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Life cycle assessment of mycelium-based composite materials

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ABSTRACT

Mycelium-based composites (MBCs) show promising acoustic and thermal insulation, fire safety, and mechanical strength properties and are suitable for multiple applications in the construction, packing or furniture industry. A life cycle assessment confirmed climate change and fossil energy demand benefits in a laboratory scale production modelled for Germany. MBC are associated with 0.3668 kg CO_2e / kg MBC (EN 15804 + A2). The electricity required to run MBC production and hemp cultivation, if used as a substrate, contribute significantly to the environmental impact categories considered. Compared to conventional insulation materials, environmental advantages of MBC can be confirmed. Particularly, MBC has a better climate change impact than extruded polystyrene, quadcore sandwich panel, foam concrete and rockwool. However, since the end-of-life is not assessed, the wood-fiber and straw panels perform better regarding climate change. Moreover, MBC has lower fossil energy demand than all conventional insulation materials. Land-use and water demand are higher than for conventional materials.

1. Introduction

Public awareness of environmental damage caused by the exploitation of non-renewable resources and their waste treatment at the end of their lifecycle is increasing (Madurwar et al., 2013). Particularly, the energy intensity and greenhouse gas emissions from the production of construction materials demand for sustainable alternatives. Moreover, a major challenge is the conversion of the linear economy towards closed-loop systems, as well as to develop strategies that focus on bio-based and sustainable solutions (Appels et al., 2019; Elsacker et al., 2021). In the last decade, mycelium-based composites (MBCs) have attracted academic and commercial interest as novel, economical, and environmentally sustainable materials (Jones et al., 2017). Mycelium is the root system of filamentous fungi. When added to an organic substrate, it forms a three-dimensional network that serves as both a fibre and a binder for the resulting bio-composite (Raffie et al., 2021). Given the properties of MBC, it has great potential to revolutionize the construction industry, which is so far dominated by energy and emission intense materials such as steel, plastic, and concrete and even wood which is only to a certain extend available in a sustainable way (Javadian et al., 2020). Since MBC can be obtained from various agricultural waste the resulting composites are not only biodegradable, but the mechanical properties can be tailored to the intended purpose (Lee and Choi, 2021). MBCs applications span from insulation to furniture applications, making them very versatile in various industrial sectors including construction (Chan et al., 2021). Furthermore, MBC production does not compete with other usage of raw materials as only waste and by-products from wood and agricultural industry that cannot be used efficiently in other processes are used.

Literature mostly portrays MBC as sustainable and with lower environmental impacts than conventional materials (Ahmadi, 2016; Elsacker et al., 2019; Jones et al., 2020; Robertson et al., 2020). However, research on the environmental aspects of MBC to date is not scientifically substantiated (Elsacker et al., 2020). Life cycle analyses (LCA) of MBC are still very limited and have only been conducted on laboratory scale (Attias et al., 2020; Jones et al., 2018; Stelzer et al., 2021; Carcassi et al., 2022; Livne et al., 2022) and lead to varying results (Cascione et al., 2022). Moreover, comparative LCA studies are missing.

A literature review in ESCOhost, JSTOR, ProQuest, ScienceDirect and Scopus with the term “mycelium AND ((((life-cycle) OR (life AND cycle) OR lifecycle) AND (assessment OR analysis)) OR LCA)” reveals only eleven peer-reviewed papers dealing with MBCs and their LCA (Table 1). Most papers focus on food production. Only few cover construction (Robertson et al., 2020; Stelzer et al., 2021; Carcassi et al.,

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Table 1
Overview and short analysis on the selected papers.

Authors	LCA done	Application Field	Scope	Fungal Species	Substrate
Robertson et al. (2020)	No	Construction	/	/	/
Stelzer et al. (2021)	Yes	Construction (Brick)	Cradle-to-gate	Fomes fomentarius	Hemp shive; Rapeseed straw; Poplar chips
Raffie et al. (2021)	No	Other	/	/	/
Carcassi et al. (2022)	Yes	Construction (Insulation)	Cradle-to-gate	Pleurotus Ostreatus	Rye spawn
Cascione et al. (2022)	Yes	Construction (Wall panel)	Cradle-to-cradle	/	/
Livne et al. (2022)	Yes	Construction (Brick)	Cradle-to-Gate	Trametes betulina	Rapeseed straw; Recycled cellulose
Enarevba and Haapala (2023)	Yes	Packaging	Gate-to-grave	/	Agricultural feedstock

2022; Cascione et al., 2022; Livne et al., 2022) and other purposes (Raffie et al., 2021; Enarevba and Haapala, 2023) (Table 1).

Robertson et al. (2020) compared MBCs with conventional insulation materials based on LCAs in literature. They find that MBCs produce about one-third less CO_2 than expanded polystyrene (EPS) insulation. Stelzer et al. (2021) conducted a full LCA (cradle-to-gate) on MBC bricks[1] produced on a laboratory scale in Germany. They tested the fungus *Fomes fomentarius* on hemp shives, rapeseed straw and poplar chips substrates (Stelzer et al., 2021) and found that the preparation process of the substrate has the greatest environmental impact. Compared to conventional bricks, MBC has less environmental impacts in acidification, climate change, water scarcity and smog. However, since the substrate is an agricultural product, MBC bricks score lower in eutrophication and land use compared to conventional bricks. Carcassi et al. (2022) assess the carbon footprint of a MBC sample prism with bamboo particles (MycoBamboo) for building insulation purposes. They found a net positive GWP of the assessed functional unit (Ø: 100 mm and thickness: 30 mm). Cascione et al. (2022) developed and assessed different wall panel designs, among other things filled with MBC. Compared to flax, alternative clay and eco-oriented strand boards (OSB), the MBC panel had the highest environmental impact due to production efforts and the required thickness of the layer. Livne et al. (2022) assessed a brick[2] on lab scale with respect to embodied energy and embodied carbon. They specifically emphasized on the quantification of CO_2 emissions during mycelium growth and found a linear relationship between dry weight loss and metabolic CO_2 emission irrespective of the used substrate. In their study, the incubation stage made up the largest portion (73 %) of the overall energy, while metabolic CO_2 comprised a significant proportion (21 %) of the overall emissions.

Whether MBCs actually provide the environmental benefits of biodegradability and low carbon footprints has yet to be scientifically proven (Robertson et al., 2020; Cascione et al., 2022). These properties are expected from the use of only organic materials and low-energy manufacturing processes (Elsacker et al., 2021; Javadian et al., 2020; Raffie et al., 2021). However, some bio-based materials/products have higher environmental impacts than expected (Carcassi et al., 2022) or than conventional products and required further design adaptation (Cascione et al., 2022). While mycelium holds great promise in addressing environmental and industrial challenges, overcoming obstacles related to scalability, raw material availability (sawdust), consistency, safety, and regulatory compliance is essential for realizing its full potential across different sectors. A significant challenge in mycelium materials production is the extended production cycle of 2 to 3 weeks, posing economic constraints for large-scale production. Moreover, a comparison with wood-based, mineral or synthetic panels that could be substituted by MBCs has not been done yet.

Thus, this study aims to quantify the environmental aspects of MBC materials production by conducting a full LCA with new data on lab scale that might substitute wood-based panels in the construction sector. Their wide range of applications from insulation to load-bearing applications might reduce the demand for wood-based panels and their chemical components. The results are compared with literature and conventional products (commercially available wood-based panels) in terms of environmental aspects.

2. Methods

2.1. Materials

Two cases of MBCs are assessed and compared using LCA: (1) MBC with hemp fiber substrate and (2) MBC with sawdust substrate. In contrast to MBC brick production (Stelzer et al., 2021; Livne et al., 2022) or MBC wall or insulation panels (Carcassi et al., 2022; Cascione et al., 2022), in the assessed MBC production in this study other production steps and different input amounts are required leading to different physical parameters of the MBC e.g. strength and stiffness, as well as to different environmental impacts. Production details and assumptions for both MBC variations are explained in Section 2.3.

2.2. Methodological framework (goal and scope)

The goal of this study is to assess the potential environmental impacts of MBCs for the construction sector through a laboratory scale study. Furthermore, the study aims to determine which substrate, whether hemp or sawdust, results in superior environmental performance in the production of MBCs. Moreover, a comparison between MBC and conventional wood-based, mineral and synthetic insulation panels used in the construction sector will be done with respect to their environmental impacts in the production stage.

The LCA procedure follows DIN EN ISO 14040:2021 and DIN EN ISO 14044:2021 standards (DIN e.V. (2021a, 2021b)). The final output of the production serves as the functional unit. The functional unit is one kilogram of hemp- or sawdust-based MBC, so a functional unit of mass is chosen. Depending on the density and thickness of the boards produced, this results into different spatial dimensions which would make a direct comparison per m^2 or m^3 difficult. For the use and end-of-life stages, we assume the same material and energy inputs and outputs and associated environmental burdens for both types of substrates so that we neglect them in the comparative assessment. This leads to a cradle-to-gate assessment. This simplification is possible since the processes after production are identical for every option. In the sawdust variant, we assume the zero-burden approach for the sawdust input. This means that the sawdust substrate which is a by-product (waste) of the wood industry is not associated with any environmental impacts (following Nakatani, 2014). The hemp-based MBC is benchmarked against an MBC with sawdust as substrate and compared with literature with respect to environmental impacts. In addition, a comparison is made with wood-fibre insulation and other conventional insulation materials to evaluate the claimed environmental benefits of MBCs.

The system boundaries include the agar plate, seed and substrate

[1] Functional unit is the standardized German "Normalform" which is the geometry of artificially formed stones in the German construction industry (Normalformat = 240 × 115 × 71 mm).

[2] Functional unit is a 20 x 20 x 40 cm “mycoblock” normalized to a functional unit of 1 m^3 of mycelium material.

preparation, mycelium growing, material handling and processing as well as cleaning processes. For all machines required for production, the energy and cleaning requirements are considered. Waste generated from cleaning or as scrap and their treatment are also considered. However, the environmental impact of the machines during their life cycle as well as maintenance activities or inputs other than electricity or water are excluded. Transportation activities are also not considered due to insufficient raw material data for Germany as the country of production and the unknown location of use. Other influencing factors such as the laboratory building or the operational area are also not modelled, since they exist already and are not specifically conditioned for MBC production.

For production of MBC materials, wood decay Basidiomycetes class of fungi are of interest such as but not limited to different species of *Ganoderma* (e.g. *Ganoderma lucidum), Pleurotus* (e.g. *Pleurotus Ostereatus*) and *Trametes* (e.g. *Trametes Versicolor*). These group of fungi can rapidly digest lignin, changing the chemical structure of lignin into lignin-based radicals. With sufficient supply of oxygen, these radicals can form cross-links and act like an adhesive (Bennet et al., 2002). These groups of fungi do not include the common Toxigenic, Pathogenic and Allergenic molds generically called "mildew" which are rising health risks if grown indoor. For the case study presented in this article, chinese strain of *Ganoderma lucidum* commonly known as Reishi was selected.

2.3. Process assessment and inventory analysis

Fig. 1 shows the modelled cradle-to-gate production process in general. The production system analysed is based on the laboratory manufacturing at Karlsruhe Institute of Technology (KIT), which is visualized in detail in Fig. 2 for hemp (A) and in Figure A-2 for sawdust (B) in the Supporting Information of this article. With respect to the product life cycle, the production stage is modelled gate-to-gate including cleaning of the equipment (foreground). Raw material supply, energy (electricity) supply, wastewater and waste treatment are considered (background). Energy supply includes electricity from the grid (German electricity mix) only, heat is not provisioned. Wastewater is treated in treatment plants and all production waste is incinerated. For each process step where contamination of the material with other fungi or bacteria may occur with some probability that would make the material useless, scrap is considered and modelled as biowaste that is incinerated. For the plastics of the petri dish and plastic bag, datasets for incineration of polystyrene and polypropylene wastes are chosen. Use and end-of-life stages of MBC are neglected since no data are available for a use and end-of-life treatment simulation. However, composting or reusing the substrate to feed the next batch of MBC materials production would be possible since all inputs are biodegradable (see Table 2). Transports are excluded since a production is modelled at a single location and transports from suppliers might vary.

The assessed production process can be divided into four stages:

1. Agar plate preparation
2. Mycelium seed preparation
3. MBC preparation

Therein, the following unit processes (A.1.x to A3.x) in Fig. 2 are modelled in the foreground (see also the aggregated process graph in Figure A-1 in the Supporting Information).

For the purpose of this study hemp hurds have been purchased from Bafa GmbH (Malsch, Germany) and sawdusts were collected from the woodworking workshop of the Karlsruhe Institute of Technology (KIT), Germany. The mycelium mother culture of *Ganoderma lucidum* china strain (*G. Lucidum*) was purchased from Tyroler Glückspilze (Innsbruck, Austria) in the form of pure culture and stored at 4 °C for up to 2 weeks. The pure culture was then used to produce the spawn as described in the following.

In the agar plate preparation, the fungus *Ganoderma lucidum* is cultivated on a Petri dish in a medium consisting of agar, malt extract and water (A.1.1). Since only a very small portion of the fungus is introduced into the culture medium and, moreover, it is not acquired from suppliers for each new batch but obtained by cultivation in the own laboratory, the fungus input is not modelled separately. The material scrap resulting from contamination of the material with other fungi or bacteria is expected to be 10 %[3] (Table 2). The incubation period for fungal growth on the agar plate is two weeks under largely uncontrolled conditions (indoors at about 22 to 24 °C and constant humidity). This corresponds to usual room conditions of the laboratory building and is not specifically conditioned. Thus, heating or air conditioning for this process step is neglected.

For the preparation of the mycelium seeds first a broth of malt extract and water is mixed and sterilized in an autoclave at 120 °C for 20 min (A.1.2). The autoclave cleaning activities including wiping out the autoclave and refilling water are modelled with wastewater as the output. The fungus is then inoculated into the broth, which serves as a liquid nutrient for the growth of the mycelium seeds (A.1.3). The mycelium remains in the liquid for five days under controlled conditions provided by an incubation shaker. During incubation, 10 % scrap due to both unwanted fungi or bacterial infections of the material is assumed. Finally, the seeds are extracted from the liquid under a biosafety cabinet where a sterile atmosphere prevails (A.1.4). However, rejects may also occur during this process and are modelled with 10 %.

In the third stage, the composite of mycelium and substrate is produced. For this, the hemp is milled to a particle size of approximately 2 mm (A.2.1). Thereof, about 1 % of the hemp is recorded as scrap and cleaning leftover in the mill. The remaining substrate is then mixed with water to provide moisture for the mycelium to grow (A.2.2). Since the production is on a laboratory scale, the mixing is performed by hand in a bowl and not with a mixing machine. Cleaning the bowl with water is considered. Before inoculation with mycelium, the substrate is sterilized in the same autoclave as the malt extract broth for 45 min, where we also account for cleaning and replenishment of water (A.2.3). Then, the substrate and mycelium are mixed and filled into a polypropylene plastic bag that allows air exchange through a cotton barrier (A.3.1). For the packaging process, it is assumed that the plastic bag is used five times before being discarded; and, that it is cleaned after each use. As the final step, the composite is kept under controlled conditions for 14 days to allow the mycelium to completely grow through the substrate (A.3.2). A controlled atmosphere is provided by an intake/exhaust fan and a humidifier, which maintain the temperature at 24 °C and the humidity at 60 to 70 %. Despite the previously described measures to prevent contamination with undesirable fungi or bacteria, the scrap rate is another 10 % at this stage. Finally, the composite is cured in an oven at 55 °C for 24 h to stop fungal growth and dry the material, where it loses about 50 % of its weight due to evaporation of moisture (A.3.3).

The production system was modeled using the open-source LCA software program openLCA (GreenDelta (2022)), with datasets from both Ecoinvent 3.8 and Agribalyse v3.0.1 databases. Ecoinvent (2022) is an established provider of LCA data and mainly used as the source for production-related data. The French Agribalyse database focuses on agricultural and food-related data streams; its data is taken where Ecoinvent does not provide suitable data (PRé Sustainibility B.V., 2022b). The impact assessment was done with openLCA 2.0.3 and EN 15804+A2 Add on for ecoinvent 3.9.1. Table 2 and Fig. 2 shows all material inputs, outputs and waste streams required for the described process that is modelled as foreground system. Material inputs are particularly required for the cultivation of the mycelium, i.e., the provision of nutrients and moisture. In the first stage, agar medium is needed, malt extract broth in the second, and moisture from water in the

[3] During production, infection with undesirable fungi or bacteria may occur. For each process step where infection may occur with some probability, 10% scrap is considered and modeled as organic waste that is incinerated.

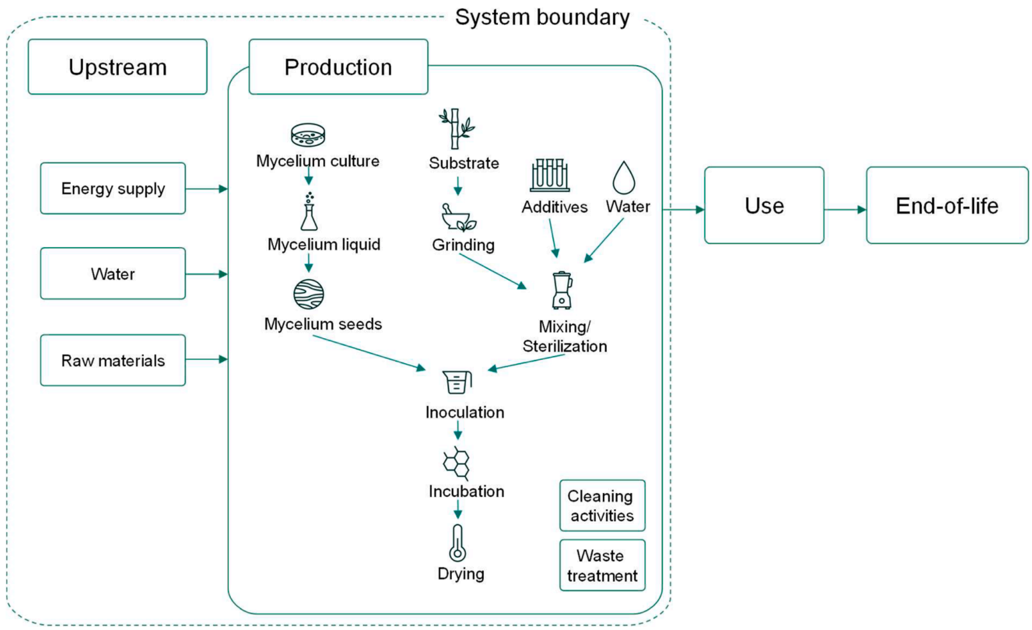

Fig. 1. System boundary of the LCA for the production of one kilogram of mycelium-based composite.

third to create optimal growth conditions. Under laboratory conditions, the agar medium consists of malt extract, agar and water. However, since datasets for malt and agar are not available, proxy values based on similar properties are used. For malt extract, the proxy barley grain is applied (dataset "0111:Growing of cereals (except rice), leguminous crops and oil seeds - barley production | barley grain | Cutoff, U – DE (2000–2021)"). Since malt extract is derived from malt and malt is extracted from barley, which leads to a weight loss, a weight adjustment of 22 % is implemented (Stelzer et al., 2021). The proxy barley grain is also used for the malt extract broth that is required for the preparation of the mycelium seeds. For agar, gelatine is used as a replacement material from the Agribalyse database, following Stelzer et al. (2021) (dataset "Miscellaneous/Miscellaneous ingredients - Gelatine, dried, processed in FR | Ambient (long) | Cardboard | at distribution/FR (2023)"). Whenever water is needed in the process flow A background dataset for deionized water is considered (dataset "3600:Water collection, treatment and supply - market for water, deionised | water, deionised | Cutoff, U - Europe without Switzerland" (2011–2021)). The *sunn* hemp dataset is taken for the substrate input (dataset "0116:Growing of fibre crops - sunn hemp production | sunn hemp plant, harvested | Cutoff, U – RoW (2016–2021)"). For all machines required for production, the energy and cleaning requirements are considered. Organic wastes generated from cleaning or as scrap and their treatment are also considered (incineration) (dataset "treatment of biowaste, municipal incineration with fly ash extraction | biowaste | Cutoff, U (2006–2021)").

Furthermore, auxiliary materials are needed for the production. These are the petri dish for mushroom cultivation as well as packaging material for the mycelium growing in the substrate material, which consists of a plastic bag and cotton. For the petri dish and the plastic bags, there is no applicable process in the databases. Therefore, the corresponding material mass of general-purpose polystyrene (petri dish) and general-purpose polystyrene plus cotton (plastic bags) is modelled (datasets "2013:Manufacture of plastics and synthetic rubber in primary forms - polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U – RER (2001–2021)" and "0116:Growing of fibre crops-seed-cotton production, conventional | seed-cotton | Cutoff, U – RoW (2016–2021)". For the end-of-life of the petri dish and plastic bag, datasets for incineration of polystyrene and polypropylene wastes, respectively, are chosen. Its waste incineration is modelled with dataset "3821:Treatment and disposal of non-hazardous waste - treatment of waste polystyrene, municipal incineration with fly ash extraction | waste polystyrene | Cutoff, U (2006–2021))").

To transform the material inputs into the final MBC, process inputs are needed as well. In the laboratory, these processes are performed by a fan, a humidifier, an autoclave, an oven and a milling machine. However, the environmental impact of the machines during their lifecycle as well as maintenance activities or inputs other than electricity or water are not considered. Only the inputs required to operate and clean the machines, i.e., electricity and water, are considered. As mentioned in the scope, the impact of machine factors, e.g., for their end-of-life, are not considered, as they are assumed to have a very small share in the total environmental impact and are therefore considered to be negligible.

For electricity, the German electricity mix is chosen (dataset "3510: Electric power generation, transmission and distribution - market for electricity, low voltage | electricity, low voltage | Cutoff, U - DE", valid: 2014–2021) and for water, the dataset for deionized water (dataset "3600:Water collection, treatment and supply - market for water, deionised | water, deionised | Cutoff, U - Europe without Switzerland", valid: 2011–2021) is used, both from ecoinvent database. The water demand is used for cleaning the autoclave, the milling machine, the mixing bowl and for rinsing the plastic bag. The input for the cleaning activities is deionized water and the output is wastewater. The treatment of wastewater is modelled with dataset "3700:Sewerage - treatment of wastewater, unpolluted, capacity 5×10^9l/year | wastewater, unpolluted | Cutoff, U – CH" (1994–2021).

Transportation activities are not modeled. This is due to the insufficient raw material data for Germany as the country of production, the unknown location of use and the non-necessity of transportation during production, as this takes place at one single location. Other factors influencing the lifecycle assessment, such as the laboratory building or the operational area, are also not modeled. The focus is on the baseline laboratory's production scale and these factors would go beyond the intended scope.

For the sawdust-based MBC manufacturing process, the milling (step A.2.1) is unnecessary, since the particle size of the sawdust does not need to be adjusted (Supporting Information). However, to achieve a similar growth rate, nutrients, namely wheat bran and calcium carbonate, are added to the substrate. Therefore, A.2.1 is deleted and the Ecoinvent datasets for loose sawdust and calcium carbonate along with the Agribalyse dataset for wheat bran are added in B.2.2 (see Figure A-2

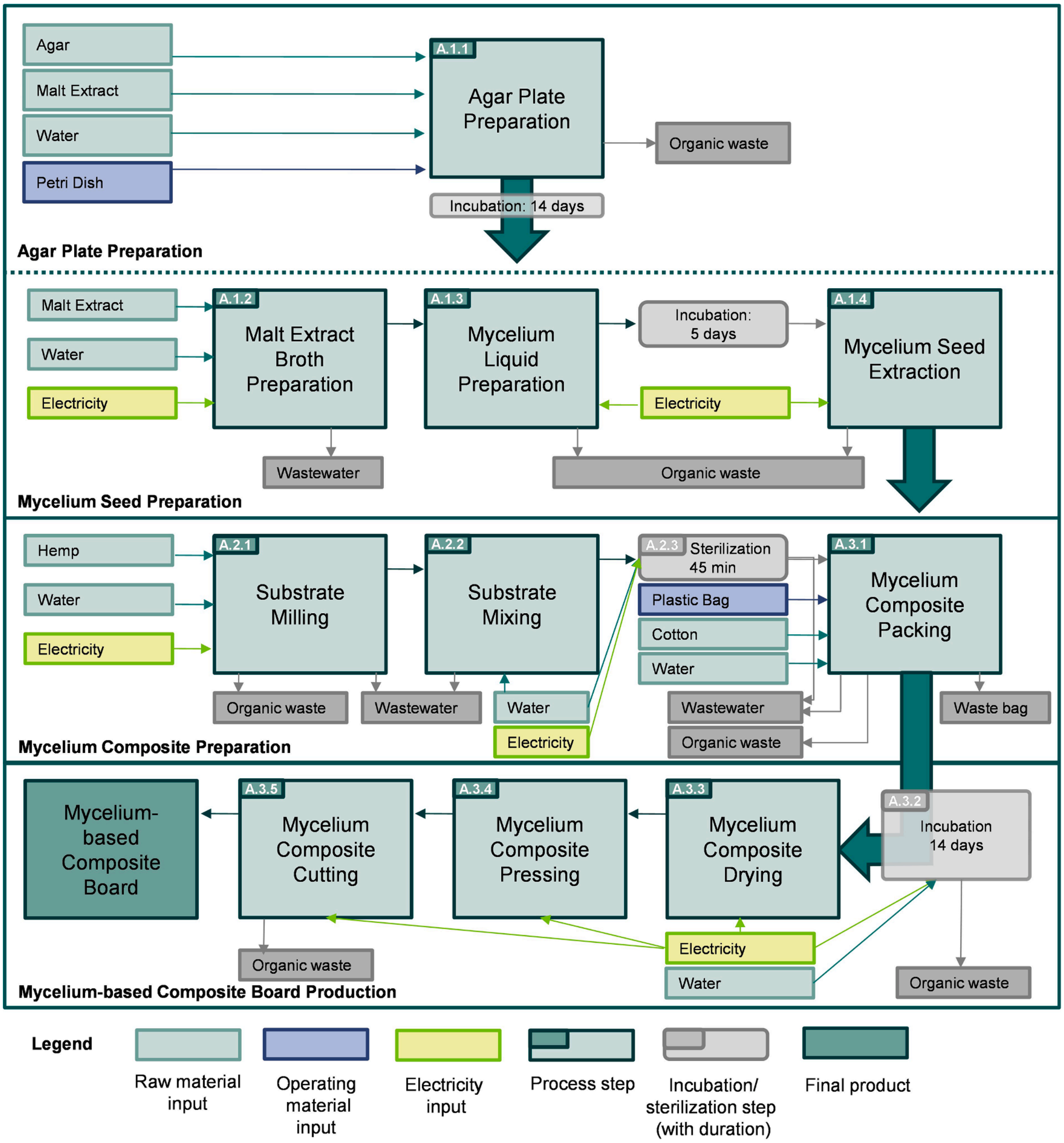

Fig. 2. Process flow diagram for the production of the hemp-based MBC (A). Unit processes involving the handling from agar plate preparation to the mycelium seeds have index 1, substrate-related processes have index 2, and the composite mixing has index 3 in the second position of the numbering nomenclature. The last digit is the chronological enumeration of the process steps.

in Supporting Information). The rest of the production process remains the same as for the hemp-based MBC.

2.4. Life cycle impact assessment

This study analyses the following environmental impacts: energy demand, climate change, i.e., the emissions of greenhouse gases into the air, acidification, eutrophication, water scarcity, ozone formation, and land use according to the listed impact assessment methods (Table 3) to compare the results with Stelzer et al. (2021). Moreover, we also assessed the MBC production process via the EN15804 + A2 method provided by openLCA 2.0.3 and EN 15804+A2 Add on for ecoinvent 3.9.1 with process default allocation method and no cutoff for evaluation of the environmental performance of building materials that provides standardized information for environmental production declarations.

For climate change, acidification, and eutrophication, the established methodology of the Leiden University Center for Environmental Sciences (CML-IA baseline) is applied (Bach and Finkbeiner, 2017; Guinée et al., 2001a). For water scarcity, the Available WAter REmaining (AWARE) method from the international WULCA working group for water use assessment is used (WULCA, 2022a). And lastly, for ozone formation and land use, the standard model (H) of the ReCiPe method version 2016 is applied (PRé Sustainability, 2022a). All impact assessments were done without any normalization and weighting methods.

3. Results

Table 4 and Table A-1 (SI) show the impact assessment results for the hemp-based MBC production process for the respective impact assessment methods. The MBC production stage has the highest impacts in all impact categories except for water scarcity and land use (Table 4). This stage dominates fossil energy demand (Fig. 3), climate change, acidification, eutrophication, and ozone formation. In the impact categories of water scarcity and land use, mainly the composite preparatory phase

Table 2
Inputs and outputs for the modelled unit processes involved in the production of one kilogram of hemp-based MBC.

Production Stage	Process Step	Material/ Process	Input/ Output	Amount	Unit
1. Agar Plate Preparation	A.1.1	Medium	Malt Extract/ Barley grain	$0.45 * 10^{-6}$	kg
			Agar/Gelatine	$2.693 * 10^{-7}$	kg
			Water	$1.797 * 10^{-5}$	kg
		Petri dish	Polystyrene	$1.045 * 10^{-6}$	kg
			Waste polystyrene	$1.045 * 10^{-6}$	kg
		Scrap	Organic waste	$1.698 * 10^{-6}$	kg
2. Mycelium Seed Preparation	A.1.2	Malt extract broth	Malt extract/ Barley grain	$1.594 * 10^{-4}$	kg
			Water	$0.6533 * 10^{-3}$	kg
		Sterilization	Electricity	$0.49 * 10^{-4}$	kWh
		Cleaning	Water	$0.392 * 10^{-4}$	kg
			Wastewater	$0.392 * 10^{-4}$	kg
	A.1.3	Incubation	Electricity	0.012	kWh
		Scrap	Organic waste	$0.593 * 10^{-4}$	kg
	A.1.4	Seed extraction	Electricity	$1.622 * 10^{-4}$	kWh
		Scrap	Organic waste	$0.541 * 10^{-4}$	kg
3. Mycelium Composite Production	A.2.1	Substrate	Sunn hemp, harvested	0.1913	kg
		Milling	Electricity	0.093	kWh
		Cleaning	Water	$0.591 * 10^{-3}$	kg
			Wastewater	$0.591 * 10^{-3}$	kg
		Scrap	Organic waste	0.002	kg
	A.2.2	Moisture adding	Water	0.351	kg
		Cleaning	Water	0.087	kg
			Wastewater	0.087	kg
	A.2.3	Sterilization	Electricity	0.091	kWh
		Cleaning	Water	0.0323	kg
			Wastewater	0.0323	kg
	A.3.1	Incubation bag	Polypropylene	0.0023	kg
			Waste polypropylene	0.0023	kg
			Seed-cotton	0.00067	kg
			Organic waste	0.00067	kg
		Cleaning	Water	1.880	kg
			Wastewater	1.880	kg
	A.3.2	Growth conditions provision	Electricity	0.162	kWh
			Water	0.151	kg
		Scrap	Organic waste	0.054	kg
	A.3.3	Drying	Electricity	0.680	kWh

Table 3
Specification of the impact categories for the life cycle impact assessment (LCIA).

Impact Category	Characterization Factor	Category Indicator	Reference	Unit	Method
Energy demand	Cumulative energy demand (CED)	Renewable and non-renewable energy demand	Frischknecht et al., 2015; Hischier et al., 2010	MJ eq.	Ecoinvent CED
Climate change	GWP 100a	Infrared radiative forcing (W/m^2) due to greenhouse gas emission into the air	Guinée et al., 2001b	kg CO_2 eq.	CML-IA baseline
Acidification	Acidification potential (AP)	Deposition/acidification critical load	Guinée et al., 2001b	kg SO_2 eq.	
Eutrophication	Eutrophication Potential (EP)	Deposition of nitrogen and phosphorus equivalents in biomass	Guinée et al., 2001b	kg PO_4^{3-} eq.	
Water scarcity	Water scarcity footprint	Potential of water deprivation	Boulay et al., 2018; WULCA, 2022b	m^3 world eq.	AWARE
Ozone formation	Photochemical oxidant formation potential	Tropospheric ozone increase	Huijbregts et al., 2017	kg NO_x eq.	ReCiPe 2016 Midpoint (H)
Land use	Agricultural land occupation potential	Occupation and time-integrated land transformation	Huijbregts et al., 2017	m^2a crop eq.	

contributes. The EN 15804+A2 impact assessment leads to almost half lower climate change impact due to (1) a different assessment method and associated databases and (2) due to a slightly changed process (in the EN15804+A2 calculation we excluded pressing and cutting, which was included in the LCIA according to Table 3). Table 5, Fig. 4 as well as Table A-1 in the Supporting Information depict all EN 15804 + A2 assessment results.

In the production steps, substrate milling (A.2.1) and mycelium composite drying (A.3.3) contribute largely to almost all impact categories, followed by mycelium composite pressing (A.3.4) (which was not assessed in the EN15804+A2 LCIA method) (Figure A-3). The agar plate preparation and mycelium seed preparation stages have rather small environmental impacts. The reason for this can be attributed to the relatively small inputs in these two production stages compared to the life cycle inventory quantities of the following stages. The fact that so little input is required can be explained by the continuous growth process of the mycelium material, which increases in mass and volume during the production steps, resulting in only a small amount of starting input being needed. Further assessment details of the EN15804+A2 LCIA can be found in the Sankey diagrams in Figure A-4, Figure A-5, Figure A-6, Figure A-7, Figure A-8 and Figure A-9 (Supporting Information).

3.1. *Energy demand*

The Ecoinvent cumulative energy demand method is used. A total of 7.7 MJ eq. is required to produce 1 kg of hemp-based MBC (Table 4) according to ecoinvent CED based LCIA and 6.68 MJ / kg MBC in the

Table 4
Life cycle impact results per production stage and in total for the production of 1 kg of hemp-based MBC (according to the impact assessment methods listed in Table 3).

Impact Category	Agar Plate Preparation	Mycelium Seed Preparation	MBC Production	Total
Fossil energy demand (MJ eq.)	$0.9 * 10^{-4}$	$0.705 * 10^{-1}$	7.6386	7.7086
Climate change (kg CO_2 eq.)	$0.734 * 10^{-5}$	0.0063	0.7033	0.6933
Acidification (kg SO_2 eq.)	$1.370 * 10^{-8}$	$1.347 * 10^{-5}$	$1.5362 * 10^{-3}$	$1.5497 * 10^{-3}$
Eutrophication (kg PO_4^{3-} eq.)	$2.55 * 10^{-9}$	$3.090 * 10^{-5}$	$3.888 * 10^{-3}$	$3.93 * 10^{-3}$
Water scarcity (m^3 world eq.)	$0.487 * 10^{-5}$	$2.373 * 10^{-3}$	0.577	0.5797
Ozone formation (kg NO_x eq.)	$0.806 * 10^{-8}$	$0.718 * 10^{-5}$	$8.2037 * 10^{-4}$	$0.8233 * 10^{-3}$
Land use (m^2a crop eq.)	$0.56 * 10^{-6}$	$2.967 * 10^{-4}$	0.1403	0.1407

EN15804+A2 assessment (Table A-1, Supporting Information), where ca. 70 % (=5.39 MJ) is accounted for by non-renewable energy resources. Thereof, fossil energy contributes the most with 53.4 %, while nuclear energy contributes 16.6 %. Electricity is the largest contributor to fossil energy, accounting for ca. 95 % of the 5.39 MJ eq (Fig. 3). The milling machine (A.2.1), the autoclave (A.2.3), the laboratory humidifier and fan (A.3.2), and especially the oven (A.3.3), which alone contributes to over half of the electricity consumption, are major electricity consumers. The high share of electricity in the fossil energy demand can be primarily attributed to the German electricity mix, which is used. In terms of electricity generation, the fossil fuels including coal, oil and gas have a share of 41.8 % in the German electricity mix in 2022 (Fraunhofer, 2022). After electricity, however, hemp and plastic bags also have a notable impact on fossil energy demand.

Compared to Silverman (2008) that calculates the energy demand for the production of mycelium-based shoe soles, here the result is around 5 times lower. In Silverman (2008), the energy requirement for the incubation facility and the oven is calculated, that amount to 38.1 MJ eq/kg. In this study, however, the comparable production steps of the oven as well as the fan and humidifier (incubation facility) add up to 4.85 MJ eq/kg MBC.

3.2. Climate change

Climate change is quantified using the global warming potential for a 100-year time horizon (GWP 100a) and expressed in kg CO_2 eq. A total of 0.6933 kg CO_2 eq is emitted during the production of 1 kg hemp-based MBC (Table 4) and 0.3668 kg CO_2 eq according to the EN 15804-A2 assessment method. 95 % of the CO_2 eq emissions are due to the electricity required to run the machines (Fig. 3), particularly in mycelium composite drying (A.3.3). Consequently, the high proportion of fossil fuels in the German electricity mix has a high impact on the GWP of MBC production. As well, the land use change due to substrate production contributes significantly to climate change (LULUC). This is not compensated by the carbon sequestered in the processed hemp.

3.3. Acidification

A total of 0.00155 kg SO2 eq. is required to produce 1 kg of hemp-based MBC (Table 4) according to ecoinvent CED based LCIA and 0.0015 mol $H+$ eq. / kg MBC in the EN15804+A2 assessment. Electricity is also the largest contributor to acidification similar to climate change due to its high fossil energy demand. However, two other material-related factors, hemp and cotton, contribute to acidification, respectively, to SO_2 eq. emissions. Fertilization of crops with nitrogen is causal to soil acidification and also limits nutrient uptake and crop yield in the long run (Dai et al., 2021). Accordingly, acidification is mainly influenced by power generation and fertilization of hemp and cotton feedstock.

3.4. Eutrophication

Eutrophication quantifies the effects of excessive levels of macronutrients in air, water, and soil, with the most important nutrients being nitrogen and phosphorus (Guinée et al., 2001b). Here, the production of 1 kg hemp-based MBC emits $3.93 * 10^{-3}$ kg PO_4^{3-} eq. (Table 4). In the EN15804+A2 assessment, the eutrophication is further differentiated into land/terrestrial (0.0035 mol N eq.), freshwater (0.0007 kg P eq.) and marine (0.0006 kg N eq.) for 1 kg of MBC in lab scale production in Germany. Again, electricity is the largest contributor with more than 80 % for the same reasons as before, while hemp is the second largest contributor. As for acidification, the fertilization of hemp plants during cultivation is responsible for this. Thus, as long as fertilized agricultural products are used on MBC production, the said acidification and eutrophication impacts have to be expected.

3.5. Water scarcity

The quantification of the potential water deficiency is expressed as world water consumption (m^3 world eq.) and referred to as water scarcity (Boulay et al., 2018). For hemp-based MBC production, the water scarcity is quantified as 0.5797 m^3 world eq. (Table 4) and 0.4274 m^3 depriv in the EN15804+A2 assessment (Table A-1, SI). As Fig. 3 shows, this impact category is mainly influenced by process step substrate milling (A.2.1) with 65 %. The substrate is input to the process step of milling. The water demand arises on the one hand from the upstream substrate cultivation (which was not modelled separately) and on the other hand from the cleaning of the mill after the milling. Circa 50 % of the total water scarcity is due to hemp cultivation. In fact, hemp cultivation requires about 30 % more water than the cultivation of commodity crops like corn, cotton, soybean, wheat or rice (Zheng et al., 2021). By using other substrates for MBC production, the water demand could be reduced. The impact of cotton used along with the plastic bags in the cultivation stage in A.3.1 is 1.6 %. Water for cleaning activities (process steps A.2.2, A.3.1 and A.3.2) adds up to 2.1 %. However, since the LCA model takes wastewater treatment into account, the used water is treated and fed back into the environment which is accredited as credit, as shown by the red negative bars. As for all other impact categories discussed so far, electricity has a considerable impact on water scarcity as well. Throughout the electricity generation and supply water is required for fuel mining and refining, but most importantly for cooling in thermoelectric power plants.

3.6. Ozone formation

The formation of ozone or smog amounts to 8.233×10^{-4} kg NO_x eq. (Table 4) in the MBC production phases. For this impact category, the electricity used to operate the machinery required for the production stages, has a total impact of more than 80 %. Smog emissions are caused by electricity generation from fossil fuels such as coal, which releases large amounts of NO_x gases (Munawer, 2018). In addition, waste treatment affects the formation of oxidants when the scrap is sent to incineration plants, that also emit NO_x gases (Johnke et al., 2001). However, its proportion of ca. 2 % is relatively low. Concerning hemp, ozone formation results from nitrogen-based fertilization during cultivation when the soil gradually releases NO_x gases over time (Almaraz et al., 2018). In addition, the plastic incubation bags contribute ca. 1 % to NO_x emissions probably due to the high electricity consumption in plastic production (Stelzer et al., 2021).

Fig. 3. LCIA results for fossil energy demand, climate change, and water scarcity for the production of 1 kg of hemp-based MBC (according to impact assessment methods listed in Table 3 and results listed in Table 4).

3.7. Land use

Land use is defined as the relative loss of species as a result of a specific land use type and quantified with the unit $m^2 \times$ year annual cropland eq. (Huijbregts et al., 2017). For the production of 1 kg hemp-based MBC, 0.422 m^2a crop eq. is used (Table 4) and 7.6672 is assessed in the EN15804+A2 assessment, which is almost entirely (92.32 %) attributable to process step A.2.1 of which the hemp input accounts for almost entirely. Milling itself does not have such a high impact but the upstream substrate cultivation which is included as an input in this process step. This is indicated by the light blue color of the bar, that shows that this impact is associated with "hemp". The other visible contributor is "electricity" (dark green) which results mainly from the milling.

Since hemp is an agricultural product that requires land for cultivation, this result is not unexpected. The other two agricultural inputs, barley (or malt extract) and cotton, contribute less than 1 % each due to their low mass required per functional unit, since the input of hemp is about 300 times larger than that of cotton and more than 1200 times larger than that of barley. Furthermore, electricity has a rather low total share (<10 %) which can be explained by land use, e.g., for coal mining or biomass used for electricity generation (Li et al., 2020).

3.7.1. Comparison with LCIA results of the sawdust variant

In a sawdust-based MBC production where the hemp substrate is replaced by sawdust, wheat bran and calcium carbonate are added for mycelium nutrient supply (Supporting Information). The milling process is omitted because the sawdust particle size is small enough. All other process steps remain the same. In all considered impact categories, the sawdust variant has between 6 and 29 % lower impacts (Table 5) except for ozone formation where it is 168 % higher. The hemp milling requires a relatively large amount of electricity that impacts the fossil energy

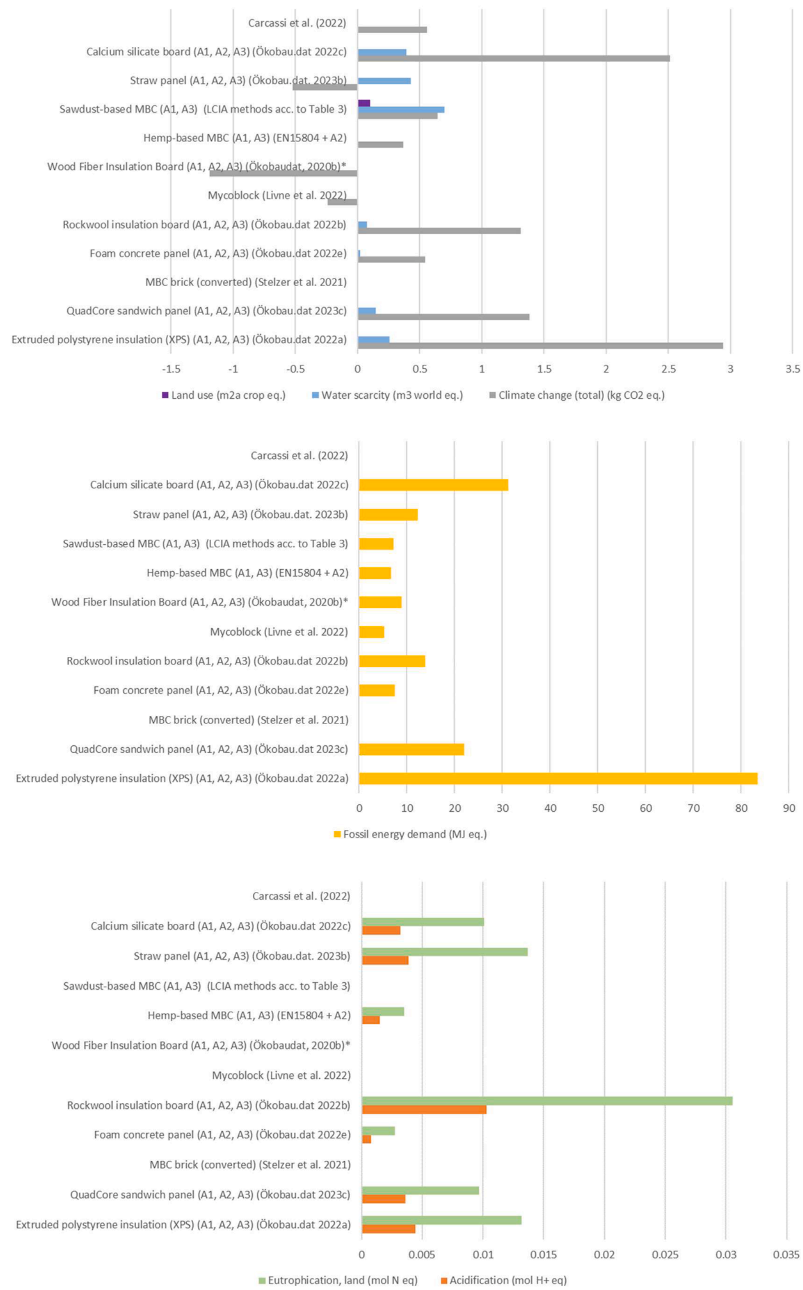

Fig. 4. Comparison of LCIA results for land use, water scarcity, climate change, fossil energy demand, acidification and eutrophication potential for the production of 1 kg of product

demand, climate change, acidification, and ozone formation categories. The elimination of the milling process is one reason for the better environmental performance of the sawdust variant. Moreover, the environmental impact of sawdust feedstock is significantly lower than hemp. This finding is supported by Stelzer et al. (2021), who compare hemp and wood chips. In particular, this can be observed for eutrophication, for water use where it accounts for almost half of the total impact, and for land use, where hemp makes up almost all of the impact. This is reflected in the comparison of the two boards (Table 5).

3.7.2. *Comparison with literature and conventional products*

Comparing our results with literature, we find considerable differences between different MBC materials and conventional insulation materials (Fig. 4, Table 5). When comparing different MBC materials with each other, the fossil energy demand and climate change impact for the MBC brick from Livne et al. (2022) (Mycoblock) are lower than the MBC materials assessed in this study. However, the MBC brick of Stelzer et al. (2021) has a much higher climate change impact despite the high conversion uncertainties. For ozone formation, the difference is 55 % and for acidification it is 64 %. However, the differences in eutrophication and water scarcity are striking. A more detailed analysis reveals that for the board, electricity has the highest share of total eutrophication, while for the brick, hemp dominates the eutrophication potential. Thus, the impact of electricity on eutrophication must be significantly lower in the LCA of brick, although the German electricity mix was used for both studies. One reason might be that Stelzer et al. (2021)'s brick is only dried, neither pressed nor cut. And, Stelzer et al. (2021) considers a transport of the rye grains and the hemp of 50 km each. The difference in water scarcity might result from the different datasets for the agricultural products. In addition, water use for cleaning was modeled only for the MBC light-weight material, resulting in higher water use. However, when analyzing the proportions of impacts on water scarcity, again

Table 5
"Comparison" of LCIA results per kilogram product of a hemp and sawdust-based MBC assessment (grey, lifecycle stages A1 and A3) based on the indicated assessment methods with other mycelium-based composites from literature (MBC bricks and samples in yellow) and conventional insulation materials based on Environmental Product Declarations (EN15804+A2) (white, lifecycle stages A1, A2, and A3) sorted according to their respective densities.

	Extruded polystyrene insulation (XPS) (A1, A2, A3) (Ökobau.dat 2022a)	QuadCore sandwich panel (A1, A2, A3) (Ökobau.dat, 2023a)	MBC brick (converted) (Stelzer et al., 2021)	Foam concrete panel (A1, A2, A3) (Ökobau.dat 2022e)	Rockwool insulation board (A1, A2, A3) (Ökobau.dat 2022b)	Mycoblock (Livne et al., 2022)	Wood Fiber Insulation Board (A1, A2, A3) (Ökobaudat, 2020b)	Hemp-based MBC (A1, A3) (EN15804 + A2)	Hemp-based MBC (A1, A3) (LCIA methods acc. to Table 3)	Sawdust-based MBC (A1, A3) (LCIA methods acc. to Table 3) *	Straw panel (A1, A2, A3) (Ökobau.dat. 2023b)	Calcium silicate board (A1, A2, A3) (Ökobau.dat 2022c)	MycoBamboo (Carcassi et al., 2022)
Specification	Insulation	Self-supporting and non-load-bearing constructions	Stability and thermal regulation	Insulation	Insulation	–	Insulation (Polyurethane resin)	Insulation	Insulation	Insulation	Insulation	Insulation	Retrofit of facades
Density (kg/m^3)	32	38	72.1 – 199 (assumed)	80	146.4	163	167	200	200	200	220	225	229
Fossil energy demand (MJ eq.)	83.4688 (PENRT)	21.9579	n/a	7.4763	13.8661 (PENRT)	5.2779 (embodied energy)	8.8503 (PENRT)	6.7799 (PENRT)	7.71	7.2600	12.3090	31.2667 (PENRT)	n/a
Climate change (total) (kg CO_2 eq.)	2.9384	1.3837	1.1514 - 3.1779	0.5425	1.3122	−0.2423	−1.1880	0.3668	0.6933	0.6417	−0.5232	2.5107	0.5560 – 0.7413
Biogenic	0.0173	−0.0152	n/a	−0.0668	0.0053	n/a	n/a	−0.0826	n/a	n/a	−1.2491	−0.0188	
Fossil	2.92063	1.3539	n/a	0.6090	1.3067	n/a	n/a	0.4451	n/a	n/a	0.7250	2.5293	
Luluc****	0.0005	0.0007	n/a	0.0003	0.0003	n/a	n/a	0.0043	n/a	n/a	0.0008	0	n/a
Acidification (kg SO_2 eq.)	n/a	n/a	0.0024 −0.0066	n/a	n/a	n/a	0.0008	n/a	0.0015	0.0014	n/a	n/a	n/a
Acidification (mol $H+$ eq)	0.0045	0.0036	n/a	0.0008	0.0103	n/a	n/a	0.0015	n/a	n/a	0.0039	0.0032	n/a
Eutrophication (kg PO_4^{3-} eq.)	n/a	n/a	0.0015 – 0.0043	n/a	n/a	n/a	0.0003	n/a	0.0039	0.0031	n/a	n/a	n/a
Eutrophication, land (mol N eq)	0.0132	0.0097	n/a	0.0027	0.0305	n/a	n/a	0.0035	n/a	n/a	0.0137	0.0101	n/a
Eutrophication, freshwater (kg P eq)	0.0000	0.0000	n/a	0.0000	0.0000	n/a	n/a	0.0007	n/a	n/a	0.0001	0.0000	n/a
Eutrophication, marine (kg N eq)	0.0012	0.0009	n/a	0.0002	0.0010	n/a	n/a	0.0006	n/a	n/a	0.0023	0.0010	n/a
Water scarcity (m^3 world eq.)	0.2589	0.1465	0.0567 – 0.1564	0.02205	0.0750	n/a	n/a	n/a	0.5797	0.7000	0.4290	0.3927	n/a
Water scarcity (m^3 depriv)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.4274	n/a	n/a	n/a	n/a	n/a
Ozone formation (kg NO_x eq.)	n/a	n/a	0.0015 - 0.0041	n/a	n/a	n/a	n/a	n/a	0.0008	0.0022	n/a	n/a	n/a
Land use (m^2a crop eq.)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.1407	0.1000	n/a	n/a	n/a
Land use (-)	n/a	n/a	49.4922 - 136.6012	n/a	n/a	n/a	n/a	7.672	n/a	n/a	n/a	n/a	n/a

[*] This value includes pressing and cutting of the material (which is not further described in the production process).

electricity seems to have a lower impact for bricks than for the board, e.g. due to the absence of pressing and cutting for the brick, or due to the assumptions in the data conversion. Livne et al. (2022) found −39.5 kg CO_2eq/m^3 for the "mycoblock" which results in −0.24 kg CO_2eq/kg and 5.34 MJ/kg given their material density of 161 kg/m^3. Main difference is their electricity in the growing stage while our process requires most energy in the drying and pressing. Cascione et al. (2022) use a different functional unit (kg CO_2eq/m^2 respective kg CO_2eq/sample) and mycelium with a density of 99 kg/m^3. However, their LCA results are not comparable since they do not calculate the environmental impacts for a mycelium panel separately but compare whole wall panels including their frame construction and cladding/coating. Carcassi et al. (2022) found 0.557 kg CO_2/kg of MycoBamboo based on their material density of 229 kg/m^3. And, they also find that drying has the highest effect on GWP (nearly 60 %).

The comparison of hemp-based and sawdust-based MBC with various conventional insulation materials in Table 7 shall evaluate whether MBC is a "green" alternative to conventional materials (Răut et al., 2021). In order to represent the most versatile set of conventional insulation materials possible, extruded polystyrene insulation (XPS) (Ökobau.dat 2022a), QuadCore sandwich panel (Ökobau.dat, 2023a), foam concrete panel (Ökobau.dat 2022e), rockwool insulation board (Ökobau.dat 2022b), wood-fiber insulation board (Ökobaudat, 2020b), straw panel (Ökobau.dat. 2023b) and calcium silicate board (Ökobau.dat 2022c) are selected for comparison. All these materials are compared with their life cycles stages of A1, A2, and A3 including raw material extraction, transport and production. In contrast to MBC, the transport (A2) is considered. The material's density is ranging from 32 kg/m^3 (extruded polystyrene) to calcium silicate (225 kg/m3). The wood fiber insulation boards have a density of 167 kg/m^3, and the fibers are bound by polyurethane resin (Ökobaudat, 2020b).

MBC from both substrates can be produced with different densities. With the assessed production process, a density of 600 kg/m^3 could be achieved for the sawdust-based MBC. To achieve similar strength to a wood fiber insulation board, the density of the MBC must be 200 kg/m^3, 700 kg/m^3 for a particleboard, and 1000 kg/m^3 to be comparable with an OSB board. For this study, we restrict to the assessment of the production of an MBC with a density of 200 kg/m^3 and to a comparison with insulation materials (Table 5). Please note that Table 5 shows the LCIA results per kg product and not per m^2 or m^3 of material or panel. To compare MBC with conventional materials, the usual functional unit in environmental product declarations of the latter of 1 m^3 has been converted via the material density to 1 kg of product.

Regarding climate change, in contrast to Ecoinvent, Ökobaudat grants an environmental advantage taking into account the carbon uptake during growth due to carbon sequestration (Figl et al., 2017) (biogenic carbon content). For the assessed sawdust-based MBC no sequestered carbon is assumed since the substrate consists of a biogenic waste which is associated with neither burdens nor credits (zero burden approach). Moreover, this material is assumed to be pressed and cut. Thus, a direct comparison of our results like depicted in Table 5 with Ökobaudat datasets is not applicable (Hischier et al., 2010). However, carbon uptake is only considered for climate change and it does not affect the other impact categories. Apart from climate change, the analysis covers the entire value chain (cradle-to-gate). In the case of the wood-fibre insulation board, however, the transport of the raw materials is included in the data. The comparison shows that the MBC performs significantly better than many of the conventional insulation materials (extruded polystyrene, quadcore sandwich panel, rockwool, calcium silicate) with respect to climate change. However, MBC has the highest water and land use demand of all compared materials mainly due to the hemp production. With respect to fossil energy demand, MBC is quite competitive with foam concrete and mycoblock (Livne et al. 2022); wood-fibre insulation board, straw panel and rockwool have a slightly higher energy demand. The quadcore sandwich panel has double the value, the calcium silicate board has triple the value and the extruded polystyrene has more than eight times the value.

3.7.3. Interpretation

MBC production with different substrate is a viable option to develop new renewable construction material, particularly if the process steps are performed with renewable energy (electricity) (see also Carcassi et al., 2022). Especially, fossil energy demand, climate change, acidification, eutrophication and ozone formation could greatly benefit from renewably generated electricity. Other production inputs (apart from fertilizers) and outputs play a rather minor role. A shift to sawdust as substrate could reduce the environmental impact particularly regarding water scarcity (−59.98%) and land use (−77.49%). Moreover, to further reduce the MBC water scarcity impact, a change of the substrate to other commodity crops like corn, cotton, soybean, wheat or rice is advised.

Comparing the MBC insulation board and brick, we found that the mycelium bricks have quite different climate impacts (Livne et al., 2022; Stelzer et al., 2021). The Mycoblock (Livne et al., 2022) has a net negative climate balance while the MBC brick of Stelzer et al. (2021) has a higher climate change impact than our MBC insulation boards. The differences might result from different process steps in production, e.g. in drying and its related electricity demand. However, both products are not directly comparable since the functional unit differs and the functionality of the construction product is different.

Comparing the MBC hemp and sawdust variants with conventional materials that have comparable physical properties and comparable functional units, we find a mixed result in all environmental indicators. The MBC is significantly less harmful to the climate compared to most of its conventional counterparts. The use of naturally propagating mycelium instead of fossil-based resins as a binder could be a major driver for this performance (Chen et al., 2019; Sands et al., 2001).

3.7.4. Sensitivity analysis through Monte Carlo simulation

Sensitivity analysis is used to determine the effects of changes in the input data on the results (DIN e.V., 2021a). For this purpose, a Monte Carlo simulation is performed in openLCA software with diversified input data for the LCIA based on Table 3. For this study, the number of iterations for the simulation is set at 100, owing to the high computational effort and processing capacity required. The simulation runs for all impact categories, and the mean value, standard deviation, as well as the 5 % and 95 % percentiles are calculated (Table A-3, Supporting Information). Except water scarcity, the mean values of the impact categories are consistent with the LCIA results (Table 4). Furthermore, the 5 % and 95 % percentiles for all categories except eutrophication are evenly distributed around the mean, indicating a symmetric normal distribution of the results (Figure A-10, Supporting Information), where the distribution is exemplified for land use. Eutrophication, for its part, exhibits a right-skewed distribution (Figure A-11, Supporting Information). The fact that the standard deviation and thus the 5 % and 95 % percentiles of water scarcity are comparatively high compared to the other categories could be due to the LCIA method AWARE.

Regarding completeness, all lifecycle inventory data are considered as far as the scope of this LCA allows. Ecoinvent datasets are used when applicable and Agribalyse otherwise. In addition, proxy datasets are defined and, if necessary, the data are adjusted to avoid biasing the results. Since all assumptions, methods and data are consistent with the goal and scope of the LCA under consideration, consistency can also be assessed as ensured. Thus, it can be concluded that the LCIA calculations are overall robust and valid. For the Monte Carlo analysis, a higher number of iterations could further increase the validity and make the simulation more robust.

4. Discussion

The LCA performed is subject to certain limitations. The production process of the KIT laboratory is modeled with as much detail as possible, but still contains assumptions and experiential values, such as how often the equipment is cleaned and how much water is consumed. Not all datasets are available for implementation in the LCA software, so proxy values are used, e.g., for the agar medium or malt. However, the sensitivity analysis shows that the LCIA result is tractable for all impact categories besides water scarcity. It is uncertain why the Monte Carlo simulation result for water scarcity deviates at such a high level from the other categories with the comparatively high standard deviation. One reason may be the algorithm used by the LCIA method AWARE to calculate this impact category.

For comparisons with the MBC brick and the conventional insulation materials, assumptions and data conversions are made, since otherwise a comparison is not possible. They lead to data fluctuations and differences that are not precisely quantifiable. In particular, the deviations in the impact categories eutrophication and water scarcity of the MBC brick lack a clear explanation. The different functional units hamper comparability.

The LCA for the hemp-based MBC board shows that environmental challenges mainly result from the high electricity consumption in the final production steps of incubation and drying. Furthermore, the cultivation of hemp affects eutrophication, water scarcity, and land use. To reduce environmental burdens, the electricity mix could be shifted to renewable energy sources (see also Carcassi et al., 2022). The sawdust variant shows lower environmental impacts in the LCIA based on methods of Table 3 probably due to the change of substrate and fewer process steps. As sawdust does not require cultivation on agricultural land, but is a waste product of the wood industry it should come with significantly less fertilization, farmland, and water demand, which should reduce the impact on the affected categories (Najafi et al., 2006). However, sawdust as a raw material is also demanded by other industries e.g. for energy carriers' production such as pellets and briquettes, as well as in wood panel board manufacturing, future bio-based products like wood-plastic composites, conventional fungal cultivation, and as bedding for animals. Therefore, there is high resource competition on sawdust expected. But, with respect to climate change the storage of the biogenic carbon in long-lasting products seems more favourable than the incineration and release of CO_2 to the atmosphere. However, the most optimal use and allocation of this resource cannot be determined by comparison against one or two reference products alone, but has to be investigated thoroughly in future LCAs considering systems expansion or consequential LCAs. But since MBC can be produced with other biogenic waste, future research on MBC production from other secondary resources such as post-consumer furniture is required and ongoing to avoid resource competition.

One major advantage of MBC is that the sequestered CO_2 is not released back into the environment through combustion, but remains bound in the long term (Shim et al., 2007) since it can be recycled endlessly. However, the assessment does not include metabolic CO_2 which can make up to 21 % of the total emitted CO_2 (Livne et al., 2022) because it is unclear if these values a transferrable to other fungi species. Also, the MBC assessment and the comparison with conventional insulation materials does not include the end-of-life stage where most of the conventional materials would release a lot of CO_2 during incineration (e.g. wood-fibre insulation board). This should be investigated in future research. Finally, to ensure sustainability, raw materials should be sourced close to the production site whenever possible (Raffie et al., 2021) to avoid transport.

The MBC under consideration has comparable environmental impacts to the mycelium brick studied by Stelzer et al. (2021) except for large differences in climate change, eutrophication and water scarcity. As confirmed by Elsacker et al. (2021), due to the use of solely natural resources, the MBC is completely biodegradable and therefore not harmful to the environment during the use and end-of-life phases. It can even serve as a source of nutrients for organisms when decomposed in the soil (Raffie et al., 2021). However, this only applies if MBCs are installed and uninstalled without the addition of adhesives such as glue or cement, or coatings like paint or fireproofing (Hill et al., 2021).

The bias caused by the considered raw material transportation of the wood-fibre insulation boards cannot be quantified. Also, for the petri dish and the plastics bags only the corresponding material mass of general-purpose polystyrene (petri dish) and general-purpose polystyrene plus cotton (plastic bags) is modelled instead of the final products. Due to lack of data in the databases, the additional environmental expenses for the production of these products are not considered.

Although the material properties are inherently promising for construction applications, the specific material properties, such as acoustic absorption or strength, are not always stable and tend to be mutually exclusive with conflicting goals, such as strength and insulation properties. This is due to the numerous variables in material composition and manufacturing processes, which have not yet been fully explored. Therefore, research is required on the optimal fungal species, substrate and additive composition, as well as the optimal production processes to achieve material properties that are optimized for the specific application (particularly with respect to fire safety, see Carcassi et al., 2022).

In terms of LCA, the process is modeled to the best of knowledge. However, since it is based on the processes of the KIT mycelium laboratory, where different production processes and input compositions are experimented with, some variances in the process flow have been considered. In addition, the assumptions made with regards to cleaning activities and the proxy datasets used, such as for agar, add to the variability. Thus, there is potential for further refinement to include in the model in future, for instance, through transport and/or to extend the scope to cradle-to-grave if suitable use scenarios and end-of-life solutions are identified. Also, the process scale could be extended which would probably result in more environmentally advantageous results per kg product. However, the LCA model of this study represents an appropriate baseline manufacturing process for lab-scale production.

Since a laboratory process is assessed, any projections on a higher level of technology readiness level and larger scale are subject to uncertainty. A higher technology readiness level or an extension to pilot or industrial scale would probably be associated with learning curves, synergy effects and process optimization, leading to e.g. a reduction of mycelium scrap due to an automated/highly industrialized process, less water and wastewater from cleaning in an industrial dishwasher instead of manual cleaning, and most importantly less electricity demand in the growing chamber, milling and drying due to synergy effects, e.g. due to full use of the equipment. All these aspects would lead to a lower environmental impact per functional unit. Moreover, the usage of local resources (like wood waste or other biogenic waste) near the production facility would reduce current production and incineration impacts and reduce energy and CO_2 emissions from transport (which was not considered in this study). Only substrate mixing (A.2.2) would require additional electricity since it is currently done by hand.

5. Conclusion and outlook

The assessed MBC production has much lower environmental impacts compared to conventional products like extruded polystyrene and rockwool. However, its production is very dependent on the availability of biogenic resources (hemp) or biogenic waste (sawdust) that might change the material properties. With respect to land use, cultivation efforts and also transport distances, processing of locally available biogenic waste to MBC boards should be given priority. Therefore, further research is needed to investigate the interplay of fungal species, substrate and additives to produce a standardized product on an industrial scale. In this context, quantification of material/resource availability and automation plays an important role as it is not only a driver for standardization but can also help to reduce costs (Robertson et al., 2020; Smunt and Meredith, 2000) which should also be assessed in future work. In addition, further studies on the environmental impacts of diverse types of mycelium products with standardized functional units are necessary for better comparability.

Moreover, the environmental impact of the electricity used in production is striking. The later contributes largely to all assessed environmental impacts. Further research should focus on the increase of the technology readiness level and the upscaling and optimization of the production process to reduce electricity demand in various process steps.

MBC is comparatively easy to manufacture but has a wide range of applications, since it is possible to enhance its physical properties according to the application requirements. Therefore, this work serves as a basis for further research, such as for more complex or more specific MBC materials, e.g. with loadbearing applications, or for scale-up calculations. Therefore, further studies are needed for large-scale production of a diverse range of products. Also, these should be compared with other conventional materials such as gypsum cardboards, plasterboards, plastic panels, particleboards, resin timber boards or gypsum fibre boards.

In terms of material properties and environmental advantages over conventional materials, they have a promising future for applications not only in the construction sector, but also in industries such as packaging, home appliances, furniture or fashion. Nevertheless, the current production scale and instability of production methods can be considered as bottlenecks for the widespread diffusion of the material.

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CRediT authorship contribution statement

Rebekka Volk: Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marius Schröter:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Nazanin Saeidi:** Supervision, Writing – review & editing, Writing – original draft, Resources, Investigation, Funding acquisition, Data curation. **Simon Steffl:** Writing – review & editing, Software, Formal analysis. **Alireza Javadian:** Writing – review & editing, Investigation. **Dirk E. Hebel:** Funding acquisition. **Frank Schultmann:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that supports the findings of this study are available in the supporting information of this article.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107579.

References

Ahmadi, H., 2016. Cellulose-Mycelia Foam: Novel Bio-Composite Material. Masterthesis at University of British Columbia, Canada (Mechanical Engineering). https://doi.org/10.14288/1.0340323.

Almaraz, M., Bai, E., Wang, C., Trousdell, J., Conley, S., Faloona, I., Houlton, B.Z., 2018. Agriculture is a major source of NOx pollution in California. Sci. Adv. 4, 1–8. https://doi.org/10.1126/SCIADV.AAU2561.

Appels, F.V.W., Camere, S., Montalti, M., Karana, E., Jansen, K.M.B., Dijksterhuis, J., Krijgsheld, P., Wösten, H.A.B., 2019. Fabrication factors influencing mechanical, moisture- and water-related properties of mycelium-based composites. Mater. Des. 161, 64–71. https://doi.org/10.1016/j.matdes.2018.11.027.

Attias, N., Danai, O., Abitbol, T., Tarazi, E., Ezov, N., Pereman, I., Grobman, Y.J., 2020. Mycelium bio-composites in industrial design and architecture: comparative review and experimental analysis. J. Clean. Prod. 246, 1–17. https://doi.org/10.1016/j.jclepro.2019.119037.

Bach, V., Finkbeiner, M., 2017. Approach to qualify decision support maturity of new versus established impact assessment methods – demonstrated for the categories acidification and eutrophication. Int. J. Life Cycle Assess. 22, 387–397. https://doi.org/10.1007/s11367-016-1164-z.

Bennet, J.W., Wunch, K.G., Faison, B.D., 2002. Use of Fungi Biodegradation. Manual of Environmental Microbiology. ASM Press, Washington, DC, 2002.

Boulay, A.M., Bare, J., Benini, L., Berger, M., Lathuillière, M.J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A.V., Ridoutt, B., Oki, T., Worbe, S., Pfister, S., 2018. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). Int. J. Life Cycle Assess. 23, 368–378. https://doi.org/10.1007/s11367-017-1333-8.

Carcassi, O.B., Minotti, P., Habert, G., Paoletti, I., Claude, S., Pittau, F., 2022. Carbon footprint assessment of a novel bio-based composite for building insulation. Sustainability. 14, 1384. https://doi.org/10.3390/su14031384, 2022.

Cascione, V., Roberts, M., Allen, S., Dams, B., Maskell, D., Shea, A., Walker, P., Emmitt, S., 2022. Integration of life cycle assessments (LCA) in circular bio-based wall panel design. J. Clean. Prod. 344, 130938 https://doi.org/10.1016/j.jclepro.2022.130938.

Chan, X.Y., Saeidi, N., Javadian, A., Hebel, D.E., Gupta, M., 2021. Mechanical properties of dense mycelium-bound composites under accelerated tropical weathering conditions. Nat. – Sci. Rep. 11, 1–10. https://doi.org/10.1038/s41598-021-01598-4.

Chen, C.X., Pierobon, F., Ganguly, I., 2019. Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) produced in Western Washington: the role of logistics and wood species mix. MDPI – Sustain. 11, 1–17. https://doi.org/10.3390/su11051278.

Dai, P., Cong, P., Wang, P., Dong, J., Dong, Z., Song, W., 2021. Alleviating soil acidification and increasing the organic carbon pool by long-term organic fertilizer on tobacco planting soil. MDPI – Agronomy 11, 1–14. https://doi.org/10.3390/agronomy11112135.

DIN e.V. (2021a). Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen. *DIN EN ISO 14044:2021-02*. /Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006 + Amd 1:2017 + Amd 2:2020); German version EN ISO 14044:2006 + A1:2018 + A2:2020. https://doi.org/10.31030/3179656.

DIN e.V. (2021b): Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen (ISO 14040:2006 + Amd 1:2020); Deutsche Fassung EN ISO 14040:2006 + A1:2020 /Environmental management – Life cycle assessment – Principles and framework (ISO 14040:2006 + Amd 1:2020); German version EN ISO 14040:2006 + A1:2020. https://www.beuth.de/de/norm/din-en-iso-14040/325953744.

Ecoinvent. (2022). About ecoinvent. URL: https://ecoinvent.org/the-ecoinvent-association/[Accessed: February 11, 2022].

Elsacker, E., Søndergaard, A., Van Wylick, A., Peeters, E., De Laet, L., 2021. Growing living and multifunctional mycelium composites for large-scale formwork applications using robotic abrasive wire-cutting. Constr. Build. Mater. 283, 1–15. https://doi.org/10.1016/j.conbuildmat.2021.122732.

Elsacker, E., Vandelook, S., Brancart, J., Peeters, E., Laet, L.De., 2019. Mechanical, physical and chemical characterisation of mycelium-based composites with different types of lignocellulosic substrates. PLoS ONE 14 (7), 1–20. https://doi.org/10.1371/journal.pone.0213954.

Elsacker, E., Vandelook, S., Van Wylick, A., Ruytinx, J., De Laet, L., Peeters, E., 2020. A comprehensive framework for the production of mycelium-based lignocellulosic composites. Sci. Total Environ. 725, 1–17. https://doi.org/10.1016/j.scitotenv.2020.138431.

Enarevba, D.R., Haapala, K.R., 2023. A Comparative Life Cycle Assessment of Expanded Polystyrene and Mycelium Packaging Box Inserts. In: 30th CIRP Life Cycle Engineering Conference, Procedia CIRP, 116, pp. 654–659. https://doi.org/10.1016/j.procir.2023.02.110, 2023.

Figl, H., Brockmann, T., Kerz, N., Kusche, O., Rössig, S., 2017. Ökobaudat – Grundlage für die Gebäudeökobilanzierung. Bundesinstitut Für Bau-, Stadt- Und Raumforschung (BBSR) 1–38. ISBN: 978-3-87994-288-6. http://d-nb.info/1136730257/34 [Accessed: May 23, 2023].

Fraunhofer I.S.E. (2022). Net public electricity generation in Germany in 2022. URL: https://energy-charts.info/charts/energy_pie/chart.htm?l=en&c=DE&interval=year [Accessed: February 21, 2022].

Frischknecht, R., Wyss, F., Büsser Knöpfel, S., Lützkendorf, T., Balouktsi, M., 2015. Cumulative energy demand in LCA: the energy harvested approach. Int. J. Life Cycle Assess. 20, 957–969. https://doi.org/10.1007/s11367-015-0897-4.

GreenDelta. (2022). The idea. URL: https://www.openlca.org/the-idea/[Accessed: February 11, 2022].

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Wegener Sleeswijk, A., Udo De Haes, H.A., de Bruijn, J.A., van Duin, R., Huijbregts, M.A.J., 2001b. Life cycle assessment: an operational guide to the ISO standards – part 2a: guide. Centre Environ. Sci.– Leiden Univ. (CML). https://doi.org/10.1007/BF02978897.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Wegener Sleeswijk, A., Udo De Haes, de Bruijn, van Duin, R., Huijbregts, M.a.J., 2001a. Life cycle assessment: An operational guide to the ISO standards - Part 1: LCA in perspective. Centre Environ. Sci. - Leiden University (CML). 10.1007/BF02978897.

Hill, C., Hughes, M., Gudsell, D., 2021. Environmental impact of wood modification. MDPI – Coatings 11 (366), 1–15. https://doi.org/10.3390/coatings11030366.

Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M., Nemecek, T., 2010. Implementation of life cycle impact assessment methods – ecoinvent report no. 3. Swiss Centre Life Cycle Inventories. https://ecoinvent.org/wp-content/uploads/2020/08/201007_hischier_weidema_implementation_of_lcia_methods.pdf [Accessed: May 23, 2023].

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

Javadian, A., Le Ferrand, H., Hebel, D.E., Saeidi, N., 2020. Application of mycelium-bound composite materials in construction industry: a short review. SOJ Mater. Sci. Eng. 7 (1), 1–9. https://doi.org/10.3929/ethz-b-000543782.

Johnke, B., Hoppaus, R., Lee, E., Irving, B., Martinsen, T., Mareckova, K., 2001. Emissions from Waste Incineration: good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. IPCC – Intergovernmental Panel on Climate Change 455–468. https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/5_3_Waste_Incineration.pdf [Accessed: May 23, 2023].

Jones, M., Bhat, T., Huynh, T., Kandare, E., Yuen, R., Wang, C.H., John, S., 2018. Waste-derived low-cost mycelium composite construction materials with improved fire safety. Fire Mater. 42, 816–825. https://doi.org/10.1002/fam.2637.

Jones, M., Huynh, T., Dekiwadia, C., Daver, F., John, S., 2017. Mycelium composites: a review of engineering characteristics and growth kinetics. J. Bionanoscience 11, 241–257. https://doi.org/10.1166/jbns.2017.1440.

Jones, M., Mautner, A., Luenco, S., Bismarck, A., John, S., 2020. Engineered mycelium composite construction materials from fungal biorefineries: a critical review. Mater. Des. 187, 1–16. https://doi.org/10.1016/j.matdes.2019.108397.

Lee, T., Choi, J., 2021. Mycelium-composite panels for atmospheric particulate matter adsorption. Res. Mater. 11, 1–6. https://doi.org/10.1016/j.rinma.2021.100208.

Li, Z., Wu, S., Zhang, S., Nie, C., Li, Y., Huang, Y., 2020. Optimization of land reuse structure in coal mining subsided areas considering regional economic development: a case study in Pei County, China. MDPI – Sustainability 12, 1–16. https://doi.org/10.3390/SU12083335.

Livne, A., Wösten, H.A.B., Pearlmutter, D., Gal, E., 2022. Fungal mycelium bio-composite acts as a CO_2-sink building material with low embodied energy. ACS Sustain. Chem. Eng. 10, 12099–12106. https://doi.org/10.1021/acssuschemeng.2c01314.

Madurwar, M.V., Ralegaonkar, R.V., Mandavgane, S.A., 2013. Application of agro-waste for sustainable construction materials: a review. Constr. Build. Mater. 38, 872–878. https://doi.org/10.1016/j.conbuildmat.2012.09.011.

Munawer, M.E., 2018. Human health and environmental impacts of coal combustion and post-combustion wastes. J. Sustain. Min. 17, 87–96. https://doi.org/10.1016/j.jsm.2017.12.007.

Najafi, S.K., Hamidinia, E., Tajvidi, M., 2006. Mechanical properties of composites from sawdust and recycled plastics. J. Appl. Polym. Sci. 100, 3641–3645. https://doi.org/10.1002/app.23159.

Nakatani, J., 2014. Life cycle inventory analysis of recycling: mathematical and graphical frameworks. Sustainability. 6 (9), 6158–6169. https://doi.org/10.3390/su6096158.

Ökobaudat. (2020b). Process Data set: wood fibre insulation boards. 2.10.01 Insulation materials /Wood fibre / Wood fibre insulation boards, reference year 2020, URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?lang=en&uuid=70d0f5b5-ab1e-40b3-b414-63978292a959&version=00.01.000 [Accessed: Jan 31, 2024].

Ökobau.dat. (2022a). Process Data set: extruded polystyrene insulation [Extrudierter Polystyrol Dämmstoff (XPS)]. 2.3.01 Dämmstoffe /Extrudiertes Polystyrol (XPS) / XPS weiß, reference year 2022, URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=37f50a3e-5445-4bce-8eda-98f01dba441f&version=20.23.050&stock=OBD_2023_I&lang=de [Accessed: Feb 1, 2024].

Ökobau.dat. (2022b). Process Data set: rockwool insulation panel [Steinwolle Flachdämmplatte]. 8.1.02 Gebäudetechnik /Heizung / Wärmeverteilung und Abgabe, reference year 2022, URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=be9b6d26-6284-4fe2-ae46-bf84e0f60043&version=20.23.050&stock=OBD_2023_I&lang=de [Accessed: Feb 1, 2024].

Ökobau.dat. (2022c). Process Data set: calcium silicate planel, [Calziumsilikatplatte]. 2.20.02 Dämmstoffe /Calciumsilikat / Calcium-Silikathydrat / Calciumsilikat, reference year: 2022, URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=e76bbf03-1aa3-4ebd-90b9-8abfeabb9766&version=20.23.050&stock=OBD_2023_I&lang=de [Accessed: Feb 1, 2024].

Ökobau.dat. (2022e). Process Data set: foam concret planel [Schaumbeton Dämmplatten]. 2.27.01 Dämmstoffe /Schaumbeton / Schaumbeton Dämmplatten, refence year: 2022, https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=37532578-b1c0-4ed6-b209-5b4cb1b15729&version=20.23.050&stock=OBD_2023_I&lang=de [Accessed: Feb 4, 2024].

Ökobau.dat. (2023b). Process Data set: straw panel [Huppenberger-Maxit Strohbauplatten], 2.23.02 Dämmstoffe /Stroh / Strohplatten, reference year: 2023, https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=313a4a06-07ce-41e4-a693-a756ec562589&version=00.00.051&stock=OBD_2023_I&lang=de [Accessed: Feb 4, 2024].

Ökobau.dat. (2023a). Process Data set: QuadCore sandwich panel [QuadCore Paneele (ems-isolier QuadCore EM und KS EM QuadCore)], 10.1.03 Komposite / Systembauteile / Aussenwände, reference year: 2023, https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=17268809-56c9-40bf-9266-33bea77ff987&version=00.02.000&stock=OBD_2023_I&lang=de [Accessed: 4 Feb, 2024].

PRé Sustainability B.V. (2022b). Why choose AGRIBALYSE agricultural and food database? https://simapro.com/products/agribalyse-agricultural-database/ [Accessed: February 11, 2022].

PRé Sustainability, B.V.. ReCiPe. (Accessed 11 February 2022).

Raffie, K., Kaur, G., Brar, S.K., 2021. Fungal biocomposites: how process engineering affects composition and properties? Bioresour. Technol. Rep. 14, 1–11. https://doi.org/10.1016/j.biteb.2021.100692.

Răut, I., Călin, M., Vuluga, Z., Oancea, F., Paceagiu, J., Radu, N., Doni, M., Alexandrescu, E., Purcar, V., Gurban, A.M., Petre, I., Jecu, L., 2021. Fungal based biopolymer composites for construction materials. MDPI - Mater. 14, 1–20. https://doi.org/10.3390/ma14112906, 2906.

Robertson, O., Høgdal, F., McKay, L., Lenau, T., 2020. Fungal Future: a review of mycelium biocomposites as an ecological alternative insulation material. In: Proceedings of the NordDesign 2020 Conference. https://doi.org/10.35199/norddesign2020.18.

Sands, J.M., Fink, B.K., McKnight, S.H., Newton, C.H., Gillespie Jr., J.W., Palmese, G.R., 2001. Environmental issues for polymer matrix composites and structural adhesives. Clean Prod. Process. 2, 228–235. https://doi.org/10.1007/s100980000089.

Shim, S.H., Dally, B.B., Ashman, P.J., Szegö, G.G., Craig, R.A., 2007. Sawdust burning under MILD combustion conditions. In: Proceedings of the Australian Combustion Symposium. https://doi.org/10.1021/EF901583K.

Silverman, J., 2008. Development and Testing of Mycelium-Based Composite Materials for Shoe Sole Applications. University of Delaware.

Smunt, T.L., Meredith, J., 2000. A comparison of direct cost savings between flexible automation and labor with learning. Prod. Oper. Manage. 9 (2), 158–170. https://doi.org/10.1111/j.1937-5956.2000.tb00331.x.

Stelzer, L., Hoberg, F., Bach, V., Schmidt, B., Pfeiffer, S., Meyer, V., Finkbeiner, M., 2021. Life cycle assessment of fungal-based composite bricks. MDPI - Sustainability 13 (11573), 1–17. https://doi.org/10.3390/su132111573.

WULCA. (2022a). Mission and Goals. URL: https://wulca-waterlca.org/wulca/[Accessed: February 11, 2022].

WULCA. (2022b). What is AWARE? URL: https://wulca-waterlca.org/aware/what-is-aware/[Accessed: February 11, 2022].

Zheng, Z., Fiddes, K., Yang, L., 2021. A narrative review on environmental impacts of cannabis cultivation. J. Cannabis. Res. 3, 35. https://doi.org/10.1186/s42238-021-00090-0.