Transfarmation

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Indoor Mushroom Cultivation Materials

MycoLogic LLC, in collaboration
with Transfarmation, created these materials.

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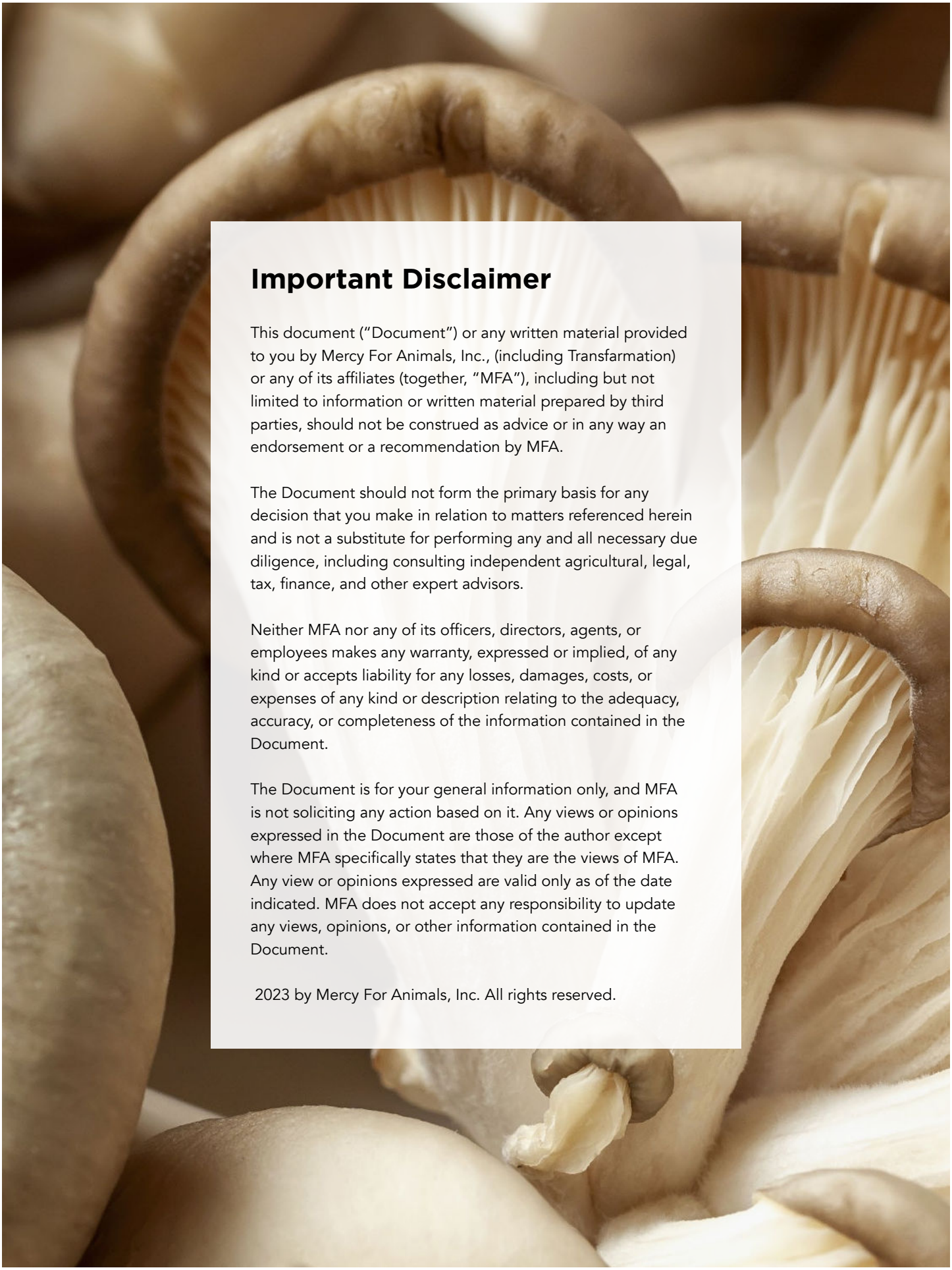

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The Mushroom Life Cycle

Mushrooms are the end stage of the complex life cycle of many fungi. For a mushroom cultivator, understanding the life cycle of a mushroom-producing fungus can be beneficial, since several crucial time points and growth stages, if not controlled, can result in poor yields. Below is a brief overview of the three main stages of cultivating mushrooms, but for a more detailed understanding, see the "Mushroom Cultivation Books" section.

Colonization

A fungus that eventually produces mushrooms requires material to grow on, or colonize. This material, or growth substrate, is used to produce a large amount of fungal mass (biomass) that will eventually produce the fruiting bodies (mushrooms). Generally, the larger the amount of growth substrate the fungus colonizes, the greater the mushroom yield. The fungus itself should be the dominant organism growing on the substrate; therefore, the substrate must first be sterilized (all organisms killed) or pasteurized (most organisms killed), typically with high heat and pressure or steam. This ensures the mushroom fungus we start growing on the substrate (substrate inoculation) encounters little, if any, competition with other organisms during the colonization phase. This colonization process will see the majority of the growth substrate converted into fungal biomass, and at some point, no more substrate will be left for the fungus to feed on, and the colonized growth substrate will be ready for the next growth stage. Pre-colonized substrate blocks are available for purchase from a number of vendors (see "Mushroom Spawn Vendors").

Primordia Formation (Pinning)

Primordia are microscopic structures that eventually form into mushrooms. Primordia, or pins, form naturally in response to a number of environmental cues, such as nutrient depletion (fully colonized growth substrate), decreased temperature, and increased humidity, depending on the mushroom species. Halted or negatively affected primordia formation can drastically reduce the final mushroom yield. Therefore, the specific mushroom variety to be grown should be researched to determine optimal conditions for inducing primordia formation.

Fruiting Body (Mushroom) Formation

Once primordia have formed, they will often swell and form mushrooms. This process can take as little as a few hours to several months, depending on the variety. There may or may not be a need to change the environmental conditions when changing from the primordia stage to the fruiting stage, but often a slight reduction in humidity reduces the likelihood of contaminating microorganisms infecting the newly forming mushrooms. During the fruiting stage, harvest time must be determined by the grower. The optimal time to harvest shiitake mushrooms, for example, is often right before or immediately after the veil that spans the stem to the mushroom cap ruptures. Oyster mushrooms have no veil, and the optimal harvest time is often before the cap edges flare upward and are still curled downward. Harvest time is a choice that is often influenced by appearance, size, perishability, and scheduling ability. Researching the varieties you aim to grow and experimenting to find the optimal harvest time are recommended.

Cultivation Environment

A mushroom cultivation environment is where growth substrates are placed in optimal conditions to induce colonization or mushroom formation. Unlike plant-based agriculture, where plants grow in association with numerous microorganisms, mushrooms are often grown in a pure culture, meaning only one microorganism is grown—the fungus that produces the mushrooms. Accordingly, extra precautions must be taken when developing a cultivation environment to reduce the introduction of contaminating microorganisms (further referred to as contaminants) that may negatively impact yields. Additionally, since mushrooms typically require high humidity to fruit, an air-tight environment both reduces the likelihood of contaminants entering the environment and promotes retention of high relative humidity.

Permanent Infrastructure

Use of permanent infrastructure allows for maximization of the cultivation area and can often simplify the required ducting for air movement. Because high humidity can damage wood and other porous materials, walls and ceilings should be covered with panels that are resistant to mold, mildew, and rot.

Insulated Metal/Plastic Panels

Insulated metal or plastic panels provide both insulation and a vapor barrier. These panels typically feature a tongue-and-groove system for interlocking the panels. Combined with sealant or stripping, all joints are rendered water- and air-tight.

- FRP CleanSeam panel – Fiberglass-reinforced plastic panel
- CF partition panel – Insulated metal panel
- Metl-Span panels – Cold storage panels
- BRUCHAPaneel® wall panels – Cold storage partition, liner, and ceiling panels
- More BRUCHAPaneel® options

- Barr 42" x 8' insulated cold storage panels – Panels for a sealed modular grow room
- More Barr options
- MBCI CF45 partition wall – Interior-wall and ceiling panels
- More MBCI options

Impermanent Infrastructure

Use of impermanent infrastructure allows for greater flexibility with the design of the cultivation space. Multiple smaller rooms can be constructed in a larger room using grow tents typically used for growing plants, enabling segregation of different cultivation environments. Consequently, the main area that houses the tents need not be hermetically sealed, since the high-humidity environments are contained within the grow tents.

Grow Tents

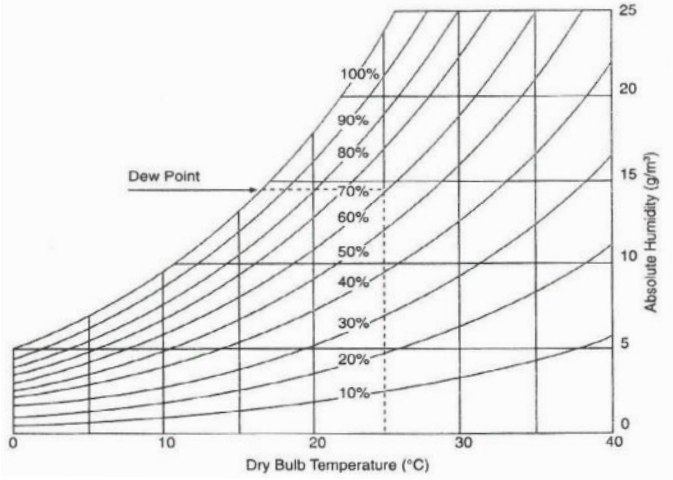
Grow tents provide an economical way to create a sealed environment that allows for both humidity and air flow to be controlled. Grow tents come in a range of dimensions, are constructed with thick mylar canvas, have large zippers for entry, and have several ports for ducting and wires. AC Infinity and VIVOSUN are two of the industry's largest manufacturers and produce comparable products, but the AC Infinity tents are made with thicker material. Gorilla manufactures larger tents, but their prices are much higher than the competition.

- AC Infinity CLOUDLAB 844 ($180) – 48" x 48" x 80" (4 ft. x 4 ft.), 2000D canvas
- AC Infinity CLOUDLAB 811 ($500) – 120" x 120" x 80" (10 ft. x 10 ft.), 2000D canvas
- More AC Infinity options
- VIVOSUN 4 x 4 ($170) – 48" x 48" x 80" (4 ft. x 4 ft.), 600D canvas
- VIVOSUN 10 x 10 ($480) – 120" x 120" x 80" (10 ft. x 10 ft.), 600D canvas
- More VIVOSUN options
- Gorilla Grow Tent 10 x 10 ($1,170) – 10 ft. x 10 ft., 1680D canvas
- Gorilla Grow Tent 8 x 16 ($1,600) – 8 ft. x 16 ft., 1680D canvas
- Gorilla Grow Tent 10 x 20 ($2,400) – 10 ft. x 20 ft., 1680D canvas
- More Gorilla options

Environmental Control

Environmental control is the most important aspect of mushroom cultivation. Fruiting and yield are directly related to how well temperature, humidity, and carbon dioxide concentration are regulated in the cultivation environment.

Regulating both temperature and humidity can be a delicate process. If relative humidity is high, temperature fluctuations can cause temperatures to drop below the dew point, resulting in condensation on surfaces (Fig. 1). Condensation and other pools of water can become breeding grounds for undesirable microorganisms and can damage sensors and electronics. Therefore, maintaining non-condensing high humidity is key to both producing higher yields and reducing the likelihood of contaminating growth.



Source: Western Australian Museum (adapted from Thomson, 1986).

Figure 1. The relationship between temperature and humidity. As the temperature decreases, the moisture-holding capacity of the air also decreases. Percentages represent relative humidity. Dew point is the temperature at which 100 percent relative humidity is reached and condensation will begin to form.

Temperature

For small- to medium-size cultivation areas, window or mini-split air conditioning (AC) systems are sufficient to regulate temperature conducive to mushroom cultivation. The BTU capacity of the AC unit can be oversized for the space to provide additional cooling capacity when high-temperature fresh air is introduced from the outside (during exhaust of carbon dioxide from the room).

Many AC systems also have integrated heating and can operate in either a cooling or a heating mode to attain the set temperature. Check the specifications of the heating system to determine whether it can accommodate the size of the

space and the likely temperature. If the AC system heater is insufficient on its own or absent from the AC system, consider using a temperature controller and an additional heater to raise the temperature in the space.

Temperature Controllers

- Store It Cold CoolBot ($375) – AC controller that enables the AC unit to reach temperatures below the minimum designated by the manufacturer (typically 61°F). This is useful for designing cold storage rooms with a residential air conditioner (window or mini-split AC). Cold storage rooms are used for storing harvested mushrooms if they are not immediately taken to market.
- Inkbird ITC-308 ($35) – Temperature controller with temperature sensor and switchable outlet to connect heating or cooling devices. The heater or cooler is energized until the desired temperature is reached. This is ideal for smaller spaces where the heater or cooler does not exceed 10 amps.

Cooling

Properly sizing an AC system for a cultivation room involves many technical aspects, accounting for the physical size of the airspace, the insulation value of the room, the lowest desired temperature within the room, and the hottest temperature likely to occur outside the room. The AC system itself has its own thermostat to regulate temperature, so an external temperature controller is not necessary unless you desire temperatures below the lowest the AC system is designed to reach (typically ~60°F). If temperatures below ~60°F are desired, a CoolBot by Store It Cold can be used.

Heating

Similar to cooling, heating a space requires understanding the thermal characteristics of the space and surrounding environment. If heating is incorporated in the AC/HVAC system, sizing the heater appropriately is crucial. If heating is to be separate from the AC/HVAC system, a bit more leeway is afforded in design options, since a heater can more easily be replaced or additional heating devices added or removed, depending on the heating needs. For separate heating, the heater can be connected to a temperature controller, such as the ITC-308 by Inkbird.

Humidity

A high relative humidity must be maintained in the cultivation environment to induce mushroom formation. Ideal relative humidity falls somewhere in the 90%–99% range, depending on the variety of mushroom grown.

Humidity Controllers

Humidity controllers operate with a humidity sensor to measure humidity and a relay to power a humidifier to raise the humidity to the desired level. Once the humidity reaches the desired level, the humidifier is turned off and waits until the humidity falls below the set point to turn on again.

- Inkbird IHC-200 ($40) – Humidity controller with humidity sensor and switchable outlet to control a humidifier

Humidification

Humidifiers raise the humidity of an environment. The amount of water the humidifier can put into the air is the biggest factor in choosing a humidifier for a mushroom cultivation environment. When exhausting air, dry air will be brought into the cultivation environment and will need to be rapidly humidified to prevent prolonged exposure of mushrooms to low-humidity air that can negatively impact yields.

Important features to look for when sourcing an appropriate humidifier include the pounds or pints of water per hour, the ability to connect a water line to keep the water reservoir full at all times, and the ease of disassembly and cleaning.

- Mainland Mart MHB12 ($600) – Ultrasonic humidifier, 6 lb/hr
- Ideal Air Humidifier ($600–$900) – Ultrasonic humidifier, 8.7 lb/hr

Dehumidification

Areas adjacent to high-humidity cultivation environments may experience higher-than-normal humidity due to leakage from the cultivation environment. Therefore, in adjacent areas that are susceptible to moisture damage, if humidity could enter or is observed to enter, a dehumidifier is recommended to remove excess humidity.

Important features to look for when sourcing an appropriate dehumidifier for your space include the size of the area, the amount of water the dehumidifier can remove from the air, and the ability to connect a hose to automatically drain collected water.

- 1500 sq. ft. dehumidifier – Removes up to 22 pints per day

Fresh Air Exchange

Air exchange promotes mushroom formation by removing carbon dioxide (CO_2) that is produced by the mushroom fungus. It also reduces the likelihood that contaminating fungi will grow. CO_2 is produced from the natural respiration of the mushroom fungus, and excessive buildup of carbon dioxide in the cultivation environment will inhibit mushroom formation. Therefore, the cultivation environment airspace must be periodically exhausted to keep carbon dioxide levels below a certain threshold. The typical environmental level (natural background concentration in the air) of carbon dioxide gas is around 400 parts per million (ppm), and many mushroom varieties begin to show signs of inhibited growth at around 800–1,000 ppm CO_2. This is highly dependent, however, on the variety of mushroom grown.

Carbon Dioxide (CO_2) Controllers

A CO_2 controller incorporates a CO_2 sensor to measure the amount of gaseous CO_2 in the air and a relay to control the power to electrical devices when the CO_2 concentration surpasses the set threshold. These devices are typically fans and motorized dampers, which allow for automated opening of ducts to the exterior of the cultivation environment and air to be exhausted and brought in with fans. Once the CO_2 concentration returns to below the set threshold, the devices are depowered, causing the motorized dampers to close and the fans to stop.

Timers are an inexpensive and reliable way to generate fresh air exchange and reduce CO_2 concentration in the environment. Keep in mind that the timer may be in a high-humidity environment or experience a power outage. Accordingly, the timer should be waterproof and contain a back-up battery.

Using either a timer or CO_2 controller, fans and normally closed motorized dampers can be powered in unison to simultaneously open a path in the air ducting and turn on the fan to move air.

- Inkbird ICC-500T ($160) – Carbon dioxide ($CO_2$) controller with CO_2 sensor and switchable outlet to connect exhaust fans. Fans are automatically energized until the desired or set CO_2 is reached.
- BN-LINK programmable timer ($20) – Waterproof timer with back-up battery and 15-amp capacity

Speed-Controlled Duct Fans

Both AC Infinity and TerraBloom make speed-controlled duct fans from four to 12 inches in diameter. These fans can be connected to timers or CO_2 controllers to turn on periodically to exhaust buildup of CO_2 and bring in fresh air.

- AC Infinity Cloudline S4 ($100) – four-inch ducted speed-controlled fan
- AC Infinity Cloudline S6 ($120) – six-inch ducted speed-controlled fan
- AC Infinity Cloudline S8 ($180) – eight-inch ducted speed-controlled fan
- AC Infinity Cloudline S10 ($270) – 10-inch ducted speed-controlled fan
- AC Infinity Cloudline S12 ($370) – 12-inch ducted speed-controlled fan
- TerraBloom ECMF-100 ($80) – four-inch ducted speed-controlled fan
- TerraBloom ECMF-150 ($100) – six-inch ducted speed-controlled fan
- TerraBloom ECMF-200 ($160) – eight-inch ducted speed-controlled fan
- TerraBloom ECMF-250 ($230) – 10-inch ducted speed-controlled fan
- TerraBloom ECMF-315 ($340) – 12.3-inch ducted speed-controlled fan

Motorized Dampers

Motorized dampers allow for electronic opening or closing of the airways in ducts. These are useful for redirecting airflow within a duct system and opening and closing airways for intake and exhaust. Dampers come in sizes from four to 12 inches in diameter and are either normally open or normally closed. When power is applied, the dampers open or close, and when power is removed, they return to their previous open or closed state.

*NO = Normally open, NC = Normally closed

- Suncourt ZO206/ZC206 ($70) – Motorized damper for six-inch duct, NO/NC
- Suncourt ZO208/ZC208 ($70) – Motorized damper for eight-inch duct, NO/NC
- Suncourt ZO210/ZC210 ($75) – Motorized damper for 10-inch duct, NO/NC
- Suncourt ZO212/ZC212 ($75) – Motorized damper for 12-inch duct, NO/NC

- S&P MD4 ($65) – Motorized damper for four-inch duct, NC
- S&P MD6 ($65) – Motorized damper for six-inch duct, NC
- S&P MD8 ($75) – Motorized damper for eight-inch duct, NC
- S&P MD10 ($90) – Motorized damper for 10-inch duct, NC
- S&P MD12 ($95) – Motorized damper for 12-inch duct, NC

Inline Filter Boxes

Air filtration is necessary to remove both contaminants from air drawn into the cultivation environment from outside and contaminants in the cultivation environment. Inline filter boxes allow for filtering of airflow in a duct and should be installed on the air intake duct. An air circulation duct with a filter box should also be installed to continuously filter the air in the cultivation environment.

- AC Infinity AC-AFB4 ($100) – four-inch inline air filter box and one high-efficiency filter
- AC Infinity AC-AFB6 ($120) – six-inch inline air filter box and one high-efficiency filter
- AC Infinity AC-AFB8 ($150) – eight-inch inline air filter box and one high-efficiency filter
- AC Infinity AC-AFB10 ($170) – 10-inch inline air filter box and one high-efficiency filter
- Fantech FB 6 ($105) – six-inch inline duct filter box, 10" x 20" x 1" (nominal) and MERV 13 pleated filter
- Fantech FBRF 6 ($30) – FB 6 replacement filter, 10" x 20" x 1" (nominal) and MERV 13 pleated filter

Additional inline filter boxes can be found here.

Wall-Mounted Vents

Vents are the interface between ducting and the external environment. They mount to a wall and provide a connection for vent ducting, coarse filtering to prevent wildlife from entering the duct, and possibly louvers that close when no air is flowing to further seal the duct. A minimum of two vents are typically used per indoor environment, one for air intake and one for air exhaust.

- Fantech FML 8 ($45) – eight-inch fixed metal supply/exhaust hood for round ducts
- Fantech FML 10 ($60) – 10-inch fixed metal supply/exhaust hood for round ducts
- Fantech FML 12 ($85) – 12-inch fixed metal supply/exhaust hood for round ducts
- Primex WCL701 ($35) – seven- or eight-inch collar with screen and removable backdraft dampers

Additional wall vents can be found here.

Light

Many mushrooms can form in complete darkness. For some varieties, however, light can be a significant factor for inducing both the formation of mushrooms and their development (Miyazaki et al. 2011, Sakamoto 2018). Most light requirements are very low, but coloration can sometimes be enhanced in some varieties by increasing intensity and duration of light exposure. Lighting is often operated with a simple timer and turned on several minutes every few hours or left on continuously.

When choosing a lighting source for inside the fruiting area, weatherproof fixtures should be considered. For portable light sources, wall outlet timers are inexpensive and easy to use. For ceiling-mounted light fixtures, consider the following:

- HALCO 4-foot weatherproof LED light fixture ($100) – IP-66 weatherproof, 5280 lumens, 40 watts, 5000 K color temperature
- HUSKY Outdoor LED work light ($85) – 12000/6000 lumens, 120/60 watts
- BN-LINK programmable timer ($20) – waterproof timer with back-up battery and 15-amp capacity
- In-wall digital timer ($35) – Combination wall switch and timer with 15-amp capacity

Additional Considerations

Vents, ducting, and fans should take into consideration the size of the cultivation environment and the rate at which air must be moved in or out of the environment. Fans are commonly rated by the number of cubic feet per minute (CFM) of air that can be moved. Theoretically, the time needed to turn over the air in the environment can be calculated using the area of the cultivation environment.

$$\textit{Air Turnover Rate (minutes)} = \frac{\textit{Cultivation Environment Volume (cubic feet)}}{\textit{Fan Capacity (cubic feet per minute)}}$$

For example, with two fans rated at 300 CFM (one intake and one exhaust), in a 2,000 cubic ft. room, it would take 6.6 minutes to move 2,000 cubic feet of air: 2000 / 300 = 6.6.

This calculation assumes ideal conditions, which are often not the case. Inline duct filters create resistance, especially as the filters fill with debris. Air becomes more difficult to move as it becomes more saturated with water as the relative humidity rises. Furthermore, the physical space often creates mixing of air, and thus merely a significant portion of air in the room is replaced in the turnover time rather than all the air in the room.

Generally, the size of the ducting will dictate the size of the vents, fans, and dampers. For example, you wouldn't want to use a six-inch vent and a 10-inch duct, since the six-inch vent will be a point of constriction. The entire ducting system should use the same diameter unless a specific design warrants mixing different duct sizes, such as a 12-inch duct splitting into two eight-inch ducts. Since the area of a 12-inch duct is 113 in^2 and two eight-inch ducts total 100 in^2, their areas are similar, which would not reduce airflow significantly on the basis of area alone.

Mushroom Cultivation Books

Organic Mushroom Farming – By Tradd Cotter, who runs Mushroom Mountain. This is an all-around great book that includes practical tips on marketing and running a mushroom cultivation business.

Growing Gourmet and Medicinal Mushrooms – By Paul Stamets, who is the de facto father of specialty mushroom cultivation in the United States. This comprehensive guide is the standard reference for many growers today and includes information on large-scale operation considerations and setting up grow rooms, as well as an extensive list of environmental parameters for nearly every cultivable variety out there.

The Essential Guide to Cultivating Mushrooms: Simple and Advanced Techniques for Growing Shiitake, Oyster, Lion's Mane, and Maitake Mushrooms at Home – Beginner-friendly book that provides practical step-by-step guidance. Although less analytical and comprehensive than *Growing Gourmet and Medicinal Mushrooms*, it's a great resource for small-scale farmers and an excellent book for people who want to advance beyond mushroom-growing kits.

The Mushroom Cultivator: A Practical Guide to Growing Mushrooms at Home – Another book by Paul Stamets. It explains numerous methods for cultivating mushrooms and details life-cycle and growth requirements for several mushroom varieties.

University/Extension/Industry Websites

American Mushroom Institute – Trade group representing American mushroom growers. AMI offers a variety of practical resources for commercial cultivators but focuses heavily on button mushroom cultivation.

Mushroom Council – Not to be confused with the above. This trade group whose incorporation was authorized by Congress is affiliated with the USDA. The council provides free marketing resources that can help growers reach customers who are unfamiliar with mushrooms.

Cornell Mushrooms – Collection of resources that presents a full overview of the specialty mushroom industry and how to get started as a cultivator. More focus is given to outdoor growers, but good information on marketing and indoor growing is offered as well.

NC A&T Mushroom Cultivation and Marketing – Brief overview of the U.S. mushroom cultivation business. Our favorite portion is this snippet about marketing, which agrees with past statements from other mushroom cultivators:

- *Make the market drive your production. Talk to potential buyers about volume and prices.*
- *Explore various marketing options: brokers, distributors, farmers' markets, restaurants, grocery stores, food service operations, and co-ops.*
- *Consider reselling other growers' mushrooms to offer more variety and larger volume.*
- *Talk to other producers and perhaps a consultant about production systems.*
- *Consider buying used equipment to reduce initial capital investment.*
- *Strike a balance between undercapitalization and a heavy debt load.*

Penn State University Mushrooms – The U.S. center of mushroom cultivation is in Pennsylvania, specifically around Kennett Square. Penn State is the top university for mushroom cultivation research. But most mushrooms cultivated and researched there are button mushrooms, which are very different from specialty mushrooms. Still, they have some similarities. The information on the Penn State website about pests, such as mushroom flies, and varieties like oyster mushrooms is still relevant for specialty mushroom production.

Cultivation Videos

Fruiting Oyster Mushroom Production Blocks – Good representation of what loading the blocks into your fruiting chamber may look like.

Elm Oyster Mushroom Harvest – Good representation of what harvesting the mushrooms may look like. We recommend wearing a respirator or at least some sort of mask to prevent inhalation of spores.

Automated Grow Tent Setup – Small, primitive controlled-mushroom-cultivation environment. Similar in concept to larger environments, this may help give an idea of what to expect.

Mushroom Cultivator Examples

Haw River Mushrooms – Grower based in North Carolina. Note the variety of products—not just fresh mushrooms but excess/not visually appealing harvests, such as dried mushroom powders, tinctures (you may be able to find a third party to sell your mushrooms to for this), and ready-to-fruit blocks (you can just resell the blocks at wholesale price to people who fruit at home).

Far West Fungi – One of the best-known mushroom cultivators, at least in California. The company supplies several restaurants around San Francisco and appears at some farmers markets. Again, note the product variety.

Big Boy Mushrooms – Based in Sacramento, California. Not nearly as many product varieties, but note the simple, streamlined business model here—mushrooms in preweighed, predefined packages to order. This is a good idea for a smaller operation that can reliably schedule its own harvests—especially if demand is so high that people want to preorder mushrooms.

Mushroom Spawn Vendors

Mushroom Mountain (South Carolina)

North Spore (Maine)

Cap N' Stem (Maine)

Field and Forest (Wisconsin)

Other

Mushroom Compost – Many mushroom growers save their spent fruiting blocks and sell them as mushroom compost. One grower we work with reports receiving about $2–$3 per spent five-pound block by selling directly to customers at farmers markets.