Affordable Mushroom Production System Design and Operations

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***Abstract*— Rice farming is the main income source for many farmers in Cambodia. However, rice farming is only possible during the wet season from May to October, reducing the income of many farmers during the dry season. From November to April, families practice subsistence farming, growing vegetables and raising livestock on their small plots of land. Men are often forced to seasonally migrate to urban areas to find work. Affordable mushroom houses are an agricultural technology innovation that offer Cambodian farming families an alternative agricultural source of income. The greenhouse-like structures are wooden and covered with fabric and plastic to create a controllable environment that facilitates mushroom growth. Over the last three years, in collaboration with partners, we have built over 120 mushroom houses in central rural Cambodia with farmers collectively producing over 4,000 kgs of straw mushrooms on a weekly basis. However, due to various factors such as the specific design, materials used, and growing methods, mushroom yields vary widely. Poor construction can lead to poor temperature control inside the structure, which greatly affects mushroom growth. There are also concerns with the structure's relatively short lifespan and its susceptibility to termite infection. In order to understand what was working well and what could be improved upon, data was collected from the mushroom houses including dimensions, materials used, production data, ingredient masses, material and ingredient prices, and cultivation process timing/methods. This paper outlines the success and failure modes of the current mushroom house designs and recommends standardized construction and growth processes to accelerate the adoption of this simple yet transformative technology.**

Keywords—mushroom production, agricultural technology, standardization, food security

I. Introduction

Rice farming is the primary occupation in Cambodia, with rice accounting for approximately 75% of Cambodia's yearly agricultural output. However, rice farming is only possible during the wet season from May to October [1]. During the rest of the year, farmers must find other sources of income. Increasing effects of climate change have made agricultural-based livelihoods progressively unstable. Relying solely on agriculture as a main income is now perceived as risky by most rural households in Cambodia. While still farming rice during the wet season, most households include at least one family member that seasonally migrates to an urban area to find work during the dry season in order to supplement their income. In addition to rice fields, most of these families own small plots of land surrounding their homes that are used to farm vegetables or raise livestock for subsistence use [2]. Intensified horticulture, for example by using greenhouses, can help farmers leverage these small plots of land to bolster their livelihoods. Cambodian climate is particularly conducive to the cultivation of mushrooms, a high value agricultural product that is easy to grow, requires less space, and given its capacity to grow in low light, can be stacked on top of each other to maximize yields. World Hope International (WHI), a non-profit with operations in Cambodia has been collaborating with Penn State, and now Lehigh University, on the design and commercialization of various agricultural technologies. This collaboration yielded a social enterprise called Thera Metrey that is based in Kampong Cham in central Cambodia and focused on engaging local communities in mushroom farming with a market-centric business model.

While mushroom production systems (MPSs), commonly known as 'mushroom houses' have been used to cultivate mushrooms for decades, Thera Metrey helped local farmers adapt the design and provided end-to-end support in the cultivation and marketing of straw mushrooms. These houses are 6m x 8m roofed wooden structures covered externally with plastic and fabric. They are built by local carpenters with foraged or purchased materials, which led to wide variation indifferent design, functionality, efficacy, and durability. Inside the structure are four 5-shelf racks that hold rice straw, which is the substrate most commonly used to cultivate straw mushrooms. Straw mushrooms (Volvariella Volvacea), are a high value crop, easily fetching $3.5/kg in local markets. Tthe ability to produce large quantities of mushrooms using few resources results in a higher profit margin for farmers. Growing and selling these mushrooms, farmers can make up to $200 in profit per month from one MPS alone . Over the last three years, this venture has quickly grown and now there are over 120 MPSs being operated by small farmers, mostly women, around Kampong Cham [3].

After a detailed description of the MPS technology and mushroom growing process, this article describes the findings of this study and provides a number of practical insights into the design and commercialization of mushroom production systems and similar agricultural technologies. This article provides a poignant case study of an aspiring technology-based social enterprise that needs to standardize product designs, supply chains, and venture operations in order to sustain growth and amplify its impact.

II. Methodology

The current MPS design and growing process is effective overall, but due to the many deviations that farmers make in their construction and cultivation processes, some farmers grow and earn significantly more than others. There were concerns about the short lifespan of some of the structures and the wooden frame's susceptibility to termite infestation. In order to understand what was working well and what could be improved upon, four researchers from Lehigh University studied 60 MPSs owned by 46 unique farmers around Kampong Cham. Data collected from mushroom houses included dimensions, materials used, production data, ingredient masses, material and ingredient prices, and cultivation process timing/methods. This data was gathered through interviews using a translator, observations, and direct measurements over a three-week period in Summer 2017.

III. Mushroom Production in Cambodia

There is a growing market for straw mushrooms in Cambodia, with the market in Phnom Penh alone exceeding 5 tons per week. However, traditional local growing methods are not very efficient and reliable transportation to urban markets did not exist until recently. This meant sales from small-scale mushroom production was constrained to local markets, which were easily saturated. Combined with inefficient growing methods, mushroom farming provided little incentive for farmers. Before mushroom houses, a greenhouse-like structure filled with racks that produce mushrooms in high volumes, were introduced, Thera Metrey established a supply chain for mushroom production and sales. Because an organizational system to help farmers obtain spores and other agricultural inputs already existed, vendors were incentivized to purchase the technology.

A. Spore Vendor

In the Kampong Cham area, a single, reliable spore vendor was already established. All the interviewed farmers purchased their spores from this vendor. He had a set production process before the significant rise in spore demand occurred. His process involves incubating the spores in gelatin, storing them in glass bottles, then cutting up the spores and transplanting them to small bags of mung bean shell and leaving the bags to let the spores spread further. The vendor sells each bag for 32 cents, and a single mushroom house usually uses 140 bags of spores per cycle. All the mushroom farmers are completely reliant on this one spore vendor and the entire business would be compromised were the vendor to go out of business.

B. Advantages of Mushroom Farming in Cambodia

Besides a history of mushroom farming, another key in its recent development and increased popularity is that rice farming is the dominant agricultural product in Cambodia. The bulk substrate used by all mushroom houses is rice straw, which is produced in abundance as a waste product of rice farming. Historically, burning the rice straw was the method of removing this waste product, but now it has grown into a commodity. Agricultural waste is already successfully being used to cultivate mushrooms in the nearby country of Malaysia [4]. Currently 1,000 kg of rice straw (approximately enough to fill one mushroom house) will sell anywhere from $40 to $100 on local markets. Moreover, one key input of rice farming is water. Rice is typically grown in rice paddies, that require the area to be fully submerged to achieve an optimal harvest. This is significant because mushroom farming also requires a high volume of water (farmers typically use 1000L to 1600L) to steam the mushroom house each cycle. The technology necessary to pump water for the mushroom houses was already established because the same technology was already being used to pump water for rice fields or for household use. In addition, rice farming takes up most of a farmer's time during the wet season. The rest of the year, farmers grow other crops on the smaller plots of land around their homes. This offseason for rice is when farmers are free to farm mushrooms to help bridge any gaps in income. The rice fields are also unavailable to farm other crops, so a high production, low land use crop, such as mushrooms, accommodates the lull in cultivation perfectly during the dry season.

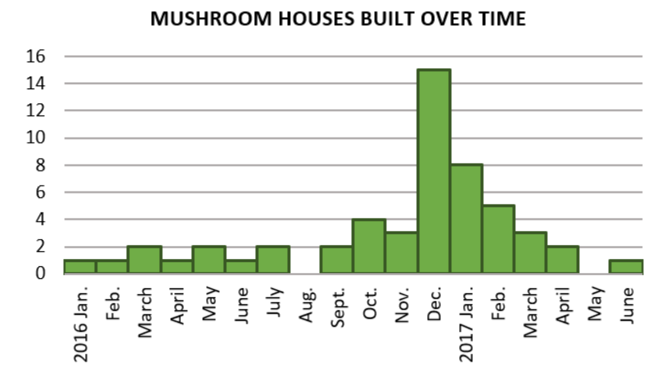

Fig. 1. Mushroom houses constrcuted each month over the past two years. Most farmers opt to delay construction of their mushroom house until the dry season, as they are busy cultivating and harvesting rice during the rest of the year.

C. Scalability

In July 2017, there were over 80 functional MPSs. The number in March 2018 stands at 120 MPSs. Fewer mushroom houses were recorded as being built in the months from April – November because many farmers decide to delay construction until after the wet season since they are preparing to cultivate and harvest rice. Figure 1 demonstrates this purchasing trend, using the past two years to show a spike in mushroom houses built during the midst of the dry season in the months of December – March.

Of those recorded, many of the first mushroom houses built are grouped together in two villages. Most of the houses that are on the periphery of the map have been built much more recently, as the technology has spread. More periphery villages are only now adopting mushroom houses as an alternative method of cultivation. Poor physical and technological

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infrastructure in the area make it difficult to disseminate information. Most of the technological spread has been the result of word-of-mouth and referrals from farmers already utilizing the mushroom houses.

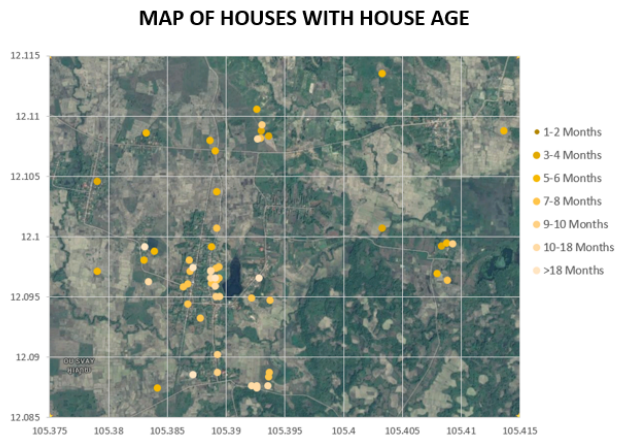

Fig. 2. Locations of the completed mushroom houses. As farmers in the area become more familiar with the technology, more and more mushroom houses are beginning to be built in periphery areas.

IV. Current Mushroom Production Technology

A. Summary

A mushroom house is a wooden 6m x 8m roofed structure that has racks stored within. The racks hold rolled rice straw which is the bulk substrate for mushroom growth. There is a layer of plastic around the racks, sealing them off from the outside, as well as an external layer of fabric that protects the mushrooms from sunlight. Currently, mushroom house designs vary widely in materials, size, and construction processes, but all include the same basic features. These features are: posts, a roof, protective plastic, protective fabric, rice straw racks, and a steaming system. Figure 3 illustrates the basic mushroom design and these common features.

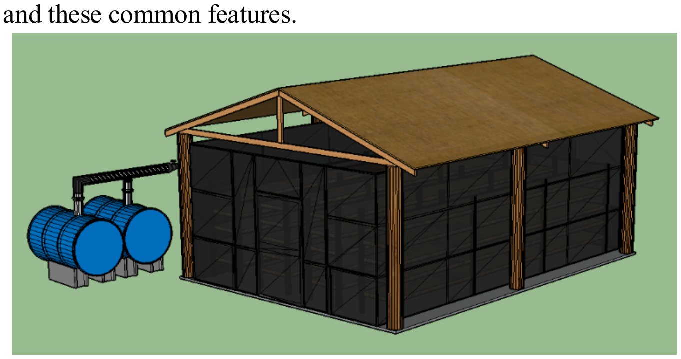

Fig. 3. Autocad sketch depicting the common, basic design of mushroom houses in Cambodia.

1) Post Design - The first part of the building process is to clear and level the land. This area should be slightly larger than the expected area to be used for the mushroom house. Most mushroom houses follow roughly 6mx8m dimensions, but farmers may increase or descrease this size depending on their wants and needs. The posts are large pieces of lumber that were locally foraged or purchased at market. The quality of wood is usually low, but it is what is most accessible to farmers. These posts have roughly a 20cm diameter. Typically, 4 posts span the length of the mushroom house and 3 posts span the width. These posts are secured in the ground by placing the base of the log approximately 0.3m underground. No farmers reported using cement to secure the posts in the ground, but a floor about 2cm thick is laid using approximately 400kg of cement. The posts are arranged so that the central posts along the length of the structure are taller than the outside posts. The side posts have an average height above ground of 2.63m and the middle posts had an average height of 4.62m. Farmers who build the mushroom house themselves reported needing help from family or neighbors to install the posts.

2) Roof Design and Materials - There are a variety of different roofing materials used. Different roof materials have different effects on the mushroom growing process. The types of roofing materials typically used are aluminum, thatched (grasses), palm leaf, plastic, and mixed. The roof material is very non-standard, as demonstrated by the wide distribution used in already constructed mushroom houses.

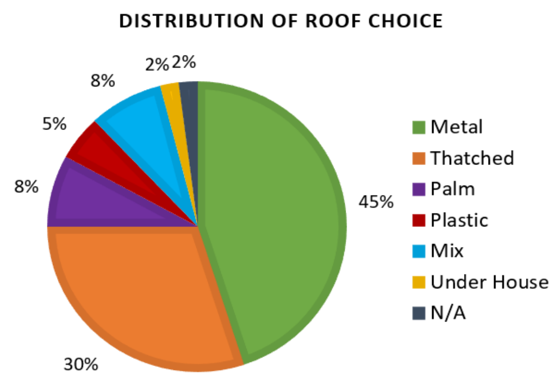

Fig. 4. Distribution of roofing materials among completed mushroom houses. Roofing material varies widely depending on the materials available to the farmer or their access to capital.

The most common roof material was aluminum, accounting for 45% of observed roofs. Corrugated aluminum is an easy material to obtain on local markets, but it does a significantly poorer job of moderating temperature than other materials. Farmer have to adjust the design, by building overhangs or putting palm leaves on the roof to mitigate heat and bring the temperature back down to an acceptable range. Before putting palm leaves on the roof, the interior temperature was reported to be 37-38 degrees Celsius, but after, the temperature dropped to 33 degrees. This is within the acceptable range of 28-34 degrees Celsius that is needed to cultivate straw mushrooms.

The thatched roof accounts for 30% of the houses observed. Farmers whose mushroom houses have thatched roofs say that obtaining enough of the material was a barrier to completing construction. One mushroom house has a half-thatched, half-aluminum roof because the farmer could not find enough material. Thatched roofs have good temperature moderating properties, so these mushroom houses do not require additional attention to maintain the optimal growing temperature. Palm leaf was used to roof 8% of observed houses. Palm leaf is about

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as effective at mediating temperature as grass-thatched houses. Palm leaf thatch is also easier to come by than grass thatch, but it is significantly less durable. Many palm leaf thatched houses use plastic to cover acquired holes in the roof, decreasing their insulation ability.

The worst performing observed roof type was the plastic roof, which 5% of houses use. This plastic is different than the plastic hung to seal the racks. Plastic typically used for roofs is taken from the bags used to store rice straw or mung bean shell, and crudely sewn together to form a roof. Not only is this plastic not sturdy or durable, but it insulates against heat poorly and allows as significant amount of sunlight to hit the racks, which is bad for growth. The rest of the roofs were mixed materials, one house was built under the stilts of a residential house, and one was being renovated so it was not available. Mixed roofing occurred in 8% of mushroom houses and was a result of either running out of the first chosen material or were patchwork due to significant sections of the previous roof failing.

3) Moisture-Sealing Plastic - A key feature of the mushroom house is the exterior plastic, which seals it off from outside pests, possible infection, and retains moisture. This is especially important when steaming, so that water vapor does not escape the mushroom house. The average dimensions of the area encased by the plastic are 5.6m x 7.6m. The average heights of the plastic are 2m high on the sides and 3.1m high on the top. The plastic is attached to the roof by being tied with string from the corners of the plastic to the roof. It is important that when the plastic is installed, that it is at least 0.2 m away from the racks. According to farmers, when the plastic is in contact with the racks, the contact can disrupt the mushrooms in the area and drip extra moisture onto the mushrooms, which inhibits growth. Close proximity between the plastic and the racks can also cause poor ventilation. Some farmers build bamboo "skeletons" around the racks to prevent the plastic from touching. The plastic in all mushroom houses have "windows", which are holes that can be opened and closed with clips to allow heat and moisture to escape when the mushroom house is too damp or too hot. Many of the mushroom houses have zippers sewn into the plastic that more effectively seal the mushroom house than clips, but most of these zippers were broken and now secured using plastic clips. Zippers are difficult to fix, while clips are consistent and easy to use. The plastic is sealed at the ground through several different methods. Most farmers have sewn together long thin sandbags that are placed on the plastic where it meets the ground on the inside of the mushroom house. This weighs down the plastic and seals it at ground-level to prevent moisture from escaping. Other farmers used bags filled with dirt or bricks. Some farmers even tuck the plastic into the ground, by piling dirt on the ends.

4) Protective Fabric - Mushrooms cannot grow if they receive too much sunlight. The plastic that is used to retain moisture is transparent, therefore fabric is needed to block sunlight that could enter through the side of the structure. The fabric used is typically a thin polyester fabric and the color varies. The choice of fabric does not impact yields in anyway. The fabric does not need to be airtight, but needs to block all the light, so it is draped from the bottom of the roof to the ground on all sides of the mushroom house. In addition to fabric, some farmers put palm leaves in the top triangle of the front face to help insulate and block light.

5) Substrate Racks - A typical mushroom house has 4 racks running lengthwise. The average rack is 7m long and 76cm wide. The average distance between adjacent racks is 59cm and outside edges of racks are an average of 30cm away from the plastic on all sides. Each rack has 5 shelves. The posts of the racks are built from locally harvested wood, as are the outside beams. The posts are secured to the beams using nails. The inner slats of the shelves are built from bamboo slats and secured to the rest of the racks using rope. When in use, the rice straw rests on these bamboo slats. One variation of the rack design utilizes 6 racks along the width of the mushroom house as opposed to 4 lengthwise. Another farmer built each rack with 6 shelves instead of 5.

Fig. 5. Substrate racks in use in a Cambodian mushroom house

6) Steaming System - To properly sanitize a mushroom house, the area encased by the plastic must be steamed between growth cycles. All farmers use a similar system to heat the mushroom house, a brick and mortar oven with 4200L steel tanks resting on top. The drums are attached to each other through welded piping and attached to the mushroom house via a rubber hose with approximately a 20cm diameter. Wood is burned in the oven, and heats the metal drums so that the water boils and steam is pushed into the rubber pipe to flow from the drums into the structure.

B. Construction Process

Mushroom houses all follow a basic design and are altered depending on the resources of the farmers and each farmer's personal preferences. New farmers follow a relatively similar design because they are unwilling to take large risks and are unfamiliar with the growing process. Farmers building their second mushroom house are more likely to make changes and almost always decide to increase size.

The construction schedule varies greatly from farmer to farmer, depending on the resources and skills available to them. From start to finish, the building process can take from 5 days to a month. If one farmer is building a mushroom house by himself, it can take a month, depending on his time availability. These farmers still need help from their family or neighbors to install the exterior posts, but the rest of the mushroom house can be built by a single person. Many farmers choose to hire workers for a few days. Farmers may choose to hire workers to expedite the process or because they do not personally have the knowledge and capabilities to build a mushroom house. Mushroom houses usually take 5 days to build when hiring 3 workers per day.

V. Mushroom Production System Operations

The steps of mushroom production are the same from farmer to farmer, but ingredients, duration, and methods vary. Mushroom production is not a continuous process and occurs in cycles that last approximately 10 – 20 days. A cycle begins when the mushroom house is ready to be steamed and ends after the mushrooms are harvested and the mushroom house is aired out. Rice straw is typically used for 2 or 3 cycles, but mushroom production decreases with each consecutive use.

A. Rolling and Loading Rice Straw

The rice straw only needs to be rolled once, but the rolls are usually turned over between cycles. The rice straw is hand-rolled by one or two people, a process that takes from 3 days to a week. One roll of rice straw is approximately 30cm long and has a diameter of 12cm. No farmer has weighed their rice straw for one use, but the best estimate is approximately 1000 kg, which translates into roughly 2,000 rolls. The rolls are placed on the racks, two by two until the entire mushroom house is filled.

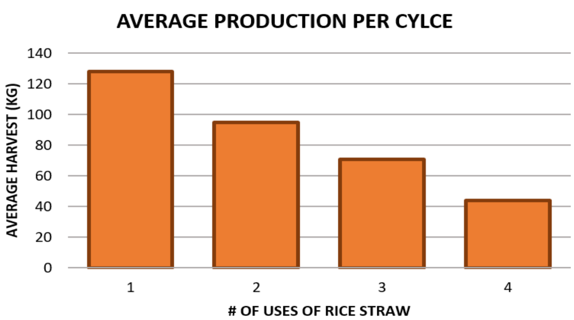

Fig. 6. The average production of mushrooms (kg) from each consecutive use of the rice straw. The quality of the rice straw diminishes with each use, causing mushroom production to decrease.

B. Mixing and Spreading Compost

Rice straw accounts for approximately 75% of the substrate, but most of the nutrients that the mushrooms need are absorbed from a compost mix. The ingredients used in the compost are consistent between farmers, but the proportions vary. The majority of the compost is composed of waste rice straw (rice straw too small to be used in the rolls) or mung bean shell. They are not supposed to be used together, because mixing rice straw and mung bean shell allegedly causes the mushrooms to turn red, which is a sign of infection. Each mushroom house uses 200kg of waste rice straw or mung bean shell. Mung bean shell is believed to be more nutritious, so when using waste rice straw, 60kg of rice bran is added to the compost, but when using mung bean shell, only 30kg of rice bran is used. The rest of the ingredients added are: 7kg of sticky rice paste, 4kg of antibacterial powder, and 1.5kg urea. These ingredients are mixed together by hand and covered with a tarp. The compost is then left to sit from anywhere from overnight to 10 days. If the farmer decides to wait longer, they mix the compost again halfway through the composting time. Mixing compost usually occurs at the end of the previous mushroom cultivation cycle, so that the compost is ready to be used at the start of the new cycle. After the compost has been adequately left to settle, it is spread evenly across the racks.

C. Steaming the Mushroom House

The morning after spreading compost, the steaming process begins. The interior of the mushroom house is sealed off by closing the windows and weighing down the sides of the plastic. Tanks are filled with water that is either pumped from a lake or a well and a fire is started in the oven under the tanks. This raises the temperature of the mushroom house to the minimum required temperature of 75 degrees Celsius in about 3 hours. The mushroom house is heated at 75 to 80 degrees Celsius for 6 to 12 hours. Water is poured into the tanks intermittently to keep the flow of steam into the mushroom house continuous. The steaming process uses approximately 1400L of water and one truckload of firewood. After steaming is done, the windows are opened so that the temperature of the mushroom house will drop to a reasonable level overnight. In the morning, 140 bags of mushroom spores are spread across the racks and nutrients are sprayed to increase the mushroom yield.

D. Maintaining Temperature and Moisture Content

Until the mushrooms begin to bud, it is important to keep the temperature of the mushroom house and moisture of the rice straw at adequate levels. The mushroom house should be checked at least 2 times per day, but ideally more. The optimal temperature of the mushroom house is between 28 and 34 degrees Celsius. This can be measured using a thermometer which most farmers keep in their mushroom house. If the temperature is too high, the windows are opened to allow heat to escape. If the temperature is too low, the windows are closed so that all of the heat is retained – though this is rare. The biggest challenge mushroom farmers have is preventing the mushroom house from overheating. The moisture content of rice straw is not measured, but adequate moisture can be determined using a simple spray test. This test is conducted by spraying water on a sample of rice straw. If all the water is absorbed by the rice straw and none runs off, then the sample is too dry. In this case, the farmer should spray down the rice straw with water until the moisture content is appropriate. If none of the water is absorbed by the rice straw and it all runs off, then the sample is too wet. When the moisture content is too high, the windows of the mushroom house should be opened to allow air flow to let the excess water be absorbed by the less humid outside air. The moisture content is appropriate when some of the water sprayed runs off slowly, but some is still absorbed. During this time between spreading spores and harvesting, farmers do not allow anyone to enter the mushroom house. Even then, people that enter should not wear any perfumes or have any foreign contaminants on them. Many mushroom farmers do not bathe during this period because they

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believe that any outside contaminants negatively impact mushroom growth.

E. Harvesting and Sorting

During harvesting the same cleanliness principles apply – only 1 or 2 people are allowed to harvest at a time to reduce exposure to outside contaminants. The harvester takes a bucket into the mushroom house and picks all budded or bloomed mushrooms. After a bucket is filled, the harvester passes it to family members outside who sort the mushrooms into three grades. Grade 1 is large, non-bloomed mushrooms. These are the highest quality and sell for approximately $3.00 per kg. Grade 2 is small, non-bloomed mushrooms. These are good quality, but too small and sell for only $1.25 per kg. Grade 3 includes bloomed mushrooms. These are undesirable, but still sell for $0.75 per kg.

In Cambodia, the mushrooms are most valuable when harvested while budding, but not bloomed because of the culture's dietary traditions. Once the mushrooms begin to bloom and form "umbrellas" their unit price per weight drops significantly. However, straw mushrooms bloom very quickly after budding. Mushrooms that form buds in the morning will likely bloom by the nighttime harvest. Farmers often harvest at night and then again in the morning to pick budded mushrooms before they bloom. These mushrooms do not keep very long, so the farmer must rely on local markets to unload their harvests.

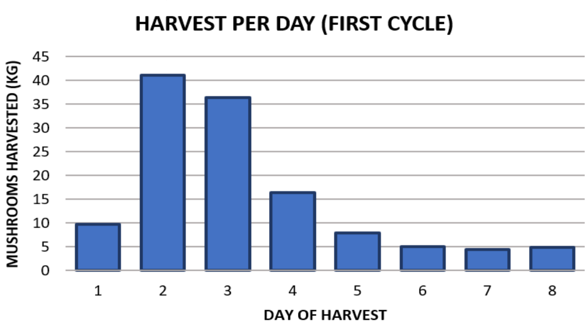

Fig. 7. The average amount of mushrooms (kg) harvested each day. After day 5, mushroom production drops significantly and it becomes more economically efficient to begin a new growth cycle.

Harvesting typically takes from 5–10 days, but the mushroom production drops off after 5 days to approximately 5 kg per day, as depicted in Figure 7. The low yield on these days makes it more economically efficient to simply begin another cycle. Most farmers only harvest for 5–7 days if they have the ability to begin a new cycle. Sometimes farmers have not yet received new spores and so continue a harvest until spores are delivered. Average production of the first cycle peaks on the second day, at 41.1kg, but many mushroom houses report their highest yields on the third day. The maximum reported yield from one day's harvest is 100kg. On successive cycles, the distribution of production by day remains constant, but yield is scaled proportionately to the average total harvest according to the number of consecutive uses of the rice straw.

F. Cleaning Between Production Cycles

Between each cycle, the plastic and fabric are pulled up to allow full ventilation of the structure. Some farmers scrape old compost off the tops of the rice straw. Many farmers also choose to add fresh rice straw between cycles, and usually flipped the rolls over after the second cycle. When the rice straw is fully depleted (usually after the third cycle), all of the rice straw is removed, the house is fully ventilated again, and all of the racks/posts are scrubbed clean. Some farmers use soap or antibacterial powder to clean their mushroom house. Many only use water because they think that the chemicals in the soap will inhibit mushroom growth.

VI. Farmer's Economics

A farmer can reach return on investment for their mushroom house in 2 months. The average fixed costs of the mushroom house are as follows:

TABLE I. AVERAGE FIXED COSTS OF MUSHROOM HOUSE

Input	Cost ($)
Wood	100.40
Cement	40.26
Roof	86.61
Plastic	35.20
Fabric	29.02
Bamboo	67.59
Steamer	84.06
Labor	14.77
Total	**689.56**

For three consecutive uses of rice straw, a farmer can expect to net a profit of $380.48 over about 1.5 months. The revenue that an average farmer can expect from three cycles with straw is approximately $790.65. The average costs that a farmer incurs during one cycle are:

TABLE II. AVERAGE COSTS PER CYCLE OF MUSHROOM GROWTH

Input	Cost per Cycle ($)
Mushroom Spawn	47.94
Rice Straw (Lasts 3 cycles)	48.64
Sticky Rice	5.89
Antibacterial Powder	1.85
Rice Bran	9.55
Mung Bean Shell	6.33
Waste Rice Straw	5.02
Urea	0.86
Water	4.66
Firewood	12.26
Total	**104.32**
Total without Rice Straw	**55.68**

VII. Effectiveness of Current Technology

The goal of the mushroom house design and process is to grow large quantities of high quality mushrooms using minimal resources and limited land. Overall, the current technology is much more efficient than traditional technology. However, there are many improvements that can be made to increase the lifespan of the structure and maximize the production per cycle.

A. Temperature and Humidity Control

The most commonly reported issue with mushroom houses is difficulty controlling the internal temperature and humidity. Currently, farmers have to check the mushroom house and adjust temperature and moisture at least 2 times per day. Checking and adjusting more than twice per day can result in larger, more profitable harvests. Most farmers work in the rice fields from early morning to sunset and are not able to check the mushroom house during the hottest time of the day. This could be remedied by investing in ventilation systems. However, these adjustments require large up-front costs and electricity to continually operate. To determine if this a cost-effective solution more research must be done on the impact of these systems on harvests compared to the cost of the units.

The primary issue with temperature control is overheating. Most farmers have this problem because the mushroom houses are poorly insulated and sunny days cause extremely high temperatures. Mushroom houses with metal roofs have the most issues and require extra attention. It is reported that if palm fronds or banana leaves are used to cover the roof, the internal temperature of the mushroom house will be lowered by approximately 4 degrees Celsius. All metal-roofed mushroom houses should use this adjustment if the internal temperature is regularly outside the ideal range. In the hottest of weather, this is barely enough to keep the mushroom house in the usable range. Metal-roofed houses can be utilized most effectively in areas that are already shaded. In very open areas, even with durability concerns, it is likely that thatched roofs are the best choice.

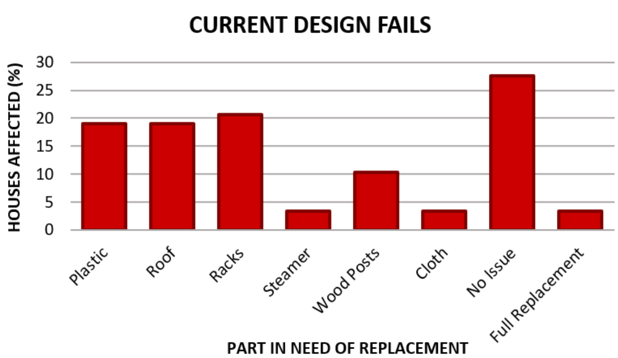

Fig. 8. The structural failures that occur most frequently and the parts affected. Most of these failures include parts that can be replaced at a low-cost and will not require complete replacement of the structure.

B. Structural Failure

There are many ways that the structural integrity of a mushroom house can be compromised. Structure features fail at different rates. Some of the resulting issues are easier to fix than others.

1) Plastic - The current type of plastic is easily torn and most mushroom houses sustain multiple tears. These tears are typically fixed with glue or are sewn back together. These tears come from regular wear and tear, but also from animals. One farmer reported a pig as the cause for a tear in the plastic. There were two separate farmers that reported rats biting holes in their plastic to eat the rice bran on the mushroom racks.

2) Roof - There are huge disparities in the percent of roofs needing repair according to material. Thatched and metal roofs fail around 10% of the time, whereas palm leaf and plastic roofs fail more than half of the time they are used.

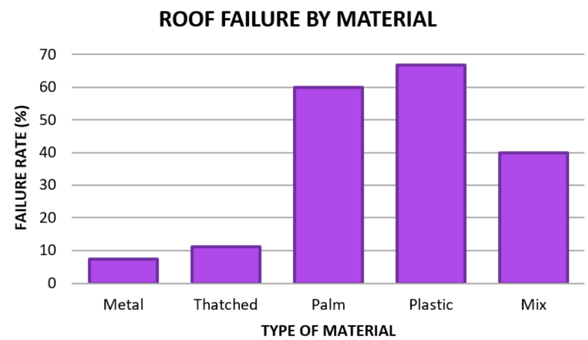

Fig. 9. The failure rates of the most commonly used roofing materials. Thatched roofs are the most reliable, but are the most difficult to find the resources for and to construct.

3) Racks - Current rack design uses split bamboo for the slats. However, bamboo does not fare well in high humidity and the slats are prone to breaking. While bamboo is relatively inexpensive and easy to replace, over 20% of mushroom houses have experienced this problem. Using a more durable wood could improve the lifespan of the racks.

4) Steamer - Because the steamer is only used once per cycle, it has a longer lifespan. The only failure issues recorded occurred when farmers used shared tanks. This increases the use of the steamer significantly and puts a lot more stress on the brick and mortar foundation.

5) Wood Posts - When farmers reported having to replace their wooden posts, they usually blamed the low quality of wood. This may have merit because most of the logs used are not processed and are therefore irregularly shaped and not treated for pressure, pests, or water. Many of the logs show signs of termites and mold. Using higher quality wood could make the structure more durable and less susceptible to pests and infection.

6) Fabric - Issues with the fabric are not usually very costly or problematic. The fabric is only used to block sunlight and therefore, is not important for structural integrity. It can be sewn back together easily.

7) Flooring - There have been no reports of people replacing the cement floor. It is likely that this is not because it hasn't cracked or broken, but rather because the floor is costly and difficult to replace. The purpose of the cement floor is to prevent absorption of water into the ground when steaming the structure. A larger concern with the flooring is the unnecessary overuse of cement resources. Many mushroom houses only used cement lay the floor, when it would be more cost-effective to mix the cement with sand and gravel aggregat to form concrete – a significantly cheaper resource.

VIII. HUMAN FACTOR ISSUES

Human error can account for decreased mushroom production and overall MPS success.

A. *Following Instructions*

According to the spore vendor, whom many farmers turn to for advice, most issues are due to the inability of farmers to correctly follow standard production methods. This includes using the wrong ratio of ingredients for substrate, failing to maintain the correct temperature or humidity, and using the wrong timetable when completing different parts of the process. Farmers may also use different ratios of ingredients based on availability. Many farmers produce less consistently because it is difficult to gather the necessary materials for a new cycle by the end of the previous cycle. Spore deliveries are not always optimal to maximize efficiency. Delivery is commonly late and farmers are required to harvest for more days despite the larger economic benefit of starting a new cycle. Discouragement is another reason that farmers wait too long to begin a new cycle. Waiting too long results in missing out on larger profits that are earned from the high-yield beginning of the harvest.

B. *Rice Straw Supply*

Current farmers are also at risk of running out of rice straw. Rice straw is abundant immediately after the rice season, but later in the year when it is more expensive to purchase, most farmers run out. This leads to some farmers deciding not to produce during times when rice straw is scarce. Although there is plenty of unused rice straw in other areas of Cambodia, transportation costs are high, causing incredibly high-priced goods. While the study in Cambodia, the most-voiced concern was the inability to cheaply obtain rice straw. An estimated price of buying rice straw for one cycle was $100, but the risk involved in investing this much money into a single harvest was is too great. Many decided they would rather wait until the end of the rice season and when they had their own stores of rice straw.

C. *Mushroom Infection*

Mushroom infections also often go unsolved. Red, soggy mushrooms are a generic sign of infection. Farmers suggested this problem may due overwatering, using rice straw too many times, or mixing waste rice straw and mung bean shell as the compost substrate. Another problem is mushrooms in a specific area dying immediately after budding. One farmer suggested steaming the structure for hotter and longer periods, but it is possible this “solution” was just coincidence.

IX. QUALITY CONTROL AND RUGGEDIZATION

Currently there are no standard measurements or quality control to ensure that a structure is built structurally sound and agriculturally efficient. Most mushroom houses are built by the farmers themselves or local contractors. The design is based on other nearby mushroom houses, leading to little or no standardization in design and construction.

When a part of the mushroom house fails, it is the farmer’s responsibility to resolve the issue. Due to the disparities between structures, there is no standard solution. This means that the farmer must take a significant amount of time to solve a simple issue that could be easily replaced if there was a standard part to buy. For example, if a section of the roof of a mushroom house failed. With the wide variety of roofing types, fixes are typically improvised, such as covering a hole with plastic bags. Plastic is a poor roofing material, and this haphazard replacement is likely to cost the farmer in production volume. Insulation also varies significantly from house to house. Farmers use several tactics, including putting cardboard under the roof or hanging fabric between the plastic and roof. These are design decisions that should be calculated, not improvised. By giving a standard design recommendation, construction of a mushroom house would be a less arduous process on the farmer.

The processes also would be much simpler and more efficient if measurements were standardized. Although structure size varies significantly, 82% of mushroom houses used the exact same number of bags: 140. Clearly this is not the most efficient method, as larger houses should use more spores, and smaller should use less. This would be easily remedied by using a standard size structure, so an optimal growing process could be more rigidly defined. One of the largest issues with current mushroom house design is the incredibly short lifespan of the structure (only 2-3 years before full replacement is needed) due to the low quality of materials used. Poor materials are impossible to remedy, leaving the structure doomed to fail in a fairly short time frame.

X. CONCLUSION

The current MPS is effective when a lot of time and care is dedicated to cultivation, but one structure can only be expected to last 2-3 years before needing full replacement. Basic standardization adjustments like pre-treating wooden posts, opting for more durable roofing materials, and using concrete rather than basic cement for flooring can improve durability and production yields. Moreover, cultivation and production practices vary significantly from farmer to farmer, suggesting that low-producing farmers could greatly increase their yields by altering their cultivation methods. This could occur by standardizing the structure itself, as well as the farming process. With higher levels of efficiency, the profitability of mushroom houses could be a strong incentive to rural Cambodian farmers.

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