Edible Mushrooms are arguably experiencing a moment. Why?

And, are they a good fit for CEA?

An argument for: Mushroom Production in CEA

Why Mushrooms in CEA?:

- Environmental benefits
- Closed modular energy and resource-efficient agriculture systems
- Growing industry
- Nutritional and Health benefits

Benefits of Mushroom Cultivation

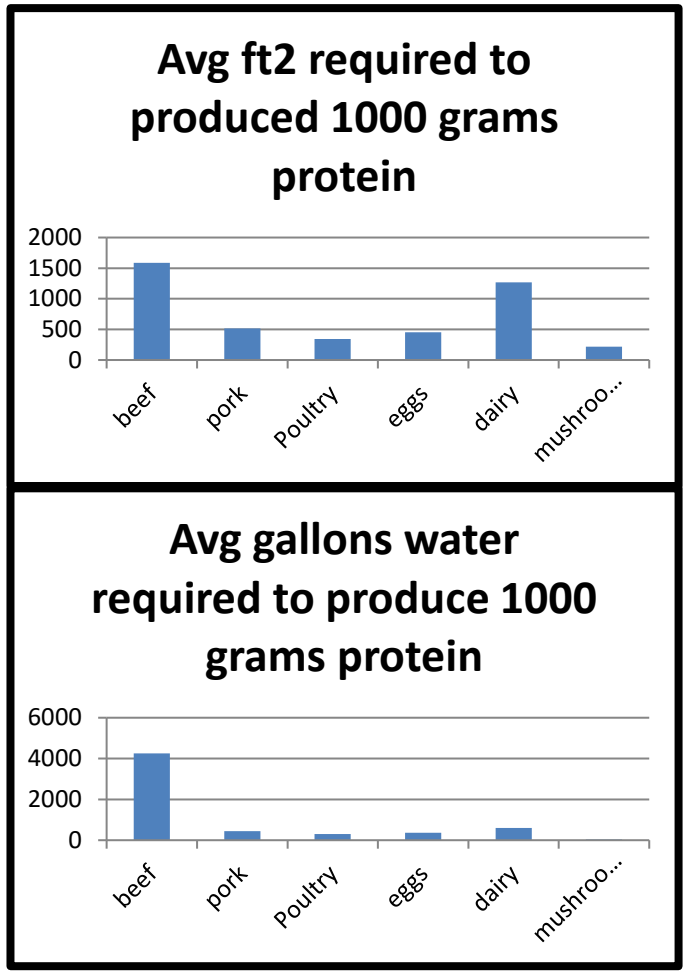
Environmental Benefits:

Highly sustainable protein source

- Low Land Use
- Low Water Usa
- Non-edible biomass

Comparison of bioefficiencies

Beef	→	5-15%
Chicken	→	30-50%
Fish	→	60-80%
Crickets	→	70-90%
Mushrooms	→	80-150%



NGM Staff. Sources: Gidon Eshel, Bard College; Alon Shepon AND RON MILO, Weizmann Institute of Science; Tamar Makov, Yale School of Forestry and Environmental Studies, *PNAS*, July 21, 2014

Please ask: Why is Pennsylvania the US mushroom capital?

Benefits of Mushroom Cultivation

Growing industry:

U.S. market:

- ~$1–1.5 billion in cultivation/value
- Volume ~1 Mt production
- 25.4 million pounds, just in specialty mushrooms
- ~7–8% share of global cultivated volume.

Global market:

- $65–70 billion in 2023
- Forecast to reach $125–145 billion by early 2030s
- Volume ~17 Mt cultivated annually.

Growth comes from tech, niche varieties, and health trends aligning with global drivers.

Integrating with the greenhouse: Waste reduction and CO_2

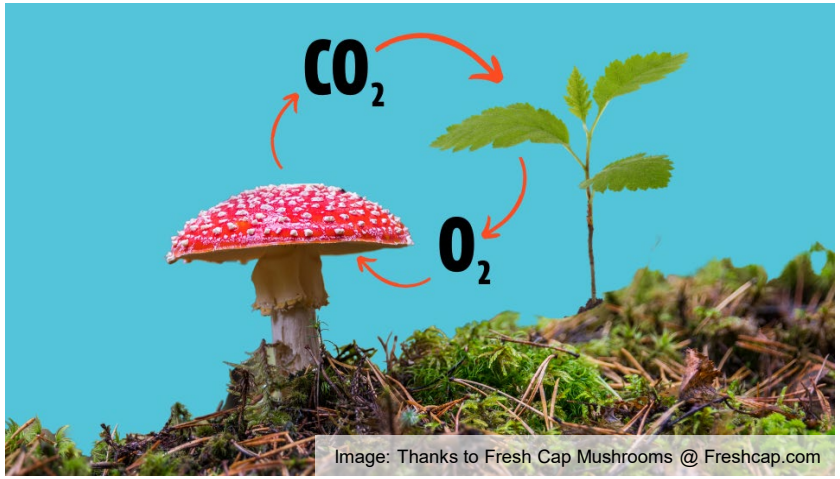
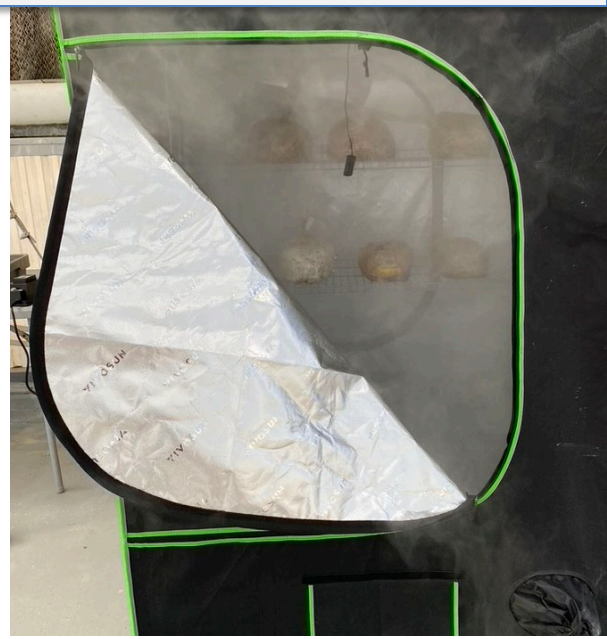


Image: Thanks to Fresh Cap Mushrooms @ Freshcap.com

Just by moving our fruiting chambers into the greenhouse we have the added benefit of extra CO_2

These projects lend themselves nicely because:
Fungi are the single most important decomposers in all ecosystems.

- Recycle nutrients (C, N and essential elements such as Fe, Ca, P, Mn, K, B and S)



Benefits of Mushroom Cultivation

Circularity

The use of lignocellulosic biomass for substrate is an exciting part of mushroom production in that it enables us to re-incorporate many agricultural or landscaping waste products to produce a highly nutritious mushroom crop.

~100 million tons of crop residues are created each year in the U. S. alone –

Los Reales Sustainability Campus is doing amazing work to divert biomass!

Major commodity crops produce large quantities of residues: rice, wheat, cotton, corn

Uses for these residues:

- Fodder
- Energy
- Compost
- Mushrooms!

Benefits of Mushroom Cultivation

Some mushrooms will grow on nearly anything!

- Corn, Corncobs, Cornstalks
- Cotton and Cotton Waste
- Textiles
- Garden and Yard Waste
- Hemp
- Nut casing
- Seed Hulls
- Paper Products
- Soybean Roughage
- Brewery Waste
- Cacao Shells
- Coconut and Coir
- Used Coffee Grounds
- Agave
- Straws, wheat, rye, etc.
- Sugarcane
- Tea waste, leaves and trimmings
- Water hyacinth
- Wood Construction Waste
- Tomato vines

Benefits of Mushroom Cultivation

So many things can be substrate:

Lignocellulosic biomass for mushrooms

Benefits of Mushroom Cultivation

Roasted agave post syrup extraction

On average:
~2000g Roasted agave post syrup extraction = 700g oyster mushroom

Benefits of Mushroom Cultivation

New "byproduct" we are working with:

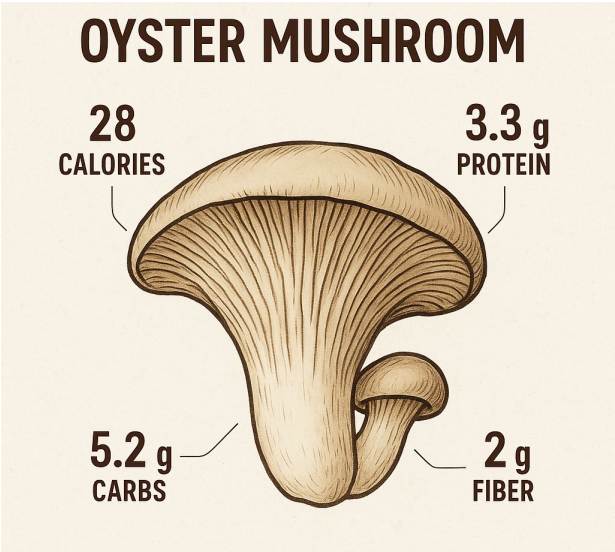
Spent Grains from Beer Production!

Goal: both remove the need to sterilize our substrate material as well as fruit in large batches without the need for the typical autoclavable, single-use bags.

Benefits of Mushroom Cultivation

Nutritional and Health Benefits

- High in Protein
  - Content varies by species, but ~15-35% protein content by dry weight
  - Complete protein, providing all 9 essential amino acids
- High in Fiber
- Antioxidants
  - **Ergothioneine** (“longevity vitamin”), specific transporter protein in our cells
    - While discovered over a century ago, its reputation as a potent "longevity vitamin" and dietary antioxidant was bolstered by the 2005 discovery of a specific transporter (ETT) in humans and animals that accumulates it in tissues
- Vitamins
  - High concentrations of B vitamins
  - UV for increased vitamin D
- Polysaccharides
  - Beta-glucans
    - Soluble fibers that can help lower LDL (the bad cholesterol)



Benefits of Mushroom Cultivation

Nutritional and Health Benefits:

Hericium erinaceus

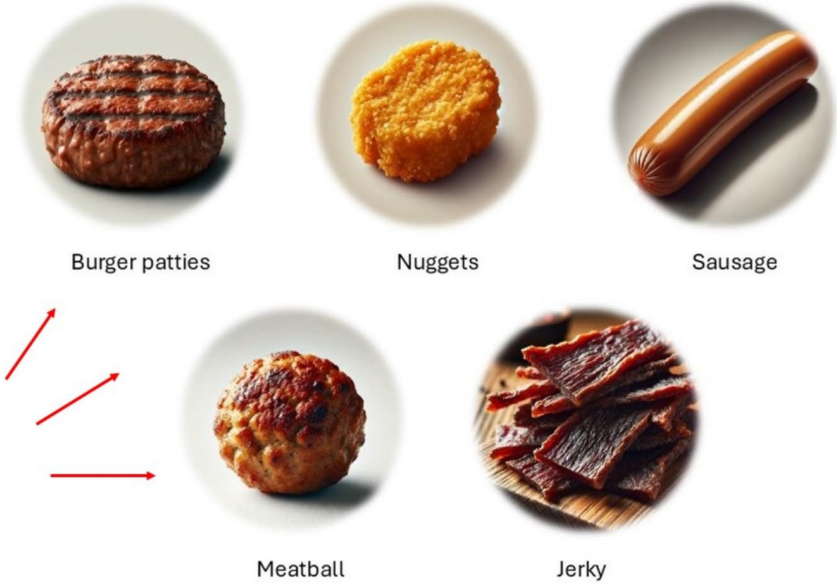
- **Cognitive Support**
- Nerve Health – Hericenones and diterpenoid derivatives found to promote Nerve Growth Factor (NGF), Neuroprotective properties, Alzheimer's & Parkinson's
- Immune System Boost
- Digestive Health

Bioactive compounds:

- **Erinacines** – mainly found in mycelia
- **Hericerins** – only found in fruiting bodies
- Steroids
- Alkaloids
- Lactones
- More than 35 polysaccharides isolated

Growing Industry of Fungal Products

Mycoprotein products - no mushrooms involved



Contato, A.G., Conte-Junior, C.A. Mushrooms as meat substitute in plant-based diets. *Eur Food Res Technol* (2025). https://doi.org/10.1007/s00217-025-04722-0

Growing Industry of Fungal Products

- Bioremediation
- Fungal compost starters
- Ag. Inoculants and bio-control products
- Composites for:
  - Packaging
  - Insulation
  - Binding of particle board

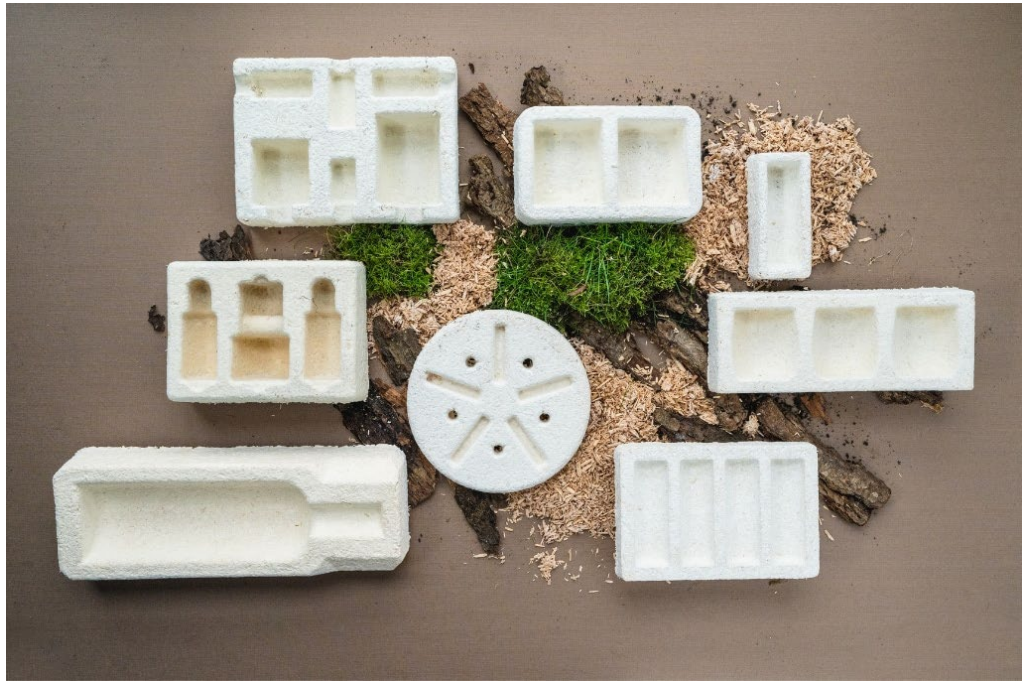


Photo from company selling mycelium-based packaging solutions
https://www.grown.bio/

Ötzi, the Iceman
Lived between 3400-3100 BC

We have a long history of using mushrooms!

Artifacts from the Iceman's kit included:

Fomes fomentarius (tinder fungus or hoof fungus), a conk used as a fire starter

Fomitopsis betulina (birch polypore or birch bracket), a conk used in primitive medicine, due to its anti-parasitic and anti-microbial properties.

From the beginning, commercial mushroom production was a CEA industry

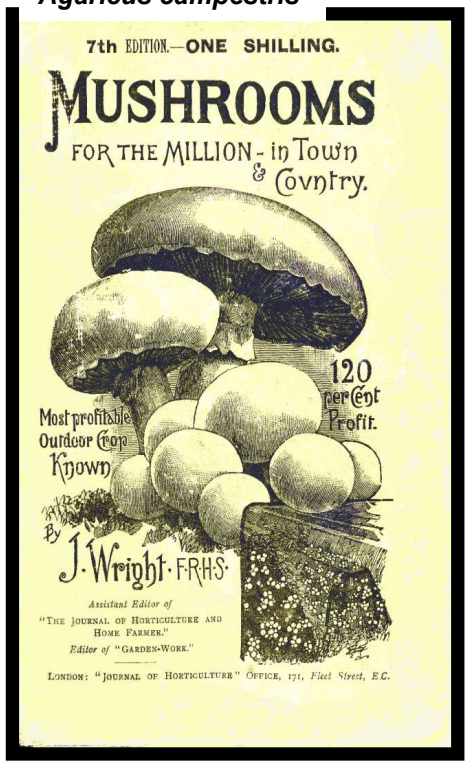
1707 France

- Tourefort describes cultivation of *Agaricus campestris*, the common field mushroom, and modern mushroom cultivation began.
  - Using straw and horse manure and as a substrate
  - Using limestone mines as the production facility

Montage des couches dans une champignonnière d'Indre-et-Loire.

Mushroom production in limestone caves: Temperature control

Agaricus campestris



(Published 1883)

Mushrooms Currently in Cultivation

Current estimates put us at having identified ~10% of fungi, of which:

- About 20,000 species fruit mushrooms
- Over 1000 mushrooms have been found to be edible
- Of these about 200 species have been cultivated, with about 20 being cultivated at a large scale.

Common Name	Scientific Name
White Button	*Agaricus bisporus*
Crimini / Baby Bella	*Agaricus bisporus* (brown strain)
Portobello	*Agaricus bisporus* (mature)
Oyster	*Pleurotus ostreatus* + others
King Oyster	*Pleurotus eryngii*
Shiitake	*Lentinula edodes*
Enoki	*Flammulina velutipes*
Beech Mushroom	*Hypsizygus tessellatus*
Straw Mushroom	*Volvariella volvacea*
Wood Ear / Black Fungus	*Auricularia auricula-judae*
Maitake / Hen of the Woods	*Grifola frondosa*
Paddy Straw Mushroom	*Volvariella volvacea*

Mushrooms Currently in Cultivation

Note:

Many of the edible mushrooms we love to eat are mycorrhizal and these we will just need to keep foraging for.

Common Name	Scientific Name	Primary Tree Partners
Truffle (Black/White)	*Tuber spp.*	Oak, hazel, beech, pine
Chanterelle	*Cantharellus cibarius, C. formosus*	Birch, beech, oak, conifer
King Bolete / Porcini	*Boletus edulis*	Spruce, pine, fir, chestnut
Matsutake	*Tricholoma matsutake*	Pine, fir, hemlock

And others are just tricky due to:

- Slow growth rates
- Environmental triggers
- High contamination
- Low yields

Common Name	Scientific Name	Why It's Difficult
Morel	*Morchella spp.*	Complex life cycle, needs sclerotia formation, sensitive to environment
Cauliflower Mushroom	*Sparassis crispa*	Cultivable but slow and contamination-prone
Hedgehog Mushroom	*Hydnum repandum*	Mycorrhizal; lab cultivation not yet scalable
Lobster Mushroom	*Hypomyces lactifluorum*	Actually a parasite of other mushrooms (usually *Russula*), so must first grow a host
Huitlacoche	*Ustilago maydis*	Plant pathogen that infects living corn plants and distorts kernels into galls.

Mushrooms Currently in Cultivation

Note on Morels:

Cultivating Coveted Morels Year-Round and Indoors

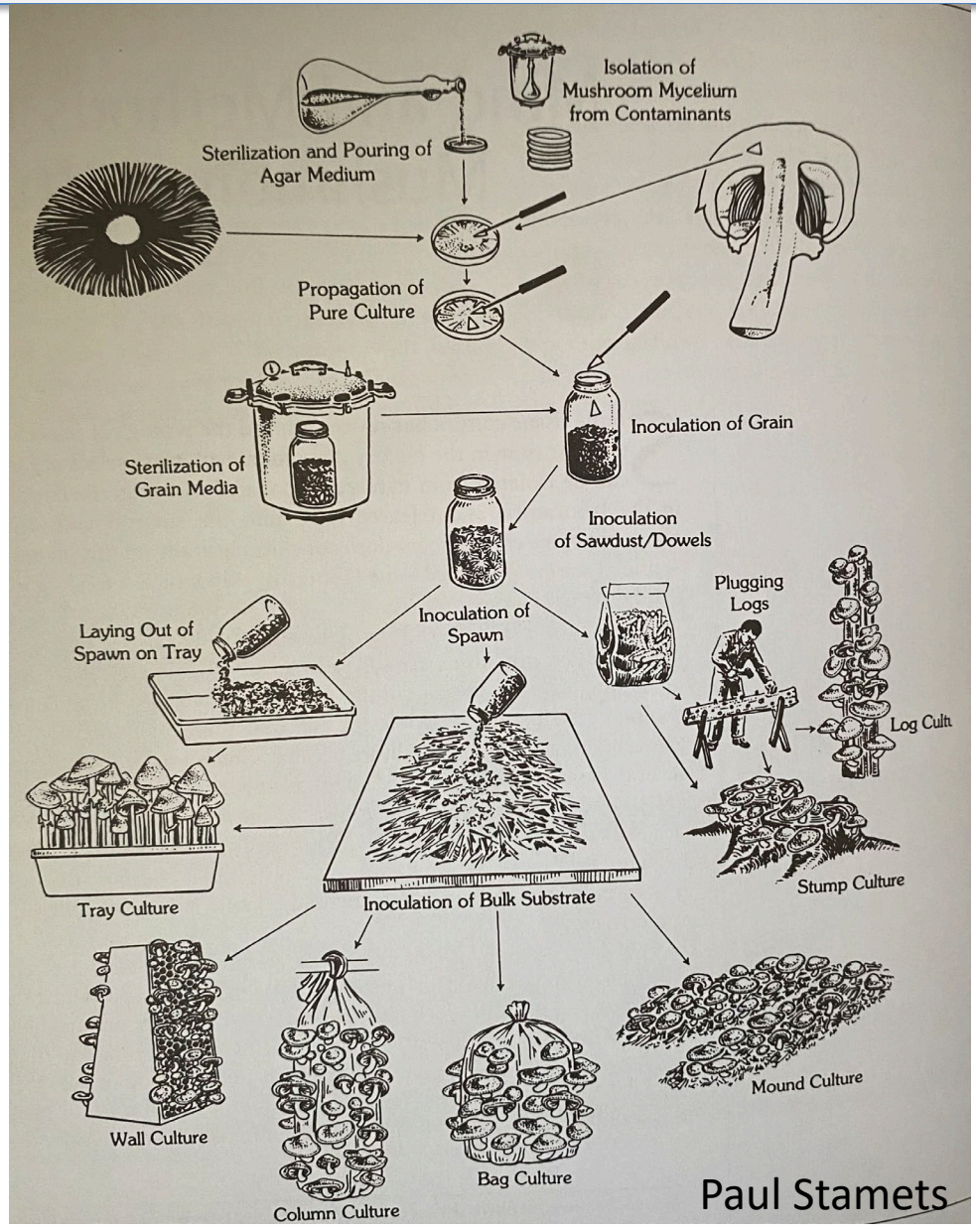
Jacob and Karsten Kirk, twins from Copenhagen, say they have devised a method to reliably grow morel mushrooms in a climate-controlled environment.

Morels growing indoors in a climate-controlled environment in Denmark, the fruit of decades of research by Jacob and Karsten Kirk. The Danish Morel Project

The General Process

- Prepare cultures
  (7-10 d)
- Spawn production
  (10-14 d)
- Substrate preparation
  (2-4 d)
- Spawn run
  (14-21 d)
- Production flush
  (7-42 d)

Total time = 40-90 days to finish



The Cultivation Process is very different for different mushrooms

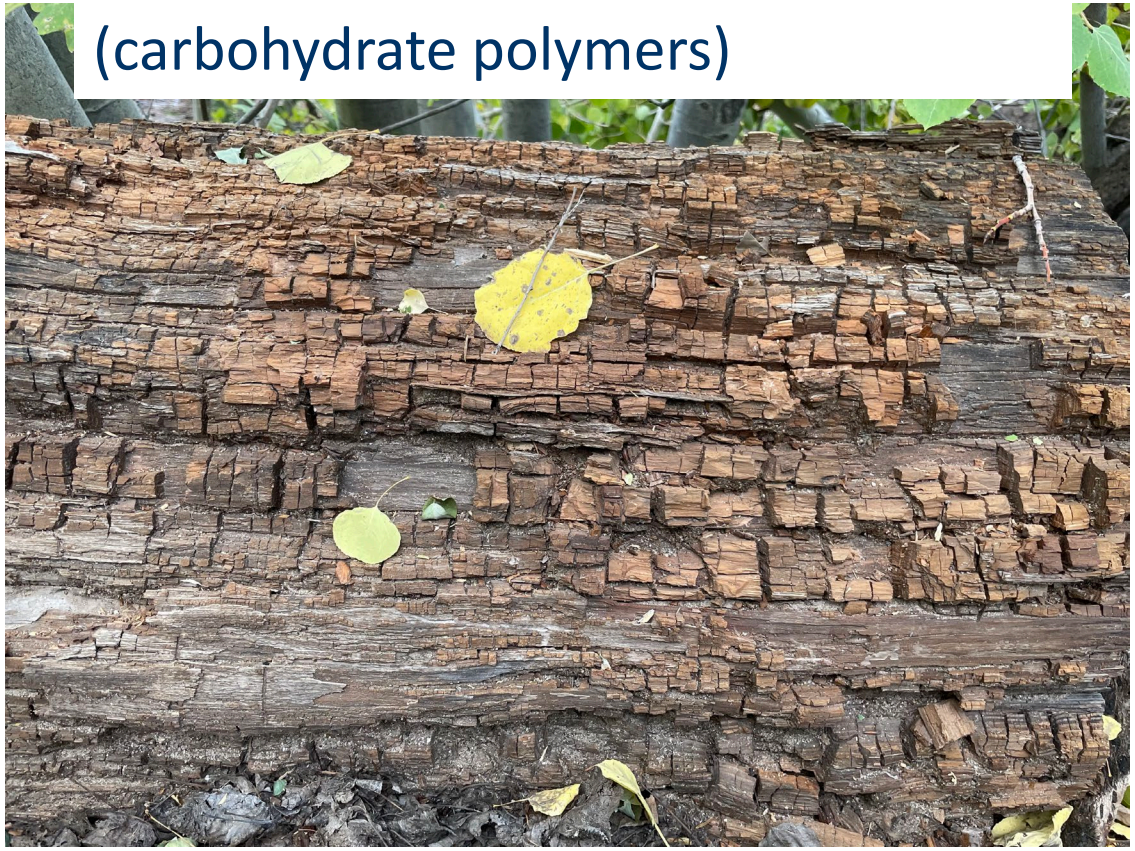
Field mushrooms

Forest mushrooms

Forest Mushrooms: White rot vs. Brown rot

White rot fungi, capable of breaking down Lignin (aromatic polymers)

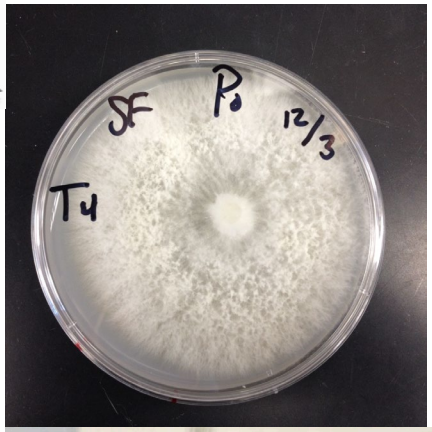
Brown rot fungi, capable of breaking down cellulose and hemicellulose (carbohydrate polymers)



Growing mushrooms: a process overview

Maintaining mushroom cultures:

Hyphal fragment propagation.



Materials:

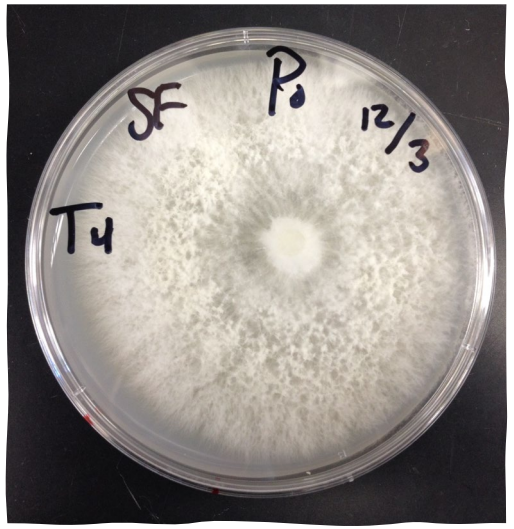
- Fungal colony
- PDA media (Potato Dextrose Agar)
- Scalpel
- An alcohol lamp

Growing mushrooms: a process overview

Spawn Production

- Allows for the bulk amounts of mycelia needed for substrate inoculation.
- Examples of grains typically used:
  - Cracked corn, millet, rye, barley, rice…

- Main Steps:
  - Soak grain to increase moisture content
  - Sterilize
  - Inoculate



Growing mushrooms: a process overview

Substrate - Composition

Carbon source + Nitrogen source + **moisture**.

Main Steps:
Soak, sterilize and inoculate.

Note: shredding the material creates more surface area for the mycelia

Growing mushrooms: a process overview

Substrate - Composition

Plant Material	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Wheat straw	33–40	20–25	15–20
Corn stover	35–40	20–25	15–18
Switchgrass	30–35	25–30	12–20
Softwood (e.g., pine)	40–45	25–30	25–35
Hardwood (e.g., poplar)	40–50	20–25	20–25
Alfalfa	25–30	20–25	10–15

Growing mushrooms: a process overview

Substrate Optimization

- Water holding capacity
- Particle size
- Carbon to Nitrogen ratios

Growing mushrooms: a process overview

Items to keep in mind:

- Moisture content
- Particle size of substrate material
- Environmental conditions of fruiting chambers

Currently working with:

Carbon Sources:

- Milled Mesquite Wood
- Milled Palo Verde Wood
- Mesquite Pellets
- Oak Pellets
- Straw Pellets
- Almond Hulls
- Rice Hulls
- Pecan Shells

1:1 →

Nitrogen Sources:

- Soy Hull Pellets
- Cotton Seed
- Mesquite Pods
- Tomato vines

Hericium

Growing mushrooms: a process overview

Substrate – **Moisture**

- Higher cellulose content usually leads to greater water holding capacity

- Higher lignin content usually leads to reduced water holding capacity

Substrate type	**Water**
Cotton Seed	55%
Mesquite Pods (chipped)	59%
Rice hulls	60%
Milled mesquite wood	66%
Milled Palo verde	67%
Milled almond Hulls	81%
Milled pecan shells	49%
Alder shavings	80%
Straw - pellets	80%
Oak - pellets	64%
Tomato vines (chipped)	76%
Corn stalks (chipped)	79%

A process overview

Substrate – Moisture

Note on Hydrating:

Aim for 70% moisture content.

We often soak and then calculate our moisture based on weight

For example:

Dry Weight: 2700g

Wet Weight: 8500g

8500/2700 = 0.31x 100 = 31.7

100% - 31.7% = 68.3%

Growing mushrooms: a process overview

Substrate – Sources

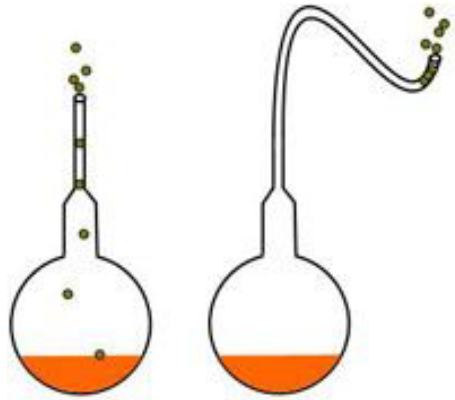
What non-edible biomass do you have in your area?

And, what's currently being done with it?

Growing mushrooms: a process overview

Sterilization vs. Pasteurization

Think of it as a spectrum



Growing mushrooms: a process overview

Sterilization vs. Pasteurization

<u>The Autoclave</u>:

Creates an environment with higher-than-normal atmospheric pressure so that water boils 20° C hotter than normal, thus creating steam hot enough to effectively kill microbes.

Growing mushrooms: a process overview

Many traditional growing tactics forgo the autoclave

Paddy Straw Mushroom, *Volvariella volvacea,* does not require sterilization with an autoclave but rather solarization or soaking and fermentation, followed by optimal environmental conditions.

The Fruiting Process

- Environmental conditions for production
  - CO_2 venting requirements
  - Humidity requirements
  - Temperature requirements
  - Lighting requirements
- Fruiting chamber
- Fruiting chamber upkeep
- Equipment

The Fruiting Process

Fruiting

Previously, sterility was key but for this Stage in the process Environmental Conditions become front and center

The Fruiting Process

The Optimal Fruiting Environment:

….Depends on the fungus, but usually:

- Relative Humidity: 80 - 85%
- Temperature: less than 80°F
- CO_2: less than 600 ppm

The Fruiting Process

Most modern mushroom production occurs in dedicated controlled environment facilities.
And this is a good thing!

Improved mushroom quality:
- Nutritional qualities (lighting)
- Optimal timing for harvest
- Removal of exposure to the elements
- Allows for us to improve on mushroom varieties

Environmental Conditions:

Temperature: 50-90 F

50-60F	Blue and pearl oysters fruit fine
60-70	Blue oyster production drops, pearl oyster increases
70-80	No blue oyster production, pearl oyster steady

Humidity 75-95%,
Low humidity results in aborted clusters, excessive humidity results in mold and bacteria.

50-60%	most mushroom primordia dries and aborts
60-80%	most mushroom production increases
80-90%	Pearl production optimum, lion's mane production increasing
90-95%	Pearl oyster mushrooms become slimy; lion's mane mushrooms thrive.

CO2

450-600 ppm	Mushroom morphology normal
800-900 ppm	Mushrooms begin to get "stemmy"
900-1100 ppm	Mushrooms begin to get deformed
> 1200 ppm	Many species fail to produce

The Fruiting Process

- Environmental conditions for production
  - Temperature requirements

Personally, I like to grow with the seasons

Cold season

Warm season

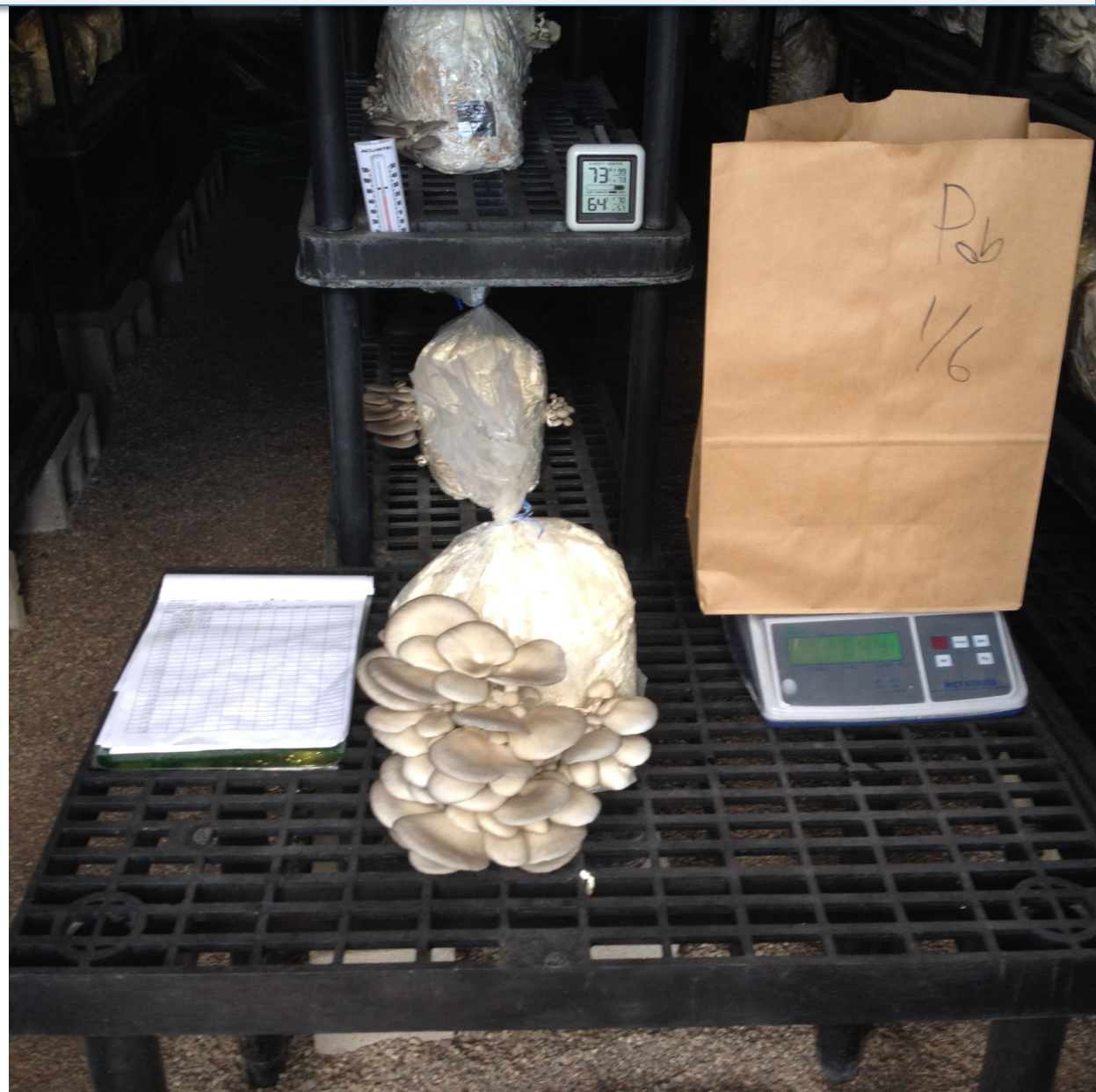
Harvesting

Bio-efficiency

The yield as related to the weight of dry material in the substrate, expressed as a percentage.

$$BE\% = \frac{Fresh\ Weight}{Dry\ Substrate\ Wt.} \times 100$$

Example:
700g Dry Material per bag
If, 525g of mushrooms are harvested per bag,
BE:
525/700 = 0.75
0.75 x 100 = **75% Bio-efficiency**

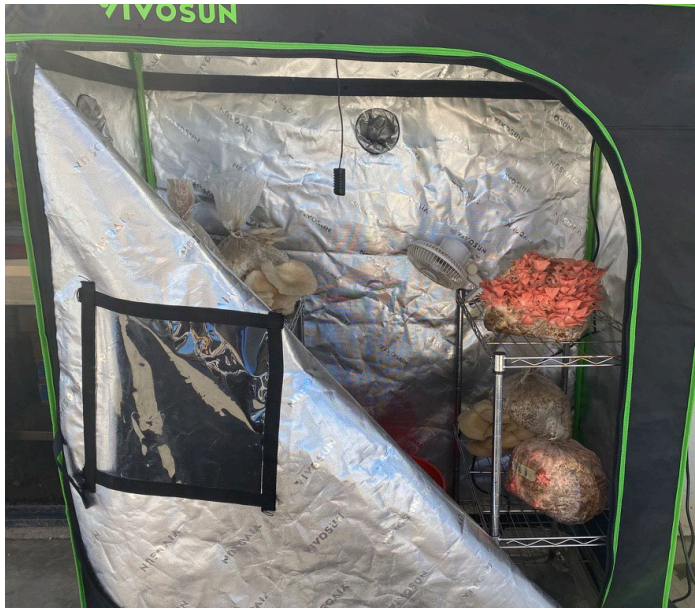


Optimization of Substrate for Hericium

Pellets

First flush, all harvested
on a single day.

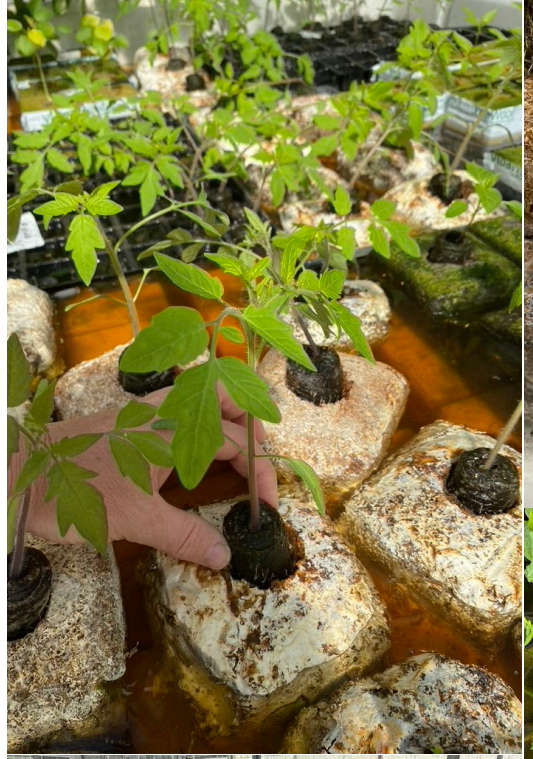
Current Projects



Current CEAC Mycology Lab Projects

- Use of Crop Residues, Non-edible biomass from CEAC operations, for Edible mushroom production.
- Fungi Blocks for Fresh Crops, shift from single use substrates to a bio-circular process.
- Bio-efficiency based on substrate
- Mushroom production placed within greenhouses so that the plants utilize the excess CO_2 produced by the fungi.
- Food production in harsh and remote environments (i.e. – the south pole or the ISS)

Fungi Blocks



Fungi Blocks for Fresh Crops

- Project Supported by: UA Campus Sustainability Fund
- 7 UA Students running the project, both mycology and greenhouse sides of the operation.
- Exploring:
  - Different fungi
  - Different particle size
  - Different base substrate materials
  - And how to best integrate with the greenhouse.

By end of year will report on:

- Harvest data
- Overall integration into the greenhouse
- Waste reduction

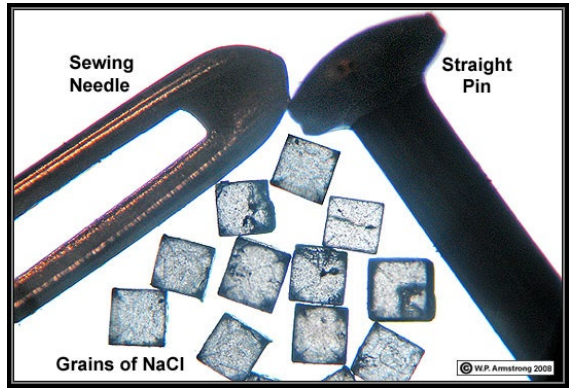
***Learning a lot of what not to do!

Spent substrate – How closed loop is this loop? …. It’s a process at the moment.

Introduction to Fungi

Mycological terms

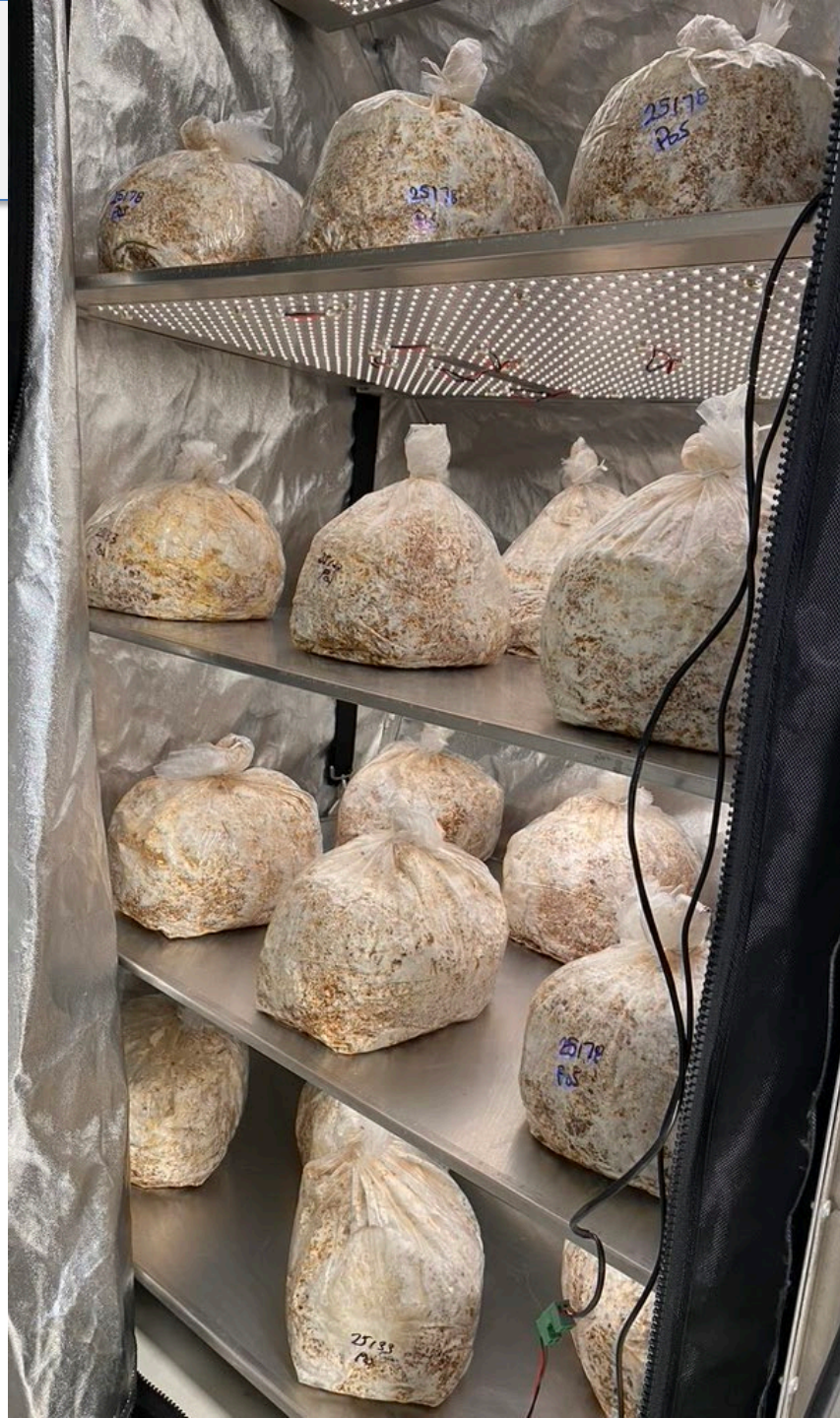
Fungi	Kingdom of organisms including what we often refer to as mushrooms, yeasts and molds
Hyphae	Filamentous fungi grow by one-cell thick filaments called hyphae.
Mycelium	Collectively, a colony of hyphae is referred to as mycelium.
Spores	How fungi get around. Most forcibly discharged, and wind blown. Small, generally 5-50um in diameter
Mushroom	Fruiting body
Sclerotia	Hardened, compact mass of mycelia.



A salt crystal is about 300 um

Introduction to Fungi

- **Achlorophyllous**,
  - and therefore: heterotrophs just like us!
- Typically, **filamentous**
  - but: yeasts are fungi too!
- Reproduce via **spores**
  - …harvest on time!
- Cell walls are composed of **chitin**
  - Which is largely indigestible, so: Cook your mushrooms
- Obtain nutrients through: Absorptive nutrition!
  - …my favorite characteristics!
- Eukaryotes:
  - …another: Just like us!
- Respire
  - Producing CO_2 …just like us!

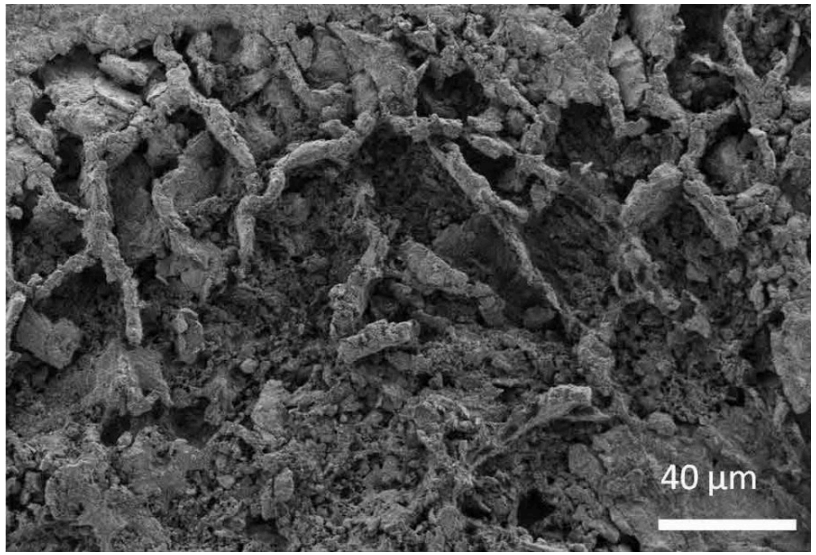


Other Fun Facts:

Fungi are their own **Kingdom**!

- Fungi are much older than plants:
  - Fungi are estimated to have evolved **1,300 million years ago**
  - Plants are estimated to have evolved **700 million years ago**
  - Symbiotic relationships with plants
    - Facilitating access to water and nutrients
- Largest and most diverse groups of living organisms:
  - Less than 10% of all fungal species have been described
- Ecologically, fungi are the single most important of decomposers in all ecosystems
  - Recycle nutrients (C, N and essential elements such as Fe, Ca, P, Mn, K, B and S)

We are re-learning in some ways how to use fungi.



https://www.nationalgeographic.com/science/article/oldest-fungus-fossils-found-earth-history

Thank you!