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Mycelium-based-composites – Vision for substitution of fossil-based materials

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Abstract

For decades, fossil-based materials have formed the basis of an almost endless range of technical products. Through variable chemical composition and several additives, especially plastics can have a wide range of properties, which form the basis for the diversity of plastic-based products. While this variability enables many sustainability strategies, such as lightweighting, it is also impeding a fully circular economy. Therefore, in recent years, a number of new raw materials have been developed, but they can only cover a very limited part of the wide range of properties of fossil-based plastics. Another promising class of materials are composites based on fungal mycelium.
However, these are mainly limited to the consumer sector, e.g. vegan leather, where there is smaller demand for durability, functionality etc. The step from consumer to engineering materials require the production (or growth) process to be reproducible within the necessary quality requirements. Cyber-physical production systems have the potential to realise necessary technical qualities despite e.g. quality fluctuations of the raw material and production processes that are susceptible to interference. For this reason, this paper analyses the state of the art in production of mycelium based composites, shows the existing gaps and draws a vision to close these gaps.

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Keywords: cyber-physical production, biological transformation., mycelium-based composites

1. Introduction

The World Commission on Environment and Development stated already in 1991 sustainable development as “developments that meets the needs of the present without compromising the ability of future generations to meet their own needs” [1]: Since that time the awareness for one of the biggest transformation processes rose further. Today, it is widely understood that meeting the 1.5-degree, which is considered the maximum permissible warming to limit climate change, target requires a virtual complete shift away from fossil resources to a circular economy. New, sustainable sources of raw materials are needed to ensure the transformation process. The utilisation of such alternative raw material sources is currently the focus of a large number of scientific studies [2]. As biological transformation per se does not necessarily have to be sustainable, systematic approaches are required to support a target-oriented engineering [3, 4].

In the field of production technology, with a focus on discrete manufacturing, a transformation process has begun

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under the narrative of biologicalisation, through which the substitution of fossil resources with bio-based materials is increasingly being tested. There has recently been an increase in research into sustainable processes on a biological basis in the field of biointegration and biointeraction. The basic idea behind this vision is that a convergence of biosphere and technosphere will enable new solutions, with reduced consumption of resources and new functions at the same time (comp. Fig. 1).

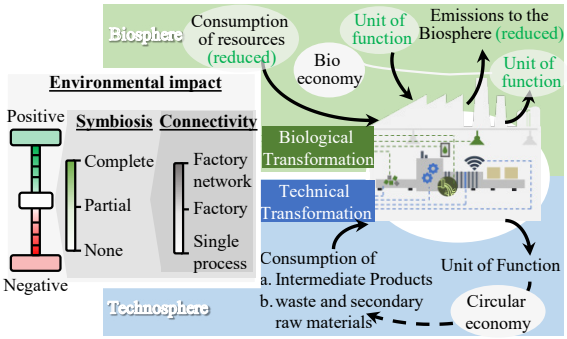


Fig. 1. Interaction of a biological transformed manufacturing system between the biosphere and technosphere according to [5]

One source that was not in the main focus of production technology yet is mycelium-based composites. The "fungal" system has been the subject of intensive research for many years, and the fundamental suitability of many mycelia for use in mycelium-based composite materials has been studied. The mycelium is the invisible part of the fungus, the totality of all the hyphae, which grows into the nutrient substrate (e.g. wood, soil, etc.) and thus naturally forms a composite material. The substrate itself, but also the different networks that the hyphae form in the substrate - depending on the fungal species and the environmental conditions - influence the subsequent properties of the composite material. The degrees of freedom in composition and production therefore enable a wide range of properties, which means that mycelium-based materials are ascribed a relevant role as a substitute for fossil-based materials [6].

Against this background, in this paper, the potential of mycelium-based composites as a substitution for fossil-based materials in discrete production is analysed, open gaps for mass production are deducted and the vision for cyber-physical production system for mycelium-based composites is shown.

2. State of the art and existing research gaps

Although the fungal system is studied for years, mycelium-based composites only gained scientific interest for the last decade. Analyzing the number of publications per year reveals an increasing scientific interest in mycelium-based composites in general (compare Fig. 2).

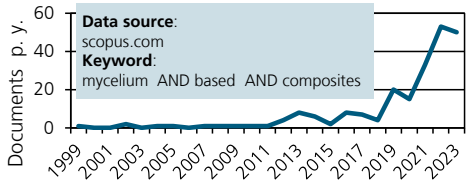


Fig. 2. Number of publications per year

2.1. State of the art

Mycelium-based composites are produced by the growth of mycelium in a substrate material, e.g. agricultural waste (lignocellulosic waste) but also many other possible substrates and reinforcements [7]. The choice of fungal strain and substrate material results in a broad spectrum of possible material combinations [8]. The hyphae can both envelop and penetrate the substrate, resulting in bonds of varying strength [9]. The mycelium can also form a "fungal skin" around the outside of the substrate and thus further improve the mechanical properties.

The growth process itself again can be influenced by controlling temperature, pH and humidity. As a result, the subsequent properties depend on a large number of influencing variables. Belletini et al. cluster these influencing factors as intrinsic or extrinsic, with humidity, for example, being listed as an intrinsic factor and the surrounding air humidity as an extrinsic factor [10]. At the end of the growth phase, the mycelium is inhibited, either by drying or, for example, thermal pressing. The pressing process results in compaction and thus a further increase in mechanical properties [8]. Analyses, mostly at the micro level, show that the mechanical properties of the resulting material are fundamentally similar to those of many fossil (synthetic) materials [11]. Aiduang et al. and Jones et al. summarize the results of various studies very well in their respective review papers and thus provide an good overview of the spectrum of achievable properties [12, 13] (comp. Fig. 3).

	Mycelium-basedcomposite materials	Synthetic foams	Wood products
Density [kg/m³]	59-552	PS: 11-50 PU: 30-100	PW: 460-680 HW: 850-1030
Materialcosts [$US/kg]	0.07-0.17	PS: 2.1-2.3 PU: 8.2-10.4	PW: 0.5-1.1 HW: 3-11
Tensile strength [MPa]	0.03-1.55	PS: 0.15-0.7 PU: 0.08-103	PW: 10-44 HW: parallel 132-162 orthogonal 7.1-8.7
Compression strength [MPa]	0.17-4.44	PS: 0.03-0.69 PU: 0.002-48	PW: 8-25 HW: parallel 68-83 ortho.12.7-15.6
Thermal conductivity [W/m*K]	0.04-0.18	PS 0.03-0.04 PU: 0.006-0.8	PW: 0.3-0.5 HW: 0.2-0.5

PS: Polystyrene; PU: Polyurethane; PW: Plywood; HW: Hardwood

Fig. 3. Spectrum of achievable (mechanical) properties compared with some plastics and types of wood according to [12, 13]

Due to this broad spectrum of properties, the low costs of raw material and the possibility of being cultivated anywhere in the world mycelium-based composites, are expected to play an increasing role in the (circular) bioeconomy [12, 14]. Mycelium-based composites are considered highly biodegradable [15] or can even be used as a substrate for a new generation of mycelium composites at the end of their life cycle.

For these reasons, various sectors have become aware of the material, such as the first art and clothing has already been made from mycelium [16]. Due to its low thermal conductivity [17], the mycelium composites are interesting as thermal isolation in construction [18, 19] as well as even machine tools [20]. However, as these properties are not necessarily sufficient to functionally replace technical materials such as plastics,

additional mechanical reinforcement is often required in the material. Similar to reinforcements in plastics, fibers [21], rigid structures or cover plates [22] can be used here for example. Früchtl et al. used mycelium as a core material in pultruded sandwich structures. In their study, the authors showed that mycelium is basically suitable as a core material, but that high demands are placed on a constant thickness of the core material in the range of usual technological tolerances (+- 0.1 mm) [22]. The authors also carry out a life cycle assessment (LCA) for the pultruded workpieces. This shows that the majority of the global warming potential (GWP) is not caused by the glass fibres in the cover body or the pultrusion process, but by the processing of the mycelium. The authors attribute this mainly to a process that was not optimally designed on a laboratory scale. They also show that the material's GWP is already comparable to that of plastics [22]. In conclusion, the current state of the art is summarized as follows:

- Mycelium composites offer the technical potential to become a broad class of materials due to their composition as mycelium stem and substrate and possibly reinforcement in combination with adjustable growth conditions.
- The availability and the resulting cost structure for mycelium composites open up the economic potential to be manufactured as a mass product.
- The bio-based basis, the recyclability and the GWP, which is already comparable to that of conventional fossil materials, demonstrate the ecological potential of the material, also with regard to other bio-based materials.

Furthermore, mycelium-based materials have already proven themselves in less technically demanding applications such as vegan leather (comp. Fig. 4 and [23]) or as insulating material in packaging [24] for example. Today, Ecovative is one of the largest producers of mycelium composites. As a commercial company, Ecovative seeks to promote innovation by opening up patents [24].



Fig. 4. Vegan leather made from mycelium (own production at Fraunhofer IME and Fraunhofer IAP), untanned (light piece) and tanned leather (blue pieces)

2.2. Existing research gaps

With all these potentials and advantages, the question remains as to why the transformation process from fossil-based materials to mycelium-based composites has not yet taken place. The main challenges that have been identified from the analysis of the state of art are therefore presented in the following.

First, from a technological point of view, the mycelium materials lie at the intersection of several specialist disciplines, which is typical of innovations based on biological transformation [25, 26]. While the cultivation and growth processes require strong competences in biotechnology, the large-scale production of the resulting piece goods requires competences in production technology and materials science for functional design. The analysis of the state of the art shows that many of the previous studies were largely driven by one of the three specialist disciplines, often resulting in challenges and limitations that could have been addressed by an interdisciplinary approach.

Second, the description of the experiments carried out shows that scaling has so far played virtually no role, as Bellitini et al. found in their analysis that cultivation takes place in polyethylene (LDPE and HDPE) and autoclavable polypropylene (PP), polyvinyl chloride (PVC) bags with a maximum load of 1500 g [10]. Früchtl et al. use polypropylene boxes with lips and a size of 40 x 60 cm² in their experiments [22]. This is an example of the very limited scale of the research to date, because although bio-welding processes for growing several individual mycelium components together have already been investigated [27], it is not possible to produce macro-economically relevant quantities of material in this way. For this reason, scalable production processes with a continuous process chain are required.

Third, the sheer size of the solution space allows for many scientifically relevant investigations, but also carries the risk of divergence between different solutions. At the same time, as a biomaterial, mycelium-based composites are inherently subject to greater variability, which hinders their use as a technical material with small tolerances allowed regarding specific properties.

A common nexus is therefore needed to establish the material as an independent class of materials. Within such a common nexus, it is then necessary to develop methods for the consistent and large-scale production of the composite material with low variance in the basic materials. In this way it is possible to deal with the existing complexity on the material side. This initially limits the size of the material class and the tunability of the component properties, but allows for a structured and harmonized approach to material, design, assembly and manufacturing. The physical and digital methods developed in this way can then be transferred to other types of mycelia and other substrates with significantly reduced effort. An approach to regulate and merge both the physical as well as the digital world can be achieved through a cyber-physical production system.

3. Vision for a cyber-physical production system for mycelium-composites

3.1. Idea and potentials of cyber-physical systems

Lee et al. define two major tasks for cyber-physical systems in the context of industry and production [28]:

- the advanced connectivity that ensures real-time data acquisition from the physical world and information feedback from the cyber space
- intelligent data management, analytics and computational capability that constructs the cyber space

Further, the authors also constructed a 5C-level architecture that gives some kind of roadmap for developing and deploying a cyber-physical system in industry and production. Since their

work a lot of scientific work was done to specify cyber-physical systems for different applications in production, e.g. 3-D printing [29], high-tech space applications [30], the biological manufacturing [31] and many more [32]. Common for all approaches of cyber-physical production systems is to get new insights in production processes, to increase productivity or to deal with uncertainties. The degree of integration / interaction between the physical and virtual worlds can be described using maturity models (see Fig. 5).

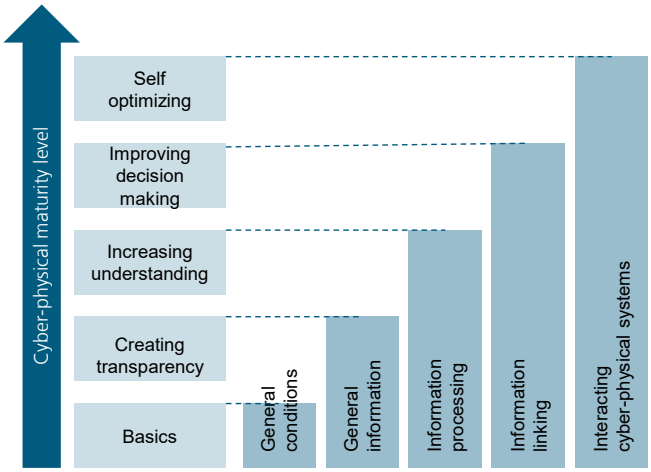


Fig. 5. Maturity model for cyber-physical systems according to [32]

Thereby, the concept of cyber-physical systems can be applied in production environments from a single process via one factory to complete production networks. Hence, the lower maturity levels mainly will help to get new insights in processes and causalities in production and thus enable and accelerate the maturation of new production processes. In addition, the higher maturity levels help to deal with uncertainties in mass production, thus reducing scrap, or finally self-optimize the production chain and processes. Having this in mind, cyber-physical production systems have the potential to be used despite, for example, quality fluctuations of the bio-based feedstock and failure-prone production processes.

3.2. Production of mycelium-composite parts based on a cyber-physical system

Based on the challenges in the production of mycelium-based materials and the new possibilities of cyber-physical production systems, it is hypothesised that by combining the two approaches, mycelium-based composites can be established as a separate class of materials, produced on a large scale and thus become a substitute for fossil-based materials. For this purpose, the cyber-physical production system must include:

- (Mechanical) construction and design methods with regard to bio-based materials
- Function-oriented combination of fungal species and substrate material, and their cultivation
- Scalable and controllable cyber-physical manufacturing processes
- After-treatment processes
- Systematic life cycle engineering
- Adapted recycling strategies

Figure 6 shows a schematic of such an integrated cyber-physical production system. The central aspect of the system is the holistic and consistent digital twin, which first ensures transparency, then understanding and finally the mastery of the overall system in accordance with the 5C maturity model. Within the emerging cyber-physical system consisting of the technosphere (production technology) and the biosphere (biotechnology), the digital twin is seen as the essential key to mastering the complexities [33, 34]. The holistic digital twin enables data to be captured consistently along the process and value chain and enriched with digital models to create information and thus an increased transparency (comp. Fig 5), for example. At the same time, it enables further analysis of correlations using causal graphs, which will make a significant contribution to understanding and controlling these processes.

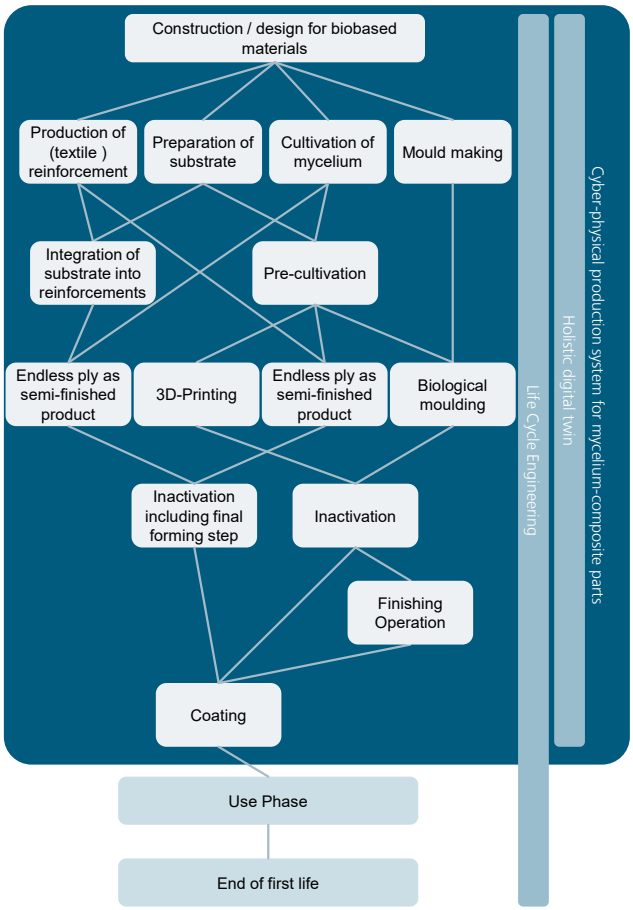


Fig. 6. Schematic depiction of the cyber-physical production system for mycelium-based composites via different manufacturing routes

The physical processing of mycelium-based routes can be realized via several paths, whereby certain process steps (e.g. cultivation of mycelium) can be found in each route equally. From a classic production engineering perspective, there is a certain analogy to metal processing. The substrate pre-cultivated with mycelium can be placed in a mould and grow to the final contour or at least close to the final contour (Fig. 6, Biological moulding). Furthermore, thin layers of mycelium composite can be produced in the form of a "sheet", which is both inactivated and formed by a pressing process after the growth phase (Fig. 6, Endless plys). Finally, the pre-cultivated material can also be 3D printed with an additional binder, whereby the mycelium grows

into the structures after 3D printing (Fig. 6, 3D-printing) [35]. Regardless of the type of processing, the resulting component must be inactivated before further processing, e.g. by drying or (thermal) pressing. This inactivation step is necessary to stop fungal growth and to prevent contamination of the environment with the remaining fungal spores. The resulting surface quality and the limited stability against the environmental conditions during operation require additional finishing steps and a (bio-based) coating [36, 37]. (Textile) reinforcements can also be incorporated into the product in all process routes. Overall, this shows that the production of mycelium-based composite components does not differ significantly from conventional materials in terms of its basic structure from a production system perspective. The key differences lie in the individual processes and the interfaces between them.

From the perspective of the individual processes, the focus must be placed in particular on the scalability and interaction of the biological processes in a scaled system. Scaling creates heterogeneous growth conditions within a component (different humidity, nutrient supply, etc.) especially in discrete form shaping processes. This requires extended and innovative digital monitoring and control concepts. In the concept of the cyber-physical system, this will be achieved through a digital twin based on the combination of data-driven approaches fed by real-time production data and biophysical process models running in parallel. As it is not yet clear whether and which process route, e.g. 3D printing or endless ply, will prevail in the processing of the mycelium, the digital twin enriched in this way also enables an early transfer of knowledge from one process route to the other and vice versa. In this way, maximum technological openness can be maintained without excessive effort. At the same time, the digital twin makes it possible to minimize the environmental footprint in terms of life-cycle engineering, for example by allowing process transparency and, subsequently, weighing and adjusting control strategies (e.g. temperature or humidity) against each other.

Even before the shaping production steps, further scaling is required in terms of process technology with the goal to increase the output of the primarily batch-based process by orders of magnitude or to convert it into a continuous process. This applies to the cultivation of the mycelial strains, the preparation of the substrate (including pasteurization or autoclaving) and the pre-cultivation of the mycelial-substrate mixture.

At the same time scaled processes offer the possibility of generating locally different properties (e.g. density, mechanical strength), in terms of functional integration and at higher maturity levels of processing, through heterogeneously set growth conditions. In addition to process monitoring, this also requires advanced material and growth modelling as well as micromechanical investigations into the interaction between mycelium and substrate during the growth phase. This again corresponds to the idea of biologicalisation, not to only being sustainable but also offering new and advanced solutions.

In addition to the establishment, maturation and scaling of the individual processes, the necessary interdisciplinary competences were identified as a further obstacle. This is certainly reflected in the individual processes, but will become even more pronounced at the interfaces between the steps of the process route in particular. Here too, the cyber-physical production system represents the decisive solution component. A common formalized language and consistent data storage will create transparency and allow cross-process insights to be gained.

Once such a holistic overall system is in place, at least in large parts, another advantage is that it can be transferred to additional variants of mycelium and substrate material with less initial effort. In this way, the entire solution space, that was to complex to handle before, can be opened and the full potential of the biological and technical degrees of freedom can be exploited. This is the basis for mycelium composites to become a material in their own right, analogous to fossil-based plastics.

3.3. Roadmap to establish mycelium-composites as a material class

A cyber-physical production system of the above-mentioned complexity and for a system with different process paths can certainly not be implemented in a single step. However, there is a particular opportunity in the fact that many processes need to be developed both physically and virtually, in parallel and coordinated with each other. In this way, the full potential of digital solutions can be demonstrated much more effectively than if they were retrofitted to an existing production system. Therefore, it makes sense to design the development process analogous to the maturity model of the cyber-physical system (see Fig. 5 and Fig. 7).

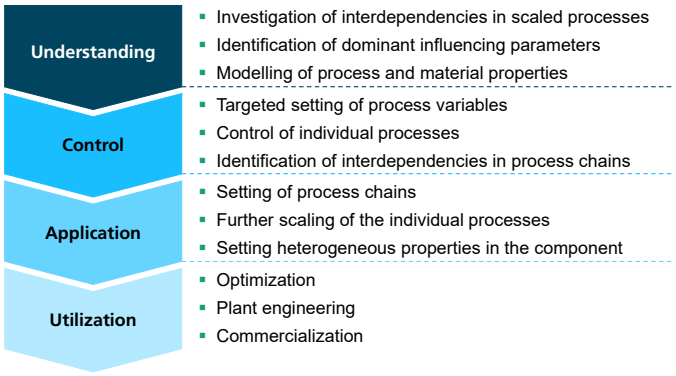


Fig. 7. Roadmap and maturity process for production of mycelium-based composites

Starting with understanding, the first step is to create transparency in scaled individual processes for simple geometries and to establish relationships between material, process and resulting properties. This is followed by process control in individual processes and analysis of interdependencies in process chains. In the next step, the knowledge gained can be transferred to the process chain and extended properties (such as functional integration) can be included for the first time in a meaningful way. The final step is the (self-)optimization of the overall system and its industrialization.

Conclusion

Climate change and geopolitical developments necessitate a shift from conventional fossil resources towards renewable materials. A number of alternative approaches have been

thoroughly analyzed in recent years, whereby mycelium-based composites are one of these. This paper analyzes the current status of this material and shows that the material is fundamentally capable of replacing a significant proportion of fossil plastics due to its properties. However, it was also shown that there are a number of challenges that need to be addressed, particularly in terms of scaling, process chain and the inherent uncertainty of biological processes in order to make mycelium-based components useful for technical products. Cyber-physical systems provide new insights into processes, enabling uncertainties to be overcome and processes to be brought to maturity efficiently. A basic process chain, including the associated cyber-physical system, for the large-scale production of mycelium-based composites as a potential substitute for fossil materials has been demonstrated.

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