Part III: Integrated Bio-Systems

Integrated Bio-Systems: Mushrooming Possibilities
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ABSTRACT
Our paper analyzes the strengths and weaknesses of a subfield of industrial ecology called integrated bio-systems (IBS). Consistent with the principles of industrial ecology, the goal of an IBS is to reduce pollution by transforming linear material flows into closed, cyclical processes that produce value-added product. The presence of large, concentrated quantities of compost, generated as a residue during the mushroom growing process, creates an opportunity to develop innovative on-farm uses for this material. We consider two potential options: (1) a mushroom farm/mycorrhizae IBS; and (2) a mushroom/biogas recovery IBS.

INTRODUCTION

Agriculture – the science, art, and business of soil cultivation, crop production, and animal husbandry – has evolved over time to meet the demands of a changing world. In general, population growth and rising demand for food has led to an intensification of agriculture characterized by increased use of capital and other inputs. This trend has increased the potential for "spillovers," or material losses, and environmental degradation.

Cyclical versus Linear Systems

Traditional agricultural systems were cyclical in nature. For example, early agrarian societies would grow crops, raise livestock, and spread the livestock manure on fields to enhance crop production. Integration of these processes created a relatively closed, self-sustaining system based on principles of conservation of resources and limited wastes. The industrialization or "modernization" of agriculture over the last century, however, has been the main factor in transforming agriculture from a cyclical process to a linear process, through which large quantities of raw materials are consumed and large amounts of waste are emitted. Figure 1 illustrates this transformation (Allenby and Graedel 1995).

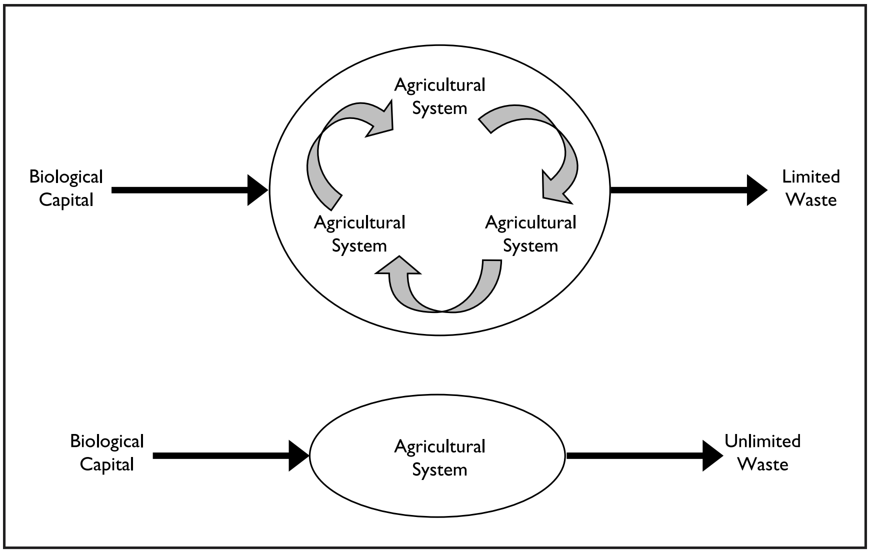

Figure 1 Cyclical versus Linear Systems

Agriculture as a Cause of Environmental Pollution

This fundamental change in agricultural practices has resulted in agriculture becoming a leading cause of some of today's most pressing environmental problems. Some of the common environmental problems associated with agriculture include: soil erosion, salinization, depletion of nutrients, methane emission, wastewater runoff, leaching of pesticides, and disposal of large quantities of solid waste (e.g., manure, crop residues).

It is important to remember, however, that the practice of agriculture is not an inherently polluting activity. It is only when such practices are poorly designed – when they concentrate and discharge large quantities of potentially harmful residues – that they undermine natural systems.

INTEGRATED BIO-SYSTEMS

Return to an Integrated System

Today, many efforts to move toward more sustainable agricultural practices are based on the theory of integrated bio-systems (IBS). According to the Zero Emissions Research and Initiatives (ZERI) Foundation, an IBS is a system that:

> ...[I]ntegrates at least two [biological] sub-systems so that the wastes generated by the first system are used by the next biological sub-system to produce a value-added product(s). The general aim of an IBS is to turn a material flow with losses that contribute to pollution into a closed and integrated one where nutrients are recovered by plants and animals.

The cyclical structure of these dynamic systems is not revolutionary. In fact, the fundamental composition of the IBS represents a return to the highly integrated agricultural systems that preceded industrialization.

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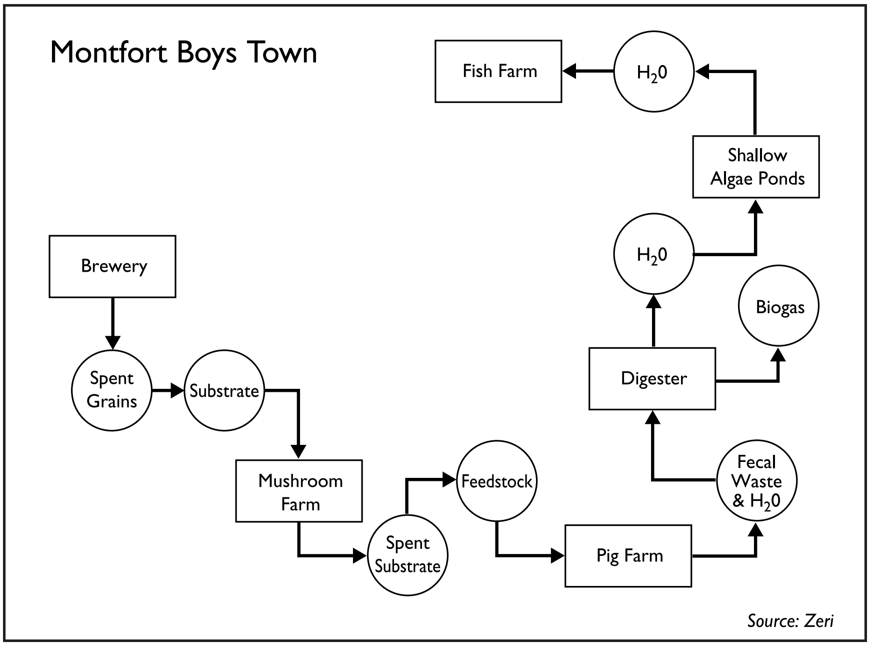
The IBS concept closely resembles that of industrial symbiosis, an area of industrial ecology that "engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products" (Chertow 1999). As is true of industrial symbiosis, the key factors in IBS are the interdependence or collaboration between component systems, and the synergistic possibilities offered by geographic proximity. Unlike industrial symbiosis, however, IBS is focused on biological, not industrial systems (UNU/IAS 2000).

A Model IBS

The Montfort Boys' Town located in Suva, Fiji, is heralded as a model IBS. The Montfort IBS was designed to alleviate off-shore dumping of large quantities of brewery waste, which was hazardous to nearby coral reefs. Montfort integrates four biological subsystems: mushroom farming, pig raising, fish farming, and vegetable growing. The primary input to the agricultural system is spent grain from the beer breweries[1] (Klee 1999). A diagram of the Montfort IBS is shown in Figure 2. The main goal of an IBS is to minimize material losses from the system, and hence, to reduce the potential for environmental impact.



Source: Zeri

Figure 2 A Model IBS (Montfort Boys' Town, Suva, Fiji)

Translating IBS in an Industrial Context

There is little doubt that integrated bio-systems are replicable. In fact, as long as a system features a set of unambiguous inputs and outputs in a simple, well-defined, and controlled environment, it is reasonable to assume that it could be installed just about anywhere. The Montfort Boys' Town model, for example,

[1] Bagasse, a fibrous waste from sugar cane processing, can also be used as an alternative input.

demonstrates that a modestly diverse array of sub-systems can be elegantly combined to match material flows between them. This particular arrangement of interrelated component systems reflects an explicit industrial ecology objective, and as such does not exhibit an architecture shaped by truly diverse, variable, or complex external forces. Any effort to recreate an IBS in a real-world industrial context would require the modification of IBS fundamentals to address and incorporate a far more dynamic and uncontrollable set of sub-systems and variables.

The major challenges involved in the adaptation of the IBS model to modern industry derive from the structure and mechanics of the marketplace. Whereas the Fiji model has operated within the confines of a micro-scale experimental program, it has not been exposed directly to the conditions and nuances of a large and highly evolved market. If an integrated bio-system is to function effectively at the corporate level in a sophisticated economy, its designers must be attentive to the following critical issues: 1) the maturity of component operations; 2) operational scale and input/output parity; 3) financial and fiduciary obligations vs. ecological objectives; 4) myriad competitive forces; 5) the complexity and diversity of material flows, and 6) co-location of component systems.

Maturity of the Component Operations: Corporate Inertia

The Fiji model incorporates sub-systems featuring very short operating histories – most did not even exist prior to development of this micro-IBS. Of course, this is not likely to be true of the component systems of an IBS in a larger and more sophisticated industrial context. Inevitably, the implementation of a large-scale industrial IBS will require the inclusion of existing, often highly mature, businesses. Since these businesses will almost certainly have established policies, strategies, and methodologies – the aggregate of which we have dubbed "corporate inertia" – integrating them into an IBS poses far greater challenges than does the integration of nascent entities. Ultimately, it is the corporate inertia of a potential component entity that will determine its suitability for inclusion in an IBS, even if the entity's underlying activities lend themselves, in theory, to inclusion.

Operational Scale and Input/Output Parity

The IBS at Montfort Boys' Town was developed to consume and metabolize the waste stream from brewing and sugar processing operations. Because the volume of the material outputs was measurable and consistent, the system designers were able to build a mushroom farming sub-system of the appropriate scale to match those volumes and to accept the flows as inputs. In a larger industrial context, characterized by operations of varying scales, input/output disparity will be commonplace. For instance, as we consider the feasibility of converting spent grain output from Connecticut brewers into a high-nutrient input for mushroom cultivation at Franklin Farms, one of the nation's largest mushroom farms located in Connecticut, it becomes abundantly clear that a material flow disparity exists. The volume of waste material emitted from Connecticut brewery operations (more than forty in all) is an order of magnitude greater than the input demand and capacity of even a large commercial mushroom operation like Franklin Farms. We believe that the input/output disparity between these industries is even wider on a larger regional and national basis.

Financial and Fiduciary Obligations vs. Ecological Objectives

The feasibility of any economically viable IBS will largely depend on the willingness and ability of the business managers to strike a balance between financial and ecological goals. While the Fiji IBS features industrial and agricultural processes that could, in theory, achieve profitability in addition to the environmental sustainability that the system has demonstrated, the development of the system was not contingent on the realization of explicit financial returns. The economic realities of modern businesses and markets, however, would be heavily involved in any decision to implement an IBS in a real-world industrial context. While we are confident that integrated bio-systems offer tremendous opportunities for both improved ecological and financial performance, we feel that it is very important that IBS feasibility studies address the economic motivations behind corporate decision making and behavior.

Myriad Competitive Forces

At the risk of redundancy, we would like to stress again how much more complex, rigorous, and uncertain the modern industrial context is compared to the environment in which the Fiji IBS was developed. It is instructive to consider that the five major forces outlined in Michael Porter's seminal tome on competitive strategy, *Competitive Strategy: Techniques for Analyzing Industries & Competitors,* have as much influence on the utility and efficacy of a corporate IBS as they do on any other aspect of a company's well-being. Competition, buyer power, supplier power, substitution, and barriers to entry are not conditions that discriminate in the manner or degree of their influence, and as such they are extremely relevant to any company's decision to participate in an IBS.

Complexity and Diversity of Material Flows

The types of materials used in large-scale mushroom cultivation, as well the distinct channels through which inputs and outputs flow, are numerous and varied. As we will discuss later in the paper, mushroom farmers have a fair amount of flexibility in choosing their sources and types of inputs. With so many options available to them, these farmers have the freedom to incorporate non-operating factors into their sourcing decisions, thus improving the likelihood that the farm could be integrated into an IBS. Nonetheless, the complexity and diversity of the material flows can also hinder attempts to combine and fully account for all of the component systems and their related material fluxes.

Co-Location of Component Systems

One idea that the diagram of the Fiji system is intended to convey (see Figure 2) is that the efficiency of the overall system depends in large part on the relative location of its component systems. It stands to reason that the integrative character of the IBS is more readily achievable when the sub-systems are located within close proximity to one another – a feature typically referred to as "co-location". Due primarily to the small scale and relative nascence of the Fiji model, there appeared to be few obstacles to co-locating the six sub-systems mentioned earlier. In a larger industrial context, characterized by mature and often disaggregated industries, co-location almost certainly constitutes a much greater endeavor than the one undertaken in Fiji.

MUSHROOMS: A KINGDOM UNTO THEMSELVES

Overview of Mushrooms

The mushroom is a fascinating form of life. Mushrooms are so distinctive that they are classified in their own "kingdom," a mostly microscopic community that performs invaluable roles in all terrestrial ecosystems (Miller 1972). Mushrooms are decomposers, releasing stored nutrients for use by host systems. In their association with living plants, mushrooms also facilitate the exchange of nutrients from organism to organism, and from one medium to another. Given mushrooms' extensive utility, it is helpful to think about how they are used in agriculture today, and to consider in what new ways the mushroom "kingdom" might be utilized in an industrial IBS context.

It has been estimated that there are 1.5 million species of fungi, of which only 5% (or approximately 69,000 species) have been identified. Out of the described species of fungi, there are about 10,000 species of fleshy macrofungi, the kind that form the fruiting bodies that enable us to readily identify them as mushrooms. While everyone is warned at some point or another not to eat mushrooms found growing wild, nearly half of all macrofungi are, indeed, edible. Further, of these 5,000 edible species, only a dozen or so are commonly cultivated. Finally, of this small, special group of mushrooms, one species predominates in agriculture: the common white mushroom of the genus *Agaricus*. The white mushroom comprises more than 99% by weight of all industrial mushroom cultivation (Miller 1972).

Mushroom Growing Trends and Economic Factors

Mushroom production is expanding worldwide. Last year in the United States (1999), *Agaricus* mushrooms totaled 848 million pounds, representing an increase of 5% from 1998, and 9% above 1997 levels. Pennsylvania accounted for half of the total volume of mushroom sales and California ranked second in production, with 16% of the U.S. total. The value of this *Agaricus* crop was estimated at $829 million, compared with $774 million for 1998. Brown mushrooms, such as the Portabello and Crimini varieties, are in fact another member of the *Agaricus* genus. The production of brown mushrooms has doubled in the past two years, accounting for roughly 5% of the 1999 *Agaricus* harvest. Brown mushrooms are nearly 10% more valuable than their white cousins (USDA 1999).

Despite the recent increase in mushroom production, the number of mushroom farms in the United States has been declining at an annual rate of 5% for the last 20 years. In 1999, only 150 farms grew *Agaricus* varieties. Nonetheless, 11 of those 150 farms realized sales of more than 20 million pounds in the 1999 season. Growers with sales exceeding 10 million pounds accounted for 60% of U.S. *Agaricus* production. Thirty-nine farms produced less than one million pounds each (USDA 1999).

As one might deduce from these statistics, the sharp decrease in the number of operations has been more than offset by significant increases in both the production footprint and yield. In 1999, the total growing area reached 35.2 million square feet in the United States, an increase of 2% over the previous year. In the same year, farm yields averaged 5.65 pounds per square foot, matching the second highest annual figure on record (the highest average yield was 5.69 pounds per square foot during the 1996-97 season) (USDA 1999).

Shiitake and Oyster mushrooms, referred to as "specialty mushrooms," are the two other major mushroom species grown in this country and constitute about 1% of the total mushroom harvest. These mushrooms have different growth requirements than *Agaricus* and bring a substantially higher price, averaging $2.97/lb. compared to $0.97/lb. for *Agaricus* varieties. In 1999, thirteen million pounds of these specialty mushrooms were grown. Their production has doubled in only the last two years (USDA 1999).

First, farm consolidation means that bigger and more productive operations are generating more waste on a per-farm basis, causing these waste streams to become highly concentrated regionally. Second, many of the gains in productivity have accrued from methods that impose greater throughput and stresses on the growing facilities and their local environment.

Mushrooms and Industrial Ecology

From an industrial ecology perspective, several things are important about modern mushroom farming trends. First, farm consolidation means that bigger and more productive operations are generating more waste on a per-farm basis, causing these waste streams to become highly concentrated regionally. Second, many of the gains in productivity have accrued from methods that impose greater throughput and stresses on the growing facilities and their local environment. Compounding this impact is the fact that mushrooms are increasingly cropped on shorter rotations. It is more efficient for the mushroom farmer to increase throughput than to wait for a second or third flush of mushrooms from a batch of compost. As a result, more nutrients are left in the waste stream.

THE MUSHROOM GROWING PROCESS

We decided to examine mushroom cultivation through the lens of industrial ecology in order to gain an understanding of how this agricultural activity might be integrated into a successful IBS. We identified the materials flowing into typical mushroom operations, pinpointed when and where in the process they are employed, and outlined the impacts of the various emissions. The mushroom growing process consists of seven general stages, each of which requires its own distinct recipe of inputs and, subsequently, releases a unique set of outputs.

In the following section, we describe in some depth the individual stages of mushroom cultivation, and begin to frame the factors that will either limit or enhance opportunities for process innovation in the context of the development of an integrated bio-system. Figure 3 provides a simplified diagram of the mushroom growing process. As noted, a full mushroom growing cycle is approximately 10 to 15 weeks from delivery of compost to harvest of mushrooms.

Authors' note: the following descriptions of the mushroom growing process are taken from Wuest et al., *"Six Steps to Mushroom Farming." Some of the information has been shortened; however, the format and text are the work of these authors.*

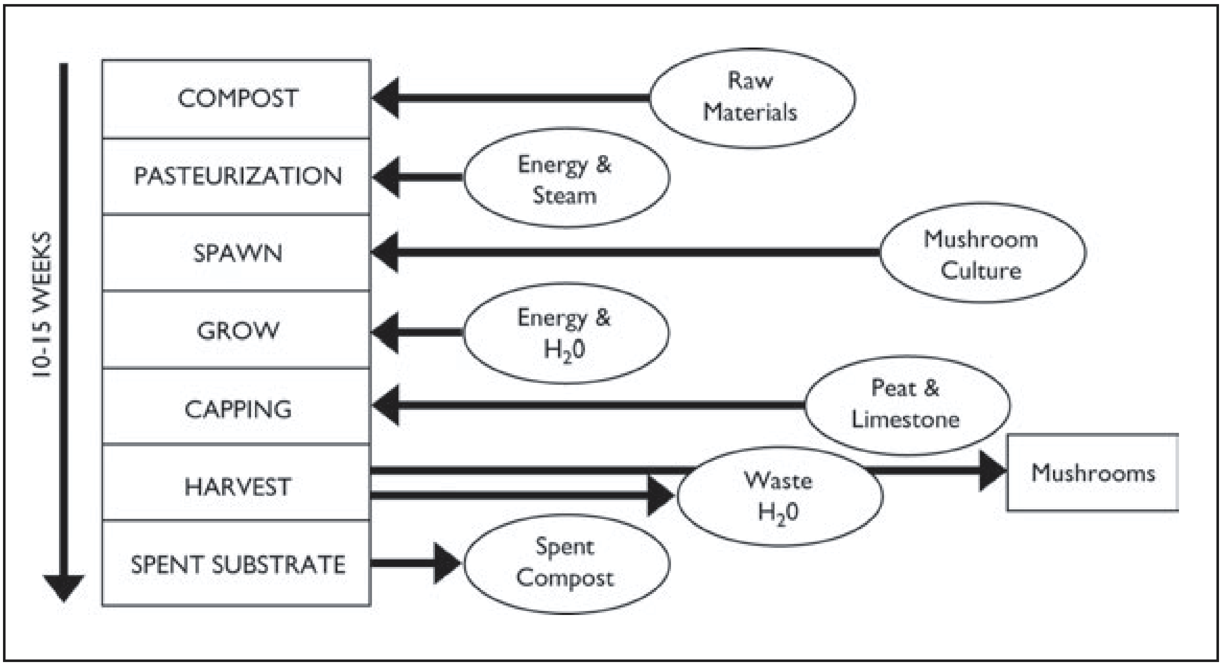


Figure 3 The Mushroom Growing Process

Stage One: Mixing Compost

The mushroom growing process starts with the formulation of a species-specific "substrate," a mixture comprised of composted organic and mineral ingredients which is intended to support the growth of the given type of mushroom. While farmers have considerable latitude in the approach they take to formulating compost, it is the most critical aspect of mushroom cultivation. Ironically, there is some evidence showing that this is the stage of the process most prone to farmer error.[2] A typical compost mixture for a modern farm is as follows:

- 50 parts straw-bedded horse manure
- 1 part dried poultry manure
- 1 part dried brewer's grain
- 1 part gypsum

[2] According to Bruce Wilkinson at Franklin Farms in Franklin, Connecticut, however, roughly 90% of farms formulate optimal compost for proper cultivation.

The quantity of materials used in a particular farm is proportional to the size of the farm. On average, farms in the U.S. produce two pounds of mushrooms per square foot of bedding each month. The ratio of compost to mushroom production is generally 2:1. Therefore, a large farm capable of producing 20 million pounds of mushrooms per year (there are 11 such farms in the U.S.) would need to utilize on the order of 1,500 tons of compost per month.

The set of potential compost ingredients is extremely broad, and varies widely according to the location of the farm, the nature of surrounding industries, and the types of mushrooms grown. Given the fundamental compost requirements and the spectrum of alternative ingredients, it is quite apparent that much of the compost material can be obtained from the waste streams of other processes.

Table 1 lists common compost ingredients, the rationale for their inclusion, and their relevance to three important environmental issues. The three environmental issues noted include: leaching potential during composting (L), energy required in production (E), and recycled vs. virgin origin (R). In order to facilitate development of a Life Cycle Assessment (LCA), we ranked each of the "rationale" and "environmental issue" elements according to its overall environmental significance.

Our ranking system revealed that the ingredients that have a high potential to leach also tend to be virgin materials, and that the processing of these materials requires a great deal of energy. One exception to this trend is that chicken manure (a waste input) exhibits a high concentration of nitrogen, which is very susceptible to leaching during the composting process.

…modern mushroom operations recycle and reuse a vast quantity of nutrients that are by-products of other industries, such as horse stables and chicken farms. The great scale and rate of this material flux amplifies the relevance of mushroom farming as a potential integral component of integrated bio-systems.

It is also interesting to note that modern mushroom operations recycle and reuse a vast quantity of nutrients that are by-products of other industries, such as horse stables and chicken farms. The great scale and rate of this material flux amplifies the relevance of mushroom farming as a potential integral component of integrated bio-systems. While it is apparent that examples of material exchanges abound in the mushroom industry, a detailed LCA of myriad exchanges was beyond the scope of this exercise. Nonetheless, we feel that it is particularly important to consider how the issue of scale effects the material inflows to a farm. For instance, it would be useful to know whether large farms use more or less raw materials than small operations. Do operations require a certain percentage of virgin material to ensure consistent quality and productivity? We believe that the trend in farm consolidation is a clear indication that economies of scale have a significant impact on the cost of production. Whether these economies of scale translate into benefits for the environment is unclear from our study of the process.

Stage Two: Managing the Pile

Once the compost ingredients are mixed, they start to decompose, a process through which the embedded nutrients are converted into forms that are useful

Table 1 Mushroom Substrate Ingredients

INGREDIENT	RATIONALE*				TYPICAL SOURCE	ENV. ISSUES		
Element ^{Rank}	N^{1}	C^{2}	B^{3}	O^{4}	Element ^{Rank}	L^{5}	E^{6}	R^{7}
Standard Ingredients								
Corncobs (whole, ground, crushed, pelletized)	X	X	X		Corn farm, corn sheller		?	?
Hay	X	X	X		Hay farm		X	
Horse manure – straw bedded	X	X	X		Horse farm			
Poultry litter/manure	X				Poultry farm	X		
Straw		X	X		Grain farm			
Possible Other Ingredients								
Adco	X				Fertilizer plant	X	X	
Ammonium nitrate	X				Fertilizer plant	X	X	X
Animal fat	X				Meat processor	X		
Brewers grains (wet or dry)	X				Brewery	X		
Corn fodder		X	X		Corn farm		X	X
Dried blood	X				Poultry or meat processor	X		
Feathers or feather meal	X				Poultry processor			
Fish solubles	X				Fish processor	X		
Grape pumice		X			Grape processor			
Ground wallboard				X	Construction industry			
Gypsum				X	Gypsum rock			
Gypsum, synthetic				X	Soil conditioner supplier			
Hardwood bark		X	X		Sawmill			
Hardwood tree leaves		X			Municipal leaf collection			
Licorice root	X					?		
Lime				X	Soil conditioner supplier			
Livestock manures	X				Livestock farm			
Mushroom stumps and culls					Mushroom farm			
Paunch		X			Meat processor	X		
Peat moss					Peat bog		X	X
Potash, potassium					Fertilizer plant	X	X	X
Potato waste		X			Food processor	?		
Seed-hulls		X			Seed processor			?
Seed-meal	X				Seed processor	X		?
Seed-oil	X	X			Seed processor			?
Shredded newspaper		X			Newspaper recycler			
Sugar cane (bagasse)		X	X		Sugar processor	?		
Sugar cane (pulp)		X			Sugar processor	?		
Urea	X				Fertilizer plant	X	X	X

KEY TO TABLE

*Rationale:
1= Nitrogen
2= Carbon
3= Bulk
4= Flocculent or pH control

Environmental Issue:
5= Leachability
6= High Energy Use
7= Virgin Material

to mushrooms. The goal of composting is to produce a food source suited to the growth of a specific mushroom, to the exclusion of competing fungi and bacteria. The proper proportions and amounts of water, oxygen, nitrogen, and carbohydrates must be present throughout the process to achieve optimal growing medium.

The preparation of mushroom compost occurs in two steps, referred to as Phase I and Phase II composting. Phase I compost preparation usually occurs outdoors, although an enclosed building or a roofed structure may also be used. The compost is managed in a compost turning yard, also referred to as a wharf yard, which consists of a flat slab of concrete, asphalt, or a low-permeability earthen material. Compost-turning machines are used to mix and water the ingredients, while bucket loaders move the ingredients on the turning yard.

Phase I composting begins on many mushroom farms with a preliminary or “pre-wet” step, in which large heaps of a hay/straw mixture are soaked with water. The wetting step accelerates the growth and reproduction of microorganisms naturally present in the mixture, which leads to the production of heat. This serves to soften the hay and straw, making it more water absorbent. These heaps may be mixed together to produce a uniform starting compost. The pre-wet stage lasts from between 3-4 days to 12-15 days, depending on a range of operating conditions.

Following the pre-wet stage, the materials are arranged in a long pile over which nitrogen supplements and gypsum are spread. The pile, often referred to as a “rick” by farmers, is thoroughly mixed with a turning machine. Aerobic composting continues after the pile is wetted and formed.

The compost pile must be carefully erected and managed. Most compost piles are roughly five to seven feet wide, five to ten feet high, and as long as necessary or practical. The rick must hold its shape, while remaining loose enough to allow for aerobic conditions throughout. Turning and watering are done at approximately two-day intervals. Turning provides the opportunity to water and mix the ingredients, as well as to relocate the compost from the cooler exterior to the warmer interior, and vice versa. The aeration accomplished by turning is short-lived, so pile construction, structure, and contents are critical in promoting aerobic degradation. The number of turnings and the time between turnings depends on the condition of the starting material and the time necessary for the compost to heat up.

Water addition is critical. Too much water will exclude oxygen by occupying pore spaces, and may lead to an unnecessary loss of nutrients due to leaching, while too little water can limit the growth of bacteria and fungi. As a general rule, most of the water is added when the pile is formed and at the time of first turning. Thereafter, water is added only to adjust the moisture content. On the last turning of Phase I composting, water may be applied generously to carry sufficient water into Phase II. Water, nutritive assets, microbial activity, and temperature are like links in the composting chain. When one factor is limiting, the efficacy of the process may be diminished.

One of the management issues that farms often face is the creation of odor during the composting. These odors, which constitute a significant negative externality, are generated if mixtures are improperly formulated, or if piles are poorly managed. One way that farms are addressing this problem is through the use of aerated silos that force air into the compost mix. These innovative silos employ air jets embedded in the floor to introduce oxygen to the substrate, and feature solid walls to ensure the even distribution of air throughout the structure.

In July 1998, Pennsylvania-based Hy-tech Compost engineered an aerated silo that enables managers to monitor and adjust temperature, airflow, and odor using a centralized computer. Hy-tech reports that, in addition to mitigating odor emissions, this technology can reduce composting runs to as few as 9-12 days, compared to 16-21 days for traditional methods. Systems such as this also increase the likelihood that future composting operations will move indoors, where leaching can be controlled or eliminated entirely.

Stage Three: Compost Pasteurization

Once the compost has reached a proper state of decomposition, the pile is transferred to a separate room, where it sits for 48 hours at 132ºF. Raising the air and compost temperature to 140ºF initiates the pasteurization process, which lasts two hours. The pile is then gradually cooled over the next five days, or until it reaches a temperature of 85ºF. Pasteurization uses far more energy than any other process during the mushroom cultivation.

Pasteurization is conducted to kill any insects, nematodes, competing fungi, or other pests that may be present in the compost. The heating process also reduces ammonia levels by favoring the growth of thermophilic (heat-loving) organisms that consume carbohydrates and nitrogen. High ammonia levels can be lethal to mushroom spawn.

Stage Four: Spawning

Spawning is the mushroom culture equivalent of planting seeds for a field crop. Whereas vegetable crops are planted using fruiting seeds, mushrooms are “planted” using fungal mycelia. Fungal mycelium propagated vegetatively is known as spawn (Latin expandere = to spread out). Making spawn requires laboratory facilities that are not contaminated by the mycelia of other fungi. The spawning process starts with the sterilization of a mixture of cereal grain, water, and chalk. Once bits of mycelia have been added to the sterilized porridge, the mix is incubated to promote mycelia growth.

At the mushroom farm, spawn is thoroughly mixed into the compost using a special machine. After the spawn has been blended with the compost, the compost temperature and the relative humidity in the growing room are managed to optimize mycelia growth. The spawn grows out in all directions from a spawn grain. The time needed for spawn to fully colonize the compost depends on the amount and distribution of the spawn, the compost moisture and temperature, and the nature or quality of the compost. Completing the spawn run usually requires 10 to 21 days.

Stage Five: Casing

Casing is a top-dressing applied to the spawn-run compost, and is necessary for mushrooms to develop from the mycelia that have grown throughout the compost. It can be comprised of clay-loam field soil, a mixture of peat moss with ground limestone, or reclaimed spent mushroom substrate (SMS) and is used not to supply nutrients, but rather to act as both a water reservoir and a rhizomorph habitat. Rhizomorphs, resembling thick strings, form when the very fine mycelia grow together. Casing holds moisture that is required to produce a firm mushroom. Immediately following casing, water must be applied intermittently to raise the moisture level of the bed to a maximum capacity, ensuring that mushroom pins will form.

We discovered that recent innovations in the casing process have already improved the environmental performance of mushroom cultivation. Traditionally, the casing mixture included peat moss – a product produced from a virgin source and trucked long distances. Early research into the growing process showed that peat moss casing improved crop production by about 6% each year. Today, the mushroom industry has found a way to reuse spent mushroom substrate (SMS), thus recycling the industry's most voluminous by-product and eliminating its reliance on peat. Farmers have also found a way to employ SMS to reduce the incidence of a disease called verticillium.

Stage Six: Pinning

Mushroom fruiting bodies – referred to as initials, primordia, or pins – are small outgrowths from the rhizomorphs that form in the casing layer. These fruiting bodies continue to grow larger through a button stage, and ultimately enlarge into mushrooms. Pinning affects both the potential yield and quality of a crop.

Stage Seven: Cropping

Harvestable mushrooms appear 16 to 28 days after casing. Following a successful pinning, blooms of mushrooms called "flushes" or "breaks" make their appearance. Once mature mushrooms are picked, an inhibitor to mushroom development is removed, and the next flush moves toward maturity. This regrowth process is repeated in a 7-10 day cycle, and harvesting can be repeated as long as mushrooms continue to mature.

The length of the harvest is a concern from an industrial ecology perspective, as well as from a business perspective. Most mushroom farmers harvest for 25 to 35 days, but harvest can continue for as long as 150 days, with yields decreasing over that period. Temperature, water management, and ventilation continue to be critical parameters throughout the growing period, but the most critical aspect is the potential buildup of disease pathogens and insect pests that can cause crop failure and lead to increased costs and use of pesticides. These pathogens and insects can be controlled through sanitary conditions, good tool cleaning, and isolation of the crop – or through the use of pesticides. However, a farm that uses shorter harvesting cycles reduces the time for pests to become established and to proliferate in the growing room. Once a crop is finished growing, the area is thoroughly cleaned, a necessary procedure to destroy any pests that might be present in the crop or the growing room. Cleaning and rinsing are a major source of wastewater, as growing areas are often treated with sanitizing agents.

END-OF-LIFE CONSIDERATIONS

The overriding industrial ecology problem facing the mushroom industry is the disposal of spent mushroom substrate (SMS). In this country, mushroom farms have to handle nearly half a million tons of SMS annually. While this material is high in nutrients and has numerous uses, there are few viable options for disposal beyond the mushroom farm. Because the mushroom industry is geographically concentrated, the number and diversity of local uses for farm waste is limited. The seasonality of local agricultural businesses compounds this bottlenecking condition, by severely restricting the scheduling of outflows of SMS.

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As a result, SMS often accumulates to unwieldy volumes, creating odor, disease, and nutrient leaching problems. Odors and nutrient runoff have a noticeable, detrimental impact on the local environment. Research has shown that a three-foot pile of SMS leaches 2,500 pounds of nitrates per acre into the soil – 25 times the average nitrate level for a fertilized cornfield. A five-foot pile releases 60 times the nitrates found in a fertilized cornfield's soil. In addition, leachate from SMS can have up to 100 times the organic carbon of pondwater (5,000 and 10,000 milligrams per liter vs. 100 to 200 for a nutrient rich swamp) (PADEP 2000).

We looked at the various means by which mushroom farmers might deal with these pollution problems and broke them down into two different categories: 1) short-term management solutions, and 2) longer-term uses for the SMS and wastewater.

Short-term Management Solutions

In general, mushroom substrate retains much of its original nitrogen and carbon content when it exits the operation and contains significant amounts of potassium, calcium, and magnesium. These five elements are highly leachable and create problems for the reuse and disposal of SMS. The traditional method for handling this problem is to allow the SMS to naturally weather in the field, either through active or passive composting. To prevent the leaching materials from entering the environment, both of these methods must be implemented with diligence and discipline (PADEP 2000).

Passive composting or curing involves creating shallow piles of SMS, and allowing it to decompose naturally into a more stable, humus-like product. This material can then be used as casing in mushroom growing operations or for other agricultural purposes. This system cannot maintain the same high temperature conditions necessary for rapid composting and, therefore, results in slower decomposition.

The advantages of passive composting come from the minimization of labor and machine inputs during the composting process. The disadvantages include longer composting times, increased exposure to runoff problems, and large land area requirements.

Active composting involves mixing the SMS, and forming it into elongated piles or windrows, which are periodically turned or agitated. This process provides faster decomposition due to higher temperatures within the mass of the pile. Turning the pile provides temporary cooling of the hot interior, transfers cool outer material to the pile interior, prevents compaction, and disperses gases and water vapor (PADEP 2000).

Best Management Practices

Many pollution problems associated with composting can be alleviated simply through the adoption of best management practices. For a passive composting operation, such practices would include:

- Maintaining shallow piles less than three feet to discourage anaerobic conditions and odors;
- Preventing stormwater runoff;
- Applying vegetative cover.

The best management practices for active composting include:

- Composting on a concrete or compacted low-permeability surface;
- Collecting waste liquids for reuse in the composting process, or for storage and treatment;
- Managing piles to maintain aerobic conditions;
- Diverting stormwater runoff to controlled areas. (PA DEP 2000)

Potential Reuse of Spent Substrate

Among the most simple and inexpensive uses of SMS and wastewater produced in a mushroom farm is to apply them to agricultural land as a substitute for nitrogen-phosphorous-potassium (NPK) fertilizers, and to use them as a conditioner to improve the organic fraction and porosity of soil. Applying SMS to fields and lawns nourishes vegetation, improves the aeration and water-holding capacity of soil, decreases soil erosion potential, and promotes the growth of beneficial soil organisms (PADEP 2000).

Unfortunately, many SMS or wastewater management systems do not fully utilize the nutrients in SMS. Applying SMS or wastewater either in excess, at the wrong time, or otherwise handling them improperly, releases nutrients into the air and water. Instead of nourishing crops, nutrients may leach into soil and groundwater. One common mistake is the practice of applying commercial fertilizer in conjunction with SMS, without accounting for the nutrient value of SMS itself (PADEP 2000).

SMS is often applied directly to an existing crop (e.g. hay) as either a mulch or fertilizer. Due to the physical characteristics of SMS, its nutrients are in a more stable form than those in raw ingredients and manure. They pose less threat to surface water resources, if reasonable care is taken to avoid application to areas where erosion is likely.

Application of SMS to Non-Agricultural Land

A number of research papers that we reviewed examined the potential of using large quantities of SMS for reclamation of mined land, as a substitute for topsoil in landscaping and construction projects, or as a material for wetland restoration.

All of these uses are potentially valuable and interesting outlets for the solid by-products of mushroom farming. In the case of mine reclamation, the potential utility of organic material is enormous, particularly if the mine site and mushroom farm were in close proximity to one another. This use could constitute steady demand for farm wastes.

An in-depth examination of the potential for using mushroom substrate to restore mine lands would include cost-benefit analyses of the various transportation options. For instance, it would be prudent to consider using existing rail lines as a means of moving SMS to the mine. Because mine reclamation is a heavily regulated activity, developing a restoration strategy that incorporates mushroom farm waste would require close coordination between industry and the relevant regulatory agencies.

The demand for other potential non-agricultural uses of SMS – for landscaping of construction sites and large land developments like golf courses – is likely to be sporadic in nature. Furthermore, if SMS is to replace traditional materials (fertilizer and topsoil) its use will have to demonstrate cost advantages.

Additionally, one of the biggest challenges to devising alternative uses/solutions is that the majority of SMS residue is concentrated geographically. In 1998, for instance, 40% of all mushrooms grown in the United States were produced in limited regions in Pennsylvania and California.

LONG-TERM SOLUTIONS

As discussed in the preceding sections, mushroom farming offers numerous attractive possibilities for green twinning between the mushroom farm and other businesses and industries that produce organic wastes. Most of the uses for SMS that we investigated are either seasonal or sporadic in character. For example, a golf course would only be a one-time user for SMS and the demand for potting soil is generally seasonal. Additionally, one of the biggest challenges to devising alternative uses/solutions is that the majority of SMS residue is concentrated geographically. In 1998, for instance, 40% of all mushrooms grown in the United States were produced in limited regions in Pennsylvania and California (USDA 1999). It is hard to say if this concentration benefits or hinders the maintenance of industries that reuse SMS, but certainly in the case of some uses, the supply far outstrips the local demand.

IBS Options for Mushroom Farms

In keeping with the principles of industrial ecology and the IBS conceptual framework discussed earlier, we looked beyond the ways in which a mushroom farm might market its SMS for off-farm uses and examined ways that a farm might develop value-added on-farm processes for integrated reuse of spent substrate.

In considering this challenge, we established certain criteria to guide the development of alternatives. Any potential on-farm solution must:

- Leverage farm's infrastructure and expertise;
- Minimize additional inputs;
- Demonstrate financial viability.

Based upon these three criteria, we developed two models, which will be discussed below as the basis for further research on applying the concepts of industrial ecology to mushroom farming.[3]

The first alternative considers a method to use spent mushroom substrate to grow additional products, while the second looks at the possibility of using the SMS as an energy source for producing steam and electricity that could be used to supply the power demands for the farm.

SMS as an Input

Cultivation of Mycorrhizae

There has been extensive work done on the process and feasibility of using SMS as a substitute for peat or as a potting medium in containerized plants. Some researchers believe that SMS can be a new source of potting medium for the greenhouse industry. One reason that this would be attractive is the need for growers to obtain a uniform product. Currently, nursery growers in Eastern North America use potting materials that are shipped great distances – peat moss from Michigan and Canada, and wood bark from North and South Carolina and Georgia. If mushroom growers can demonstrate the substitutability of this product to the greenhouse industry and as long as shipping costs are not prohibitive, then it could be a valuable outlet for the industry.

The idea of cultivating mycorrhizae builds on the potential of using SMS as a potting medium. Mycorrhizae are highly valuable, difficult-to-culture fungi which facilitate nutrient uptake by green plants. Because they are fungi (like mushrooms), there are numerous similarities in their culture; however, it is commonly believed that cultivation of mycorrhizae on a large scale is difficult and expensive. Because of this, we propose the idea of creating a system for cultivating mycorrhizae in tandem with the production of mushrooms. In this manner, a mushroom farm enters the market for a new valuable product, while at the same time benefiting from numerous synergies on the production side. Such synergies might enable a mushroom farm to have lower costs, as compared to a stand-alone

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[3] Note that as we were unable to investigate financial considerations and numbers for an actual working farm, our third criteria, financial viability, is beyond the scope of this paper.

mycorrhizae operation. For example, a mushroom farm is likely to have the following infrastructure in place:

- Existing heating and steam generating facility;
- Steam pasteurization equipment;
- Laboratory facility for culturing mushrooms;
- Scientific expertise in growing fungus;
- Large amount of organic material suitable for growing plants (SMS).

Several other requirements for mycorrhizae horticulture must also be considered. For example, most of the appropriate fungi are obligate symbionts, meaning that they cannot be grown in pure culture. Mycorrhizae must be cultivated in the roots of green plants and, to avoid contamination, they must be grown in sterile conditions. Except for the symbiotic relationship with green plants, all of these conditions are true for mushroom farming.

Conceptually, then, mycorrhizae could be grown in greenhouses and harvested from the roots of plants grown in the spent compost from the mushroom house. The waste stream from this process would be fully composted as the green plants and the mycorrhizae further take up and use the nutrients in the SMS (See Figure 4).

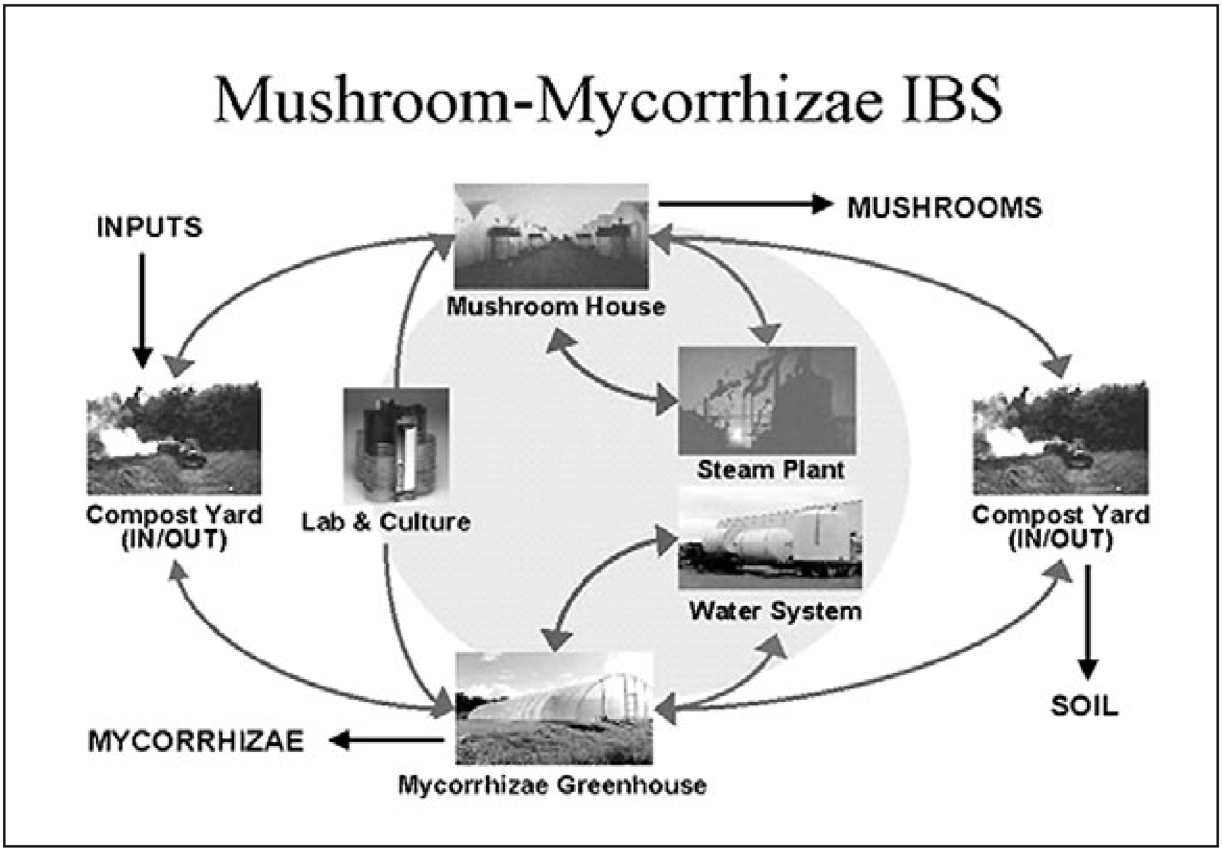

Figure 4 Mushroom/Mycorrhizae Farm

While we found several companies which are marketing mycorrhizae, suggesting that there are commercial uses for the fungus, the details of the growing process appear to be closely-guarded trade secrets. Therefore, it is difficult to realistically estimate the amount of SMS that would be diverted from the waste stream under this scenario.

Potential Markets for Mycorrhizae

Essentially, mycorrhizae are fungi (myco = fungus, rhizae = root) which attach to plant roots in order to exchange nutrients in a symbiotic relationship (Harley and Smith 1983). When a fungal spore germinates in the soil, it forms a sheath around the root. The presence of mycorrhizae can have significant effects on the morphology of a plant's root system. For instance, many fungi are capable of producing plant growth hormones that change the branching pattern of the root system (Allen 1992).

The most well-known benefit to plants from mycorrhizae is an increased uptake of phosphorous. In general, mycorrhizae will increase the uptake of any nutrients that move through the soil primarily by diffusion. The fungus is able to extend out from the root much farther than the plant's own root hair can, and thus it reaches the nutrient sooner than a root hair would. Also, the surface area of the fungus can be many hundreds of times larger than the root's (Altman 1993).

Greater surface area and reach is not the only way mycorrhizae can aid plants in the uptake of minerals. While many nutrients in the soil are in a chemical form that plants can neither absorb nor use, mycorrhizae can secrete enzymes that break down the substance extracellularly. The fungus then absorbs the nutrient and transports it to the plant, indirectly helping the plant gain nutrients (Altman 1993).

To some extent, mycorrhizae can also aid plants in drought and pest resistance, though the mechanisms involved are poorly understood. Mycorrhizae can help control pests such as pathogenic fungi and nematodes by releasing antibiotics into the soil which reduce the risk of infection. In the case of other fungi, sometimes the mycorrhizae will simply out-compete the potential pathogen for nutrients and food. Even the very presence of the mycorrhizae can trigger the plant to produce natural defenses in the root (Abbott and Robson 1984).

In addition, mycorrhizae offer benefits that could improve crop value, including increases in seedling survival rate, plant growth rate, number of flowers produced, and even the survival period for cut flowers.

Currently, the literature about the practical use of mycorrhizae suggests that it is still more expensive than traditional NPK fertilizers. However, it is also suggested that excessive fertilization is not only a costlier, but also an inferior way to enhance plant performance. We spoke briefly with Professor Graeme Berlyn at the Yale School of Forestry & Environmental Studies, whose company "ROOTS" markets a product that uses mycorrhizae. Dr. Berlyn felt that the full value of mycorrhizae might lie more in adding them to products to recover heavily degraded, eroded, or compacted soil.

Despite the current problems with commercial mycorrhizae production, some companies are producing innoculum available to both large scale nurseries and backyard gardeners and farmers. One company in Oregon (Bio-Organics 2000) sells three pound boxes of mycorrhizae spores to spread on a plant's roots during transplanting, or to mix with seed. The recommended rate is one pound per acre with an advertised cost of $25.00 per acre. There is also some potential to sell very specific mycorrhizae for particular applications; for example, a product could be developed to target just one type of crop or flower.

SMS Used as an Energy Source

Biogas Recovery

A conceptual alternative to developing another sub-system or process that uses the SMS as a supply source (i.e. mycorrhizae production) is to use the SMS as an energy source to meet the potentially high energy demands of a mushroom production facility.

One method that has potential in this application is anaerobic digestion. This concept is particularly compelling in light of the high energy and water demands of a mushroom farm. The material flows in this process are outlined in Figure 5 below.

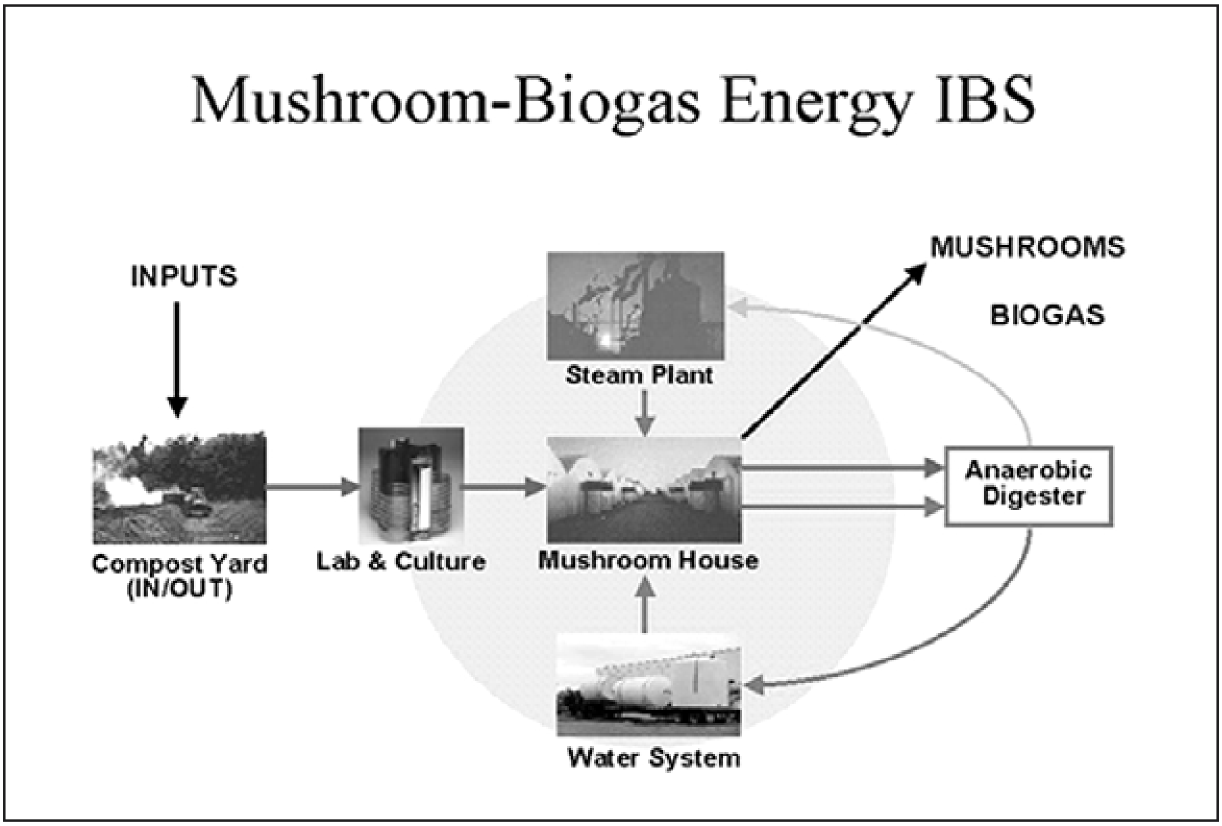

Figure 5 Mushroom/Biogas Recovery IBS

Anaerobic digestion reduces the bulk of organic waste by converting it into a relatively stable solid residue (digestate) similar to compost. Unlike composting, however, anaerobic digestion requires an oxygen-free environment and specialized bacteria.

The byproduct of this bacterial action is a "biogas," which is composed of methane and carbon dioxide. Anaerobic digestion has been used in sewage treatment for some time, and there are numerous examples of waste water treatment plants recovering biogas to meet energy demands for heat and power.

Another aspect of anaerobic digestion is that it is considered most useful for wet wastes since the water helps in the process and maintenance of the anaerobic bacteria. It is therefore likely that a digester built for a mushroom farm would have to combine the farm's water treatment capacity with a biogas plant.

A recent development is the fuel cell technology for electrical generation. Increasingly, fuel cells are being used in conjunction with biogas recovery operations at landfills to create electricity.

After SMS leaves the growing process it would move into the anaerobic digester where microbial activity begins. The steam for this process can be generated using the biogas, raising the temperature of the waste to increase the rate of degradation within the reactor. Waste degradation is also made more effective by adding a bacterial innoculum. This innoculum is supplied from either the waste stream from the reactor or from the farm's waste water. The mixed waste is then fed into the reactor, in which degradation occurs, producing a relatively solid residue and biogas. The biogas can be used for energy generation directly, or can be used to generate steam. The solid waste that is produced is de-watered before further treatment or disposal.

There are numerous designs and configurations of anaerobic digesters. Some operate at warm temperatures (about 30-40°C – the "mesophilic" range). Generally speaking, the higher the temperature, the faster the process, but thermophillic processes may be harder to control and need more biogas for heating to keep them at the required temperature. Other variations include low or high volume systems, single or multi-stage digester vessels, and continuous flow or batch processes.

The size of a digester depends on the amount of organic matter to be processed into gas and liquid fertilizer. Practically Green^{TM}, a company in Ireland, offers the following guidelines for estimating the volume and outputs of an anaerobic digester: "for a 'rule of thumb' figure, use a loading rate of six kg dry matter per day per cubic meter of digester" (Practically Green^{TM} 2000).

Based on the production figures for a large mushroom farm that can produce a million pounds of mushrooms per month, the amount of SMS produced would be on the order of 30 metric tons per day (or 2,000,000 pounds per month). Assuming this material is 20% dry weight, using the formula from Practically Green^{TM}, we estimate that a large farm would produce six metric tons per day dry weight. This translates to a 1,000 cubic meter digester.

The production of gas and electricity from a digester is heavily dependent on the efficiency of the digester – the rate of conversion of dry matter to biogas. Practically Green^{TM}'s estimates for the efficiency of digester systems are about 50%. However, they note that for some old organic wastes, which may have already been partially composted, the gas production may be reduced by two-thirds – yielding an efficiency of 16% in the conversion of dry matter.

In most systems with electrical generation, the engine will produce about 2 kWh of hot water for each 1.7 kWh of electricity produced. Half of the hot water is needed to heat the digester. Determining the economic feasibility of building a digester would require a sound estimate of the amount of gas that would be produced from SMS, as well as a consideration of the long-term cost savings attributable to using the gas as a supplemental energy source.

CONCLUSION

From an environmental perspective, the elimination of waste represents the ultimate solution to pollution problems. For individual businesses, achieving a "zero emissions" outcome often translates into greater efficiency, enhanced productivity, and competitive advantage. Such improvements also represent "...a shift in our concept of industry away from linear models in which wastes are considered the norm, to integrated systems in which everything has its use. It heralds the start of the next industrial revolution in which industry mimics nature's sustainable cycles" (ZERI 2000). Mushroom farming has the potential to offer a zero-waste production process that contributes to this goal.

Mycorrhizae cultivation could represent a new and potentially lucrative market, in which cost savings can be achieved through synergies between the mushroom and mycorrhizae production processes. Likewise, biogas recovery provides an opportunity to realize substantial energy cost savings.

This paper identifies potential short-term and long-term options for dealing with spent mushroom substrate, the most voluminous residue of the mushroom cultivation process. In the short-term, best management practices, recycling, and certain non-agricultural uses appear to be the most feasible solutions. Long-term solutions, however, offer the possibility of developing integrated bio-systems, which combine mushroom farming with other on-farm uses for the substrate. We identified two such systems: a mushroom farm/ mycorrhizae IBS and a mushroom/biogas recovery IBS. Both of these models utilize emerging, innovative technologies to make efficient use of substrate residue. In the first case, it serves as an input to another agricultural process; in the second, it is employed as a source of energy.

The addition of another biological sub-system (either mycorrhizae cultivation or biogas recovery) to the typical mushroom farming operation increases the potential to turn linear material flows into closed and environmentally-sound systems that reduce waste emissions.

In addition to environmental benefits, a mushroom farm IBS may also supply economic benefits to both the individual business and the community. For instance, the addition of another biological sub-system to an existing mushroom farm should be viewed as a business growth opportunity. Mycorrhizae cultivation could represent a new and potentially lucrative market, in which cost savings can be achieved through synergies between the mushroom and mycorrhizae production processes. Likewise, biogas recovery provides an opportunity to realize substantial energy cost savings. Admittedly, an individual mushroom farm would need to conduct a detailed analysis of these separate investments, in order to determine their operational viability and profitability.

Finally, the development of a mushroom farm IBS creates the potential for upsizing. By adding more components to the existing system, one can create new production chains, new jobs, and more diverse revenue streams. Thus, what initially was conceived as a solution to a waste problem has become a valuable tool for realizing both economic and environment gains.

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