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27 April 2024

Systemic Design of a Productive Chain: Reusing Coffee Waste as an Input to Agricultural Production

A case study from Turin uses coffee waste for mushroom farming

With the increasing complexity of production in today's economy, it has become fundamentally important to free ourselves from focusing solely on individual products and their life cycles. In the design sphere, we must expand our attention and apply our skills to understanding the many connections that are spawned by the production process.

We need to regain the cultural knowledge and experience that allows us to define and design production flows that can traverse different systems in a continuous process that decreases the ecological footprint of products while increasing income throughout the economy. Such a systemic approach can design flows of material and energy in a way that enhances productive processes and creates a new economic model based on open industrial cycles.

Background: Coffee Waste Research Project

The research discussed here proposes a cycle for reusing a resource that is currently considered waste. Specifically, it focuses on deriving value from waste produced during the preparation of coffee for consumption.

The case study discussed in this article is part of an overall research project aimed at examining how coffee waste can be used in three stages: first as a source of lipids and waxes for pharmaceutical production, then as a substrate for farming mushrooms, and finally as a medium to grow worms for vermicompost.

The implementation of this research project was carried out in partnership with one of the largest coffee companies in Italy. The project tested the feasibility of the proposed process in the local area around Turin. The process described here has also been demonstrated in other locations around the world (including Colombia, Zimbabwe, and Belgrade).

Silvia Barbero and Dario Toso

Understanding and Applying Systemic Design

Designing Industrial Systems

Designing products on an individual basis cannot address complex environmental problems. Even when the designer tries to coordinate a range of factors (including functional, technical, symbolic, cultural, and production issues), the solutions identified will be specific to the product itself and will generally overlook larger or systemic issues.

The systemic design approach seeks to create not just industrial products, but complex industrial systems. It aims to implement sustainable productive systems in which material and energy flows are designed so that waste from one productive process becomes input to other processes, preventing waste from being released into the environment. This model is inspired by the theoretical structure of generative science, according to which every modification in resources generates by-products that can represent added value.

The theoretical model for the project discussed here focuses not only on increasing the value of coffee wastes and retrieving packaging materials at end of life, but also on designing an entire complex system.

Applying Systemic Design to Coffee Waste

The theoretical model for the project discussed here focuses not only on increasing the value of coffee wastes and retrieving packaging materials at end of life, but also on designing an entire complex system.

The preparation of coffee for drinking produces waste with a high water content, but it does not fundamentally change the substances involved (such as cellulose, minerals, polyphenols, and lipids). Coffee is packaged in layers of valuable materials, including aluminum and polyethylene terephthalate (PET) plastic. However, the packaging is not used to its full potential. Instead, it generates a social cost when it is disposed.

Potential Uses for Coffee Waste

The applied research discussed in this article centers on evaluating the potential uses for coffee waste. Our study demonstrates that this waste material can be a useful resource for new productive activities, and that it can generate new opportunities for services and products that offer environmental and economic benefits.

Through the application of systemic design, the output (waste) from preparing coffee for consumption becomes input for other uses:

- *Lipids and waxes*: One of the processes normally used to leach caffeine from coffee beans in order to produce decaffeinated coffee (high-pressure and supercritical carbon dioxide) could also be used to extract lipids and waxes from coffee waste for use in pharmaceutical factories.
- *Substrate for growing edible mushrooms:* The lipid extraction process creates a compact paste that could be used in making a substrate suitable for growing a species of edible mushroom (*Pleurotus ostreatus*) that has excellent nutritional and pharmaceutical characteristics.
- *Natural fertilizer:* After mushroom growing has been completed, the exhausted substrate could be further used in agriculture for growing worms to create vermicompost.

Systemic Design Project: Deriving Value From Coffee Waste

Coffee Production and Consumption

Coffee plants, which grow best in tropical and subtropical climates, are farmed commercially in over 70 countries in Latin America, Africa, and Asia. Coffee farming occupies around 10 million hectares (ha) of land and employs about 25 million families worldwide, working in more than 5 million productive units.[1] The most widely grown varieties of coffee plant are *Coffea robusta* and *Coffea arabica*.

Coffee beans are exported as green coffee, with beans being selected for size, dimension, shape, weight, and color. They typically are packed in 60-kilogram bags made of jute (burlap). The material is natural and durable, and allows the coffee beans to breathe.

Coffee beans generally are roasted in the countries where they are imported. The roasting process uses flows of hot air (180–240°C) that pass over the beans as they are lightly shaken in containers (often horizontal drums that rotate).

Worldwide production of raw coffee totals around 7 million tonnes per year. Italy imports about 410,000 tonnes of raw coffee each year,[2] of which around half is *arabica* and half is *robusta*. Italy also exports about 3,800 tonnes of roasted coffee per year, produced by about 750 coffee roasters.

In Italy, about 70 percent of coffee is consumed at home. Another 25 percent is consumed in public places, such as coffee shops. The rest is consumed in offices.

Coffee Waste in Turin

The project discussed here focused on deriving value from the waste that is left after coffee has been prepared for drinking. We worked with one of the largest coffee companies in Italy to formulate concrete steps that could be applied in the short term at an industrial level.

In the early stages of our research, we reviewed the state of the art with regard to coffee distribution in Turinese coffee shops, with special attention to the quantity and quality of coffee waste. Defining the area involved in the study and the kind of coffee used was very important because these factors define the boundaries of the system.

We chose to deal with coffee waste from coffee branded shops/bars because that kind of waste is more homogeneous and easier to trace than coffee waste produced from domestic consumption. See **Exhibit 1**.

The coffee company we worked with controls about 65 percent of the market share for homes and coffee bars in Turin, selling about 976 tonnes of coffee per year. The company stocks approximately 60 percent of the coffee shops in the province (around 600 establishments). This quantity of coffee produces about 1,952 tonnes of coffee waste each year (since 7 grams of coffee generate about 13 grams of coffee waste), of which 470.270 tonnes come from coffee shops.

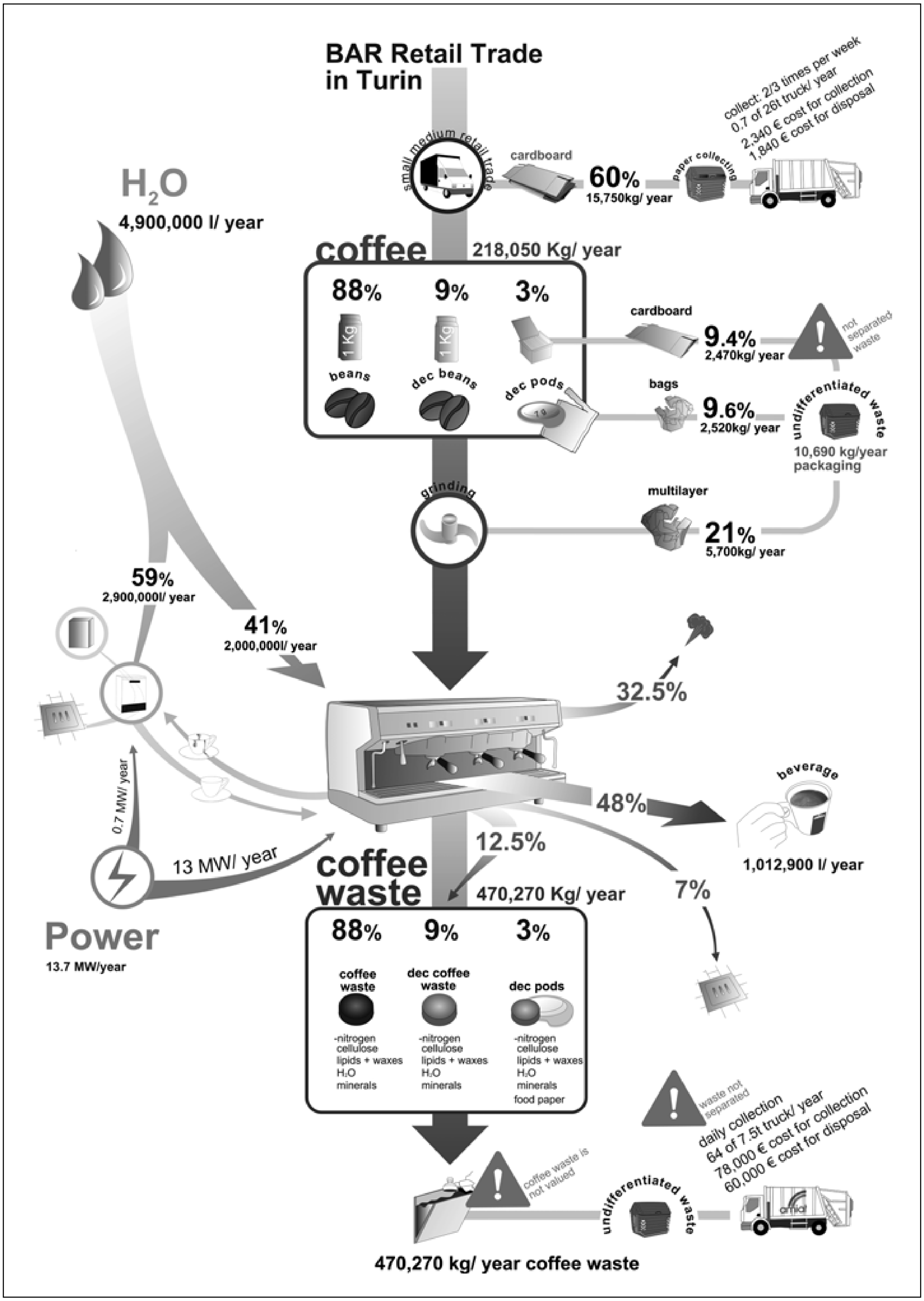
The project discussed here focused on deriving value from the waste that is left after coffee has been prepared for drinking.

The coffee is distributed through a small to medium network. The cardboard containers in which the coffee is shipped generate about 15,750 kilograms (kg) of material each year. These containers are picked up by an organization that handles the collection of items for recycling, at a cost of €4,180 per year.

Most of the coffee intended for coffee shops (88 percent) is distributed in 1-kg packages of coffee grains (beans). Another 9 percent is distributed in 1-kg packages of decaffeinated grains. The remaining 3 percent is distributed in paper coffee pods, which may be packed in pouches made with aluminum.

Once the coffee reaches its destination, it is ground and put into coffee machines that process it for drinking. These machines use about 2,000,000 liters of water per year. In addition, another 2,900,000 liters of water per year are required for cleaning and washing coffee cups. So coffee making and cup washing account for 41 and 59 percent, respectively, of the total water

Exhibit 1. Coffee Waste in Turin



consumed in connection with preparing and drinking coffee.

Only about 48 percent of the water put into coffee machines becomes part of the actual beverage. Another 32.5 percent is emitted as steam, while about 7 percent goes into the wastewater disposal system.

Coffee waste is usually collected in boxes that are placed near coffee machines for convenience. Most of the waste is then disposed of in bins with other materials. In many cases, coffee waste is not considered "organic" because it may contain some waste from pods.

In Turin, the organization that collects and disposes of rubbish is Azienda Multiservizi Igiene Ambientale Torino SpA (Amiat). This company disposes of 2,045 tonnes per year of coffee waste and packaging. Some essential data on coffee packaging shows that it amounts to 10,690 kg per year. About 2,470 kg per year of this waste is cardboard, another 2,520 kg per year is pod waste, and 5,700 kg per year is multilayer waste.

Currently, coffee wastes are considered to have no value. They are disposed of as undifferentiated rubbish, at a cost of about €60,000 per year for about 470,270 kg of coffee waste annually.

Identifying Key Issues

The most critical issues that emerge from analysis of the current situation are the following:

- coffee wastes are considered to be discards, and are not seen as a potential resource, and
- coffee wastes are processed in a linear way from cradle to grave, rather than as part of a system that could capture value; the potentially usable materials found in coffee waste, such as polyphenols and lipids, are simply thrown away, increasing costs and depriving the local community of a beneficial resource.

Disposing of coffee waste in garbage dumps involves both economic costs (for collection, transportation, and treatment) and environmental costs that fall directly on the community.

Our analysis also reveals policy lapses with respect to packaging reuse, especially for multilayer materials. There currently is no organization or consortium in Turin that deals with collecting and recycling such wastes, making it even more critical to recover these materials for reuse.

The main problem connected with deriving value from multilayer waste is related to the fact that it is composed of several different materials (including polypropylene, polyethylene, and aluminum), which cannot be separated easily, even if they have high value. Recently, some producers have begun pilot projects to collect and recycle aluminum packaging, but the number of units collected is still very small.

Disposing of coffee waste in garbage dumps involves both economic costs (for collection, transportation, and treatment) and environmental costs that fall directly on the community.

Although our preliminary analysis underscored the importance of addressing the packaging issue, our research study focused specifically on coffee waste.

Generating New Value Chains for Coffee Waste

Based on the critical issues highlighted by the analysis discussed earlier, our research project focused on developing a new hypothesis premised on the idea that wastes from linear processes can be treated as inputs to other activities, thereby generating complex and branched productive systems.

Our proposal involved collecting coffee waste from coffee shops, using the same bags in which the coffee was packaged during the distribution phase, and then transporting the waste to a plant for separation of coffee waste and packaging. Because the physical characteristics of the two wastes are so different, the process can be mechanized very easily, integrating two products into a single distribution system.

The design hypothesis specifies that packaging will be treated at the plant in order to divide multilayered packaging into different secondary raw materials (such as PET, polyethylene, and aluminum). This would decrease transportation costs for Amiat, the rubbish collection organization.

The coffee waste will then be treated to extract lipids. The regulatory and technical aspects of this process are such that it could be done in the same machinery that is used to extract caffeine from coffee beans. The extraction technology proposed would use carbon dioxide (CO_2) at its supercritical point, which allows for nonaggressive extraction of lipophilic substances. The lipids and waxes obtained would be used in the pharmaceutical industry, giving them high economic value: 470,270 kg per year of coffee waste could produce about 19,500 kg per year of lipids and waxes.

After the lipids are extracted from the coffee waste, the compact paste that remains could be used as part of a mixed substrate for growing edible mushrooms.

After the lipids are extracted from the coffee waste, the compact paste that remains could be used as part of a mixed substrate for growing edible mushrooms. There are many varieties of edible mushrooms that can be farmed. After analyzing a number of relevant factors, such as nutritional and pharmaceutical properties, ease of cultivation, and place of origin, we chose to focus on the species *Pleurotus ostreatus*, commonly known as the "oyster mushroom."

After mushroom growing is completed, a large amount of exhausted substrate (about 783,000 kg per year) would remain. This substrate would not contain cellulose, but would be rich in lignin and minerals and would have a pH value in the range of 6 to 7. It could be used as a medium for cultivating worms that would produce vermicompost, which in turn can be used to make soil more fertile and suitable for cultivation.

For a diagram of this proposal, see **Exhibit 2**.

Case Study: Using Coffee Waste for Mushroom-Growing Substrate

We carried out a field experiment to verify some of the research project's hypotheses. These hypotheses were formulated using a systemic approach, based on our coffee company partner's distribution chain within the boundaries of Turin.

The experiment focused specifically on how coffee waste could be used as a component of the substrate needed for growing mushrooms. The main goals of this field experiment were to verify:

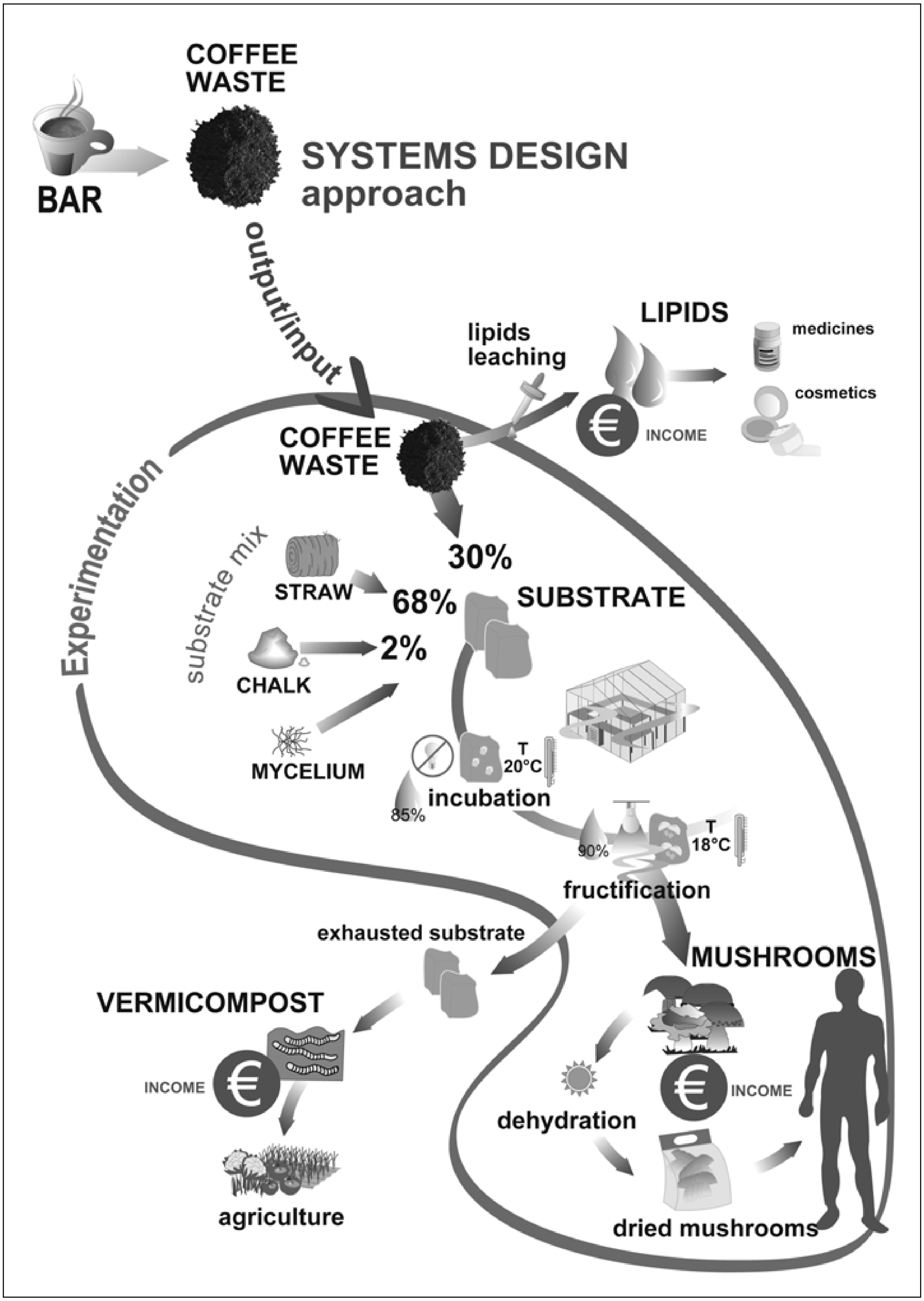
- production feasibility (ability to create good substrate material, considering local availability of resources and the suitability of coffee grounds for growing edible mushrooms) and
- logistical feasibility (ability to find the necessary raw materials, equipment, and other essentials in the local area).

Applying Systemic Design Principles

The field experiment was carried out over a period of four months, during which we tested mushroom growth to determine the most suitable set-up. Our starting point was a series of case studies carried out by the Zeri Foundation[3] at several locations around the world.

Experimentation allowed us to verify each mushroom's growth-process phases using an instrument donated by Città dei Ragazzi. We were able to carry out a number of different tests to find

Exhibit 2. Creating Value From Coffee Waste



the best trade-off between energy costs and production yields. For example, we generally sought to optimize the duration of straw pasteurization (one of the steps involved in mushroom cultivation), thereby reducing energy consumption.

Our experimental mushroom production process was designed to use raw materials available in or around the city of Turin. All the resources we used came from the Turin area except for the mycelium (mushroom culture), which came from Italspawn, a mushroom laboratory in Treviso.

Reliance on local resources is a fundamental aspect of systemic design, the primary aim of which is to create a web of relationships within a specific area. This approach seeks to reduce transport emissions and increase economic value for the local community.

Systemic design focuses on the unique characteristics of local regions and communities in order to enhance the value of their biodiversity.

For optimum growth, mushrooms need a proper substrate into which mycelium can be introduced or "inoculated." Mushrooms typically require only low-level energy resources during the growth phase.

Once we identified the correct substrate for growing *Pleurotus ostreatus*, our research analyzed the local availability of raw materials on a seasonal basis. This allowed us to determine the best substrate composition with regard to the components available in the local area, knowing that the substrate must contain cellulose, hemicellulose, lignin, minerals, and organic salts.

Systemic design focuses on the unique characteristics of local regions and communities in order to enhance the value of their biodiversity. In this case, we analyzed the main geographical features of Italy's Piedmont Region, where Turin is located, in order to identify input materials for a suitable mushroom substrate. The Piedmont Region is composed of mountainous areas (43.2 percent), hilly areas (30.3 percent), and plain areas (26.5 percent).

The main resources identified as possible inputs for mushroom substrate in the Piedmont Region (in addition to coffee waste) were exhausted straw, husks, grape seeds, pruning vines, fruit waste, and sawdust. The exact amounts of these additional components would vary somewhat depending on the locality within the region. See **Exhibit 3**.

Study Results

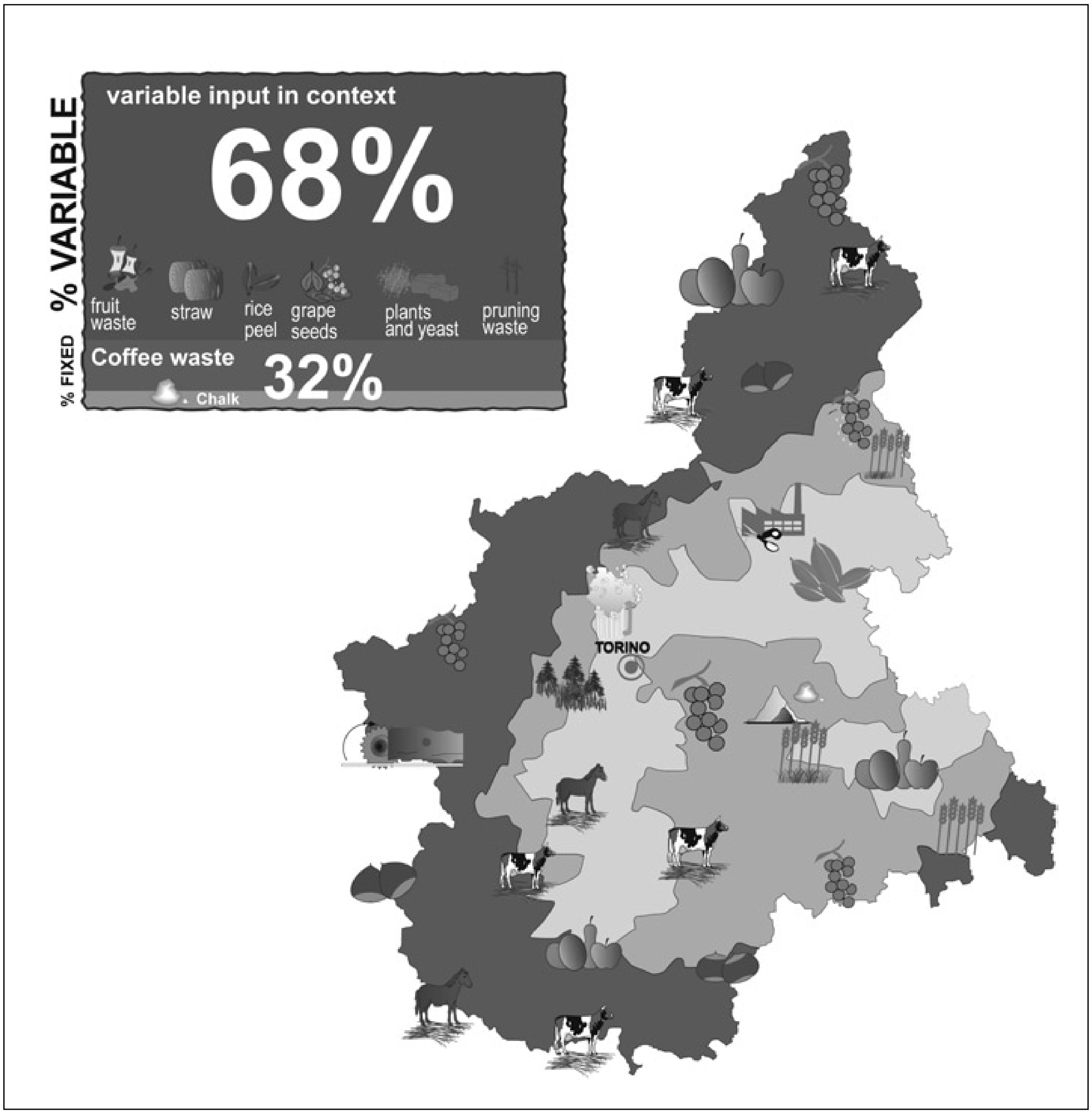
Our experiment yielded positive results, confirming all the hypotheses put forth and proving the feasibility of the proposed project. The average production of fresh mushrooms was around 1.5 kg for each 3 kg of substrate used during the growth period. This harvest was double the estimated biological efficiency.

We were able to increase the quantity of mushrooms harvested through step-by-step changes implemented during the growth phase, using a feedback loop that improved substrate preparation techniques and enhanced the ambient conditions (ventilation and moisture) in the growth room. The *Pleurotus ostreatus* mushroom was found to have good resistance to varying environmental conditions, growing without difficulty.

The experiment described here was concerned with more than the quantity and quality of the mushrooms produced, however. The principal aim was to find the best available substrate and the optimum growing process in relation to the specific territorial context. The experiment achieved the main goals of the research project, allowing us to develop a good combination of substrate composition, energy consumption, and short growth periods.

We achieved good results with regard to the production process, reducing straw pasteurization

Exhibit 3. Input for Mushroom Substrate



time by one hour and carrying out the fructification phase in a room with natural lighting and ventilation, thus halving energy consumption.

We obtained straw from two locations, once from Alessandria and once from Treviso. The dry straw was stored in the open air, under a roof to protect it from bad weather. We kept the mycelium refrigerated in order to maintain high quality throughout the full experimentation period.

We tested the conditions necessary to prevent the coffee grounds used in the experiment from becoming moldy or undergoing other alterations. In order to prevent such problems from occurring, we organized a weekly collection of coffee grounds in collaboration with a coffee bar run by the coffee company with which we partnered.

We needed to maintain contact with the coffee bar staff in order to obtain good-quality coffee grounds, without any scraps, so that we could preserve uniformity in our input data. We would note that, in order to move the process described here from the experimental level to larger-scale industrial production, it will be necessary to set up training for coffee bar staff members.

Future Research

The case study described here, which focused on growing mushrooms in a substrate of straw and coffee waste, represents just one aspect of a larger research project involving the reuse of coffee waste. The overall project encompasses lipids extraction, mushroom growth, and use of exhausted substrate for vermicompost production.

Possible future experiments might focus on the remaining areas of interest, including finding beneficial uses for certain substances present in coffee grounds (such as lipids) and extracting additional value from coffee waste-containing substrate once it has been used to grow mushrooms.

Our research established the feasibility of the proposed production process, optimized key aspects of the process through experimentation, and established the elements of a suitable substrate mix.

Conclusions

The experiment described here has validated an innovative approach that goes beyond the linear "cradle-to-grave" production process, showing how production can be viewed from a wider perspective.

The research project outlined in this article used materials that today are considered waste, finding value in substances that otherwise would represent only a social cost. The coffee waste material used in this case study proved to be a valuable input for a new mushroom-growing process that is able to generate economic, social, and environmental benefits.

In our research, we developed a good mushroom-growth substrate on an experimental scale. This should help clarify the steps necessary for using coffee waste in mushroom production and also simplify the process of applying it on an industrial scale.

Our research established the feasibility of the proposed production process, optimized key aspects of the process through experimentation, and established the elements of a suitable substrate mix. We were able to determine the optimum conditions for mushroom growth using a feedback loop approach.

The knowledge gained through our research could be transferred to industrial production. In particular, the management and logistics involved in the production process could be based on the plan that we worked out with our coffee company partner.

Our research on production feasibility included both qualitative and quantitative aspects in order to obtain reliable results. The research described here underscores how strongly systemic design of production processes is linked to local surroundings. Given these location-specific aspects, the project outlined in this article cannot simply be transferred immediately to other locations. Instead, it will be necessary to design a suitable substrate mix for each specific local area.

Our research studied the correct substrate mix for use throughout the Piedmont Region, analyzing conditions in the different areas (plains, hills, and mountains). The principal materials adopted in the research, in differing percentages, were straw, coffee grounds, and mycelium.

This project has validated the systems approach by using a perspective that considers "waste" to be an input for other productive processes, in the same way that natural processes use materials. This innovative approach creates economic benefits (by reducing disposal costs and generating income from new activities), environmental benefits (by reusing organic substances in the bio-cycle and other substances in the techno-cycle), and social benefits (by creating new jobs and reducing the amount of waste that must be disposed in landfills).

The case study described here also suggests that further research in this area would be valuable, including investigation of experimental technologies that might use coffee waste as biofuel.

Notes

1. Based on 2007 data from the International Coffee Organization.

2. Based on data from the European Coffee Federation (2006).

3. The Zero Emissions Research and Initiatives (Zeri) Foundation is a research institute established in 1994 by economist Gunter Pauli and professor Heitor Gurgulino de Souza. Zeri seeks "to view waste as resource and seek solutions using nature's design principles as inspiration." See http://www.zeri.org/index.htm.

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