10
Fungal Products as Food

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Fungi are ideal food because they have a fairly high content of protein (typically 20-30% dry matter as crude protein) which contains all of the essential amino acids. Fungal biomass is also a source of dietary fibre, and is virtually free of cholesterol. Mushrooms are cultivated around the world, global annual production being in the region of 8 million metric tonnes. *Agaricus* spp. account for something close to 30% of the total. About 60% of the world's mushrooms are grown in China. The biggest change during the last quarter of the century has been an increasing interest in a wider variety of mushrooms. Supplies of fresh mushrooms are now intercontinental commodities. The only successful fermenter-grown fungal food on the market is myco-protein (the mycelium of a species of *Fusarium)* which is the major component of the Quorn product range. Because its filamentous nature allows it to simulate the fibres of meat, it is sold as a healthy alternative to meat. Large scale collecting of mushrooms for food has become an industry in many regions and the commercial picking industry is bound to continue to expand. It raises several issues, including conservation, ownership, and sustainability of supplies. The key reaction seems to be effective holistic management of the forest resource.

10.1. Introduction

Fungi are an ideal food because they have a fairly high protein content (typically 20-30% crude protein as a percentage of dry matter) which contains all of the amino acids essential to human and animal nutrition. Fungal biomass is easily digested except the chitinous wall which provides a source of dietary fibre, and although filamentous fungi, in contrast to yeasts, have a relatively low vitamin content, they do contain some B-vitamins and are characteristically low in fat. Also, an extremely important attribute of all fungal food is that it is virtually free of cholesterol. Consequently, fungal protein foods compete successfully with animal protein foods (i.e. meat) on health grounds. Since, in

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principle, fungal foods can be produced readily using waste products as substrates, fungal foods should also be able to compete successfully on grounds of primary cost. In this chapter we will emphasise the technology, which is often hidden, on which traditional exploitation processes depend. We emphasise 'exploitation' not just usage. Exploitation is the act of successfully applying industry to any object. This chapter is not a guide for mushroom pickers with notes about tasty subjects and piquant recipes. This chapter deals with fungi as food on an industrial scale and will indicate how both old and new industries could, and in some cases should, develop in the future. We include some mention of supplementary nutrients and health products under the heading 'food', and will also deal with products which have important roles in processing or as components of food. Our focus is on the filamentous fungi but we must acknowledge that the yeasts play a dominant role where biotechnology is applied to the food industry, being essential in brewing and bread making, and important sources of single-cell protein and dietary supplements. Although these fungal activities are crucial to human existence (life without bread and wine would be poor life indeed!) and support massive industries (annual global consumption of ethanol is currently 30 billion litres) they are excluded from this account because the yeasts concerned are not filamentous fungi. On the other hand, traditional solid state fermentations for producing mushrooms and other food products, plus in recent years myco-protein (for use in Quorn products) [Quorn™ and the Quorn™ logo are trademarks of Marlow Foods Ltd] via fermentation provide us with a sufficient range of examples where filamentous fungi are almost equally crucial to human affairs (Table 10.1).

Judging from archaeological and similar finds, mushrooms, toadstools and bracket fungi have been used since before recorded history for both food and medicinal purposes. Western recorded fungal history includes ancient Egyptian murals and tomb ornaments depicting bread and wine making, but probably more relevant to the present topic is that the Greek first century physician, Dioscorides, wrote that a type of bracket fungus was effective against cuts and sores, fractured limbs and bruises from falls and was also valuable for liver complaints, asthma, jaundice, dysentery, kidney diseases and cases of hysteria. Extravagant claims like these are readily found also in Chinese and Japanese traditional medicine. For example lingzhi (= fruit bodies of the fungus *Ganoderma*) is described as 'the rarest and most precious Chinese medical herb' which legend claims even to have '... the miraculous power of raising the dead to life ...'. Less extravagant claims for lingzhi are '... preventing and mitigating a variety of clinical conditions: chronic bronchitis, asthma, neurasthenia, insomnia, amnesia, hypertension and hypotension, coronary heart disease, arrhythmia, stroke, hyperlipidemia, thrombosis, female endocrine disorder, female physiological disease, menstrual disorder, chronic hepatitis, gastric diseases and duodenal ulcer, allergic and chronic rhinitis, dysuria, arthritis, rheumatism, allergic dermatosis,

Table 10.1. The most important direct food uses of fungi.

Application		Species
Cultivated edible macrofungi		
	Champignon, Button mushroom	*Agaricus bisporus* (= *A. brunnescens*), *A. bitorquis*
	Shiitake, xiang-gu or shiang-gu,	*Lentinula edodes*
	Chinese or straw mushroom	*Volvariella volvacea*
	Winter mushroom, enoki	*Flammulina velutipes*
	Oyster mushroom	*Pleurotus* spp.
	Truffle	*Tuber melanosporum*
Cheeses		
	Roquefort, 'blue' Stilton	*Penicillium roquefortii*
	Camembert, Brie, soft ripened cheeses	*Penicillium camembertii*
Oriental food fermentations		
	Ang-kak	*Monascus purpureus*
	Hamanatto	*Aspergillus oryzae*
	Miso	*Aspergillus oryzae, A. sojae*
	Ontjom	*Neurospora intermedia*
	Shoyu (soy sauce)	*Aspergillus oryzae, A. sojae*
	Tempeh	*Rhizopus oligosporus*

Adapted from Wainwright (1992)

cancer.' Interestingly, this quotation does not come from some ancient medical text, but from a leaflet picked up in a department store in Hong Kong in April of 1999! So the material is being sold now to well-educated first world consumers. And it's being sold on the basis of a written medical tradition, which goes back more than 5 000 years.

That a similarly ancestral, but sadly largely unwritten, tradition occurred in Europe is indicated by material carried by the Alpine traveller who has become known as 'The Iceman' (Peinter *et al.* 1998). About 3200 BC a Neolithic traveller set out across the Alps. He didn't make it. Somehow he was caught in the ice and snow, and died, to be entombed and preserved in the glacier. Eventually, as a result of the glacier's slow descent of the mountains, his corpse was exposed at the edge of the ice sheet in 1991 close to the present Austrian/Italian border. A well-preserved 5 000-year-old corpse with all of its clothes and equipment is a remarkable find by any measure. But possibly most remarkable is that there were three separate fungal products among the Iceman's equipment. One of these is easy to account for. It was a mass of fibrous material in a leather pouch together with flints and a bone tool like an awl. This fungus has been identified as one with a long history of use as a tinder, so clearly it was part of the Iceman's fire-making kit. The other two are more problematical. Both are pieces of a bracket fungus (*Piptoporus betulinus*) and both are threaded onto leather thongs. One piece is essentially conical, about 5 cm in its longest dimension, and is on a simple leather thong. The other is spheroidal, about 5 cm diameter and is on a thong, which has a lobed tassel at one end. These objects were clearly carefully made and must have been important to the owner to be included as part of the kit he chose to take with him in his trek across the mountains. *Piptoporus* is known to produce (and accumulate in its fruit bodies) antiseptics and pharmacologically active substances, which are claimed to reduce fatigue and soothe the mind. With due ceremony and additional magic, these objects may well have been seen as essential to a traveller in the mountains. The conical one might be a sort of styptic pencil to be applied to scratches and grazes. Perhaps the flattened, spheroidal one was chewed or sucked when the going got tough and the tough needed just a little help to keep going.

Our distant European and Asian ancestors held fungal products in such high esteem that they were necessary accessories for daily life, including the most hazardous of journeys. Today, alcohol and citric acid are the world's most important fungal metabolites in terms of production volume, although, penicillin can still lay claim to be the most 'important' in social and medical terms. Since the introduction of penicillin, many millions of chemicals and metabolites have been screened for antimicrobial and other pharmaceutical activities. The lesson has been well learned and screening for bioactive compounds is a major activity of the pharmaceutical and agrochemical industries around the world. Antibiotics obtained from fungi which are presently of clinical use as antibacterial agents include the still-important penicillin, cephalosporin and fusidic acid (both of the latter are useful against penicillin-resistant bacteria), and the antifungal griseofulvin (used to control fungal infections of the skin, nails and hair). Obviously, antibiotics are the products which come to mind first when thinking of medically-useful fungal products. More recently, though, several of the mushrooms cultivated in Asia, especially shiitake or shiang-gu (*Lentinula*) have been shown to produce materials with antitumour, anticancer, antiviral, antihypertensive and anticholesterol effects. Indeed, it may be that the consumption of wood ear (*Auricularia*) is a contributing factor in the low incidence of antherosclerosis amongst Asians (Chang *et al.* 1993; Mizuno *et al.* 1995).

Cultivation of mushrooms for food is on the increase, but wild mushrooms have declined disturbingly in some parts of Europe, possibly as a result of air pollution. Such losses would be of obvious concern to gourmets, but there are much deeper implications. The species most affected seem to be those that form mycorrhizas with the roots of forest trees. Dying fungi might mean dying forests.

These fungi are more important than meets the eye!

10.2. Cultivated mushrooms and other fruit bodies

Agaricus bisporus (replaced by *A. bitorquis* in regions with Mediterranean climates) is by far the most commonly cultivated mushroom around the world (Table 10.2; cultivation procedures are described in the next section). In the mid 1970s the *Agaricus* crop accounted for over 70% of total global mushroom production. Today, it accounts for something closer to 30% even though production tonnage has more than doubled in the intervening years. The biggest change during the last quarter of the twentieth century has been the increasing interest shown in a wider variety of mushrooms. Even in the most conservative of markets (like the United Kingdom) so-called 'exotic' mushrooms have now penetrated the market and supplies of fresh *Lentinula* and *Pleurotus* are routinely to be found alongside *Agaricus* in local supermarkets (Fig. 10.10). Most of these mushrooms are cultivated fairly close to the point of sale. Otherwise, preserved mushrooms are imported as canned or dried products, sometimes at a lower retail price. In some markets the demand for fresh mushrooms is so great that it easily exceeds the ability of the local farming community to satisfy it and the current efficient transport system for chilled products enables the import of good quality fresh mushrooms. For example, most UK imported mushrooms originate in the Netherlands or Ireland. In Hong Kong, nearly all the mushrooms are imported across the border from 'mainland' China, from Taiwan and from Japan. The industry is truly intercontinental, however, and a small supermarket local to DM's home in south Manchester regularly displays punnets of fresh enoki (*Flammulina*) which are grown in Chile. This indicates (a) that intercontinental air transport makes the approx. 12 000 km distance irrelevant and (b) that the production costs are sufficiently low to enable reasonable pricing in such a distant market.

Another reason for the remarkable increases seen in production of certain mushrooms has been the use of substrates which are waste products from other industries. For example, oyster mushroom species (*Pleurotus ostreatus*, *P. cystidiosus*, *P. sajor-caju*) are all easily grown on cotton wastes. Similarly, although the straw mushroom *(Volvariella volvacea)* is traditionally grown in South-East Asia on rice straw, it too can be grown on cotton waste. Cotton waste gives higher yields and is also more widely available than is rice straw so it is a far cheaper substrate (the higher cost of rice straw does not derive from any intrinsic value but in the cost of transporting it to a non-rice-growing

Table 10.2. The mushroom cultivation industry over the final quarter of the twentieth century

	World Production (metric tonnes x 1 000)		Proportion of Total production (1991 figures)	Production increase in 1976-1991
	1976	1991	%	%
Agaricus bisporus and *A. bitorquis*	675	1 590[a]	37.2	2.4
Lentinula edodes	130	526[b]	12.3	4.1
Volvariella volvacea	49	253	5.9	5.2
Pleurotus spp.	15	917	21.5	61.1
Flammulina velutipes	38	187	4.4	4.9
Auricularia spp. and *Tremella* spp.	7	605	14.2	81.8
Pholiota nameko	15	40	0.9	2.7
Hericium erinaceus	?	66	1.5	n/a
Others incl. *Tuber*	<1	89	2.1	29.7
TOTALS	930	4 273[c]	100	4.6

[a] = *Agaricus* spp. global production in 1996 reached 2 million tonnes.
[b] = *Lentinula edodes* global production in 1995 was 840 000 tonnes fresh weight of which more than 80% was produced in China.
[c] = Total world production of mushrooms in 1996 was estimated to be around 5.8 million tonnes (China contributing 3.5 million tonnes).

region). Cotton waste substrates are generated by the textile and garment industries (major industries in the past, and still strong, in places like Hong Kong and the UK) and are produced in bulk by recycling schemes around the world. Disposal of an abundant bulky solid waste coupled with currency earning by sale of a mushroom crop is a good example of an organic farming system integrated with a waste treatment system. The concept of using mushroom cultivation in waste remediation has become a popular model in recent years. All agricultural production generates enormous waste because so little of each crop is actually used; 95% of the total biomass produced in palm and coconut oil plantations is discarded as waste, 98% of the sisal plant is waste, 83% of sugar cane biomass is waste, and in 1995 the global production of cereal straw was estimated at 3.2 x 10^9 metric tonnes (Chang 1998). *Pleurotus* spp. in particular grow readily on so many lignocellulosic agricultural wastes that it becomes an attractive notion to use the fungus to digest the waste and by so doing produce a cash crop of mushrooms. Even more attractive is that after the mushrooms have been harvested the 'spent compost' can be a useful animal feed (the mushroom mycelium boosts its protein content), soil conditioner (it is a compost still rich in nutrients and with polymeric components that enhance soil structure) and even used to digest pollutants (like polychlorinated phenols) on landfill waste sites because it contains populations of microorganisms able to digest the natural phenolic components of lignin (Chiu *et al.* 1998a). Some care must be exercised in applying this attractive concept, though, because *Pleurotus* is also able to accumulate certain metal ions in the fruit body. If the waste material which is to be used as substrate comes from an industrial source which is likely to be contaminated by 'heavy metals' then the mushroom crop may be unsuitable for consumption. For example, Chiu *et al.* (1998b) showed that cadmium could be accumulated in *Pleurotus* fruit bodies to such high levels that a single modest serving of mushrooms could cause the consumer to exceed the tolerable food limit recommended for a full week of intake of this metal.

Truffle cultivation is rather different from that of the other fungi listed in Table 10.2, which can be grown intensively in mushroom farms. The truffle is the underground fruit body of an ascomycete that is mycorrhizal on oak (*Quercus*), so it is dependent on its host tree. The truffle develops a few centimetres below the soil surface as an irregularly shaped, 2-8 cm diameter fruit body, which has an outer rind of tissue protecting an inner mass of ascospores. There are almost seventy different species of truffle, and since they are mentioned in ancient Greek texts they must have been collected for over 2 000 years. The most highly prized - the 'diamond of French cuisine' - is the black truffle of the Périgord region of France (actually more common in Provence), *Tuber melanosporum*. Only 200 tons are harvested every year in France; they sell for nearly 3 000 francs per pound on average. Traditionally, truffles are found using pigs or dogs trained to detect the volatile metabolites produced by the fruit body. Truffle 'cultivation' was first achieved early in the nineteenth century when it was found that when seedlings adjacent to truffle-producing trees were transplanted, they too began producing truffles in their new location. 'Truffiéres' or truffle groves have been established throughout France in the past hundred years and the value of the crop is such that the practice is now extending around the world. Truffiéres are started by planting oak seedlings in areas known to be infested with truffle fungi. The truffles begin to appear under such trees 7 to 15 years after planting and cropping will continue for twenty to thirty years. Most plants infected with *Tuber melanosporum* are now raised in greenhouses although pure cultures of this species cannot be used yet to inoculate the roots of oak seedlings. Recently, methods have been developed to colonise plant roots with the related *T.*

magnatum (a white truffle), encouraging the hope that the same might be done with other truffle species.

A cultivated mushroom, which does not appear in Table 10.2 is *Ganoderma lucidum,* even though the global production in 1997 was about 4 300 metric tonnes (about 3 000 tonnes of which were grown in China). *Ganoderma*, however, is unique in being consumed for its pharmaceutical value (real or imagined) rather than as a food. Under the names lingzhi or reishi, several *Ganoderma* spp. of the *G. lucidum* complex provide various commercial brands of nutriceuticals, in the form of health drinks, powders, tablets, capsules and diet supplements. *Ganoderma* is highly regarded as a traditional herbal medicine (some of the claims made for it have been outlined above), and its popularity in China has spread to other Asian countries, and also to the wider world. Current research is focussed on purification and characterization of the bioactive components and determination of clinical value, especially putative anti-tumour and anti-aging properties. As a nutriceutical, though, it is strictly outside the scope of this chapter. It is cultivated by being inoculated into short segments of wooden logs which are then covered in soil in an enclosure (often a plastic-covered 'tunnel') which can be kept moist and warm. The fruit bodies then emerge in large number quite close together and the conditions encourage the fungus to form the desirable long stemmed fruit body.

10.3. The mycelium as food

The emphasis given in the 1950s to the 1970s to the production of single-cell protein (SCP) is now almost forgotten. The hope that microbes could provide a means of solving the world's food shortage by industrial production of cheap protein alternatives to meat protein were dashed by the realisation that resolution of problems on that scale has more to do with politics and economics than with biotechnology. Today, the emphasis has moved towards the use of wastes as substrates for microbial biomass production, for animal feed and food grade materials as substrates in the production of biomass for use in new foods for sale in advanced economies. Fungal SCP must compete with established animal feeds like soya meal, the price of which can be kept artificially low for long periods. Any novel microbial protein that requires costly research and development and/or unusual and expensive production facilities will not to be able to compete. The two most successful applications for fungal protein in the food industry illustrate the different ways of coping with this economic fact of life. One example is the conversion of brewery wastes, using low-technology processes into flavourings, diet supplements and products like Marmite and Vegemite. Of course, these are yeast products but the example illustrates one successful model - start with a cheap (ideally, a waste-material) feedstock and use conventional production processes to make a product that sells at a relatively high retail price.

The oriental example is the production of *Monascus* products, which can be obtained from submerged fermentation of food processing wastes and were valued at over US $ 2 million in the Japanese market in 1992.

The alternative successful model with a fungal product currently on the market is the Quorn product range based on myco-protein. This is the mycelium of a species of the filamentous soil-fungus *Fusarium*. Production details are given below but the mycelium is grown in a very large air-lift fermenter in a continuous-culture mode (Fig. 10.9). It is consequently a high-technology product. The market virtues of the material centre on its filamentous structure, which enables it to simulate the fibrous nature of meat (Fig. 10.13). Coupled with the inherent nutritional value of fungal biomass, this permits the product to be sold as a low-fat, low-calorie, cholesterol-free health food to consumers who can afford to choose Quorn product as a meat substitute. The retail prices of Quorn product and some other foods in the south Manchester supermarket to which we have already referred are shown in Table 10.3. This little survey illustrates the difference between market value and market price. Quorn product is more expensive than most meat products (and most mushrooms), but it is sold as a 'meat alternative'. Evidently, it is not positioned in the market to be sold to consumers who cannot afford meat, but rather to those who can afford to pay a premium price for a health food. The retail price of Quorn product reflects the perceived value created by the marketing, not the intrinsic value of the product. On the other hand, the retail price of mushrooms is their intrinsic value because severe competition in this sector of the market ensures that retail price very closely reflects actual costs of production, distribution and sale.

With a view to future product developments there is a good deal of research under way on growing fungi such as *Tricholoma* sp. on cheap cellulosic materials, mainly agricultural wastes (Chang 1998). Fungi can also be used to improve the nutritional quality of cereals like barley to compensate for the latter's deficiency in the amino acid lysine. Inoculating soaked barley with *Aspergillus oryzae* or *Rhizopus arrhizus* increases the protein content as the fungus grows. The product is used as pig food.

10.4. Fermented foods

As well as being used directly as food, fungi are also used in the processing of various food products. In these applications the fungus is primarily responsible for the production of some characteristic odour, flavour, or texture and may or may not become part of the final edible product. Growing filamentous fungi on water-soaked seeds of plants is the basis for production of several human food products in Asia, including soy sauce and various other fermented foods. In soy sauce production soybeans are soaked, cooked, mashed and fermented with *Aspergillus oryzae* and *A. sojae*. Depending on the size of the factory, the soybeans may be fermented in fist-sized balls (the traditional method) or on trays. When the substrate has become overgrown with the fungus the material is mixed with salt and water and the fermentation is completed in the brine. The biggest industrial units today use a continuous process in which defatted soybean flakes, moistened and autoclaved are mixed with ground, roasted wheat. The mixture is turned mechanically to ensure even growth of *Aspergillus oryzae* and *A. sojae* for two to three days; then it is transferred to brine and inoculated with *Pediococcus halophilus* and 30 days later with *Saccharomyces rouxii.* The brine fermentation takes six to nine months to complete, after which the soy sauce is pressure-filtered, pasteurised and bottled.

Indonesian tempeh is a white cake produced by fermentation of partially cooked soybean cotyledons with *Rhizopus oligosporus*. The fungus binds the soybean mass into a protein-rich cake that can be used as a meat substitute which is being increasingly widely sold in the vegetarian market. There are a variety of other fermented products of this sort. Ang-kak is a rice product popular in China and the Philippines, which is fermented using *Monascus* species. *Monascus purpureus* produces the characteristic pigments and ethanol, which are used for red rice wine and food colouring (Fig. 10.8). The pigments are a mixture of red, yellow and purple polyketides and about ten times more pigment is obtained from solid state fermentation than from submerged liquid fermentation.

Cheese could be considered the occidental equivalent of the fermented soya products which are popular in Asia. Cheese is a solid or semisolid protein food product manufactured from milk. Before the advent of modern methods of food processing, like refrigeration, pasteurisation and canning, cheese manufacture was the only method of preserving milk. Although basic cheese making is a bacterial fermentation, there are two important processes to which filamentous fungi contribute; these are the provision of enzymes for coagulation and mould-ripening. Cheese production relies on the action of enzymes which coagulate the proteins in milk, forming solid curds (from which the cheese is made) and liquid whey. Traditional cheese-making uses animal enzymes, specifically chymosin and pepsin, extracted from the stomach membranes of unweaned ruminants. Rapid expansion of the cheese-making industry caused attention to shift to alternative sources of such enzymes and moulds like *Aspergillus* spp. and *Mucor miehei* have supplied these to the extent that around 80% of cheesemaking now uses non-animal coagulants. Very recently, animal enzymes produced by genetically-modified microbes have entered the market, but for the moment most industrial cheese production still depends on enzymes from filamentous fungi for the coagulation step. Mould ripening is another matter, being a traditional method of flavouring cheeses which has been in use for at least two thousand years. Blue cheeses, like Roquefort, Gorgonzola, Stilton, Danish Blue and Blue Cheshire, use *Penicillium roquefortii* which is inoculated into the cheese prior to

Table 10.3. Retail price comparisons of fungal food products and other equivalents

Product	pack size (g)	pack price (GBP)	price per 100 g (GBP)	Comments
Quorn mince	350	2.99	0.86	
Quorn pieces	350	2.99	0.86	
Agaricus white mushrooms	750	1.49	0.20	Unwashed 'value' pack, grown locally in UK
	500	1.29	0.26	closed-cups, grown locally in UK
	150	0.99	0.66	'Baby-buttons', grown locally in UK
Agaricus brown cap mushrooms	1 000	3.50	0.35	sold loose, imported from Ireland
Oyster mushrooms (*Pleurotus* sp.)	125	0.99	0.79	grown locally in UK
Shiitake mushrooms (*Lentinula edodes*)	100	1.59	1.59	sold fresh, grown locally in UK
Girolle mushrooms (*Cantharellus cibarius)*	125	1.79	1.43	sold fresh, imported from Italy, presumably collected, not cultivated
Beef, mince	500	1.03	0.21	Fresh meats, all UK produce
Beef, diced	750	4.99	0.67	
Pork, 'casserole' style	500	1.99	0.40	
Pork, 'stir-fry' style	340	2.49	0.73	
Lamb, diced	400	3.69	0.92	
Lamb, diced ('organic')	400	4.59	1.15	
Chicken, diced skinless	400	2.99	0.75	
Turkey, diced	300	0.99	0.33	
Turkey, 'stir-fry'	600	3.99	0.67	
Fish, 'Cod nuggets'	600	1.49	0.25	Sold frozen and bread-crumbed, North Atlantic origin but probably landed in UK
Cheese 'medium fat'	554	3.54	0.64	Fat-reduced, cheddar-style 'industrial' cheese

GBP = pounds sterling. Survey made on 5 September 1999 at Tesco, East Didsbury, Manchester, UK.

storage at controlled temperature and humidity. The fungus grows throughout the cheese, producing methyl ketones, particularly 2-heptanone, as the major flavour and odour compounds. Camembert and Brie are ripened by *Penicillium* *camembertii*, which changes the texture of the cheese rather than its flavour. This fungus grows on the surface of the cheese producing extracellular proteinases, which digest the cheese to a softer consistency from the outside towards the centre.

10.5. Industrial cultivation methods

On all criteria, the biggest (non-yeast) biotechnology industry in the world is mushroom cultivation (Figs 10.1-10.7). Most definitions, however, take the much narrower view that industrial microbial cultivations, the very stuff of biotechnology, are submerged cultivations done in stirred tank reactors (Figs 10.8-10.9). These are popularly thought of as the 'real' fermentations, where the activities of the microorganisms generate a vigorous ferment within the medium. However, if brewing activities are put to one side (on the grounds that they exploit a yeast rather than a filamentous fungus) these aspects of biotechnology are only a very small fraction of the whole - whether calculated in terms of value of product, mass of product, number of people involved in the industry, or geographical area over which the industry is practised. By far the greatest level of exploitation of filamentous fungi uses cultivation in the absence of free-flowing water - the so-called solid state fermentations.

10.5.1. Solid state fermentations

The mushroom industries of the world all depend on some form of solid state fermentation. In the European tradition (Fig. 10.1-10.3) this has come to mean cultivation of a mushroom crop on composted plant litter. Similar approaches were developed for oyster and paddy straw mushrooms in the Orient (Figs 10.6-10.7), though in the Chinese tradition (Fig. 10.4) the typical approach is to cultivate the crop of choice (*Lentinula*) on wood logs.

10.5.1.1. Commercial mushroom production in the European tradition

The European mushroom industry is said to have originated in the caves beneath Paris at the end of the nineteenth century. It probably emerged from the food provisioning functions of the kitchen gardens on the estates of the European aristocracy. Some of the surviving records of such estates refer to manured and composted plots set aside for mushroom production. The compost used, and its preparation, would definitely be familiar to the very competent gardeners of the day. The current industry depends on a compost which is very selective for the crop species *Agaricus bisporus*. Although widely distributed in nature, this fungus is rarely noticed because established mycelia produce relatively few mushrooms, and then only infrequently. The industry we know today seems, therefore, to be the result of a remarkable 'joint evolution' during which an otherwise ordinary horticultural compost was developed that achieves high cropping densities with an otherwise unremarkable and not very abundant mushroom. And all without a genetic engineer in sight!

10.5.1.2. Composting

Good compost is the essential prerequisite for successful mushroom farming (Figs 10.1-10.3). For *Agaricus* farming, compost preparation is a smelly process because a nitrogen-rich animal waste is included. Even the most modern installations have a severe impact on their neighbours! The human nose can sense 10 ppm ammonia but the ammonia emitted from a fermenting compost can reach 600 to 1 000 ppm. To make mushroom composting environmentally friendly, the air from compost producers must be collected and treated chemically and biologically to remove the generated pollutants (ammonia and sulfur-containing compounds). The basic raw material for mushroom compost in Europe is wheat straw, although straws of other cereals are sometimes used. Ideally, the straw is obtained after it has been used as stable bedding and is already mixed with horse manure. On a commercial scale this is not possible and other animal wastes, like chicken manure, are mixed with the straw, together with gypsum and large quantities of water. The use of gypsum (calcium sulphate) in the preparation of compost was generally introduced in the late 1930s. Excess calcium reacts with and precipitates the mucous and slimy components of manure, and so prevents water logging of the compost. This generally improves aeration and, most importantly, the mechanical properties which aid thorough mixing. Its introduction resulted in large crops being grown reliably for the first time because uniformly digested compost could be readily produced.

Composting proceeds in two phases. In phase I the straw, manure and other components are mixed into large heaps. After the water is added the heaps are thoroughly mixed by mechanical compost turning machines. This 'pre-wetting' treatment continues for a few days and then the machines arrange the compost into long stacks about 2 m wide, 2 m high and many metres long. Within a few days the bacterial activity heats the stack to around 70 ^{o}C in the centre, though it is considerably cooler at the surface. Higher temperatures, which would kill the microorganisms, are avoided by regular 'inside-out' turning of the compost heap. As well as heat, the bacterial degradation process releases large amounts of ammonia. An important aim in phase I of composting is to achieve uniformity by thorough mixing (so that all of the compost spends some time within the hotter core of the stack). A week after the stack was first laid it is mixed, or 'turned', by large, self-propelled 'turning' machines (Fig. 10.1). It is left for a further week, then turned again. Three weeks after the process begins, the compost is ready for phase II.

Phase II, also known as peak-heat, pasteurisation or sweat-out is a continuation of the composting process but without further mixing and under more controlled conditions. The compost may be treated in bulk or loaded into the eventual growing containers. In either case the process is done in a building which allows air to be circulated around the growing containers or through the bulk of the compost. To begin with, air and compost temperatures are raised to about 60 °C for several hours. This pasteurisation stage is usually completed in a day and then the amount of ventilation is increased and compost temperature is kept at about 50 °C for 4-6 days. The beds are then allowed to cool to around 25°C and are ready for use. A natural drop in temperature and absence of free ammonia are signs that the composting process has been completed.

10.5.1.3. Spawning

Spawning is the process that introduces the mushroom mycelium into the compost. This is generally done with some form of carrier that can be easily-mixed into the compost, fungus-coated cereal grains (often barley) being the most usual. About 5 kg spawn per tonne of compost (= 0.5% by weight) is used. From these inoculation centres the mycelium grows out to invade the compost (= 'spawn running'), filling the compost bed after 10-14 days at a compost temperature of 25 °C. Slow-release nutrients might be added at the casing step or separately.

10.5.1.4. Casing

To encourage fruiting of *Agaricus*, the spawn run compost must be covered with a 'casing layer' - originally of soil but now most usually a mixture of moist peat and chalk, the chalk being used to adjust the otherwise acidic pH to a neutral one. Casing is required only by *Agaricus*, the procedure is not necessary when cultivating other species such as *Volvariella* spp., *Pleurotus* spp., *Auricularia* spp. and *Lentinula edodes*. The optimum depth of the casing is 3-5 cm and it should be an even layer applied to a level compost surface. The mushroom mycelium grows into the casing layer in similar conditions to those for spawn running. But the mycelium reaches the upper surface of the casing layer as strands - a necessary start to the fruiting process. To encourage completion of fruiting the growing room is ventilated to lower the concentration of carbon dioxide (usually < 0.1%) and to help reduce the temperature to 16-18 °C. Throughout these steps the casing layer must be kept moist by mist-spraying with water at intervals. Moisture, temperature and atmospheric gases all have to be stringently controlled to match the requirements of the particular mushroom strain being cultivated. After allowing 7 to 9 days for the *Agaricus* mycelium to grow into the casing layer, a machine with rotating tines is run across the mushroom bed to mix the casing layer thoroughly. This is called 'ruffling' and it serves to break up the mycelial strands and encourage the mushroom mycelia to grow and colonize the surface of the casing layer.

10.5.1.5. Cropping

A few days after ruffling, the sudden change in microclimate sensed by the mushroom mycelium on the surface of the casing soil triggers the formation of mushroom primordia in *Agaricus*. These juvenile mushroom fruit bodies, called 'pins' or 'pinheads' which are more or less spherical and have a smooth surface, will be seen about 7 to 10 days after casing (Fig. 10.2). It will be 18 to 21 days after casing before marketable mushrooms can be harvested (Figs 10.3, 10.11). Successions of mushrooms then develop in a series of flushes about 8 days apart, and each taking about 5 days to clear from the beds. During the cropping period, the casing needs to be kept moist and the air temperature must be maintained in the 16 to 18 °C range. Ventilation must also be maintained to keep carbon dioxide levels low. Accurate balance is required here: humidification is essential to minimise desiccation, but excessive humidity encourages disease.

Growers expect to harvest between three and five flushes from each spawning cycle, with a total yield of around 25 kg m^{-2} of growing tray. After the final pick (seven to ten weeks after spawning) the compost is spent, and the cropping room is emptied, cleaned, sterilised and filled with the next crop. On most large commercial farms a new crop is filled every one or two weeks throughout the year. So a mushroom farmer is likely to see more crops in one year than a cereal farmer will see in a lifetime!

10.5.1.6. Cropping and service systems

Although the basics of mushroom production are the same however the crop is produced, growing containers differ and the process can be separated into specialised stages. Mushrooms may be produced in large wooden trays, in beds on shelving and in plastic bags. Trays, made of wood in sizes varying from 0.9 x 1.2 m to 1.2 x 2.4 m and 15 to 23 cm deep, are arranged in tiers 3 or more high, separated by wooden legs. Fork lift trucks are needed to move the trays and some sort of mechanised tray handling line is necessary. Shelving is usually made of metal and arranged to give four to six layers of fixed shelves in a cropping room with centre and peripheral access gangways. Each shelf is about 1.4 m wide and extends almost the whole length of the room. Special machinery for compost filling, emptying, spawning, casing and other cultivation operations is necessary. Growing bags of about 25 kg are usually supplied to the farm already spawned and may be arranged on the floor of the cropping house or on tiered shelving. Each arrangement makes its own demands on techniques and equipment. It is also often the case that the outdoor stages of composting are completed by a specialist compost producer, with the ready-to-use compost delivered in bulk to a mushroom farm. Indeed, the compost may even be delivered ready spawned so that the farm process starts with spawn running. Nowadays, the mushroom production industry comprise spawn makers, phase I compost, phase II compost and phase III compost suppliers. Phase III compost is completely colonized by the mushroom mycelia which if placed in a suitable environment in a mushroom farm will produce the fruit body crop readily. Cardboard boxes of phase III compost are now widely available as 'home grown mushroom kits'. For a commercial mushroom farmer, the use of phase I compost gives the most flexibility to optimise farm conditions for cultivation of any mushroom strain. Purchase of phase II compost enables a farmer to choose which mushroom strain to spawn. The use of phase III compost, though it is obviously more costly, guarantees the production of a crop in a short time and requires the least prior investment in facilities for mushroom production.

The production method for *Pleurotus* (oyster) mushrooms is in sharp contrast to the approach just described for *Agaricus* because the needs of the organism are much less stringent. This goes some way to explaining the rapid boom in oyster mushroom farming from the late 1980s to the present day. Both composted/pasteurised and sterilized, but uncomposted, substrate of a wide range (sawdust, wheat straw, etc.) can be used. No casing is required. The crop can be adapted to different countries depending on their climates by growing different species of oyster mushrooms, e.g. *Pleurotus pulmonarius* (misnamed as *P. sajor-caju*) in India; *P. ostreatus* (commercially called *P. florida* - another inaccurate name) in Europe.

10.5.1.7. Commercial mushroom production in the Asian tradition

Lentinula edodes (shiang-gu) is traditionally cultivated on hardwood logs (oak, chestnut, hornbeam) and is still very widely grown like this in the central highlands of China. To put this statement into perspective, the traditional log-pile approach is still the most frequently used method in China over a growing region which covers an area about equal to the entire land area of the European Union. The logs considered suitable for shiitake production are over 10 cm diameter and 1.5 to 2 m long. The logs are normally cut in spring or autumn of each year to minimise pre-infestation by wild fungi or insects. Holes drilled in the logs (or saw- or axe-cuts) are packed with spawn, and the spawn-filled hole then sealed with wax or other sealant to protect the spawn from weather. The logs are stacked in laying yards on the open hillside in arrangements which permit good air circulation and easy drainage and provide temperatures between 24 °C and 28 °C (Fig. 10.4). The logs remain here for the five to eight months it takes for the fungus to grow completely throughout the log. Finally, the logs are transferred to the raising yard to promote fruit body formation. This is usually done in winter to ensure the lower temperature (12-20 °C) and increased moisture which are required for fruit body initiation. The first crops of mushrooms appear in the first spring after being moved to the raising yard. Each log will produce 0.5 to 3 kg of mushrooms, each spring and autumn, for 5 to 7 years.

This traditional approach to shiang-gu/shiitake production is expensive and demanding in its use of both land and trees. Some commentators estimate that there are 10 million mushroom farmers in China; if true, the traditional use of locally-cut logs is likely to devastate the hill forests. For this and other reasons more industrial approaches are being applied to shiitake growing. Hardwood chips and sawdust packed into polythene bags as 'artificial logs' provide a highly productive alternative to the traditional technique (Fig. 10.6), and the cultivation can be done in houses (which may only be plastic-covered enclosures) in which climate control allows year-round production.

The straw mushroom (*Volvariella volvacea*) is grown mainly on rice straw (Fig. 10.5), although several other agricultural wastes make suitable substrates. Preparation of the substrate is limited to tying the straw into bundles which are soaked in water for 24 to 48 hours. The soaked straw is piled into heaps about 1 m high which are inoculated with spent straw from a previous crop. In less than one month, a synchronized flush of egg-like fruit bodies appear. These immature fruit bodies (in which the universal veil is intact and completely encloses the immature fruit body, Fig. 10.7) are sold for consumption just like the young fruits ('baby buttons', Fig. 10.11) of *Agaricus* (though this is not the case with oyster and shiitake mushrooms which are sold mature). Comparatively low yields of *V. volvacea* are generated from the substrate, and it is difficult to maintain good quality in post-harvest storage. Within 2-3 days the crop turns brown and autolyses even in cold storage. These factors restrict production of the crop.

10.5.2. Quorn product manufacture

Myco-protein is the name agreed with the Ministry of Agriculture Fisheries and Food in the UK to serve as the generic name for a food product resulting from the continuous fermentation of a selected strain of *Fusarium venenatum* (originally called *F. graminearum*). The material is produced by Marlow Foods Limited a subsidiary company of Astra-Zeneca, a major global health care company. The product was originally intended to be dried and powdered for sale as a high-protein SCP flour but the organoleptic qualities and physical properties of the hyphal mass were recognised as being of value in creating meat-like textures which led to the development of the Quorn product range.

The fungus is grown on food-grade glucose as the carbon source, usually derived from wheat or maize starch, and a 45 m tall airlift fermenter is used in continuous culture mode (i.e. medium is added continuously and mycelium plus spent medium is harvested at a rate equal to the production of new hyphae)

(Trinci 1992). Fast-growing fungal cells contain 8 to 9% RNA (w/w) but since some humans are intolerant to high levels of nucleic acids (which are metabolised to the sparingly-soluble uric acid which can accumulate in the joints - in other vertebrates the much more soluble allantoin is the end-product of nucleic acid catabolism) myco-protein must therefore be processed so that the WHO (World Health Organisation) recommended maximum daily intake of nucleic acid (4 g) is not easily exceeded. Immediately after harvesting the temperature of the biomass is raised (in less than 10 sec) to 64 °C and held for 20 to 30 min. This stops growth, disrupts ribosomes and activates endogenous RNAases which digest cellular RNA to nucleotides which then diffuse out of the tissue. Loss of protein and fibrous structure is minimised though about 30% of the dry weight is lost in the treatment. The RNA content is reduced to about 1%, well within the upper limit recommended by the WHO. After RNA reduction, the mycelia are harvested by centrifugation to give a mycelial biomass containing about 25% solids. Myco-protein typically contains 44% protein, 24% dietary fibre and only 12% fat on a dry weight basis (the values for beef are 68%, 0% and 30% respectively)(and see Table 10.4).

The sole use for myco-protein at the moment is as the primary ingredient of the Quorn product range of 'meat-alternative' products. The *Fusarium* biomass is mechanically processed to align the hyphae and this alignment is 'set' by mixing with a small amount of egg albumin which binds the filaments together when heated. This mimics the muscle fibre and connective tissue structure of meat. Quorn products are marketed as 'The tasty, healthy, alternative to meat ...' and the makers claim '...It is mushroom in origin and provides the taste and texture of a full range of meat products and ready meals but is entirely meat free...' (see Marlow Foods Limited web site at http://www.quorn.com/). The web site glossary describes myco-protein, more accurately, as 'The harvested filamentous cells of a distant relative of the mushroom family (*Fusarium* species (Schwabe) ATCC20334) grown by a continuous fermentation process.'

The simplest forms of myco-protein which are marketed are Quorn product mince and Quorn product pieces intended for use in home cooking recipes in much the same way as meat products. A widening variety of products is emerging, which now include: Quorn product burgers, sausages and fillets; Quorn product ready meals; and the 'Quorn Deli' range of cold cuts - a sliced meat alternative for salads, sandwiches or snacks (Fig. 10.13). The main thrust of the marketing for all of these products is 'healthy eating' - the headlined 'Quorn product facts' being: low in fat, good source of protein, good source of dietary fibre, low in calories, cholesterol free. The absolute content of the various components in the retail product depends more on the process recipe than the myco-protein (Table 10.4). Given that the sparsely-branched filamentous structure of *Fusarium* is crucial to the creation of the meat-like texture of Quorn product, it could be argued that the use of myco-protein in the manufacture of

Quorn products is the only true example we have in which it is the ***filamentous*** character of the fungus that is exploited.

Monascus pigments (Fig. 10.8) and ethanol, and enzyme production by *Aspergillus* and *Mucor* (in relation to cheese production) have been mentioned earlier. Many other enzymes produced by filamentous fungi in fermentation cultures are used for processing foods. For example, amylases (from *A. niger, A. foetidus, Rhizopus foetidus*) are used to convert starchy substrates to sugars prior to alcoholic fermentation, and also to make chocolate syrups from cocoa, and invertase (from *Aspergillus oryzae, A. niger*) is used for sucrose conversion in confectionery. Some other industrial uses for fungal enzymes include proteinases and lipases from *Aspergillus oryzae* used in detergents and proteinases used in hide processing in the tanning industry. The global value of enzymes from filamentous fermentations is in the region of US $ one billion. The single most important fermentation metabolite is citric acid, 300 000 tonnes of which are produced (mostly by *Aspergillus niger* and *A. wentii*) each year to be used mainly in effervescent soft drinks. The standard production method is a fermentation of sugar beet, cane molasses or a glucose syrup. Important though these liquid fermentations are, in all cases the enzyme or metabolite product is purified from the fermentation liquor (in some cases the enzyme is extracted from the biomass), so the fungus itself is not a component of the final product.

10.5.3. Wild harvests

Collecting mushrooms for food is an age-old tradition which is on a par with collection of berries and other forest fruits. It becomes an exploitation when the collection becomes an industry which is pursued in order to supply a commodity.

10.5.3.1. Commercial mushroom picking

Several wild mushrooms have reached the 'exploitation' state. Masutake, chanterelles, morels and truffles probably represent the best expression of this in the popular imagination because of the history and mystique associated with the industries in their home countries; in Europe, particularly in France and Italy. These histories include festivals and markets which associate folk events and heighten interest in and appreciation of the qualities of the products themselves. Those qualities contribute to the mystique, prompting discussion of how tasty and flavourful competing collections might be. The truffle probably has more mystique than most because this subterranean delicacy is still hard to find and harvest so there is the added mystery of detecting the presence of a truffle ten or twenty cm underground with the help of forest lore, flies, or trained pigs and dogs. There are about seventy different truffle species. The most highly prized in French cuisine is the black truffle of the Périgord, *Tuber melanosporum,* but in

Italy it is the white truffle of Alba which is considered the true delicacy. Deciding these matters creates lots of fun and innocent enjoyment, and makes a lot of money! The world market for chanterelles (collected, not cultivated) was estimated recently at more than 1.5 billion US $ (Watling 1997). Add the value of tourism and peripheral matters like television cookery programmes, recipe books and magazine articles and the collection and appreciation of these fungi becomes a very big industry indeed. Unfortunately, mycorrhizal species like these have shown a significant decline in fruit body formation in recent years (Arnolds 1991, 1995). The widened and increasing market and heightened commercial demands for forest fungi are appearing at a time when the woods and forests are under pressure from many other dangers like urbanization, global warming, deforestation and industrial pollution.

Although mushrooms have been important sources of food and medicine for a great many years, the demand for wild mushrooms has grown sharply since about the early 1980s. Speciality mushrooms have always been harvested and shipped to distant markets. For example, as early as 1872 New Zealand had a fungus-based industry earning, eventually, hundreds of thousands of pounds (sterling) annually by collecting the wood ear fungus (*Auricularia polytricha*) for sale in China. This fungus trade was initiated by a New Plymouth merchant, Chew Chong and provided much-needed income for New Zealand's settlers.

The then Colonial Secretary of Hong Kong, in answer to an inquiry from the New Zealand Colonial Secretary in 1871, reported that the fungus was used as a medicine "...much prized by the Chinese community..." It was also used as a food, 'mu-erh', eaten with noodles and bean curd, as well as in soups. Chong paid colonial farmers four pence per pound weight of sun-dried fungus and is said to have purchased an average of 65 pounds sterling-worth on each New Plymouth market day (equivalent to 1.8 metric tonnes!). Retail prices in the Hong Kong market were four to ten times that. This trade in New Zealand wood ear was maintained until the 1950s, eventually being effectively killed off when commercial cultivation of *Auricularia* made collection from natural sources uncompetitive. This story emphasises the rural ideal of collection of a cash crop by local residents for sale elsewhere. Generally small and scattered enterprises where pickers sell and ship most of their own harvest. The trade may be seasonal, and the volume of mushrooms picked may be relatively small. All of this changed during the late 1980s, mainly in the amount and manner in which mushrooms were harvested, sold, and handled. The commercial picking industry has now expanded to a system of harvesters, buyers, processors, and brokers. Harvesters locate and pick the mushrooms. Buyers, typically associated with a specific processor, set up buying stations near wooded areas known to produce mushrooms and advertise their willingness to buy. Processors grade, clean, pack, and ship the product while providing the cash directly to the field workers. Brokers market the mushrooms around the world. This is a model which has become common in Europe and the United States. One of the things that makes it viable is the easy access to rapid trans- and intercontinental transport. As transport and communications continue to improve, the commercial picking industry is bound to expand further.

10.5.3.2. Regulate or be damned

In most areas in which commercial mushroom pickers operate the operation is seen as a 'problem', though the exact perception of what the problem consists of depends very much on the standpoint of the observer. In any one region there may be thousands of pickers harvesting fungi for commercial purposes from both private and public lands. The knowledge we have about the ecology of wild edible mushrooms is incomplete and this ignorance is at the centre of the conflicts which are arising between commercial pickers and conservationists and local residents. The three parties do not always align as might be expected. A successful commercial picking job can see a region of woodland completely denuded of marketable mushrooms in just a few hours. Local residents see this as destruction of a natural resource which 'belongs to the people' and expect the support of conservation-minded mycologists in the campaigns which result. Unfortunately, ownership of the resource is not always entirely transparent. 'The people' may be allowed to enjoy a woodland for what it is by a generous landowner who subsequently is enlightened to the cash value of its mushroom crop. Similarly, it is not at all clear that picking mushrooms does any damage that a conservationist should be concerned about. In the UK the activities of commercial pickers have been likened to the activities of factory fishing boats which take fish of all ages and consequently damage the breeding stock of the fishery to the point where the fish population declines catastrophically. This is an emotive comparison for the UK, which has experienced a catastrophic decline in its own fishing industry, but it has almost no biological relevance to commercial mushroom picking. Mushrooms are not individuals, but simply the fruiting structures arising from underground mycelia. Removing one generation of fruit bodies will probably encourage a new generation to emerge. Certainly, continued productivity of mushroom farms beyond the first flush of cultivated mushrooms is enhanced by regular harvesting.

Table 10.4. Nutritional comparison of Quorn products with their meat equivalents

Per 100g	**Units**	**Quorn** Pieces	Skinless Chicken Pieces	**Quorn** Southern Burgers	Breaded Chicken Burgers	**Quorn** Burgers	Beef Burgers	Low Fat Beef Burgers	**Quorn** Sausages	Low Fat Pork Sausages
Energy	(kJ)	355.0	621.0	746.0	1128.0	490.0	1192.0	777.0	491.0	728.0
Energy	(kcals)	85.0	148.0	178.0	270.0	117.0	287.0	186.0	115.0	174.0
Protein	(g)	12.3	24.8	10.7	12.9	12.8	15.0	17.6	13.5	13.0
Carbohydrate	(g)	1.8	0.0	12.3	17.1	5.8	3.5	3.7	5.2	9.6
of which: sugars		0.8	0.0	1.5	0.5	2.5	0.7	0.7	1.0	0.4
Oil/Fat	(g)	3.2	5.4	9.6	16.7	4.6	23.8	11.3	4.7	9.3
of which: saturates		0.6	1.6	1.2	6.5	2.3	10.0	4.8	2.8	3.5
Fibre	(g)	4.8	0.0	3.1	0.6	4.1	0.4	trace	3.4	1.6
Sodium	(g)	0.2	0.1	0.6	0.5	0.5	0.5	0.5	0.6	0.9

The table shows typical values for the same amount of six meal types. The data were obtained from the Marlow Foods Limited web site (http://www.quorn.com/) which states that the information comes from official sources. Quorn pieces contain a high % of myco-protein and are therefore close to representing its native composition. Note how the composition depends more on the product recipe than on the myco-protein.

What must be safe-guarded, of course, is the health of the mycelium and so there probably is a need for regulation aimed at avoiding unnecessary trampling and disturbance. But this is not the sole reason regulation is required. The USDA has studied commercial mushroom picking in forests of the North American continent, highlighting the issues in several reports (Molena *et al.* 1993; Pilz and Molina 1996; Hosford *et al.* 1997). These reports make it clear that mushroom harvesters range from the curious recreational collector, via temporarily unemployed workers needing additional income to highly skilled and almost professional commercial pickers. The ranks of the latter often include individuals who work in forestry supplementing income during periods of slack employment by collecting and selling mushrooms. Mushroom harvest dollars are often part of the 'black economy' in which much of the cash value is not reported. Even if unreported, harvest dollars benefit local communities.

Even remote areas may experience commercial picking of especially valuable species. Helicopters are routinely used to transport matsutake collected in roadless areas of interior British Columbia (Hosford *et al.* 1997). Relatively inaccessible areas are unlikely to experience significant commercial picking when retail prices are low. There is significant international competition and international markets and prices can fluctuate wildly from year to year, and even within a season, as global weather patterns produce good or poor crops in various locations. Competition and price fixing affect prices paid to pickers. When prices are high, large numbers of pickers may congregate in small areas '... sometimes to the consternation of land managers and the local communities' (Amaranthus and Pilz 1996).

The regulatory issues created by commercial mushroom picking across the Pacific Northwest include: overharvesting, undesirable harvest methods, competition between harvesters for 'picking rights' (sometimes armed conflict! See McRae 1993; Hosford *et al.* 1997, p. 45), wildlife harassment, traffic safety and road repairs, campground crowding and maintenance, littering, trespass, firearm safety, vandalism, and research site security. The report concludes: '...Regulations for protecting the mushroom resource may take the form of implementing harvest rules and permit systems, limiting permit numbers, allocating or rotating collection areas, or providing contracts for exclusive harvest rights. Prevention of inappropriate harvest methods requires communication through meetings, videos, posters, handouts, press releases, presentations, and other public education efforts. Road closures may be necessary to control traffic, road deterioration, and wildlife harassment or to protect research and monitoring areas. Law enforcement is needed to deter unauthorized or illegal activities in the forest. Large numbers of harvesters and avid competition for a valuable commodity can increase the potential for crime, and because buyers often handle large amounts of cash, they are tempting targets for robbery' (Amaranthus and Pilz 1996).

10.5.3.3. Managing the ecosystem towards sustainable development

The growth in commercial mushroom picking of recent years is unlikely to have generated so much concern had it not coincided with the growing debate about conservation and the damage done to natural biodiversity by commercial pressures. Revelations of the extent of commercial picking, or indeed the arrival of commercial pickers in a woodland, fuel concern that both timber and mushroom harvesting adversely affect the sustainability of wild mushroom populations. It is not necessary to be an expert in order to recognise that our woods and forests are being changed by commercial pressures of all sorts; from pressure to use the land for other purposes to pressure to grow a more profitable tree crop. Couple this with the known adverse effects of atmospheric pollution (especially severe in northern Europe) and one can readily appreciate how commercial mushroom picking amplifies existing concern among mycologists, forest managers, recreational pickers, commercial harvesters, buyers, and processors alike.

The decline of fungal populations in Europe and its correlation with increases in various types of pollution are well documented (Arnolds 1991; Frankland *et al.* 1996). Industrial pollution effects on fungal populations in China and other emerging nations is also likely, but lacks documentary evidence! Acid rain, caused by the use of high-sulfur coal for power generation, has been linked to decline in European temperate forests and mycorrhizal fungi. For example, the decline in *Cantharellus cibarius* has been correlated with acid rain deposition patterns (and specifically *not* with mushroom harvesting) (Jansen and van Dobben 1987). Pollutants from heavy industry harm trees directly and thereby damage the soil and mycorrhizal fungal associates. These pollutants are at much lower levels in the Northwest US forests, but it is not known whether nitrous oxides and ozone values typical of the Pacific Northwest could influence production of wild edible mushrooms. Fruit bodies may still be produced in polluted environments, yet be inedible due to contamination, including heavy metal accumulation. As many of the commercially valuable fungi are mycorrhizal, genuine fears have been raised that mushroom harvesting at current rates could adversely affect forest health and productivity or food webs for wildlife species. Unfortunately, we again encounter the problem that so little research is done on the Kingdom Fungi that we just do not know whether the catastrophe is happening, is about to happen, or has already happened!

Some US agencies are restricting mushroom harvest in particular forest areas because of these uncertainties and additional regulation and legislation will no doubt be called for. Data from Europe, however, has not attributed decline in populations of mycorrhizal fungi in the last thirty years to collection of mushrooms by commercial pickers. Rather, alterations in forest habitats by agriculture and urban development has led to changes in fungal biodiversity. Importantly, decline in mushroom populations over these years has outpaced the loss or alteration of habitat, changes in forest age, change in tree composition, and change in forest structure. Again, we find our own ignorance at the end of our search for reasons.

The key reaction to all this seems to be to call for effective management of the forest resource. Coupled, of course, with the recognition that the mushroom harvest is part of that resource and its demands must be anticipated. Land managers play key roles here because their tree management decisions influence the abundance and distribution of wild mushrooms. Managers must appreciate that wild mushrooms are an important forest product, both economically and ecologically. Mycologists must contribute, too. Historically, mycologists have not been used to thinking in terms of conservation, and for that matter, conservationists have not paid much attention to fungi. Even though the decline of biodiversity has been expressed in Red Data lists of threatened plants and animals for several years, fungi are only just making an appearance. We need to encourage 'ecosystem management', which is an holistic approach to managing land, based on understanding and maintaining the components, interactions, and processes of ecological systems, while simultaneously producing products and services for society. The USDA principles are worthy of wider adoption: '... to be effective, ecosystem management must be "adaptive;" that is: (i) the best information currently available should be used for immediate decisions; (ii) monitoring and research activities should be started to address critical areas of ignorance; (iii) management strategies should be adapted (modified) as improved information becomes available...' (Pilz *et al.* 1996).

An ecosystem is an interactive network of the organisms and their environment. Every organism plays a part. Thus changing a natural ecosystem into a monoculture (say, a plantation with just one type of tree) in the hope of creating a mushroom farm in forest area, is unlikely to be successful. Rather, by preserving the natural habitat as a whole and implementing a proper holistic management, a consistent mushroom yield can be guaranteed with secure replenishment from natural resources. This should be a way to maintain a sustainable resource which the public can enjoy while the mushroom harvester also profits from it.

10.6. Concluding remarks

As a readily manipulated group of saprobic and mycorrhizal organisms, fungi will continue to be used for commercial exploitation. Future uses are unlikely to be limited solely to food production. Opportunities for exploitation are already expanding into the fields of nutriceuticals (nutrients which have some additional medical value) and food supplementation with a special flavour, taste, texture and/or colour. Advances in cultivation technology guarantee control of product quality and consistency and permit modification as required to meet market demands.

Both developed and developing countries grow and sell mushrooms, and the cultivation industry is currently structured in a way that allows considerable benefit to be returned to the mushroom farmers of the world. If there are ten million mushroom farmers in China, and there are certainly over a million decentralized mushroom farms, the cash return on the mushroom crop is making a considerable contribution to rural income. This remains true even though farm-gate prices are much lower than retail prices. Exploitation, however, is an economic concept; it has nothing to do with altruism and little to do with science. Indeed, the view from the academic's office may be very different from the view of the accountant's. Current biotechnology theory is likely to include the phrases 'market pull' (the extent to which product success is determined by the demands of the market and positive response of the consumer) and 'science push' (the introduction of innovative products to the market as a result of scientific innovation). We hope it is not too cynical to suggest that the really critical contribution is made by what we would call 'accountant shove' and define this as the tendency to take decisions that seek to maximise return on past investments as well as future profits solely for the benefit of the balance sheet. Future developments in the exploitation of filamentous fungi must give due weight to the community impact of the exploitation. In developing cultivation methods we think this means applying the latest research in adapting traditional methods, and integrating mushroom cultivation with waste disposal and remediation. In developing commercial picking we think this means combining conservation with picking so that the industry is sustainable. In the fermentation industries this should mean ensuring that the real value of the product far outweighs any adverse environmental impact of the industrial process itself or its wastes. Above all, there is a need for wider and deeper research into the biology of fungi. Too often, it seems, literature surveys reveal our ignorance more explicitly than our knowledge. Exploit the fungi, not the consumers, communities or cultivators.

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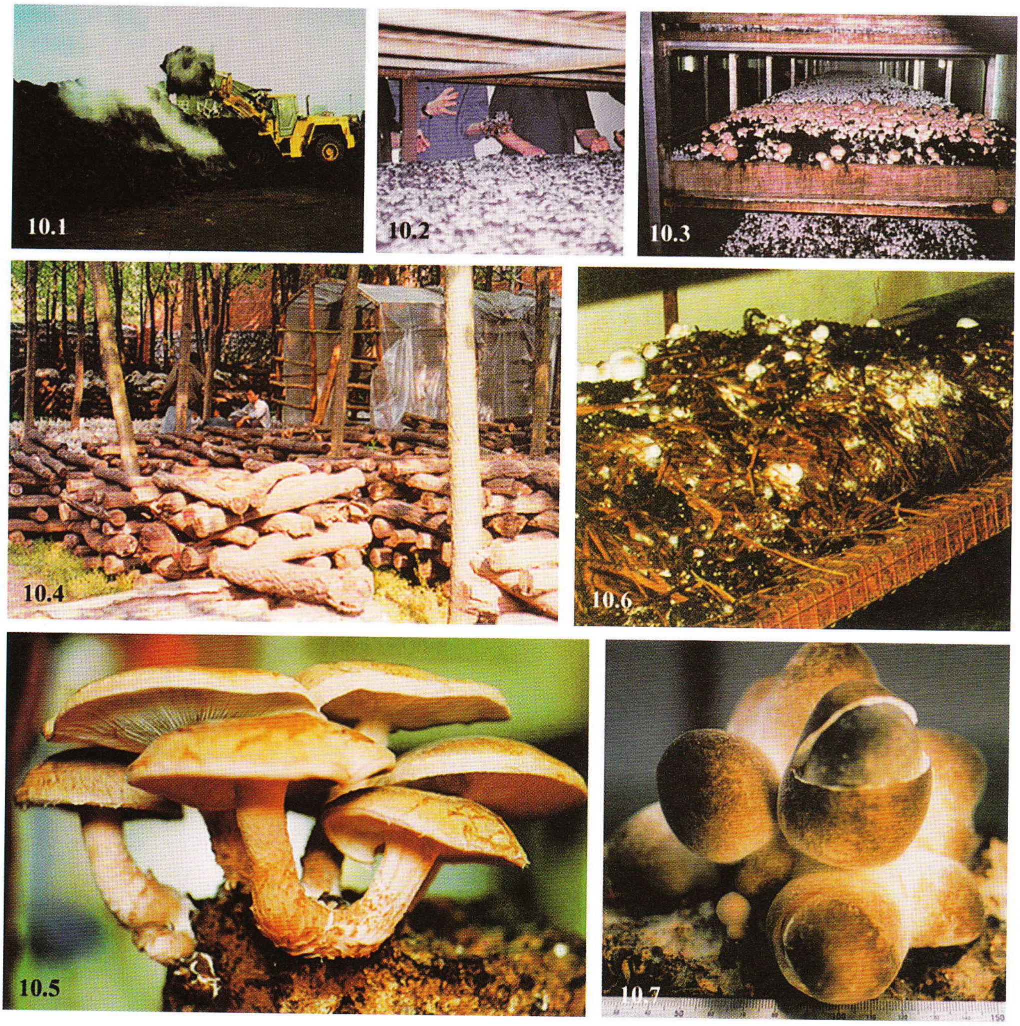

Figs 10.1 – 10.7. Mushroom production. **Fig. 10.1,** turning the hot, steaming *Agaricus* compost. **Fig. 10.2,** "... never mind the pins, feel the compost ..." it is considered very important for the farmer to feel the texture and moisture level of the compost. This sort of subjective judgement of the state of the compost is highly valued even though most of the environmental conditions (light, relative humidity, air temperature, compost temperature) for *Agaricus* cultivation are likely to be computer-controlled. **Fig. 10.3,** the middle tray in a three-tier *Agaricus* growing house in The Netherlands. **Fig. 10.4,** an outdoor shiitake farm using natural wood logs in Hubei Province, China. **Fig. 10.5,** *Volvariella volvacea* growing on rice straw in the Department of Biology, The Chinese University of Hong Kong. **Fig. 10.6,** *Lentinula* mushrooms fruited on an artificial log in the Department of Biology, The Chinese University of Hong Kong. **Fig. 10.7,** immature *Volvariella* 'eggs' grown on cotton waste compost (mixed with lime and wheat bran) in the Department of Biology, The Chinese University of Hong Kong.

Figs 10.8-10.13. Figs 10.8, 10.9. Fermenter growth of fungi. **Fig. 10.8,** an experimental fermenter of 12 l capacity, growing *Monascus purpureus* in the laboratory in the Biology Department, The Chinese University of Hong Kong. **Fig. 10.9,** the world's largest continuous flow culture systems are used to produce the Quorn™ mycoprotein. **Fig. 9a,** the Quorn 2 fermentation tower (50 m tall, 155000 litre capacity) installed in 1993; **Fig. 9b,** installation of the twin Quorn 3 fermentation tower in May 1994; **Fig. 9c,** the completed (and current) process plant. **Figs 10.10 – 10.13.** Point of sale. **Fig. 10,** supermarket mushrooms in Didsbury, Manchester. **Fig. 11,** selling mushrooms in Nathan Road, Hong Kong. **Figs 12, 13.** Fungi as food for sale in Manchester. **Fig. 12,** fresh *Agaricus bisporus* button mushrooms in their natural state. **Fig. 13,** Three packs of Quorn Deli slices, manufactured from myco-protein. [Quorn™ and the Quorn™ logo are trademarks of Marlow Foods Ltd; images in Fig. 10 are copyright Marlow Foods Ltd and reproduced with permission].