Uses of Fungi: Our world is molding!

Miss: I love mushrooms in food (especially in pasta), but I just heard of dresses made of mushrooms: can that be possible?

Image courtesy of Hanneke Wetzer

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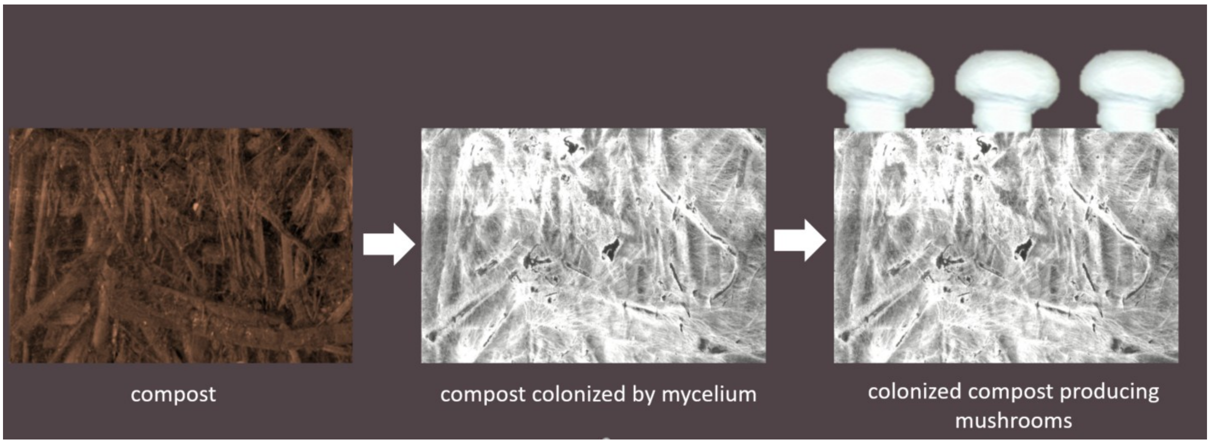
Storyline

Mushrooms are often associated with disease, death and decay. This is illustrated by the names of mushrooms, such as death trumpet, witch boletus and devil's egg. Indeed, there is some truth behind the reputation of mushrooms. For example, some of these fungi can infect trees. The most famous example is an individual of a honey mushroom that killed many trees in a forest in Oregon in the United States. In fact this individual is the largest organism on earth. How is this possible? To understand this, we have to realize that mushrooms are the reproductive structures of a fungus. Most of the "body" of these fungi grows undetected in the soil, in a log of a fallen tree, or, in the case of an infection, in a living organism such as a tree. This body comprises a network of thread-like cells called hyphae. The network, called mycelium, can be very large and decides at specific moments when to make mushrooms to make spores (similar to fruits in the case of plants). For this to happen, some of the hyphae escape the soil, log, or living organism to grow into the air. The mycelium of the largest organism on earth had colonized 10 km^2 of soil of a forest in a few thousand years time period and was able to infect the trees in this forest.

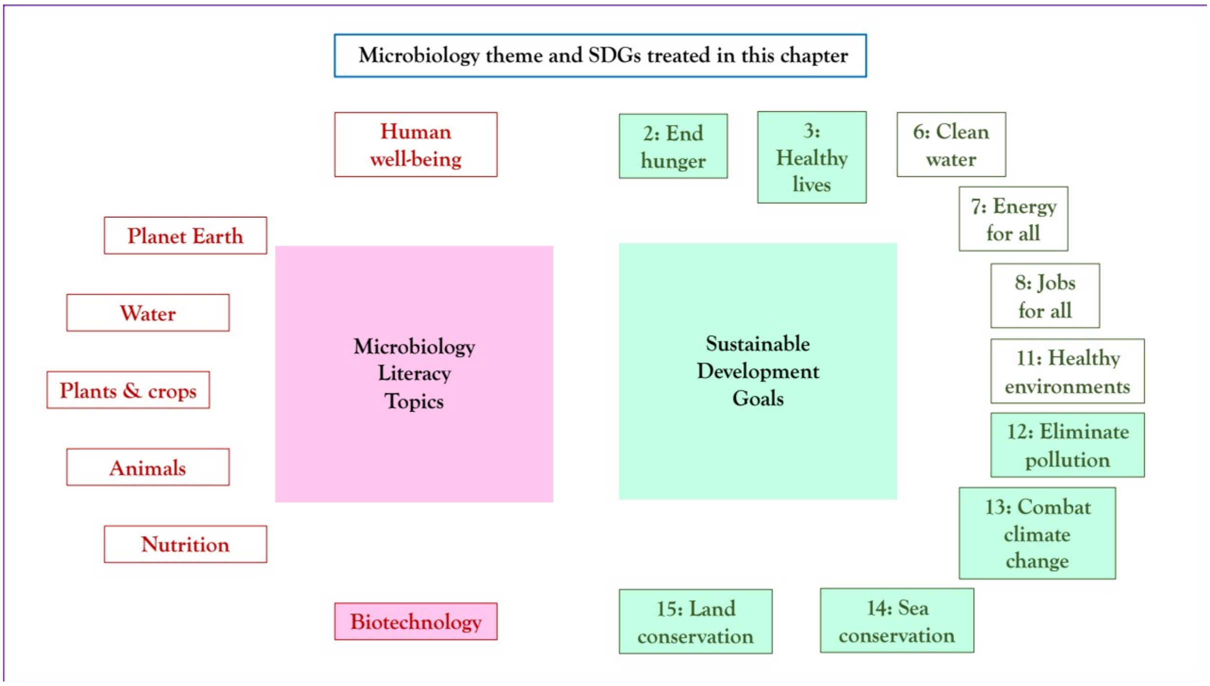


Life cycle of the white button mushroom. Spores that are formed in the mushroom are dispersed (e.g. by wind) and may end up in a fresh substrate like a heap of compost (left). The spore germinates and forms a mycelium within the compost, in this case visible by its white appearance. After the mycelium has reached a "critical mass" that can feed mushrooms, the fungus may decide to make these fruiting bodies. A drop in temperature and ambient levels of CO_2 trigger white button mushroom formation.

People can also die from mushrooms; 1-2% of mushrooms are poisonous. For example, the Roman emperor Claudius was murdered in AD 54 by his wife Agrippina. She had convinced Claudius to appoint her son Nero as his successor instead of his own son Britannicus. To hasten this succession, Agrippina is said to have mixed the highly poisonous sticky turnip manite into his evening meal, which consisted of a dish of the very tasty Caesar's mushroom. The latter shows that mushrooms can also be very useful (see Video 1). For instance, they serve as food, promote our health and provide sustainable materials that can replace non-sustainable materials such as plastics. Mushrooms thus can significantly contribute to the Sustainable Development Goals.

The Microbiology and Societal Context

The microbiology: Mushrooms; mycelium; meat replacement; food security; pharmaceuticals; immune stimulation; mycelium materials; upcycling of waste. *Sustainability issues:* food; health; recycling and circular economy; climate change; reduce pollution.



Uses of Fungi: Our world is molding! The Microbiology

1. ***Circular economy and upcycling***. In a circular economy, agricultural waste streams are not considered a debit entry of a budget as in a linear economy but rather as valuable resources. Currently large amounts of straw are being burned on the fields, despite legislation to ban this practice because of the resulting pollution and emission of greenhouse gases. For instance, 250 billion kg of straw was burned in 2009 in China alone. This agricultural waste could instead have been used in a wide variety of processes that convert it into valuable products. For instance, straw could have been upcycled by growing edible or medicinal mushrooms on it or by converting it into fungal sustainable materials that can replace plastics or non-sustainable construction materials.

2. ***Mushrooms as food.*** The Food and Agriculture Organization of the United Nations has calculated that food production has to increase by 70% by 2050 to feed the global human population. This is largely due to the increase in the number of people on the planet, but also because people will become wealthier. Yet, the total volume of arable land is expected to increase only by a few percent. This implies that arable land has to be more productive but also that less acreage is used to grow animal feed for meat production.

Mushrooms are highly attractive to help to reduce meat consumption because these fruiting bodies can be grown on low quality waste stream straw that cannot be used as food or feed. In doing so, mushrooms upcycle these low quality waste streams into a high quality food. Mushrooms consist of 5-15% dry matter, of which 20% is protein. Moreover, mushrooms are rich in fibers, low in calories (27-30 kcal/100 gr), and have a balanced composition of minerals and vitamins. Also of interest, mushrooms like the oyster mushroom have a mouthfeel similar to that of meat. This makes them also of interest as a meat replacement.

Mushroom consumption had increased from 1 to 4.7 kg per capita in the period 1997 to 2013. This was accompanied by an increase in production of edible mushrooms to 35 billion kg globally and a sales exceeding 39 billion US dollars in 2013. Consumption is expected to further increase in the coming years, due to a growing awareness of the need to reduce meat consumption and to replace this part of the diet with more sustainable alternatives.

About 7000 species of mushrooms are considered edible, of which 2000 are regarded as high-value edible fruiting bodies The white button mushroom (*Agaricus bisporus*) is the most popular edible mushroom in the Western world but is only on 4th position internationally. *Lentinula* (shiitake and relatives), *Pleurotus* (oyster mushrooms), and *Auricularia* (wood ear mushrooms) make up the global top 3 of most consumed mushrooms. Of interest is the fact that more than 80% of the edible mushrooms cannot be grown on mushroom farms. Thus, many tasty edible mushrooms such as boletus have still to be picked in the wild. Understanding how these mushrooms develop will help to grow these fruiting bodies on farms as well.

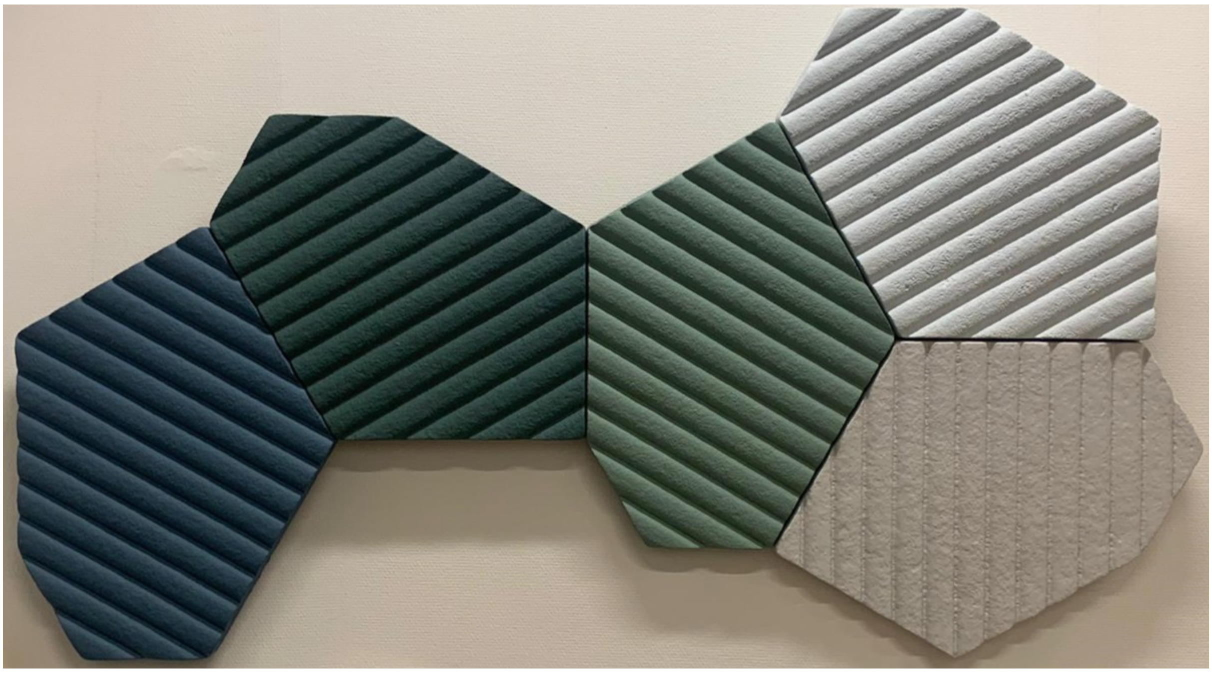
A selection of gourmet mushrooms including shiitake and oyster mushroom.

3. ***Mushrooms as sources of pharmaceuticals***. More than 700 edible mushrooms are known to possess substantial pharmacological properties and the market of these mushrooms represents a global annual sales of 24 billion US dollars in 2013. Mushrooms produce a wide variety of molecules with pharmaceutical and nutraceutical activity. In the following, only some

examples are described. Mushrooms such as the top 4 cultivated mushrooms produce antioxidants that protect against free radicals that can induce diseases such as cancer (note that vitamin C is an antioxidant). Mushrooms such as *Agaricus* also produce anticancer molecules. For instance, extracts of the almond mushroom, *Agaricus blazei*, can kill cancer cells in lab experiments. Moreover, edible mushrooms produce immune boosters helping to prevent various diseases. Mushrooms also appear to have anti-diabetic and anti-obese properties. For instance, extracts of the golden oyster mushroom *Pleurotus citrinopileatus* reduce the weight of obese mice and help to improve glucose tolerance and reduce triglycerides, cholesterol and low-density lipoprotein. In addition, edible mushrooms such as shiitake produce statins, which are used to lower cholesterol in blood. Sales of these compounds represented a value of 5.8 billion US dollar in 2018.

Non-edible mushrooms are also of interest for their pharmaceutical properties. For instance, extracts of the Reishi mushroom *Ganoderma lucidum* have high activity against *Candida* that causes oral thrush, vaginal candidiasis (also known as yeast infection), as well as life-threating infections in people with a compromised immune system. About 1.5 million people each year die of fungal infections in the world, *Candida* being one of the most prevalent fungal pathogens. With the development of anti-fungal resistance there is a need for new anti-fungals to be able to effectively treat patients. Another example of a non-edible mushroom is *Fomes fomentarius* (see also next section). These mushrooms were used as a styptic to stop bleeding of wounds but also have anti-inflammatory, anti-infective and anti-tumor activities.

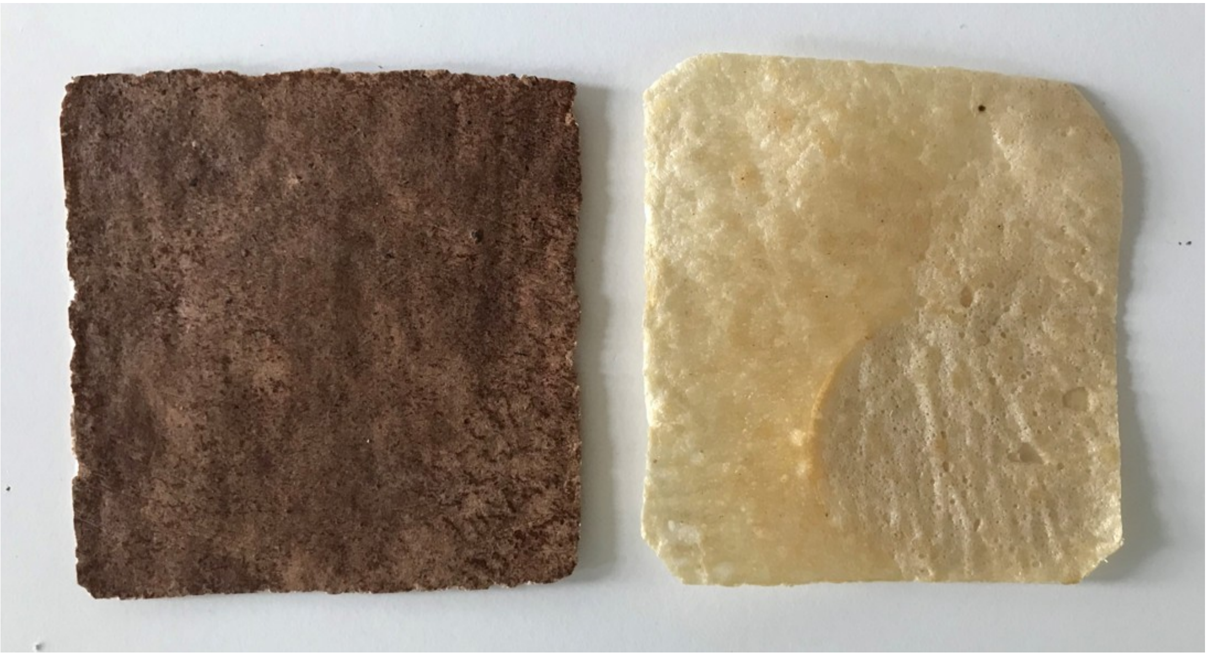
4. ***Mushrooms as materials.*** Mushrooms and their mycelia can be used to produce a wide variety of materials. The inner part of the mushrooms of the hoof fungus *Fomes fomentarius* has been used for thousands of years as tinder (see Video 2). Iceman Ötzi, who lived around 3300 BC, had such a mushroom in his bag when going into the mountains at the border of Austria and Italy. The *Fomes fomentarius* mushrooms have also been used to produce clothing and hats and is known as Amadou. So, the use of mushrooms, or their mycelium, as a material is not new but their potential uses have been more thoroughly explored over the last two decades.



Composition of composite mycelium panels (Mogu) on a wall used to improve acoustics in a building.

Two types of fungal materials are distinguished; pure fungal materials and composite materials (see Videos 3 and 4). The mycelium of mushroom-forming fungi can grow through dead organic material such as agricultural waste streams. During their growth, for instance in straw, they partially degrade the substrate to feed the hyphae. At the same time these hyphae bind the non-digested straw fibers together. The fungus is subsequently inactivated at a certain moment by drying the substrate or by a heat treatment. This prevents the fungus from completely degrading the straw, resulting in a composite material that consists in the main of the waste stream with the fungal mycelium binding the substrate fibers together. This foamy material has excellent thermal insulation and acoustic properties and can be used to replace non-sustainable thermal insulation materials such as glass wool and rock wool or non-sustainable acoustic materials. Moreover, it can replace oil-based packaging materials. The density of the foamy composite material is increased by pressing. As a result, a chipboard-like material is produced that does not involve use of non-sustainable glues that are normally used in the chipboard production process. This type of fungal material can not only be used to replace chipboard but also as a construction material replacing for instance bricks.

A pure fungal material is produced when the fungus is allowed to degrade the whole



waste stream that is used as the food source. The fungal skin formed at the surface of the substrate or mushrooms are also pure fungal materials. These materials have textile-like properties or can replace leather. In addition, they can have mechanical properties that make them interesting to replace polymers such as plastics or even elastomers like rubber.

Pure mycelium with leather-like (left) and textile-like (right) properties.

Taken together, mushrooms and their mycelia can be used to make a palette of materials that can be used to replace non-sustainable materials. The main advantages are that fungal materials are made by using waste streams and that they do not need a high energy input for their production. Moreover, they can be degraded in nature when they are no longer needed.

Clearly, their biodegradability means that they have to be protected against degradation during use; the same holds for other natural products such as wood and cotton. Coatings can prevent fungal materials becoming wet and thereby vulnerable to microbial degradation. A lot of research still needs to be done to further widen the material portfolio and to improve properties of the fungal materials that have already been developed. This can be done by varying the waste stream and the mushroom forming fungi that are used, and by varying the growth conditions and / or the post-processing such as coating or pressing.

Relevance for Sustainable Development Goals and Grand Challenges

The microbial dimension of mushroom and fungal material production relates to several SDGs (microbial aspects in italics), including

- **Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture** (*end hunger and malnutrition, increase agricultural productivity*). Mushrooms and even their mycelia can be used as a high quality food that can be used in a meat-free diet. Mushrooms can be grown on organic waste streams and do not require arable land for their production.
- **Goal 3. Ensure healthy lives and promote well-being for all at all ages** (*improve health, reduce preventable disease and premature deaths*). Edible mushrooms produce many nutraceutical and pharmaceutical compounds that can prevent or treat diseases. These molecules range for instance from minerals to vitamins and from antibiotics to molecules that boost the immune system, that are anti-inflammatory or anti-cancer.
- **Goal 12. Ensure sustainable consumption and production patterns** (*achieve sustainable production and use/consumption practices, reduce waste production/pollutant release into the environment, attain zero waste lifecycles, inform people about sustainable development practices*). Agricultural waste streams can be upgraded in the circular economy to produce edible and medicinal mushrooms and to produce materials. The edible mushrooms can be used in meat-free diets. Moreover, the sustainable fungal materials can replace non-sustainable and toxic materials such as plastics and construction materials.
- **Goal 13. Take urgent action to combat climate change and its impacts** (*reduce greenhouse gas emissions, mitigate consequences of global warming, develop early warning systems for global warming consequences, improve education about greenhouse gas production and global warming*). Meat production produces substantial quantities of greenhouse gas emissions. The levels of emission are much lower in the case of production of mushrooms from agricultural waste. The net emission will be even positive when waste streams are used that otherwise would be burnt on the fields. Production of fungal materials will also retain carbon in the waste streams (known as carbon sequestration). In contrast, materials produced from non-renewable resources such as oil highly contribute to greenhouse gas emission.
- **Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development** (*reduce pollution of marine systems by toxic chemicals/agricultural nutrients/wastes like plastics*). Plastics are polluting oceans and seas. By replacing plastics for biodegradable products such as fungal materials further accumulation of plastics in oceans and sees will come to a halt.
- **Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss** (*reduce pollution of terrestrial ecosystems, reduce land use for agriculture and halt biodiversity loss*). Plastics are polluting terrestrial ecosystems. By replacing plastics for biodegradable products such as fungal materials further accumulation of plastics in these ecosystems will come to a halt. Moreover, mushroom production can be done on non-arable land reducing the need to exploit natural ecosystems like forests, which will also contribute to reduce biodiversity loss.

Potential implications for decisions

1. ***Individual***
    a. Replace meat by alternatives such as mushrooms (do environmental benefits outweigh benefits of meat such as taste and optimal protein content?).
    b. Replace current textiles by fungal fabrics (do environmental benefits outweigh the restricted choice currently available for fungal fabrics in terms of different materials, colors, and shapes?).
    c. Replace current building materials such as bricks by fungal materials (do environmental benefits outweigh time investment to maintain fungal materials in a good condition?).

2. ***Community policies***
    a. Local economic activity (reduction of the number of farmers that produce meat).

3. ***National policies***
    a. Subsidies to introduce the more expensive sustainable fungal materials in the market
    b. Disincentives, such as taxes, for non-sustainable economic activities.

Pupil participation

1. ***Class discussions***
    a. The consequences of a change from a linear to a circular economy for our daily lives
    b. Will waste management become subject to a linear economy again when there is more demand than supply of waste streams?

2. ***Pupil stakeholder awareness***
    a. Does individual expression needing a wide choice of consumer products created by the industry in a linear economy outweigh the consequences of a sustainable economy with less diversity in consumer products?
    b. Can you think of other non-sustainable products that could be replaced by fungal materials?

3. ***Exercises***
    a. Mushrooms and fungal materials can be grown on farms but may also be created by yourself at home. How would this work?
    b. Is it possible to produce a pure fungal material starting from a fungal composite material?
    c. Can you think why people prefer to use straw fibers and not a straw dust?

The evidence base, further reading and teaching aids

Evidence base

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https://drug-dev.com/generic-statins-to-slash-global-market-value/
Appels FVW, Wösten HAB (2021). Mycelium Materials. Encyclopedia of Mycology 2: 710-718.

Teaching aids

Video 1; Six ways how mushrooms can save the world: https://www.youtube.com/watch?v=XI5frPV58tY.
Video 2; How mushrooms can be used as tiner: https://www.youtube.com/watch?v=tM1DE5zERZU.
Video 3; How fungi can be used to make materials: https://www.youtube.com/watch?v=jnMXH5TqqG8.
Video 4; How mushrooms can be used to replace plastic: https://www.youtube.com/watch?v=cApVVuuqLFY