Autonomous Environment for Enhanced Primordia Formation and Fruit Body Development of Mushroom Cultures

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***Abstract* — A concept for a self maintaining mushroom nursery is presented, striving to enable the growth of consumption ready gourmet mushroom varieties by the average household without requiring specialized tools or skill set of the operator. Tightly controlling the environmental conditions of the fungi's mycelium (the vegetative, root like part of a mushroom) allows for improved primordia formation resulting in quickly developing, large, nutrient rich fruit bodies, on par or better than what is expected from a commercial grow facility. Continuously sensing and controlling relative humidity as well as managing carbon dioxide levels and light exposure resulted in our prototyped solution producing harvest ready mushroom fruit bodies in as short as 3 days from a pre-inoculated growing medium consisting of straw and spent coffee grounds, while the provided web application and wifi connectivity of the nursery greatly simplified the user experience.**

***Index Terms* — Automatic control, Autonomous systems, Control engineering, Home automation, Humidity control, Internet of Things.**

I. Introduction

People love mushrooms, they're delicious and rich in nutrients, it is no wonder that US consumers devoured over 928 million pounds of fresh mushrooms in 2017 [1]. However 97% of the mushrooms available and sold in stores that year where either white button or brown (portobello) button mushrooms [1]. This lack of variety is aggravating for many home cooks and professional chefs alike, especially considering that countless different edible varieties of mushrooms exist, some often with additional uses besides just gourmet dishes, for example nutritional benefits and even traditional medicine applications.

In countries and communities that support small local growers with vibrant farmers markets this lack of variety is not as existent, and many gourmet varieties are often available fresh and directly from the farmer. Commercial growers, while capable of growing gourmet varieties in bulk, are discouraged due to gourmet varieties having a much shorter shelf life and them being more prone to damage during shipping compared to the button mushroom. For example the oyster variety only has a marketable shelf life up to 5 days after harvest with noticeable differences in appearance, taste and smell thereafter, hence declining their marketability drastically [2]. Additionally many gourmet varieties produce a thin and fragile cap, making them very susceptible to bruising or breaking during shipping and handling and thus reducing the mushrooms value significantly. Thus it seems the only way to acquire gourmet varieties is through a local approach.

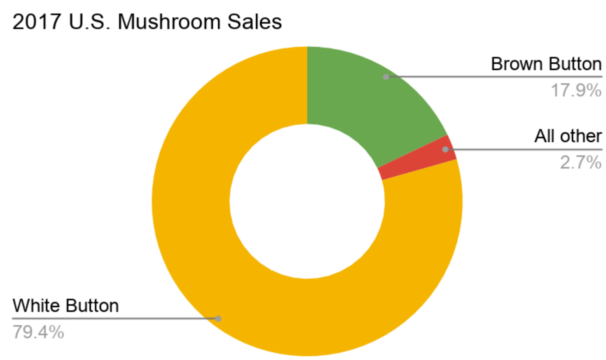

Fig. 1. Volume of U.S. Mushroom Sales by Type in 2017 [1].

Some counter this problem by foraging for wild mushrooms themselves, though this approach is often cumbersome and without proper knowledge and training can be deadly if a poisonous wild mushroom is wrongly identified as safe to eat. We propose a different solution to this problem, one that mimics the growing of herbs on your kitchen counter. A fully automated portable mushroom greenhouse, or nursery as we call it, that can be placed on a spare table, kitchen counter or any available space that is not in direct sunlight. The consumer purchases spawn blocks typically consisting of pasteurized ground up straw, rice or spent coffee grounds. These brick shaped blocks have been inoculated with an isolated mushroom strain of choice, and in this state have a shelf life of up to 8 weeks without requiring any attention or special environmental conditions, hence they are perfect for storage and shipping. Once the spawn blocks arrive at the consumer's home he or she simply places them inside the nursery, selects the chosen mushroom type on the web application and periodically refills the water tank of the nursery. From here on the nursery takes care of tightly maintaining proper humidity, carbon dioxide, and light levels while nursing the spawn block into the next stage of its life called Primordial stage, following that stage it adjusts the environmental conditions to trigger the fungi into fruit body creation. Depending on the variety of mushroom chosen the consumer can then harvest fresh home grown mushrooms within 4-7 days of placing the block into the nursery. Additionally if the block is kept inside the nursery it will reproduce mushrooms up to 5 more times without any additional effort required.

II. Environmental Factors Affecting Mushroom Cultivation

This project is mainly concerned with two stages of the mushroom life cycle, namely the Primordia Formation stage and the Fruitbody Development stage. During both stages four environmental factors are of utmost importance: moisture (as in high humidity), air exchange, temperature and light [3]. During the primordia formation stage a rapid shift in environmental conditions triggers the formation of primordia, or tiny phinheads that will in the second stage, again through a change in environmental conditions be stimulated to turn into mushroom fruit bodies.

Fig. 2. King Oyster mycelium showing primordia and juvenile fruit bodies [4].

During the primordia stage, the mycelium of the spawn block should be exposed to fog like conditions with relative humidity levels of 95-100% [3], depending on the variety of mushrooms being cultivated, humidity is then gradually decreased but typically not lower than 85%. Fresh air exchanges are used during both stages to flush out the carbon dioxide that is produced by the fungus. Carbon dioxide levels below 1000 ppm, and ideally below 500 ppm are traditionally considered to be ideal for maximum growth [3], however these values also vary based on the variety of mushrooms cultivated. Many gourmet varieties also require a drop in temperature to transition from the primordia stage into the fruit body stage, luckily during the primordia stage the mycelium generates heat and once complete temperatures will naturally decline, so often intervention is not necessary. Lastly lighting is a growth factor that is a bit controversial, while most experts agree that direct sunlight or high-intensity exposure is destructive [3], the benefits of ambient lighting are often disputed, nevertheless the wavelengths produced by a typical blue LED light are not harmful to growth and some species will produce more appealingly shaped fruit bodies and more vivid colors when cultivated using an 8 hour on and 16 hour off light cycle [3]. Additionally exposing the mushroom fruit body to Ultraviolet light prior to harvesting results in a significantly increased Vitamin D content of the mushroom [5].

III. System Components

A brief description of the major components that comprise this system is given below, and shown in Fig. 3, in an effort to give an overview of the proposed solution. The components that are placed on the PCB, unless otherwise described communicate via onboard copper traces, the peripheral devices and sensors communicate via wired connections and data is exchanged with the web server wirelessly via WiFi, the controlled devices are enabled and disabled via MOSFETs as described in the Device Control section.

A. Controller Unit

The controller unit, is the core of the hardware components of this project. It interacts with the sensors and interprets their inputs to control the operation of devices such as the ultrasonic disc atomizer, lights and fans. It is also in charge of connecting to the Internet via WiFi and transferring data to and from our web server. The ESP32 System on Chip (SoC) in the WROOM-32D packaging by Espressif, from here on referred to as simply ESP32, was chosen to be the Controller Unit of this project, as it either met or exceeded our individual component minimum requirements. Most notably the ESP32 features 21 GPIOs including DACs and ADCs, has an internal WiFi chip capable of soft AP and connection to 2.4 GHz b,g, and n WiFi networks, 16MB internal flash memory, hardware support for common wired communication protocols such as UART, SPI, I²C and is supported by a variety of programming environments.

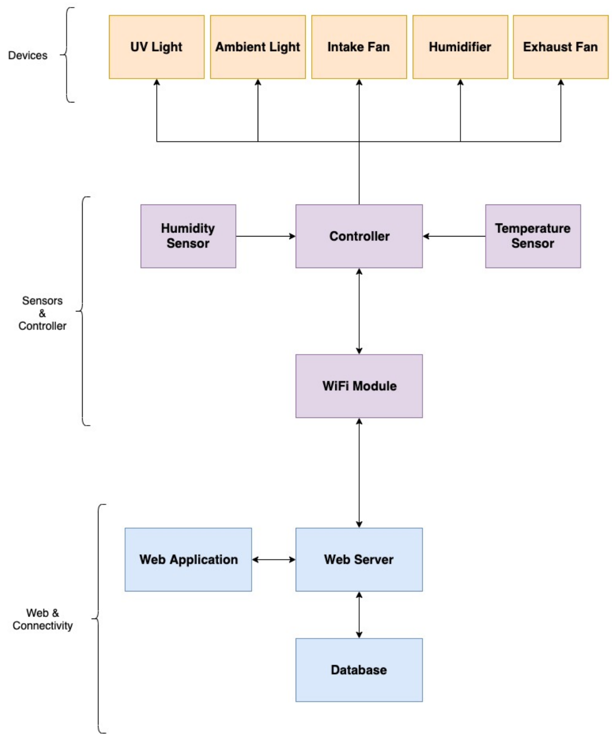

Fig. 3. Overview of System Components.

B. Humidity Control

As described during the introduction, relative humidity plays an important role in successful mushroom cultivation. Our design consists of a humidity sensor that is placed inside the growing chamber of the housing. The ESP32 periodically reads the relative humidity level and if the current value (V) is less than or equal to the Humidity Set Value (HS) minus the Humidity Differential Value (HD) as shown in (1) the humidification system will be enabled.

$$V \leq HS - HD . \quad (1)$$

The values for HS and HD are dependent on the strains of mushrooms being cultivated, the consumer has the option to manually define these values or choose from a pre-compiled set of mushroom growth profiles from within the Web Application. The humidification system is located as a dedicated chamber inside the nursery, this chamber consists of a water tank that is refillable by the consumer, an ultrasonic disc atomizer that is submerged approximately 3 cm below the surface of the water and a positive pressure fan that forces ambient air into the humidification chamber and pushes humidified air into the growth chamber. Optionally a particle filter or mesh can be placed on the outside of the positive pressure fan's air intake to filter out airborne contaminants and hence reduce contamination risk of the mycelium, this may be more useful if ambient air is known to be more rich in contaminants however in our tests this produced no measurable differences. The ultrasonic disc atomizer chosen is manufactured by AGPTek and operates on 24V DC at 700mA with an atomization output of 400 ml/Hour and is encapsulated in a waterproof housing, while the positive pressure fan is manufactured by RDEXP and operates on 5V at 300mA. For the humidity sensor a combination humidity and temperature sensor model DHT22 manufactured by Aideepen was selected, this sensor communicates using a single wire protocol and operates on 3.3V with a humidity accuracy of ± 2 RH and a temperature accuracy of ± 0.5 Celsius.

C. Fresh Air Exchange

Fresh Air Exchange (FAE) is a means of reducing carbon dioxide build up inside the growth chamber, this is achieved with a negative pressure exhaust fan placed at the bottom of the growth chamber, when in operation this fan forces the carbon dioxide that accumulated at the bottom of the chamber out creating a negative pressure inside the growth chamber, this negative pressure draws fresh air in through the water tank in the humidification chamber which additionally results in a beneficial evaporative humidification effect that helps minimize a drop in humidity inside the growth chamber. The negative pressure fan is manufactured by RDEXP and operates on 5V at 300mA. While a solution containing a carbon dioxide sensor that triggers FAE on demand was considered, a more budget friendly and just as effective solution was derived by periodically enabling the exhaust fan. Additional research found that professional mycologists parameterize FAEs in periodic terms anyway, hence allowing our solution to complement their method easily. The consumer using the web application, is able to manually set the exhaust fan's ON and OFF interval times in minutes or can simply pick from a list of pre-compiled mushroom growth profiles that contain this information.

D. Lights

The lighting solution consists of two distinct LED strips inside the growth chamber, one in the 450-500 nm wavelength used to simulate daylight conditions, the other producing ultraviolet light in the 380-400nm range for enhancing Vitamin D production of the mushroom. Both lights operate on 12V DC at 1.2 A and are controlled via

MOSFETs. The daylight LED strip operates in an 8 hour on, 16 hour off configuration, however this schedule can be manually overridden by the consumer via the web application. The ultra violet LED can manually be enabled and disabled by the consumer towards the end of the growing cycle in an effort to increase the mushroom's Vitamin D content [6]. Effects of UV exposure on Vitamin D content are quite considerable and can be seen in Fig X, for comparison the US Institute of Medicine recommends an average daily Vitamin D intake of 10-20 µg [6].

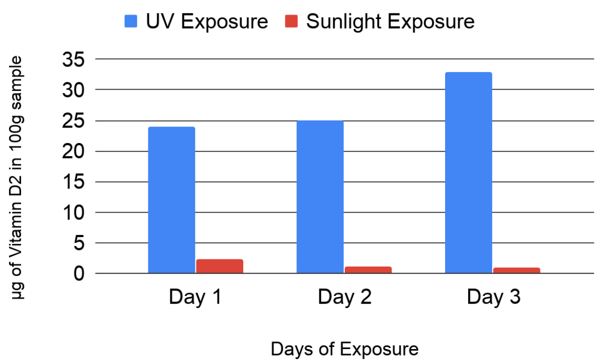

Fig. 4. Vitamin D2 concentration comparison of mushrooms exposed to UV vs Sunlight as found by Hanne L. Kristensen, Department of Food Science, Aarhus University [5].

E. Temperature Control

Our prototyped solution senses temperature inside the growth chamber and stores this data for analysis, however to date it does not include active temperature control. We are considering utilizing peltier devices along with an insulated housing to achieve a temperature controlled environment in the future, this could be utilized for improved primordia to fruitbody transition as well as to allow cultivation of mushroom species that require vastly different temperatures compared to the consumer's ambient temperature. The Temperature sensor utilized is the DHT22 combination humidity and temperature sensor as described in the Humidity Control Section.

IV. Solution Design

This section aims to summarize the conclusions drawn and research done into the components and software tools that were utilized to develop the project.

A. PCB Board Design

An important part of this project was the assembly of micro electronic components onto a board. While this could initially be done with a breadboard, due to the amount of SMD components our project requires the breadboard option is difficult to unusable. Instead we designed a Printed Circuit Board (PCB) that has the required components soldered on to it. Another important component is the design software used to create the schematic and PCB board design. We compared AutoDesk Eagle, EasyEDA, Fritzing and DesignSparkPCB design suites and ultimately decided on EasyEDA. It provides a great balance between an easy to use interface with all the features one requires to develop a professional schematic and PCB design. Besides those features we really liked the fact that it is available as a web based tool, making collaborating across the team very easy, and that it's parts library had high quality components and was the largest we encountered in our research.

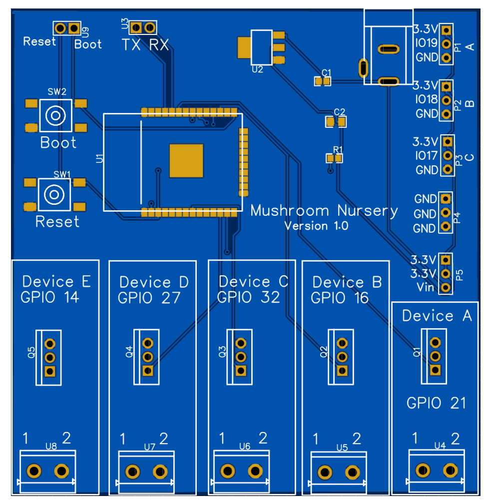

Fig. 5. PCB Board Layout.

Fig. 5 illustrates our main circuit board, schematic and component layout are organized by grouping components according to their function with clear labeling. Additionally a few ports were broken out for debugging and troubleshooting as well as the TX and RX pins of the ESP32 for programming. A Reset and Boot switch are placed on the board, with the Boot switch allowing the ESP32 to be switched into flashing mode. The board is a two layer board with the top layer consisting mostly of a ground copper plane and the bottom layer being used for most of the component connections.

B. Device Control

As far as our project is concerned, the term device is used to refer to peripherals that are being enabled or disabled by providing or cancelling power to the peripheral's power circuit. Specifically, these devices are the ultrasonic disc atomizer, the fans, and the LED lights. The device sections labeled Device A - E consist of screw terminal connections that are wired into the desired device's power circuit, each has a dedicated N-channel

MOSFET with its gate connected to one of the ESP32's GPIOs for control.

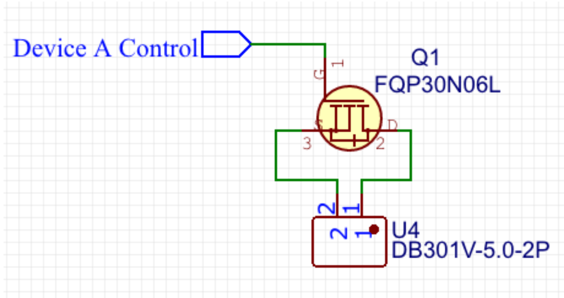

Fig. 6. The device control circuit utilizing an N-channel MOSFET.

The MOSFET utilized is the FQP30N06L N-channel MOSFET manufactured by Fairchild, it's relevant performance specifications have been summarized in Table 1. Heat build up inside the MOSFET junction was a concern and junction temperatures for each device's operation were estimated in Table 2 using

$$T_j = T_a + R_{\theta JA} * P_d . \qquad (2)$$

Where T_j is the junction temperature, T_a is the ambient temperature, $R_{\theta JA}$ is the junction to ambient thermal resistance of the device and P_d, as calculated by (3), is the power dissipated by the MOSFET due to internal resistance R_{ds}.

$$P_d = R_{ds} * I^2 . \qquad (3)$$

Additionally heat build up of the PCB traces connecting the device's power to the MOSFET are a concern. To limit heat rise to at most 25C above ambient temperature, the trace thickness has been increased to 2 oz/ft^2 and width has been increased to 1.8 mm, using the trace width calculation based on the IPC-2221 Standard on Printed Board Design this permits for a current of up to 4.5 A.

TABLE I
Specification Summary of the Fairchild FQP30N06L

Max. Drain-Source Voltage	60 V
Max. Drain Current	32 A @25 C 22 A @100 C
RθJA	62.5 C/W
Rds(on)	0.035 Ohm
Max. Operating Temp.	175 C

TABLE II
Estimated junction temperature caused by device operation, using 25C as ambient.

	Voltage	**Current**	**Temperature**
Light	12 V DC	1.2 A	28 C
Fan	5 V DC	300 mA	25 C
Atomizer	24 V DC	700 mA	26 C

C. Sensor Connection

Three sensor connectors have been added to the PCB, each connector consisting of a GPIO line, a 3.3V power and ground line. Temperature and relative humidity are sensed through these connections, the additional connectors were added for support of future feature set such as carbon dioxide or pH level sensing.

D. Power Regulation

Power is supplied to the board via an AC to DC Wall adapter with an output of up to 15V DC, which is attached via barrel jack connector. The incoming voltage is then regulated to 3.3V DC using the LD1117 voltage regulator by STMicroElectronics. Just as with the device control heat build up was a concern and (2) was used to estimate an operating temperature of 49C, assuming 5V DC Input and 300mA draw, given the RθJA of 50C/W of the device. Figure 7 and 8 show the power regulation schematic as well as additional connectors that were broken out for ground and voltage connection and access.

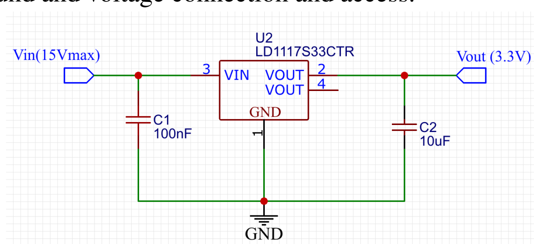

Fig. 7. Power Regulation Schematic using the LD1117.

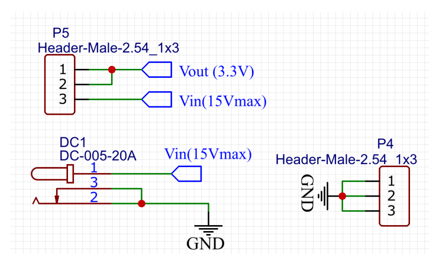

Fig. 8. Connectors for main board power and regulated power access.

E. Web Features

A mobile responsive web application, as seen in Fig. 9, allows the consumer to check up and control the Nursery remotely via their computer or smart device. The ESP32 on the nursery connects to the consumer's WiFi network either automatically if the ssid and credentials have previously been provided or collects the required connection info by starting a soft AP that serves a collection UI. Once connected to the internet the Nursery communicates periodically to a Server, during said communication status information is provided by the nursery and setting changes, if any, are fetched from the server. The communication happens over HTTPS using JSON message bodies.

The web application provides features for the user to check up on the status of the grow, manually fine tune the desired growing conditions, or use a collection of pre compiled mushroom profiles to easily configure a grow. Additionally the server sends push notifications to the user if any of the parameters inside the grow chamber fall outside of an acceptable range. The web application uses a mobile responsive SPA architecture based on the React web framework.

The web server deployed on a dedicated container environment is developed using Nodejs and utilizes the Express framework, due to its architecture it can be scaled vertically and horizontally to accommodate large traffic requirements. It interacts directly with the MongoDB database, which is also deployed on a dedicated instance.

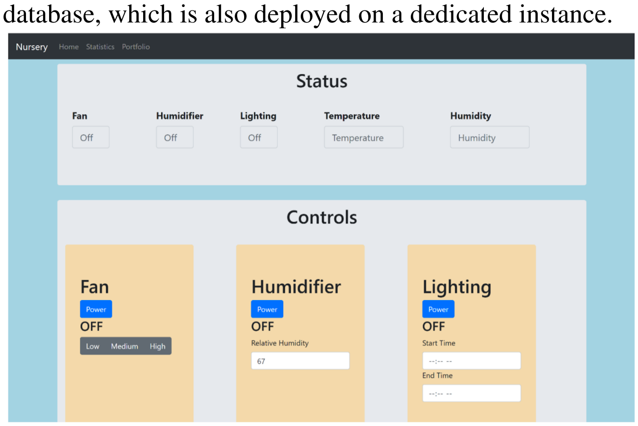

Fig. 9. Screenshot of the Desktop UI.

F. Housing

The housing as illustrated in figure 10 consists of a two chamber design, and is hand assembled using plexiglass. The growing chamber, taking up 75% of the housing volume is where the spawn blocks are placed and mushrooms are harvested from. This chamber has mounting for the LED lights, an exhaust fan, the temperature and humidity sensor as well as a hinged lid for easy access.

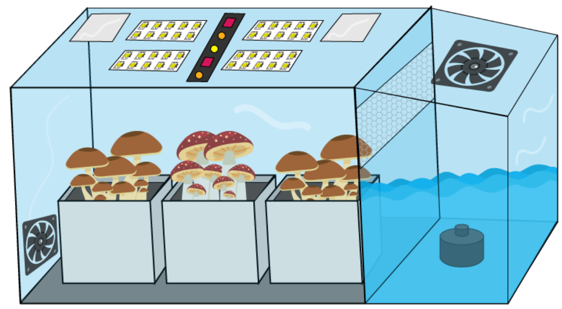

Fig. 10. Artist representation of the Housing Design.

It is connected to the second chamber via an air exchange cutout at the top. The second chamber is the humidity chamber and when in operation is filled up to the water level mark with water, it houses the ultrasonic disc atomizer as well as the air intake fan which is attached to the lid.

V. Testing & Observations

Our testing methodology focused on testing early and often, we aimed to test hardware components and software modules individually as much as possible, preferably in configurations where we could execute rigorous testing scenarios by either directly manipulating the inputs or in scenarios where we could still easily reason about the input states, and then were able to directly observe their results. As the project continued we would assemble larger subunits and again test those larger units for functionality before assembling the entire solution. Once the solution was fully assembled we employed a more behavior focused testing approach that involved cultivating multiple mushroom varieties, specifically Golden Oyster (Pleurotus citrinopileatus), Pink Oyster (Pleurotus djamor), and a warm weather Brown Oyster (Pleurotus ostreatus) strain.
For comparison and to get a quantitative result on the effectiveness of our solution, we grew the same 3 varieties in the most commonly recommended home mushroom cultivation method, called the "spray-and-tent" (SPAT) method. In both methods, each strain was grown using a freshly inoculated 2 pound spawn block consisting of straw and spent coffee grounds. We collected the following results from the tests:

1. Shortest number of days until the majority of mushroom bouquet was ready to be harvested.
2. The total wet weight of all harvests.

3. How many times the spawn block was able to flush, i.e. how many times the same block was able to regenerate additional mushroom fruit bodies.
4. Observation of obvious deformities.

A. Spray and Tent

The SPAT method involves taking a spawn block and spraying it directly with a water spray bottle followed by covering the block with a perforated plastic tent that is designed to trap moisture but still allows the carbon dioxide to escape. Following the most commonly recommended SPAT procedure, the tent was temporarily removed and spawn blocks as well tent were sprayed in the morning and at night until small droplets were visible. Blocks were placed in a room with a window and exposed to indirect light at a room temperature of 77F. The results have been recorded in Table IV, using this method the shortest harvest time observed was 8 days, with the longest taking 17 days, yield was low due to few pins forming and major deformities preventing the fruit bodies from bulking. The number of flushes were acceptable, except for the brown oyster spawn which produced mold toward the end of the first flush and had to be discarded.

Fig. 11. Golden Oyster Mushroom grow attempt using SPAT method, showing severe stem and body malformations.

B. Nursery

The nursery was placed in a 77F room with a window and away from direct sunlight, 2 blocks were placed into the nursery at a time. The nursery was configured to the growing parameters listed in Table III, these parameters were compiled from the book "Growing Gourmet and Medicinal Mushrooms" [9] by Paul Staments. The results have been documented in Table IV, using this method the shortest time to harvest we observed was 3 days and the longest was 10 days, yield was quite considerable and sufficient for fresh use in multiple meals as well as drying for later use. One deformity was observed in a brown oyster flush, however we believe this was due to us placing the brown oyster side by side with a very active pink oyster spawn that grew quickly and ultimately overcrowded the growth chamber. In summary, we were able to achieve much shorter grow times, larger yields and a reduced amount of deformities using the nursery instead of the SPAT method.

Fig. 12. Pink Oyster (left) and Brown Oyster (right) grow using the nursery, both are displaying large and plentiful fruit bodies.

VI. Conclusion

The solution as proposed allows the consumer to cultivate their favorite edible mushroom varieties in a convenient way. During our testing we were able to grow multiple gourmet strains quickly, some flushes were mature in as short as 3 days with large flavorful fruit bodies. In comparison we attempted to grow the same strains without the nursery and only achieved small yields that required daily manual intervention for durations of up to 17 days, with all attempts showing signs of malformed and underdeveloped fruit bodies.

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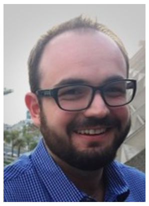
Biography



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References

[1] United States, Congress, Parr, Broderick, et al. "*Vegetables and Pulses Outlook.*" Vegetables and Pulses Outlook, Department of Agriculture, 27 Oct. 2017. https://www.ers.usda.gov/webdocs/publications/85540/vgs-359.pdf.

[2] Stamets, Paul. *Growing Gourmet and Medicinal Mushrooms*. 3rd ed., pp. 436, Ten Speed Press, 2000.

[3] Stamets, Paul. *Growing Gourmet and Medicinal Mushrooms*. 3rd ed., pp. 202-205, Ten Speed Press, 2000.

[4] Smith, Wendell. *Primordia, Pins, Small Mushrooms.* https://www.flickr.com/photos/wendellsmith/16920124135.

[5] Kristensen, Hannel., et al. "Increase of Vitamin D2 by UV-B Exposure during the Growth Phase of White Button Mushroom (Agaricus Bisporus)." *Food & Nutrition Research,* vol. 56, no. 1, 2 Apr. 2012, doi:10.3402/fnr.v56i0.7114.

[6] Bjarnadottir, Adda. "How Much Vitamin D Should You Take For Optimal Health?" *Healthline*, Healthline Media, 4 June 2017, https://www.healthline.com/nutrition/how-much-vitamin-d-to-take.

TABLE III

Environment Parameters for three types of Oyster Mushrooms [3].

	Primordia Formation				Fruit Body Development			
	Temp. In F	RH %	Duration In Days	FAEs / hour	Temp. In F	RH %	Duration In Days	FAEs / hour
Gold	70-80	98-100	3-5	4-8	70-85	90-95	3-5	4-8
Pink	65-75	95-100	2-4	5-8	70-85	85-90	3-5	5-8
Brown*	50-60	95-100	3-5	4-8	60-70	85-90	4-7	4-8
*Note that we acquired a warm weather variety of Brown Oyster that in terms of temperature was more in line with the Pink Oyster parameters.								

TABLE IV

Results of Nursery vs SPAT method.

	Days until Harvest		Wet Yield in grams		Number of Flushes		Deformities	
	SPAT	Nursery	SPAT	Nursery	SPAT	Nursery	SPAT	Nursery
Gold	13	7	75	200	3	3	1, 2, 3	None
Pink	8	3	160	433	2	3	1, 3	None
Brown	14	8	14	315	1	4	1, 3	1
1 - Elongated Stem due to oxygen starvation, 2 - Lack of color development due to insufficient light exposure, 3 - Malformed and/or brittle cap due to lack of moisture.								