peaks.

2.2.4. Mechanical properties

Different mechanical properties may be required depending on the application of thermal insulation materials. Liu et al. provide a comprehensive overview of the necessary properties for each type of insulation. The compressive strength represents a material's load-bearing capacity and is vital for all insulations except for loose-fill particles in the roof and wall cores and thin-film insulations for doors and roofs. The compressive strength depends mainly on the material's density and, in the case of fibrous materials, on the fibre's thickness and orientation. The internal bonding or tensile strength perpendicular to the plane stands for the bonding force between the individual composite substances. For instance, wind suction can exert a perpendicular force on the surface plane of exterior wall insulations. Therefore, sufficient internal bonding or tensile strength perpendicular to the plane is critical to prevent the insulation from delamination. In contrast, the tensile strength in the fibre direction is less influenced by the adhesion of the fibres or particles and more by the tensile strength of the fibres themselves. This strength will be referred to as tensile strength in the following. It is of less importance for most applications and only relevant for thin-film insulations. The flexural strength (or bending strength or modulus of rupture) refers to the strength of materials to resist bending without breaking. It is a necessary property when insulation boards are, for example, installed between supports without a backing material (Liu et al., 2017; Pfundstein et al., 2013).

2.2.5. Fire performance

The standard DIN EN 13501 defines specific requirements for insulation materials regarding fire development, fire propagation, smoke development and the formation of flame droplets. The standard defines seven material classes (A1, A2, B, C, D, E, F) to classify the fire propagation and development and additional criteria regarding smoke development (s1-s3) and flame droplet formation (d0-d2). The required material class is dependent on the type of building and construction. To be approved as a thermal insulation material, a classification of at least “normally inflammable” is necessary, achieved with E or better. For a material to achieve an “E” classification, material samples are exposed to a small flame for 15 s and observed for a further 5 s in a small burner test according to DIN EN ISO 11925–2. The flame must not exceed 15 cm in height.

2.2.6. Water vapour diffusion resistance and water absorption

Depending on their microstructure, building materials have a certain resistance to the distribution of water vapor molecules. The resistance is determined based on the materials thickness and its water vapor diffusion resistance factor μ, which is defined in relation to the water vapor tightness of air with a thickness of 1 m (Pfundstein et al., 2013):

$$\mu = \frac{vapor\ tightness\ of\ material\ (d = 1\ m)}{vapor\ tightness\ of\ air\ (d = 1\ m)}\ [-] \tag{6}$$

When materials are exposed to liquid water or water vapour diffusion during their service life, the short- and long-term water absorption is crucial. Any type of water absorption is undesirable because water has high thermal conductivity and thus increases the thermal conductivity of the insulation (Pfundstein et al., 2013). In addition, high moisture content can lead to the rotting of biodegradable materials, and thus damage the insulation. The water absorption rate W_{Abs} given in Table 1 is defined by Eq. 7. as the difference between the mass of the water saturated sample M_{Sat} and the mass of the dry sample M_0 divided by M_0 (Ndagi et al., 2021):

$$W_{Abs} = \frac{M_{Sat} - M_0}{M_0} 100 \quad [\%] \tag{7}$$

2.2.7. Durability

Ensuring durability for a defined period under specific conditions in the use phase is critical to increasing the commercial use of bio-based insulation composites. Nevertheless, durability has been little studied in bio-composite research. Liu et al. examined 144 original research papers on bio-based insulation materials. They found that only 6 studies (4.2 %) investigated durability. This was explained by the need for long-term testing and the lack of suitable advanced testing methods (Liu et al., 2017). The durability of bio-composites is affected by biological deterioration, e.g., mould growth and environmental ageing due to temperature and humidity variations. Marceau et al. developed a protocol for accelerated environmental ageing, submitting bio-composite samples to 8 wetting and drying cycles with a cycle period of 4 days (Marceau et al., 2015). Stefanowski et al. developed a rapid screening method to evaluate the susceptibility of bio-composites to mould growth. They tested medium density fibre boards (MDF), laminated MDF, chipboards, laminated chipboards, wood fibre, hemp, and sheep wool. They found that sheep wool was the least susceptible to mould growth while chipboards were most susceptible (Stefanowski et al., 2017).

3. Binder, hydrophobizer and flame retardants

To compensate for insufficient adhesion, high water absorption and low fire resistance of organic residues, binders, hydrophobizers, and flame retardants have been used. Binders and hot-pressing processes can be used to produce mats and boards from loose fibres or particles. To produce mats, synthetic bonding fibres are predominantly used (Ökobaudat, 2020; Pfundstein et al., 2013). Insulation boards are produced either by using adhesives or by hot-pressing. In addition to conventional synthetic adhesives, natural binder, e.g., starch, casein, sodium alginate (Palumbo et al., 2015, 2018), gelatine (Ismail et al., 2021) and natural rubber latex (Tangjuank, 2011), as well as inorganic binders, e.g., gypsum (da Rosa et al., 2015), lime (Ismail et al., 2020, 2021) and sodium silicate (Bakatovich et al., 2018; Bakatovich and Gaspar, 2019), were studied to produce insulation boards. Since the binding capacity of mineral materials like gypsum and lime is low, high proportions of these binders are necessary to ensure sufficient stability (Ismail et al., 2020). However, mineral binders have a high global warming potential (GWP). The GWP of lime and gypsum is 1.44 and 0.14–0.26 kg CO_2 equiv./kg, respectively (Ökobaudat, 2020). Lime has a GWP even 5–10 times higher than gypsum. In addition, mineral binders usually have a higher thermal conductivity than plant fibres (λ_{Lime}: 0.168 W m^{-1} K^{-1}; $\lambda_{Wheat\ straw}$: 0.051 W m^{-1} K^{-1}). Therefore, the binder to fibre ratio should be as low as possible while ensuring mechanical stability to optimize the thermal conductivity. Ismail et al. reduced the ratio of lime to wheat straw from 5:1–5:2 by adding 20% gelatine and thereby reduced the thermal conductivity from 0.064 to 0.051 W m^{-1} K^{-1} vertical to the fibre direction and from 0.075 to 0.057 W m^{-1} K^{-1} horizontal to the fibre direction. Also, because of reducing the mineral binder amount, the density declined from 450 to 300 kg m^{-3} (Ismail et al., 2020).

The hot-pressing process has the advantage that no additional adhesives are needed. A disadvantage, however, is the resulting densification of the material, which leads to an increase in thermal conductivity. Nevertheless, some hot-pressed thermal insulation materials achieve low thermal conductivities (Lenormand et al., 2017; Panyakaew and Fotios, 2011; Xu et al., 2004).

The main components of plant fibres are cellulose, hemicellulose, and lignin. Lignin is hydrophobic. On the other hand, cellulose and hemicellulose are hydrophilic, causing plant fibres to absorb water, which makes the materials susceptible to microorganisms, reduces thermal insulation, and causes dimensional variations. To increase the hydrophobicity of plant fibres, a wide range of treatments are available, for instance, sodium chloride, silane and plasma treatment, benzoylation, and grafting (Ali et al., 2018). Expanded cork boards are impregnated with bitumen or formaldehyde resins. Wood fibreboards are sometimes hydrophobized with bitumen or natural resins (Pfundstein et al., 2013). Flax and hemp mats are impregnated with 4 wt% sodium carbonate (Ökobaudat, 2020). Kremensas et al. tested fluoroalkyl acrylate copolymer, widely used in the textile industry, as hydrophobizer for hemp shive and corn starch-based composites finding that the addition of fluoroalkyl acrylate copolymer resulted in a three times lower water absorption (Kremensas et al., 2021).

Several fire retardants have been used to increase the fire resistance of bio-composites and meet fire safety requirements. However, the most used fire retardants are halogen-based, which are usually added in proportions of 5–15 wt% (Künzel, 2022). Halogen-based fire retardants such as boric salts are hazardous to health and the environment. Therefore, non-halogen-based agents are becoming increasingly popular. Bio-based flame retardants based on cellulose, e.g., lyocell, saccharide, polyphenolic, and aromatic compounds, have promising fire-retardancy. Aromatic compounds, e.g., lignin and tannin, have been used due to their high char and phosphorus yield during combustion. Furthermore, chitin, a compound of the mycelial cell wall and structural membrane, shows fire-retardant properties (Madyaratri et al., 2022).

4. Availability of organic residues

Since biomass is only available to a limited extent due to scarce land resources, the utilization of organic residues must be increased. Large quantities of organic residues accumulate in forestry, agriculture, gardening and landscaping, and the food, textile, and construction industries. A study commissioned by the German Federal Environment Agency investigated organic residues' availability and utilization options for energy generation, which can also be seen as a basis for estimating the availability of organic residues for material recycling. Concerning competition for use, preference should be given to material recycling with the aim of cascade utilization. The study focused mainly on Germany as a sourcing area and investigated twenty-four biogenic residue streams. Regarding material recycling, the following nine residue stream might be relevant: Forest residue wood (8.95 – 11.26 Mio. t dry matter), straw (2.7 – 19.9 Mio. t wet weight (WW)), crop residues (5.88 – 49.75 Mio. t WW), green waste (4.1 – 6.0 Mio. t WW), waste wood (6.3 – 11.0 Mio. t), landscape maintenance residues (no estimation), textiles (37,000 – 100,000 t), solid substrates from the food industry (1.7 Mio. t – 2.8 Mio. t.), and industrial waste wood (3.85 Mio. t WW). Wood residues may be available in the form of wood chips. It should be noted that industrial wood and waste wood can be contaminated with minerals and chemicals and might not be useable as a raw material for composite production. Stalks can be available from green waste and landscape maintenance waste in the form of chaff, silage, and bales. Solid substrates from the food industry can be, for instance, husks, powders, kernels, stalks, and nutshells.

It is vital that detailed knowledge of the local availability of residual materials is available and made accessible to the composite manufacturers. This requires more precise information on substrate qualities, e.g., grade purity and possible contaminants. Other significant factors for material recycling are the storability or year-round availability, chemical composition, and the consideration of necessary processing steps. Regional databases or residual material brokerage companies could help fill these knowledge gaps and transfer the knowledge. The locality is essential in this context because long transport routes are economically and ecologically inefficient for insulation materials with low material density. Furthermore, nutrient-rich residues from the food industry, e.g., coffee grounds and brewer's grains, which were not considered in the study mentioned above, can serve for nutrient supplementation in mycelium-based composite production.

5. Bio-composite materials

Table 1 shows a variety of studies on the use of organic residues to produce thermal insulation materials. These residues accumulate in agriculture or industries in different climatic zones. Further investigations of a wide range of these residual materials could offer great opportunities for the sustainable production of thermal insulation materials. Creating a database of raw materials with low thermal conductivity could enable local and diversified production of insulation materials, adaptable to regional waste streams as well as to fluctuating raw materials prices and changing climatic conditions. Experimental studies are listed that investigate the thermal conductivity of materials made from organic residues and whose minimum thermal conductivity reaches values lower than 0.07 $W\,m^{-1}\,K^{-1}$. The selection criterion is based on the classification by Pfundstein et al., according to which insulation materials with thermal conductivities lower than 0.03 $W\,m^{-1}\,K^{-1}$ are regarded as very good, thermal conductivities between 0.03 and 0.07 $W\,m^{-1}\,K^{-1}$ as moderate and thermal conductivities over 0.07 $W\,m^{-1}\,K^{-1}$ as relatively high (Pfundstein et al., 2013). Bio-based composites with organic residue contents below 50% were excluded from this study, e.g., concrete, epoxy resins, or polylactic acid (PLA) reinforced with minor amounts of natural fibres or particles. A total of 32 raw materials were selected that meet these requirements. These raw materials were used for boards, mats, loose fibres, or pressed bales. From an environmental perspective, it is of relevance that bagasse (Manohar, 2012; Manohar et al., 2006; Panyakaew and Fotios, 2011), banana fibres (Manohar and Adeyanju, 2016), coconut fibres (Manohar, 2012; Panyakaew and Fotios, 2011), cotton stalk fibres (Zhou et al., 2010), flax tow (Hajj et al., 2011), kenaf (Xu et al., 2004), oil palm fibres (Manohar, 2012), reed (Asdrubali et al., 2016), and straw bale (Goodhew and Griffiths, 2005; Sabapathy and Gedupudi, 2019) have been applied as loose fibres without the application of binders. Hot pressing has been revealed as a method when boards are needed, and no binders should be applied (Manohar, 2012; Panyakaew and Fotios, 2011). In a couple of composite materials, binders on formaldehyde (Khedari et al., 2003) or cyanate (Bakatovich et al., 2018; Khedari et al., 2003; Wei et al., 2015) basis with or without paraffin wax emulsion or polyurethane have been used for coconut coir, durian peel, and straw (barley, oats, rice, rye, and wheat). Other approaches considered adding sodium alginate, sodium silicate, gypsum (20–22%), or blending with up to 20% bicomponent fibres.

Furthermore, synthetic resins and aluminium sulphate or lignin sulphonate are used as binders (Pfundstein et al., 2013). Those additives counteract the benefit of state-of-the-art insulation materials from renewable resources to capture carbon during cultivation. Due to the use of non-biodegradable additives, those materials could not be composted at their end of life and must be deposited or incinerated. From the point of view of a circular economy, it is necessary to develop either 100% recyclable or 100% biodegradable materials (Rafiee et al., 2021).

The density-thermal conductivity relationship of loose-fill fibrous thermal insulation materials is associated with a hook-shaped curve, with thermal conductivity increasing when density is lower or higher than the optimum (Manohar, 2012). As visible in Table 1, thermal insulation boards usually have higher densities than loose-fill materials. Most studies on bio-based insulation boards from Table 1 show a positive relationship between density and thermal conductivity: The higher the density of composite boards, the higher the thermal conductivity (Mawardi et al., 2021). The particle size affects the porosity and density of the composites. If convection is prevented, larger particles result in lower thermal conductivities but also in lower mechanical strength of the composites (Mawardi et al., 2021). The worst thermal conductivity and thus best insulation properties have loose fibres. For instance, loose fibres from bagasse with a density of 70–120 $kg\,m^{-3}$ (Manohar et al., 2006) or from banana with a density of 20–120 $kg\,m^{-3}$ (Manohar and Adeyanju, 2016) revealed a thermal conductivity of 0.046–0.053 or 0.041–0.076 W m^{-1} K^{-1}, respectively. Contrarily, a high density of 357–907 kg m^{-3} and thermal conductivity of 0.063–0.185 W m^{-1} K^{-1} were achieved for boards made from durian peel under consideration of chemical binders (Khedari et al., 2003). However, Hasan et al. and Ilangovan et al. found the inverse relationship for insulation composites based on coconut coir and coffee husks. Both studies produced insulation boards with high densities of 360 (respectively 500) to 1000 kg m^{-3}. The boards with the highest density of 1000 kg m^{-3} had the lowest thermal conductivity of 0.046 W m^{-1} K^{-1} (coconut coir) and 0.052 W m^{-1} K^{-1} (coffee husks) (Hasan et al., 2021b; Ilangovan et al., 2019).

In addition to the effect of density, Khedari et al. investigated the impact of three different chemical binders (urea formaldehyde, phenol formaldehyde, and isocyanate) on the thermal conductivity showing no significant effect (Khedari et al., 2003). In Table 1, the lowest thermal conductivity of 0.015 W m^{-1} K^{-1} was achieved with bagasse and coconut coir. Finely ground fibres of 0.5 and 1 mm were mixed with 33% Gum Arabic (Ndagi et al., 2021). This value is surprisingly low, as other studies have reported a minimum thermal conductivity of 0.046 W m^{-1} K^{-1} for both bagasse and coconut coir (Manohar, 2012; Manohar et al., 2006; Panyakaew and Fotios, 2011). Also, very low thermal conductivities of 0.018–0.037 W m^{-1} K^{-1} were found for composites made of banana leaf powder 10–40% polystyrene. Here, the lowest value of 0.018 W m^{-1} K^{-1} was obtained with the lowest polystyrene content of 10%. This value is particularly astonishing as it is significantly lower than the other values of the measurement series (0.031–0.037 W m^{-1} K^{-1}) and significantly lower than the thermal conductivities of the composite's components, banana leaf powder (0.112 W m^{-1} K^{-1}) and polystyrene (0.022 W m^{-1} K^{-1}) (Mohamed et al., 2021).

The specific heat capacity is not given for all materials in Table 1. Those which could be found range from 1063 to 2152 J kg^{-1} K^{-1}, exceeding the specific heat capacities of conventional insulation materials such as mineral wools with 840–960 J kg^{-1} K^{-1}, polyethylene with 1280 J kg^{-1} K^{-1}, and polyurethane with 1537 J kg^{-1} K^{-1} (Al-Ajlan, 2006). Higher specific heat capacities can improve structural protection against summer overheating, given that the materials are in direct contact with the indoor air.

Table 1 shows a wide range of mechanical strengths. The compressive strength of thermal insulation boards ranges from 0.10 to 3.5 MPa, and the compressive stress at 10% strain from 0.05 to 1.50 MPa. The lowest compressive stress of 0.05–0.21 MPa was found for moss composites using liquid sodium silicate as a binder (Bakatovich and Gaspar, 2019), followed by rice husk composites bonded with toluene diisocyanate-based polyurethane (20%) with a compressive stress of 0.06–0.49 MPa (Bakatovich et al., 2018). Thereby, the lowest densities (120 and 223 kg m^{-3}, respectively) resulted in the lowest compressive stress. The low compressive stress and strength values are comparable with those of EPS (0.06–0.20 MPa (Pfundstein et al., 2013)), while the highest values even exceed those of XPS (0.15–0.70 MPa (Pfundstein et al., 2013)). The internal bonding strength is 0.01–0.74 MPa (EPS > 0.10 MPa, XPS > 0.20 MPa (Pfundstein et al., 2013)). The flexural strength is 0.08–55.6 MPa. Very high flexural strengths of 38.5–55.6 MPa were achieved with sheep wool boards bonded with 10–20% polypropylene (PP) fibres. The highest flexural strength was found for a ratio of 85/15 sheep wool/PP (Guna et al., 2021). These high flexural strengths exceed by far those of conventional insulation boards such as EPS > 0.05 MPa (Pfundstein et al., 2013). The tensile strength is 7.8–24.2 MPa. It was investigated for sheep wool/PP boards (7.8–10.3 MPa (Guna et al., 2021)) and coffee husk/PP boards (13.0–24.2 MPa (Ilangovan et al., 2019)). Tensile strength is only important for a few insulation applications, e.g., thin-film insulation of roof and door surfaces (Liu et al., 2017).

There is a positive correlation between the mechanical strength and the material's density. For instance, the flexural strength of hot-pressed bagasse and coconut boards increased with the board density from 0.43 to 4.16 MPa and 0.12–1.94 MPa, respectively (Panyakaew and Fotios, 2011). The same relationship exists between particle size and mechanical strength. Larger particles correlate with lower density and lower compressive strength (Pundiene et al., 2022). Therefore, the choice of density in the manufacturing of thermal insulation materials is a trade-off between mechanical strength and thermal conductivity. Compared to boards, mats have a much lower mechanical strength. The tensile strength of flax, hemp and jute mats was 0.006–0.023 MPa and the compressive stress at 10% strain was 0.0002–0.0112 MPa (Korjenic et al., 2011).

The fire behaviour of bio-composites has been investigated using a variety of tests: horizontal and vertical burning tests, cone calorimeter testing, the limiting oxygen index test, thermogravimetric analysis, differential scanning calorimetry, and dynamic mechanical analysis (Madyaratri et al., 2022). Due to the different tests applied, a comparison of the fire behaviour is complex. Although ignitability is one of the main criteria for fire classification of building materials according to EN 13501, this parameter has been investigated only in a few of the studies listed in Table 1. Kremensas et al. found that hemp shive- and starch-based composites exceeded a flame height of 15 cm after 40 s in the small burner test and thus did not meet the EN 13501 specification for an E classification. Adding expandable graphite significantly reduced the ignitability—a loading of 10 wt% expandable graphite resulted in a maximum flame height of only 5.5 cm (Kremensas et al., 2021). Lignocellulosic materials are usually flammable due to their high cellulose content. However, those materials with a high lignin content show lower ignitability because the lignin leads to a high char yield, forming a fire-retardant layer on the surface during combustion. Sheep wool also shows a high flame retardancy due to its charring ability (Guna et al., 2021). Ilangovan et al. found comparable flammability of coffee husk-PP boards to commercially gypsum boards (Ilangovan et al., 2019).

Fibres from organic residues are usually water vapour permeable. However, water vapour diffusion resistance has only been investigated in a few studies, where it ranged from 3 to 114. It was found that the water vapour resistance increases with the board's density (Marques et al., 2020). Biomaterials can absorb moisture from the air and thus positively balance indoor humidity. However, a relative moisture increase in materials lowers their thermal conductivity and makes them more susceptible to mould formation. Korjenic et al. found that a relative air humidity of 70% results in a relative material humidity of 5–10% for composites based on jute, flax, hemp fibres and shives. Moreover, it was shown that an increase in material moisture from 0% to 10% increases the thermal conductivity from 0.039 to 0.049–0.045–0.057 W m^{-1} K^{-1} (Korjenic et al., 2011). The water absorption rates in Table 1 range from 21 to 449 wt%.

Large quantities of bio-based insulation materials are expected to be generated as waste in the following decades. To date, only a few studies have investigated end-of-life scenarios of bio-based insulation materials. Besides of producer's declaration of being recyclable, these materials are usually deposited in landfills or incinerated. Selective deconstruction and accurate sorting of materials are required to achieve higher recycling rates in the future. During demolition work, care must be taken to ensure that bio-composites are not mixed with other materials. For direct recycling, for instance, to produce new wood fibreboards from waste wood fibre, large quantities are required to establish economically viable recycling routes (Rabbat et al., 2022). As an alternative to recycling, composting biobased insulation materials is only possible if these do not contain synthetic or hazardous additives.

6. Mycelium-based composites

Instead of using binders to hold fibres together, several studies demonstrated that mycelia from fungi could form firm mycelium-based composites. Fungi are not only able to bind longer fibres with particle sizes up to 30 mm, but also sawdust of around 1 mm (Wimmers et al., 2019). Longer fibres have been obtained from hemp, flax, wheat, and straw (Elsacker et al., 2019; Shao et al., 2016; Xing et al., 2018), cotton waste, cotton carpel, and cotton seed hulls (Holt et al., 2012; Ziegler et al., 2016). In Table 2, a couple of approaches are shown.

Mycelium can form materials with a wide range of densities between 51 and 552 kg m^{-3}. High densities of 185–552 kg m^{-3} were produced from different types of sawdust. The highest densities of 493–552 kg m^{-3} were obtained by Ghazvinian et al., achieving an ultimate compressive strength of 1018–1381 kPa (Ghazvinian et al., 2019). Bruscato et al. also produced a dense material of 300–350 kg m^{-3} and a compressive strength of up to 1300 kPa using pine sawdust (Bruscato et al., 2019). Other types of sawdust used are eucalyptus, oak, apple tree, and vine bush (Attias et al., 2017), beech (Appels et al., 2019), birch (Yang et al., 2017), aspen, spruce, and fir (Wimmers et al., 2019).

The lowest densities were achieved with straw-based substrates and are 51–277 kg m^{-3}. In addition to sawdust and straw, further substrates used for mycelium-based composites and tested for thermal conductivity are hemp and flax shives (Elsacker et al., 2019), cotton carpel, and cotton seed hulls (Holt et al., 2012). Furthermore, non-organic additives can be mixed with organic substrates to achieve special properties, e.g., Jones et al. added glass fibres to the organic substrate to reduce flammability. The mycelium grows around the non-organic components and can thus bind them into a solid composite. The addition of glass fibres resulted in even higher densities of up to 589 kg m^{-3}. However, the composite obtained in this way is not 100% compostable and therefore is more challenging for subsequent recycling (Jones et al., 2018).

The thermal conductivities of mycelium-based materials range from 0.040 to 0.180 W m^{-1} K^{-1}. The selection of the substrate type and the optimization of composite density in the fabrication process are the most influencing factors on the thermal conductivity. Mycelium-based composites produced with hemp shives achieved the lowest thermal conductivity of 0.040 W m^{-1} K^{-1} and a low density of 99 kg m^{-3} (Elsacker et al., 2019). The lowest thermal conductivity using sawdust was 0.050 W m^{-1} K^{-1} (Yang et al., 2017). However, in both studies, no information was provided on the measurement temperature and humidity of the sample.

Furthermore, thermal conductivity measurements of the outer fungal skins of mycelium-based composites can show species-dependent differences. The fungal skin of *Ganoderma lucidum* has a much lower thermal conductivity of 0.052 W m^{-1} K^{-1} ± 0.004 W m^{-1} K^{-1} compared to *Trametes versicolor* of 0.070 W m^{-1} K^{-1} ± 0.007 W m^{-1} K^{-1} (Schritt et al., 2021). Since only a few species were tested for material development, there is still a high research potential. Species that form much aerial mycelium might be good insulators. This ability could be used to reduce the thermal conductivity of mycelium-based composites. However, this might only significantly affect materials with high mycelium proportions or pure mycelium materials.

The raw materials listed in Table 1 can also be potential substrates for producing mycelium composites with low thermal conductivities. Local availability and production-relevant criteria such as substrate qualities, storability or year-round availability, chemical composition and additional processing are further preselection criteria. More research is needed to find suitable fungal substrate combinations based on this preselection.

The cultivation of fungi on agricultural residues requires an appropriate supplementation of nutrients. Often nitrogen-rich substrates such as peptone, malt, and yeast extract (Wimmers et al., 2019) have been added to achieve fast growth through the material and a high degree of colonization (Schritt et al., 2021). Other supplements tested were wheat bran (Shao et al., 2016; Yang et al., 2017), milled grain (Yang et al., 2017), gypsum (Holt et al., 2012; Shao et al., 2016), and calcium carbonate (Bruscato et al., 2019). The type and amount of inoculum must also be considered under the aspect of supplementation. The inoculums listed in Table 2 are based on different grain types and nutrient solutions and were added in the proportion of 5–30 wt%. For the development of sustainable mycelium-based building materials, the aspect of substrate supplementation and inoculum needs to be considered regarding the sustainability of resource use and costs for raw materials – for instance, the use of wheat bran and grains conflicts with the food supply. To avoid the use of food, organic residues, e.g., spent coffee grounds, have been tested as nitrogen-rich substrates for fungal growth (Escaleira et al., 2021). Using organic residues can also reduce the costs for raw materials, increasing the competitiveness of mycelium-based composites. In addition, the moisture content is an essential factor determining the mycelial growth rate. In the reviewed studies, moisture content mainly was between 65 and 70 wt%. Since the saturation point of sawdust is lower compared to straw-like raw materials, a substrate including straw-like components enables an increase in moisture content and thereby accelerates mycelial growth.

The mechanical strength of mycelium-based insulation materials is in the lower half of the range of bio-composite thermal insulation materials. The compressive strength is 0.03–1.38 MPa (Bruscato et al., 2019; Ghazvinian et al., 2019; Yang et al., 2017; Ziegler et al., 2016), the flexural strength of non-pressed mycelium composites is 0.05–0.29 MPa (Appels et al., 2019), and the tensile strength is 0.01–0.20 MPa (Appels et al., 2019; Ziegler et al., 2016). The compressive strength could be increased by adding natural fibres to sawdust-based composites and prolonging the incubation time (Yang et al., 2017). Furthermore, heat-pressing enhanced the flexural and tensile strength (Appels et al., 2019).

Only a few studies investigated the fire reaction of mycelium materials. Jones et al. assessed the fire safety regarding time to ignition, heat release rate and smoke release. The time to ignition was 7–12 s, which is similar to that of XPS foam with 9 s. Mycelium showed no flame-retardant properties. The average heat release rate of mycelium materials grown on wheat grain and rice hulls was 107 kW m^{-2} and 85 kW m^{-2}, respectively, lower than XPS foam with 114 kW m^{-2}. The heat release rates could be further reduced to 33–42 kW m^{-2} by adding glass fines to the composites. Furthermore, mycelium composites released less smoke than XPS. Compared to XPS, the CO and CO2 development was lower for mycelium grown on rice hulls and higher on wheat grain. Overall, mycelium composites were considered safer than XPS (Jones et al., 2018).

The water absorption of mycelium-based composites is 24–200% after 24 h (Appels et al., 2019; Attias et al., 2017; Elsacker et al., 2019; Holt et al., 2012; Ziegler et al., 2016), which is in the lower half of the range of bio-composite thermal insulation. As in the case of bio-composites, water absorption of mycelium-based composites decreases with increasing density (Attias et al., 2017). However, the lowest water absorbency was found for mycelium-hemp composites, which also had the lowest densities (Elsacker et al., 2019). This inverse relationship could be due to a denser fungal skin on the samples' surface. Appels et al. found the lowest water uptake for samples of *T. multicolor* grown on beech sawdust compared to *T. multicolor* grown on rapeseed straw and *P. ostreatus* grown on cotton fibre and rapeseed straw, most likely due to the densest fungal skin of *T. multicolor* grown on beech sawdust (Appels et al., 2019). Furthermore, Ziegler et al. and Elsacker et al. observed a nonlinear water absorption rate, which was attributed to the hydrophobic nature of mycelium and the hydrophilic nature of cellulosic fibres (Elsacker et al., 2019; Ziegler et al., 2016). Further research should focus on decreasing the water absorption of mycelium-based insulation composites to improve their durability. To date, there are no durability studies for mycelium-based composites. To prevent the regrowth of mycelium in humid air conditions, drying and heating protocols should be standardized, and the killing of the fungi verified (van den Brandhof and Wösten, 2022).

If mycelium-based insulation materials meet all requirements for insulation applications without synthetic and hazardous additives, these materials can either be composted (Van Wylick et al., 2022) or directly recycled (Schritt et al., 2021) at the end of their life. Further research is needed to evaluate the fulfilment of these requirements sufficiently. However, as with the above hurdles for recycling bio-composites, selective deconstruction and accurate sorting are prerequisites.

7. Conclusions

Given the variety of biomasses available, the application of more bio-based insulation materials is expected in the future to meet national and international climate and energy reduction goals. To achieve the climate protection goals, Germany needs to double the production of insulation materials. At the same time, bio-based and biodegradable alternatives need to replace synthetic insulation materials and mineral wools due to their environmental impact. This fact leads to enormous demand for sustainable insulation materials. To ensure a sustainable life cycle, using organic residues is crucial to not compete with food production. More work, however, is necessary to reproducible produce materials that meet the standards of the building sector. Fungi, for instance, can be applied to produce bio-based thermal insulation materials from side-streams of low value to prevent the overexploitation of nature as the source of biomass. However, to increase the utilization of organic residues as raw materials for bio- and mycelium-based insulations, more knowledge needs to be accessible, for instance, regarding local and seasonal availabilities, residue qualities, storability, and chemical composition.

Both bio-composites and mycelium composites show in comparison to conventionally applied materials promising thermal insulation properties. The heat storage capacities of bio-composites can exceed those of conventional materials, which might result in new applications for structural summer heat protection. The bio-composites listed show good mechanical strengths comparable to or exceeding those of conventional materials such as EPS and XPS. The mechanical strength of mycelium composites is in the lower half of those of bio-composites. Few studies on bio-composites investigated fire performance. However, due to the high cellulose content, poor fire performance seems to be one of the main disadvantages of bio-based insulation materials compared to conventional materials. Promising results have been obtained for bio-composites with high lignin content, which act as a natural flame retardant. Furthermore, mycelium composites were considered safer than EPS. Bio-composites have low water vapour diffusion resistance combined with high moisture absorption. As a result, they can have a balancing effect on relative humidity, provided they are in direct contact with it. The water absorbency can be reduced by using fungi due to the hydrophobic nature of mycelium. More research is needed to assess the durability of bio- and mycelium composites. In addition, standardized and accelerated testing methods need to be developed. Bio- and mycelium composites have a low carbon footprint due to the carbon capture during cultivation of the renewable raw materials. However, using binders, hydrophobizers, and flame retardants counteract this benefit. Therefore, the challenge remains to develop non-toxic, 100% recyclable or 100% biodegradable competitive thermal insulation materials. Binder-free bio-composites and mycelium composites sourced from organic residues are promising in this regard and could lead to environmentally friendly and recyclable insulation materials capable of replacing conventional mineral and synthetic insulation materials.

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