CHAPTER 10

INDOOR COMPOSTING : GENERAL PRINCIPLES AND LARGE SCALE DEVELOPMENT IN ITALY

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1. HISTORICAL BACKGROUND

INDOOR COMPOSTING is a widely accepted expression in the mushroom industry used for defining most of the composting techniques carried out "indoor" under conditions of strictly controlled environment and process. It seems that Lambert was the first one to use that expression in a paper published in 1941. Mushroom compost is a unique support for the growth and fruiting of *Agaricus bisporus*. It must be altogether selective and productive (Ross & Harris, 1983 ; Stone & Laborde, 1991 ; Fermor & Macauley, 1991) ; i.e. favorable for the sole growth of the cultivated mushroom, and generating high yields of fruit bodies. In order to positively control composting, it is essential to have the best knowledge of the complex characteristics of a good compost, and to determine what specific steps should be taken to reproduce them. Historical background has been recently reviewed (Van Griensven, 1993).

Improving our understanding of composting has been, for the past sixty years, the permanent goal of all scientists involved in mushroom cultivation, starting from Waksman and colleagues in the thirties, continuing with Stoller, Lambert and Sinden in the late thirties, the forties and fifties, and many more from the sixties onwards.

Sinden & Hauser (1950, 1953) developed the Short Composting method, through which they demonstrated that complete composting could be successfully achieved in two short successive phases : Phase 1, outdoor, lasting 7 days, at relatively high temperatures, between 70 and 80°C, in long, narrow piles, rectangular in shape ; Phase 2, indoor, in trays or in shelves, under well controlled conditions, at medium uniform temperatures, between 45° and 58°C, lasting 5 to 7 days. Prevailing aerobic conditions were a prerequisite during the whole length of the process. Present composting techniques, referred to as classical or traditional, are mostly derived from this Short Composting scheme.

An important advance in the understanding of mushroom nutrition and substrates was brought

about by Till (1962) who succeeded in growing *Agaricus bisporus* under conditions maintained axenic up to fruiting, on sterilized complex substrates. Regular yields were then obtained under non-sterile conditions. Till's method was improved by colleagues, von Sengbusch (1965), and Lemke (1965), then modified by Huhnke & von Sengbusch (1968) and Huhnke (1971) : they replaced autoclaving by semi-sterilization at lower temperatures (80° to 100°C), then, by reinoculating with specific microorganisms, they were able to avoid spawn run under aseptic conditions. Maintaining sterile conditions was considered too technical and too expensive for large scale projects. Nevertheless their contribution, following the great step forward by Sinden and Hauser, demonstrated in the mid sixties that a high quality substrate for the cultivation of mushroom could be obtained from a wide range of raw materials, under well controlled conditions, and in a much shorter period than used to be the case at that time.

In the sixties, and early seventies, a profusion of scientific investigations on the microbiology of composting gave a series of publications by Bels-Köning *et al.* (1962), Fergus (1964), Hayes (1968), Laborde *et al.* (1968), Imbernon & Leplae (1971), Stanek (1971) and Olivier & Guillaumes (1978). The result was a clearer picture of the compost ecology which led to new interest into the development of "rapid composting techniques".

In France, Laborde & Delmas (1969, 1971) developed a process named P.E.S.(Express Preparation of Substrates), a fast, 3 to 6 days, indoor composting process in trays under strictly controlled environmental conditions. This was, in fact, a novel composting process carried out indoor, but also in trays rather than in bulk (not known at that time), thus disadvantaged by less efficient control. Today, P.E.S. is considered as a single phase medium temperature process, as opposed to the present double phase higher temperature process adopted by INRA and Italian specialists since 1984.

In England, Hayes (1968), Randle & Hayes (1971), Smith (1974), Smith & Spencer (1976), worked on the basics of composting, first in revolving drums, then later in trays and pasteurizing chambers. Revolving barrels or drums had been used previously by Stoller *et al.* (1939), Delmas (1953), Trocmé & Sarazin (1956), and on a large industrial scale in the U.S. by Campbell Soup Co (Murphy, 1972), a true early indoor composting process. They were also used later in Australia (Baker & Baker, 1981). Smith and colleagues kept working for many years on the elaboration of short duration composts (Smith, 1983).

In Germany, Huhnke and von Sengbusch (1968), and Huhnke (1971) modified the Till method by substituting sterilization of the substrate with a high temperature treatment followed by incorporation of specific microorganisms and a short Phase 2 at lower temperature. In fact, they were recommending, years earlier, a very short composting process close to the one proposed, after many more years of experimentation, by Laborde *et al.* in 1984. The scheme described by Huhnke appears today as a forerunner of current Indoor Composting techniques. It is not known why such a visionary work was discontinued : for lack of financing or interest in another research subject ?

In Holland, Bels Köning, as early as 1962, conceived a composting process involving the partial predigestion of lignocellulosic materials by strong acids or bases (liquid ammonia was on the list), followed by a transformation period by inoculated selected thermophilic microorganisms, mainly fungi, working at their optimum growth temperature range. Such a scheme was also visionary; the value of thermophilic fungi has been widely demonstrated in recent times, not only during the conditioning period of Phase 2, but also as a key element in the rapid preparation of indoor composts by the single phase medium temperature process, experimented since 1985 to a large extent in Australia, Holland, England and Belgium. Muller (1965), Gerrits and coworkers (1965, 1968, 1971, 1974) contributed very strongly to a better knowledge of the biochemical transformations occurring

within a compost either outdoor or indoor, and after spawning. Despite such wide interest in developing new composting techniques, our understanding of the basic chemical and biological reactions involved remained limited. Simple questions could be only partially answered such as :

- What are the desired characteristics of a nutritive and selective compost ?
- What substances, or families of substances, at what level, what balance, are we aiming at through composting : for example, do we need black substances ; what are they ; are they useful for the mushroom ?
- What specific steps should be taken to regularly produce such substances, under what conditions?

More basic approaches to composting was, and still is, needed to make real progress in this field. British scientists have been doing a tremendous amount of research, from the mid-seventies up to early nineties, to clarify the biological mechanisms involved both during composting and the mushroom growth and fruiting, work extensively reviewed recently by Fermor & Wood (1991), Fermor & Macauley (1990), Wood & Fermor (1985). Even more recently, more data have been made available by French scientists on the biological mechanisms occurring during Indoor Composting, including both the microbial activity and the availability of nutrients, all evaluated on a process very similar to the INRA Indoor Composting process (Chalaux *et al.*, 1991; Savoie *et al.*, 1992a; Savoie *et al.*, 1992b).

But, in the eighties, an empirical approach was sufficient to permit the explosive development of Indoor Composting on a large industrial scale in Italy, and to a smaller extent in Austria (Sohm, 1989), Switzerland (Kuhn, 1990 ; Leendertse, 1988)), Holland and Australia.

It was also in 1968 and the following years that two of the authors, Francescutti and Giordani, became responsible for introducing the presently worldwide used technique of Phase 2 or Pasteurization in bulk in tunnels. Conducting the composting process in bulk had been proposed by Stoller (1951) twenty years earlier, himself impressed by the existing similarity between composting for mushroom growing and malting for beer making. Franscescutti and Giordani, associated with Derks (1973), decided to first experiment with, then to adopt completely, Phase 2 in bulk. Although Stoller had presented his views in an extensive review of the scientific and practical problems of mushroom cultivation (Stoller, 1954), they remained almost unknown until the late sixties. Of course, the new types of tunnels were designed with characteristics widely different from Stoller's first version. But it is certain that such a development was not expected at the time to become the main worldwide technique adopted to run the Phase 2 stage of composting, and in more recent years, the whole process of Indoor Composting. Sarazin, in France, started experimenting with tunnels at about the same time (1969), and in 1972, pasteurization in tunnels became adopted by large Italian and French mushroom growers (d'Hardemare & Talon, 1974). Years later, other European growers followed.

Running Phase 2 in bulk in tunnels meant blowing air through the compost mass instead of around it. Formerly, Phase 2 was carried out with compost in trays or shelves. Phase 2 in bulk meant more uniform environmental conditions across the whole compost mass with a very precise control. The main difficulty which arose was that optimum conditions during Phase 2 were not well established and could only be set through more trial and error experimentation.

But the Italian developers were so enthusiastic about this new technique that they readily visualised extending its use, not only to Phase 2 of composting but to Phase 1 (formerly outdoor) as well, and "Phase 3" or spawn run after spawning. Their ideas were summarized by Derks (1973) under an elegant formula : the 3 Phase in 1 process : in fact a complete Indoor Process including Phases 1 and 2 of composting as well as spawn running, the three operations being carried out in bulk, in tunnels.

Phase 2 in bulk has presently been adopted by the majority of mushroom growers and compost

makers except in the USA where Phase 2 in trays or shelves is still predominant.

However, extending that technology to either Phase 3 or Phase 1 presented some difficulties i.e. economical reasons: it was cheaper to compost outside (Derks, 1992) ; technical difficulties : the best conditions to select and maintain throughout the process were not really known ; more research and experimentation have been required to adopt such a process either for Phase 3 or Phase 1.

As far as Phase 1 was concerned (Indoor Composting), two questions needed precise answers.

1. Is a short phase at higher temperatures (70 to 80°C) better than usual medium ones (50°C) to obtain both selectivity and nutrition ? And if such is the case, how to compensate for the loss of microorganisms at such very high temperatures ?
2. How to determine the temperature range and duration, and the oxygen levels, throughout the process, in order to end up with an optimum substrate ?

Answers to these questions are still debated, but the processes adopted to-day on a large scale are an indication that the options retained must be valid.

In Denmark, Bech (1978), developed a very rapid composting process, first on wood pallets acting as a double floor, then in a tunnel. Total duration of the process (Phase 1 plus Phase 2) varied from 5 to 8 days. As in standard composting, a wide range of high temperatures was obtained and maintained through Phase 1 which eliminated the need for reinoculation of the compost before Phase 2.

In France, Laborde *et al.* (1978, 1980) produced more data about the positive effects on indoor processes of high temperatures applied for a limited time, provided biological activators (i.e. microorganisms) could be introduced following the high heat treatment. Later, they presented, the INRA Indoor composting process, a double phase higher temperature process (Laborde *et al.*, 1984, 1986). Indoor Composting is successively carried out under two different temperature ranges : from 2 to 3 days at around 80°C, then from 5 to 7 days at around 50°C, except for a short peak heat at 58°C. Following the higher temperature period, the introduction and mixing of a limited quantity of pasteurized outdoor compost provided reinoculation of the partially sterilized indoor compost. Such a technique combined the positive effects on compost bulk density and nutritional quality of a higher temperature treatment, with the benefits provided by the development of thermophilic fungi and actinomycetes at the medium temperature range. Additional data have been regularly presented since 1984 : Laborde *et al.* (1986, 1987), Houdeau *et al.* (1991), Laborde (1990, 1991, 1992). Despite slight modifications, the principles of the technique remain the same.

Around 1985, research work was almost simultaneously started in England, Holland, Australia and Belgium along an entirely different line. The idea was to maintain optimal environmental conditions for the growth of thermophilic fungi, *Humicola* or *Scytalidium* (Straatsma & Samson, 1993), which are viewed as indicators of a good compost. The process was run at a medium temperature, the range 45°C to 50°C appearing as the most satisfactory. A good productive compost could then be obtained in about seven days. A very positive point of that technique was the large reduction in emissions of both malodorous and polluting gases. Many publications presented the progress realized in experimenting with such a new technology : Perrin & Gaze (1987), Gerrits (1987), Gerrits & van Griensven (1991), Derrikx *et al.* (1990 a & b, 1991), op den Camp *et al.* (1991), Nair & Price (1991), Miller (1992), Gulliver *et al.* (1991), Overstinjs (1992). Large scale development of that process was recently undertaken in Holland, Australia, New Zealand and Belgium.

It must be remembered that such a single phase medium temperature process was a logical development of the former P.E.S., but in bulk instead of trays, abandoned in the late seventies by Laborde *et al.* (1978) for the simple reasons that mushroom yields and quality were not consistent, and compost bulk density was below that of composts made at normal higher temperatures. It now

seems evident that such arguments were of value, since most new Indoor Composting development projects are managing a phase at higher temperature, previous to the longer period at lower temperature. From 1985 onwards, Francescutti on one hand, and Giordani on the other, started to develop their own conception of large scale Indoor Composting, followed closely by several Italian mushroom growers and compost makers. All these projects, developed in Italy in the past six years, have included a hot temperature phase lasting from two to three days, conducive to very consistent results. Some of these we are now going to present to you. Such is the choice being made in recent development projects, in Holland by Theewen and Pleunis (Janssen, 1992 ; Dicks, 1993), in Australia (Gulliver *et al.* 1992) and in Belgium (Janssen, 1992).

2. REQUIREMENTS FOR COMPOSTING INDOOR

A. Preparation stage: objectives to be attained before the temperature treatment.
(Many of the factors presented here were recently reviewed by Miller (1992) and Laborde (1992)).

2.1. Nutritionally Balanced Mix of Raw Ingredients

The raw materials employed, and their proportions, are the same as for a traditional outdoor compost. But the much shorter duration of the process means reduced losses of useful nutritive elements, i.e. a larger proportion of organic matter, more carbon, less ash, in the final compost. This means more filling capacity from a given initial volume of raw ingredients, and more organic matter per cropping area, or a larger potential yield (Harper *et al.* 1990).

It is a well admitted fact that higher yields are cropped on composts with a low C/N ratio, between 14 and 17. With short duration composts, C will remain high. Therefore N must be raised to a higher level. Higher N levels are generally obtained in straw plus poultry manure composts, up to 3% of D.M. Poultry manure is a rich source, not only of interesting organic substances, but also of important minerals like potassium, phosphorous, magnesium, calcium, sulphur and iron and, of course, nitrogen. With shorter composting, the general ratio of inorganic elements over organic ones will be much smaller, requiring an adjustment in both level and balance of these elements (Table 1). Therefore, in order to obtain a high nitrogen level in the finished compost, high level and high balance of P, K, Mg, Ca, Fe and S are needed, brought about by large, but not excessive, volumes of poultry manure (Laborde, 1991). The nitrogen level may be increased even more by the addition of an inorganic fertilizer such as ammonium sulphate. Although high levels of inorganic elements are correlated with maximum yields, they increase the risk of salinity, i.e. excessive osmotic pressure and toxicity (Treschow, 1944; Bohus, 1959) which can only be reduced by a higher water content of the compost. But beware of overwetting!

Specific organic additives may profit from being applied at this early stage: they are sugar, fat or protein rich activators, and enzyme complexes. They all contribute to a rapid build up of active

TABLE 1. Optimum Levels of Inorganic Elements (% D.M. of compost) (From Laborde, 1991).

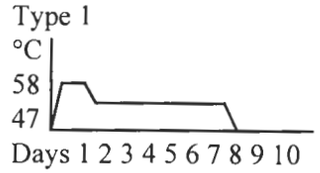
	N	P_2O_5	K_2O	CaO	MgO
Mixing	1.7-1.8	1.2-1.5	2.0-2.3	1.5-3.0	0.4-0.5
Spawning	2.3-2.4	1.6-2.0	2.7-3.2	2.0-4.0	0.5-0.7

microorganisms, which in turn will generate more heat.

2.2. Uniform Mix of Raw Ingredients

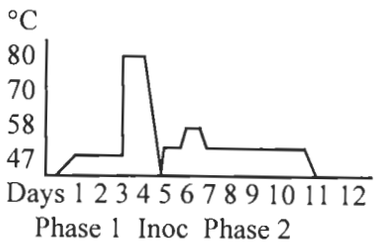
Premixing operations: To improve both the mix and the degradation process, it is a requirement that most raw materials should be shredded or milled. Mixing following milling disperses evenly compost nutrients and microorganisms (Miller, 1992) and permits a rapid and complete wetting of all the ingredients (water is readily absorbed by straw), and will promote vigorous thermogenesis through the action of thermophilic microbes. An important consequence of milling is that bulk density is immediately increased to the value which used to be obtained only at the end of composting. Better moisture content and distribution, smaller particles, and higher density all mean a more uniform and active compost.

Mixing equipment proposed nowadays is getting more efficient with auger type systems as used in feed wagons, and delivering a very uniform product in a shorter time. New blenders are so



SINGLE PHASE MEDIUM TEMPERATURE PROCESS
Filling tunnel
One Phase
Constant aerobiosis
Strong ventilation
Temperature rise: 1-2 days
Plateau 45-50°C : 5-7 days
Peak-Heat 58°C : 4-6 hours
Total duration : 6-9 days from filling to spawning.

FIGURE 1. Single phase medium temperature process.



DOUBLE PHASE HIGHER TEMPERATURE PROCESS
Filling tunnel for Phase 1
Aerobiosis + reduced ventilation
Range 45-50°C : 1-3 days
Up to and at 80°C: 1-2 days
End Phase 1; empty tunnel
Addition of microbial inoculum
Filling tunnel for Phase 2
Aerobiosis + strong ventilation
Plateau 45-50°C: 5-6 days
Peak-heat 58°C : 4-6 hours
Total duration : 8-12 days from 1st filling to spawning

FIGURE 2. Double phase higher temperature process.

efficient that all the water needed may be added and absorbed in a single pass.

B. The two thermal processes used to-day are shown in Fifures 1 and 2 (from Laborde, 1992).

2.3. Influence of the Temperature Level

Composting is an accelerated humification process at high temperature. In a compost pile, we find a full range of temperatures up to 80°C. Their effects are quite different at 50 to 60°C than at 70 to 80°C.

50-60°C: at this level, most mesophilic microorganisms are either destroyed or inactivated. Around 50°C, thermophilic microbes are booming and comprise fungi, actinomycetes and bacteria, while at 60°C, only bacteria remain active. *Scytalidium*, (*Humicola*), grows best between 45 and 50°C. Most predators and competitors are eliminated. The heat surge destroys many organisms, permitting the start of ammonification, or the release of free ammonia. Free ammonia acts as a sterilant, but is also a strong chemically active product which reacts with soluble sugars, other carbohydrates and phenols, to yield complex nutritive brown substances available only to the mushroom (Stone & Laborde, 1990). The higher the temperature, the stronger these reactions with ammonia. Thermophilic fungi, working at about 50°C, will rapidly use the ammonium ions and stop the production of free ammonia, known for its toxicity to the mushroom mycelium. So, when running a process continuously at around 50°C, the compost may be ready for spawning when no more free ammonia is detected. In fact, selectivity is also attained when the level of soluble sugars and phenols is very low. Dry matter losses at such temperatures are very high, between 3 and 4% per day, since they result from an intense biological activity (Table 2). The substrate is fully colonized by friendly microorganisms at the end of such a medium temperature treatment, mainly fungi and actinomycetes.

70°-80°C: above 70°C, a partial sterilization occurs, more pronounced at 80°C. Most microbial life is eliminated. Production of free ammonia is even greater, causing a larger complexing of products under self-sustained chemical reactions. Cellulose is also getting more pliable. Bulk density increases (Table 3). The compost is darker, almost black. Black products are complex substances useful to the mushroom (Eddy & Jacob, 1976, Goulas, 1987, Laborde, 1992). Dry matter losses are very low, 1 to 1.5% per day, since almost all biological activity has stopped, (Table 2). But the substrate is almost devoid of microorganisms, making it very susceptible to contamination by undesirable organisms. Following such a hot treatment, reinoculation with useful microorganisms is a must and their growth should be stimulated by maintaining optimum lower temperatures for a certain duration, generally several days.

TABLE 2. Losses during Indoor (2 phase) Composting Process (in % Fresh Weight or Dry Weight). From Laborde *et al.* (1984).

	Exp. 1		Exp. 2		Exp. 3	
	F.W.	D.W.	F.W.	D.W.	F.W.	D.W.
Phase 1	8.4	6.8	14.8	5.3	9.9	3.5
Phase 2	18.9	13.1	15.0	14.6	17.8	14.4
TOTAL	24.8	18.6	25.9	18.6	25.4	16.9

TABLE 3. Bulk densities as measured in tunnels (not compacted). Indoor (2-Phase) Process (kg/m3). From Laborde (1992).

	Exp. 1	Exp. 2	Exp. 3
End Phase 1	510	450	550
End Phase 2	430	420	450

2.4. Influence of Oxygen

The relationships between oxygen and compost have been thoroughly reviewed by Miller & Dahlberg (1990). Derikx *et al.* (1990b) found the highest consumption rate of oxygen at a temperature of 50°C, and lower consumption rates at all other temperatures.

Cellulose decomposing organisms may be found under aerobic or anaerobic conditions. But under lower oxygen levels, chemical products toxic to the mushroom may be formed such as short chain organic acids, amides, volatile sulphur compounds; and the residual microflora may not survive during spawn run under fully aerobic conditions, making room for competitors. So, even if some benefit may be obtained by maintaining anaerobic conditions for a certain length of time (Houdeau *et al.*, 1991), it seems preferable, either to entirely avoid them, or to limit them to very short periods of time if for no other reason than to avoid the production of offensive odors (Miller & Dahlberg, 1990). This is the reason why all Indoor Composting facilities, adopting the double phase higher temperature process, are trying to maintain, during the hot phase, a minimum oxygen level inside the compost mass of 10 to 12%. Such a level is interesting because it allows for limited introduction of colder fresh outside air, while maintaining sufficiently aerobic conditions. It may be regulated by small ventilation rates or alternate ventilation schedules, thus limiting the need for steam heating and its detrimental effect on compost aeration and moisture content through condensation. Let's not forget that fungi and actinomycetes require high oxygen levels, while *Chaetomium* (Olive green mold), will develop readily when high temperatures and low oxygen levels are combined.

2.5. Emission of Malodorous Gases and Ammonia

A recent review of odours and composting is available, (Miller & Macauley, 1988). It has been demonstrated (Op den Camp *et al.*, 1991; Derikx *et al.*, 1990a, 1990b, 1991) that very much reduced emissions of odorous sulphur compounds were produced with Indoor Composting conducted according to the single phase medium temperature process, under constant and very high aerobic conditions. Higher temperatures, between 70 and 80°C, do not generally result in increased emissions (Dicks, 1992) when truly aerobic conditions are maintained; much lower biological activity at these temperatures means a much reduced oxygen consumption, or very low fresh air intake, and low volumes of polluted air released in the atmosphere. Therefore, higher temperatures may not be associated with increased environmental problems.

Free ammonia, (gas), is beneficial to the composting process. Larger volumes may be expected to be released in the atmosphere under high fresh air admission, and exhaust, as customary with the single phase medium temperature process; under higher temperatures, we have just seen that very low volumes of air are rejected, i.e. less ammonia. In both cases, to remove any trace of ammonia, the exhaust air should be treated with sulphuric acid before being released outdoor.

2.6. Biological Activators

Activators commonly used in the composting process are generally bringing more nutrition to the microorganisms to generate maximum activity (Laborde, 1992) ; they are chemical activators, for example, sugars, oils and proteins.

Biological activators are designed to bring specific microorganisms to intervene at a preset stage of the process. For example, to replace destroyed microbial biomass immediately after the higher temperature treatment of the 2 Phase process. The objective is to introduce the right organisms doing the right work under the right conditions, which implies the following questions:

- What kinds of microorganisms and at what stage ?
- Under what form ; what volume of inoculum ?
- To carry out which reactions leading to which compounds ?
- Under what optimum conditions ?

The microflora of a compost is quite different at the beginning and at the end of composting. It is constituted predominantly of thermophilic microorganisms at the end, and of more mesophilic ones at the start (Wood & Smith, 1988 ; Fermor *et al.*, 1979) (Table 4).

Fungi like *Scytalidium* (formerly *Torula* and *Humicola*) appear massively at the end (Straastma & Samson, 1993). General evolution is presented in Table 5; we obtain a 1,000-fold increase in actinomycetes and fungi when incorporating a balanced biological activator at the end of Phase 1.

Pure cultures of thermophilic fungi have been introduced recently as biological activators in Indoor Composts by Straastma *et al.* (1988), and Houdeau *et al.* (1991), following earlier extensive studies by Gerrits *et al.* (1962) and Olivier & Guillaumes (1978). Other proprietary formulas may include thermophilic microorganisms. It seems evident that the chemical and physical conditions of a compost may not be suitable for the development of such micoorganisms at the early stages of composting (Gerrits *et al.*, 1962), as far as pH, concentration of ammonium ions, and temperature

TABLE 4. Major groups of microorganisms that can be isolated during substate preparations for *Agaricus* cultivation. From Wood & Smith, 1988.

Bacteria	Actinomycetes	Fungi
Mesophiles		
Flavobacterium	*Streptomyces* spp.	*Mucor* spp.
Pseudomonas spp.	*Nocardia* spp.	*Aspergillus* spp.
Serratia marcescens	*Micropolyspora* spp.	*Penicillium* spp.
Thermotolerants		
Pseudomonas spp.		*Aspergillus fumigatus*
Bacillus licheniformis		
Thermophiles		
Bacillus coagulans	*Thermoactinomyces* spp.	*Torula thermophile*
Bacillus stearothermophilus	*Thermomonospora* spp.	*Humicola insolens*
Bacillus subtilis		*Rhizomucor pusillus*
		Talaromyces lanuginosa

TABLE 5. Number of microorganisms isolated at several stages duting a 2 Phase Higher Temperature Indoor Composting Process (activator added at end of Phase 1). From Laborde *et al.*, 1986.

	Beginning Phase 1	End 50°C Stage	End Phase 1	End Phase 2
BACTERIA				
No activator	10^{10}	10^{8}	10^{6}	$>10^{9}$
+ activator				$>10^{9}$
ACTINOMYCETES				
No activator	10^{7}	10^{5}	10^{3}	$>10^{3}$
+ activator				$>10^{6}$
FUNGI				
No activator	10^{5}	10^{3}	10^{3}	$>10^{3}$
+ activator				$>10^{6}$

levels, among other factors, are concerned. Also, in order to increase their chances, pure cultures should preferably be introduced in a previously sterilized (Huhnke, 1974), or semi-sterilized medium (Laborde *et al.*, 1984). This would almost completely eliminate the risk of competition from other thermophiles or even mesophiles.

On these grounds, the single phase medium temperature process does not permit to reach temperatures high enough to eliminate most undesirable microbes. In fact, yields obtained so far from Indoor Composts inoculated with pure cultures of thermophilic fungi are lower than when incorporating a mixed culture of bacteria, actinomycetes and fungi (Houdeau *et al.*, 1991) (Table 6).

When using raw materials relatively deficient in active microflora, like wheat straw, adding a strong inoculum may be stimulatory. Otherwise, the expected chemical reactions may not proceed as expected and the optimum selectivity may not be attained (Savoie *et al.*, 1992b).

Addition of microorganisms at a given composting stage, for example following a semi-sterilization at the higher temperature, may also be made more effective by the previous or simultaneous use of specific enzyme complexes (Savoie & Libmond, 1993 ; Hayes, 1992).

Composition of the inoculum to be introduced is very critical, since it may bring along some undesirable competitors or antagonists after the hot phase ; for example yellow molds. Ways of checking the inoculum quality have to be developed. Adopting a short peak heat following introduction might be safer, but it may also reduce the effectiveness of the activator before it becomes strongly established in the compost.

Such problems demonstrate clearly that successful Indoor Mushroom Composting depends in a large part on the definition and the critical use of an effective biological activator (Oldham, 1992).

TABLE 6. Addition of pure cultures of thermophilic fungi at the end of Phase 1 in the 2-Phase Indoor. Composting Process. Effect on yields. From Houdeau *et al.*, 1991.

	Yields (kg/ton)	% of control with mixed culture
Torula	225.4	86.5 %
Humicola	216.8	88.0 %

3. INDOOR COMPOSTING FACILITIES

Indoor composting has been going through a booming development in Italy for the past five years, under the leadership of the authors of this publication. In 1992, total spawned compost production in Italy was probably in excess of 500,000 tons, representing a mushroom output of over 125,000 tons, uncut. More than 60,000 tons of compost were made Indoor, under stictly controlled conditions. The three Italian co-authors of this publication contributed to the production of over 45,000 tons of spawned Indoor Compost, i.e. 3/4th of the total output. This is why they feel ready to share their experiences to-day.

All four systems which will now be presented and evaluated have adopted the double-phase higher-temperature process, with some important adaptations, for the three Italian large-scale facilities. The French INRA system, already presented, remains the same. It must be pointed out that in France, public research has the charge to do most of the work for developing a fully controlled composting process. In Italy, this remit falls within the competence of the private mushroom industry, and their technicians, to improve on existing technologies and to design new processes based, of course, on scientific principles.

Each one of the three cooperating authors from Italy, E. Giordani, B. Francescutti, and G. Lanzi, has perfected his own method. The four systems may be regrouped into two categories, A and B, A for Giordani and Laborde, B for Francescutti and Lanzi. All have adopted the same type of Phase 2. For A, Phase 1 is conducted in closed tunnels with strictly controlled environmental conditions. Uniform and high temperatures between 75 and 80°C are reached, killing most of the microbial biomass. Reinoculation with a biological activator must be carried out following Phase 1.

For B, tunnels with open doors are used for Phase 1. Temperatures in the range 60°-80°C are reached in about 75 % of the compost mass, 25 % remaining below that level. No activator is needed before Phase 2, only a good mixing of warmer and cooler zones to get a uniform distribution of the remaining microorganisms.

There are strong differences between the two systems. In Group A, uniformly high temperatures during Phase 1 are inducing a semi-sterilization of the substrate. A specific, useful inoculum, has to be thoroughly mixed with the compost before the medium temperature Phase 2. The selection and the definition of such an inoculum are of primary importance for the subsequent success of the process : they rely to a great extent on scientific progress in that field. Biological inoculum must be able to carry out the most useful transformations of the raw lignocellulosic materials, but also to contribute to the defence of the mushroom by creating a state of selectivity. This is probably the best technique for the future, but experimental data are lacking to finalize it.

In Group B, 25 % of the microbial biomass are staying alive in almost one fourth of the compost mass during Phase 1. Less than 75 % of the compost mass undergoes a partial sterilization. Following Phase 1, the mixing of both zones distributes evenly the microorganisms throughout the compost. These may be useful ones, as well as resistant forms of less desirable ones. Here also, reinoculation is made out of an unknown microbial biomass, which may vary from one tunnel to the other, and in function under highly variable external environmental conditions. Process control appears less efficient than in Group A.

Despite such important disparities between both groups, both ways of preparing Indoor Compost are presently successful, except for some small periods, 2 to 3 weeks in a row, where detrimental conditions may be expressed by reduced yields.

In fact, dry matter losses of raw materials are considerably smaller than those observed with classic outdoor composting ; the savings may represent a 20 % bonus. But average yields obtained

with Indoor Compost are always at least equal to, and more often larger than, those from traditional compost : 25 to 30 % for the traditional as compared with 30 to 36 %, and sometimes 40 % for the Indoor Compost (of uncut mushrooms and as related to the weight of spawned compost). Such yields explain the rapid expansion of Indoor Composting processes in Italy : savings in raw materials, in occupied areas, in duration of the process, resulting finally in a lower production cost of the mushroom associated with larger yields. Also, quality of hybrids is given as exceptional when going through the double-phase higher-temperature process.

4. COMPARATIVE DESCRIPTION OF EACH PROCESS

For the past three years, the company Agrifung of B. Francescutti has been making over 30,000 tons of Indoor Compost a year, prepared in specific "Agrifung type" tunnels and partly spawn-runned in tunnels. The Company G.S. Pleurotus of E. Giordani is presently preparing around 10,000 tons of Indoor Compost a year, in very sophisticated tunnels. Both the above companies make custom compost. G. Lanzi prepares Indoor Compost in four Italian Mushroom farms, with a yearly output of over 6,000 tons of spawned compost. The different processes are compared in Table 7 and the thermal treatments shown in Figure 3.

Demand for Indoor Compost is increasing so fast in Italy that most other compost facilities are now experimenting with, or switching to, that type of product.

TABLE 7. Comparative characteristics of the four processes.

Outdoor preparation	A1 (INRA)	A2 (GIOR.)	B1 (FRANC.)	B2 (LANZ.)
Raw materials				
Straw	+	+	+	+
Horse manure	+	+	-	-
Poultry manure	+	+	+	+
Gypsum	+	+	+	+
Ammonium sulphate	+	+	+	+
Shredding of straw ; toring of horse manure ; grinding of mix of poultry manure plus gypsum and ammonium sulphate. Water addition and mixing in very efficient machines. Mix immediately filled in tunnels or left in large pile overnight.				
Immediate fill	+	+	-	-
Overnight pile	-	-	+	+
Duration in days	0.5	0.5	1	1
Heat treatment : 1/Phase 1	A1	A2	B1	B2
Fill in open tunnels	-	-	+	+
Fill in closed tunnels	+	+	-	-
One filling	+	-	-	+
Two fillings (ea. 2 days)	-	+	+	-
Constant air recycling	+	+	-	-
Constant admission fresh air	+	-	-	-
Alternate admission fresh air	-	+	+	+
Steam addition	+	+	-	-
Air recycled in M3./T/Hr.	200	50-80	-	-
Fresh air in M3./T/Hr.	20	var.	var.	25-50
Regulation from 02 levels	-	+	+	+
Regulation from CO2 levels	-	-	-	-
Perforated concrete floor	-	-	+	-
Perforated nets	-	-	-	+
Other floor types	+	+	-	-
Tons compost per tunnel	1.5	100	350	40
Higher temperature reached	80	76	80	80
Lower compost temperatures	76	72	45	50
Average duration in days	3-5	4	4	4
End Phase 1				
Addition of Inoculum	+	+	-	-
Kind of inoculum	Compost	Comp/Air		
Heat treatment : 2/ Phase 2	A1	A2	B1	B2
Average duration in days	6	3	5	5
Short Peak Heat at 58°C	+	-	+	+
Conditioning temperature	50	50	50	50
Total duration of process in days				
Outdoor preparation	0.5	0.5	1	1
Phase 1	3-5	4	4	4
Phase 2	6	3	5	5
TOTAL DURATION IN DAYS	9.5-11.5	7.5	10	10

Additional information about each process

INRA

Raw materials always shredded or milled
Mixing in an auger-equipped mixer of raw ingredients and water
Immediate filling in tunnel for Phase 1.
Following Phase 1, emptying, addition of biological activator + water.
Filling tunnel for Phase 2, including peak heat and conditioning.
Constant volumes of air recirculated in process: over 200 m^3/ton/hr.
Constant volumes of admitted fresh air: 20 to 30 m^3/ton/hr.
Temperature regulated through steam addition.
Temperature reached in Phase 1: 80°C.

GIORDANI

Raw materials either milled or coarsely shredded. Three methods have been experimented; a,b and c; b being consistently the best one.

a) Milled ingredients:
Mixing of raw products and all the water in an auger-equipped mixer.
Immediate filling in tunnel for Phase 1.
Constant high volumes of recirculated air: 200 m^3/ton/hr.
Constant small volumes of admitted fresh air: 5 m^3/ton/hr.
Monitoring of O_2 levels, by constant analysis. O_2 must exceed 10%.
Uniform temperatures in Phase 1, around 75°C.
Following Phase 1, addition of biological activator, and water..
Activator is 5% by weight of pasteurized compost.
Refilling and short Phase 2 with excess fresh air, no peak heat.

b) Coarsely shredded or non shredded straw.
Phase 1 is run with 2 fillings and 2 emptyings at 2-day intervals.
Prewatering of ingredients to get 60% moisture et 1st filling.
Much reduced air flows (recirculation and intake) at this 1st stage.
Temperature reached at 1st stage: 72°C.
Emptying, water addition to get 70% moisture, and filling.
Strong activity needs high air volumes, 200 m^3/ton/hr. recirculation.
Fresh air admitted function of oxygen level.
Temperature reached at 2nd stage: 76°C.
Emptying; addition of biological activator (5% pasteurized compost).
Addition of water to get 75% moisture.
Filling for standard short Phase 2 with no peak-heat.

c) Activator introduced by air-flow.
Same as a), with milled ingredients; but tunnel is filled only once.
Emptying only once at end of Phase 2.
Activator = 20000 m^3 air extracted in 4 hours from tunnel stage end Phase 2.
Activator injected in tunnel stage end Phase 1 = 50 m^3/ton/h in 4 hours.

FRANCESCUTTI

Raw materials shredded.
Mixing and water addition in auger-equipped mixers.
Large pile for overnight stay: water added during the night.
Filling of 350 tons tunnel for 1st stage of Phase 1: doors left opened.
Small volumes of fresh air blown underneath the compost.
No recirculation of air; no steam addition.
Fresh air admission regulated by O_2 measurement: above 8% at all times.
Maximum temperatures: 80°C; Minimum; 45°C bottom and sides compost pile.
2 days later, emptying, mixing, water addition and refilling of tunnel.
Same 2-day process with no air recirculation.
Emptying, 4 days after 1st fill, 2 days after 2nd fill.
Water addition and mixing before filling tunnel for shorter Phase 2.
No biological activator added before Phase 2; only mixing of zones.
5 day Phase 2 with short peak heat at 58°C.
High volumes of fresh and recirculated air during Phase 2.

LANZI

Process very similar to Francescutti's, except for:
One 4-day Phase 1 with no intermediate emptying and filling.
40 ton tunnels. 12-24 hrs with 50 m^3 fresh air per ton.
Later, reduced fresh air admission to maintain high enough temperatures.
No air recirculation during Phase 1. No steam used. No O_2 measurement.
Tunnel emptied, mixed and refilled, after water addition, for Phase 2.
Activator (non pasteurized) added when too high temperature reached at Phase 1.
Generally, no activator added.
As activator, non pasteurized compost is logically better than pasteurized one.
Standard 5-day Phase 2 with excess air and short peak-heat.

5. DISCUSSION

Indoor Composting has several advantages over traditional composting:

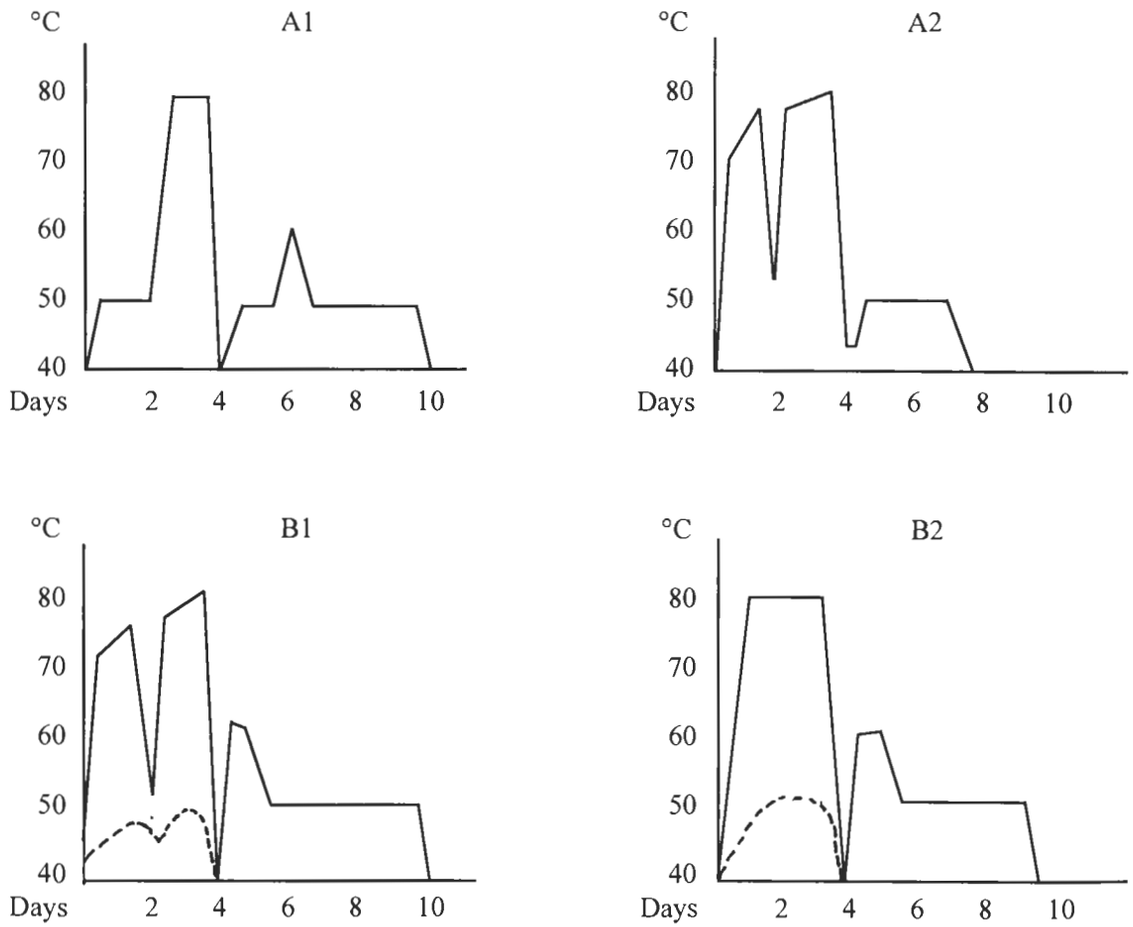


FIGURE 3. Thermal treatments in tunnels. —— Higher temperature; - - - lower temperature in compost.

1) Savings:
savings in storing and working areas.
savings in raw materials; more compost from starting material.
savings in time and energy.
2) Controls:
controlled substrate composition and physical condition.
controlled environmental conditions.
controlled process.
controlled inoculation with optimum biological activator.
controlled chemical and physical analysis.
monitoring of CO_2, O_2, and NH_3.
better sanitary control.
3) Yields and quality:
in general, higher and better than for traditional composts. Good response of hybrids.

Problems:

Controlling means sophisticated facilities with computerized monitoring and regulation.
Heat treatment level, schedule and duration still experimental.
Oxygen levels throughout process set empirically.
Imprecise definition of effective biological activators.
Optimum nutritive status of compost still ill-defined.

6. CONCLUSION

Investigations for the past thirty years or more in the field of Process Controlled Composting, or Indoor Composting, have recently come good, with the development of large commercial scale Indoor Composting Facilities, mainly in Italy. Results obtained so far are very promising. Further success in this new field relies upon continuing and extensive research for understanding the mechanisms involved in composting and their translation into efficient processes. It seems agreed that a short higher temperature stage results in improved compost quality and productivity. But more work is required in the definition and the optimum use of biological activators, and also in the field of mushroom nutrition, about the best ways to obtain a nutritive substrate for the mushroom, a very wide area of research. Meanwhile, it is hoped that growers will adopt more widely such an environmentally-friendly new way of making compost because of the good results obtained, and despite its present limited imperfections.

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