Journal of Industrial Microbiology & Biotechnology (2002) 29, 99–110

www.nature.com/jim

Influence of straw types and nitrogen sources on mushroom composting emissions and compost productivity

R Noble[1], PJ Hobbs[2], A Mead[3] and A Dobrovin-Pennington[1]

[1]*Department of Plant Pathology and Microbiology, Horticulture Research International, Wellesbourne, Warwick, CV35 9EF, UK;* [2]*Institute of Grassland and Environmental Research, North Wyke, Okehampton, Devon, EX20 2SB, UK;* [3]*Biometrics Department, Horticulture Research International, Wellesbourne, Warwick, CV35 9EF, UK*

The effects of different straw types and organic and inorganic nitrogen (N) sources on the chemical composition and odor concentration (OC) of mushroom composting emissions, compost parameters, and mushroom yield were examined using bench-scale and large-scale (windrows and aerated tunnels) composting systems. There were close correlations between the butanol or combined H_2S+dimethyl sulfide (DMS) concentration and OC of air samples taken from different composting ingredients (r=0.83 and 0.76–0.87, P<0.01, for $\log_e$-transformed data). Differences in N availability, in terms of NH_3 and N losses during composting, were found between different N sources. Materials in which the N was less available (chipboard and digester wastes, cocoa shells, ammonium sulfate) produced lower mushroom yields than materials in which the N was more readily available (poultry manure, urea, brewers' grains, hop and molasses wastes, cocoa meal). Replacement of poultry manure with the other N sources at 50–100% or wheat straw with rape, bean, or linseed straw in aerated tunnel or windrow composts reduced the OC and emissions of odorous sulfur-containing compounds, but also reduced yield. Urea and cocoa meal may be suitable for ''low odor'' prewetting of straw, with addition of poultry manure immediately before aerated tunnel composting. Rape straw in compost reduces the formation of anaerobic zones and resulting odorous emissions, since it maintains its structure and porosity better than wheat straw.
Journal of Industrial Microbiology & Biotechnology (2002) **29,** 99–110 doi:10.1038/sj.jim.7000292

Keywords: mushroom compost; straw; nitrogen sources; odor; emissions

Introduction

Preparation of mushroom (*Agaricus bisporus*) compost can result in the production of environmentally unacceptable malodors. This work was aimed at reducing odorous emissions by changing the ingredients used in preparing compost, and at comparing mushroom yields of the resulting composts.

The traditional ingredient of mushroom compost, straw bedding horse manure, provided both a source of carbon (C) and nitrogen (N) to the composting microbiota and satisfied the subsequent nutritional requirements of the mushroom [8,18]. Due to difficulties in availability and variability in the material, compost formulations with straw and various N sources were developed. In most countries, wheat straw is preferred to other cereal straws such as rye, barley, and oat since it maintains its structure during composting and it is widely available [8,18], although rice straw and other plant wastes are used depending on local availability [24]. N sources include poultry, pig, and bullock manures [13,26]; other organic wastes such as dried blood, cotton seed meal, brewery wastes, horn, whey powder, molasses, and sewage-based products [3,8,25,27]; and inorganic N sources such as ammonium nitrate and sulphate, calcium nitrate, urea, and urea formaldehyde [2,3,14,25]. Due to its low cost, high N content (Table 1), and ease of handling, broiler poultry manure is now an integral part of most mushroom composting in many countries [8,23]. However, poultry manure has a serious odor problem, mainly due to the sulfur (S)-containing amino acids which are precursors of volatile, odorous, S-containing compounds particularly under anaerobic composting conditions [15,22].

Conventional mushroom composting involves wetting and mixing straw and N sources in heaps (prewetting) for 4–7 days and then in windrow stacks for 7–14 days (Phase I) [8,22]. These stages are followed by a containerized, controlled temperature, and usually controlled airflow phase in which the compost is pasteurized and conditioned for about 7 days (Phase II) [18]. More recently, Phase I composting has also been conducted in aerated systems to reduce the development of anaerobic zones in the compost, from which malodors are emitted [5,22]. Odor emissions are a major problem facing compost production in the UK and other developed countries [4,15,22,23]. This problem has arisen from an increased public sensitivity to odor pollution, and urban development bringing housing closer to centers of production. In addition to the use of aeration, in the Netherlands, this problem has been addressed by biofiltration of emissions. However, this first requires ammonia to be removed from the odorous air using ''air washers,'' which adds considerably to the cost [10].

We examined the effects of straw types and organic and inorganic N sources on the availability of N to the compost microbiota, composting odors, and subsequent mushroom yield. We used a bench-scale flask composting system to screen a large number of potential straw and N sources; subsequent composting

Correspondence: Prof Ralph Noble, Department of Plant Pathology and Microbiology, Horticulture Research International, Wellesbourne, Warwick, CV35 9EF, UK
Received 8 January 2002; accepted 20 June 2002

Table 1 Analysis of straw types and N sources used in the experiments and quantities used in the compost formulations in experiments 1 and 2

Straw type[a] or N source	Rate[b] % wt/wt	DM%	% of DM			Price (£)[c]		Source
			N	NH_4^+	Ash	ton^{-1}	kg^{-1} N	
Wheat straw	17–97	88 (±1.4)	0.5 (±0.15)	0.05 (±0.007)	7 (±1.3)	36	8.18	Hutsby Farm, Stratford-upon-Avon, Warwick
Rape straw	57–73	85 (±2.6)	1.2 (±0.09)	0.04 (±0.008)	6 (±1.8)	30	2.94	Hutsby Farm, Stratford-upon-Avon, Warwick
Bean straw	72	88 (±2.1)	0.6 (±0.12)	0.01 (±0.006)	4 (±1.2)	35	6.63	Hutsby Farm, Stratford-upon-Avon, Warwick
Linseed straw	68	87 (±1.3)	0.7 (±0.08)	0.01 (±0.006)	4 (±1.1)	30	4.93	Hutsby Farm, Stratford-upon-Avon, Warwick
Broiler poultry manure	23–49	69 (±6.8)	5.9 (±0.59)	0.98 (±0.361)	15 (±0.8)	3	0.07	Poultry Unit Contractors, Lyneham, Wilts
Digester waste	40–73	27 (±1.6)	2.8 (±0.51)	1.03 (±0.110)	22 (±2.7)	0	0	Holsworthy Bioplant, Holsworthy, Devon
Cocoa meal	29–50	93 (±2.5)	4.2 (±0.23)	0.07 (±0.004)	5 (±1.5)	50	1.28	Cadbury, Chirk, Wrexham, Clwyd
Cocoa shells, pulverized	50–75	98 (±0.7)	2.6 (±0.15)	0.12 (±0.002)	9 (±0.6)	25	0.98	Cadbury, Chirk, Wrexham, Clwyd
Hop waste powder	38–60	90 (±2.0)	3.3 (±0.52)	0.05 (±0.007)	8 (±0.5)	50	1.68	English Hop Products, Tonbridge, Kent
Brewers' grains	69–83	24 (±5.2)	2.8 (±0.30)	0.04 (±0.001)	5 (±0.9)	22	3.27	Everards Brewery, Narborough, Leicester
Chipboard waste	39–67	87 (±4.5)	3.1 (±0.58)	0.26 (±0.149)	1 (±0.2)	0	0	Pelican Fabrications, Northfleet, Kent
Ammonium sulfate	5–12	100	21.2	27.27	–	235	1.11	LBG, Badsey, Evesham, Worcs
Urea	3–5	100	46.7	0	–	260	0.56	LBG, Badsey, Evesham, Worcs
AminoPro	15–26	61 (±2.2)	6.3 (±0.32)	3.37 (±0.053)	9 (±1.6)	70	1.82	United Molasses, Burton on Trent, Staffs
Sporavite	23–44	75 (±1.9)	6.6 (±0.54)	2.30 (±0.099)	16 (±1.9)	150	3.03	Amycel-UK, Burton on Trent, Staffs

All sources of materials were in the UK. Each value is the mean of five determinations (±SD).
[a]Wheat straw was used in combination with all the N sources; inclusion rates with individual N sources were (100 − N source) % wt/wt; rape, bean, and linseed straws were only used with poultry manure.
[b]Original fresh weight in compost excluding added water and gypsum.
[c]Average UK prices, excluding transport and tax (*Farmers Weekly* and companies listed in experiment 1).

experiments were conducted using large-scale turned windrows and aerated tunnels.

Materials and methods

Experiment 1: bench-scale composting different straw types and N sources

Substrate ingredients were composted in multiadapter flasks immersed in six thermostatically controlled waterbaths, each holding two 10-l flasks [21]. The ingredients, new season straw, and N sources with gypsum added at 3% wt/wt [8,18] were mixed and wetted to a 78% wt/wt moisture content over a 5-day period. Samples (3 kg) were placed on a perforated stainless steel platform within each flask and the flasks were immersed in the waterbaths such that the water level was above the level of the enclosed substrate. Each flask was connected to ancillary equipment providing independent aeration of the compost. An O_2 concentration of 11±1.5% vol/vol was maintained in the substrate by regularly adjusting the airflow through the compost in each flask within the range 0–16 l kg substrate^{-1} h^{-1} by means of flow meters. All of the airflow was vented from the flasks through an exhaust opening at the top. The temperature of the substrate in the flasks was monitored with multipoint temperature loggers [21]. Ammonia concentration in the headspace of the flasks was measured daily with a Dräger Accuro bellows pump with appropriate detector tubes (Drägerwerk, Lübeck, Germany) [22].

For the first 48 h, the thermostat of the waterbath was set at 48°C to allow a natural succession and gradual build-up of microorganisms in the compost. The substrate temperature was then increased to 72°C for 5 days to simulate Phase I composting temperature [8,20]. The substrate was then remixed and the temperature reduced to 47°C for the remainder of the compost conditioning period (Phase II), which was 7 days, or prolonged for a further 1–2 days until the air in the flask was clear of NH_3 (Figure 1).

Compost ingredients were prepared from wheat (*Triticum aestivum*) straw and organic, inorganic, and proprietary N sources (Table 1). The straw and N sources were selected on the basis of availability and low cost in the UK, and high N and dry matter (DM) contents (Table 1). The digester waste was animal manure-based. Cocoa meal, extracted from cocoa shells, consisted of a dry powder. AminoPro, a proprietary animal feed supplement, consisted of molasses waste liquid including amines and ammonium chloride. Details of the other organic N sources are given in, Refs. [8,18,24]. Oil seed rape (*Brassica napus*) straw was used with poultry manure. The proportions of straw and N sources in the formulations were calculated on the basis of their N and DM contents [18] to achieve blended ingredients with N contents of 1.6%, 2.1%, and 2.6% of DM (Table 1). Each of the 12 compost ingredient × three N content treatments was replicated three times, with each replicate subdivided into three blocks, each containing 12 treatment combinations, comprised of four compost ingredients at each of the three N contents. The allocation of compost ingredients to blocks followed an alpha design, ensuring that each pair of compost ingredients was only assessed together in a block at most once. Brewers' grains, cocoa shells, and digester and chipboard wastes could not be used at the highest N rate (2.6% of DM) because the N content was too low (Table 1). The nine "blocks" of 12 treatment combinations were assessed consecutively over time, each replicate being completed before the next replicate commenced. Treatments were randomly allocated to the six waterbaths, each waterbath containing two different treatment combinations.

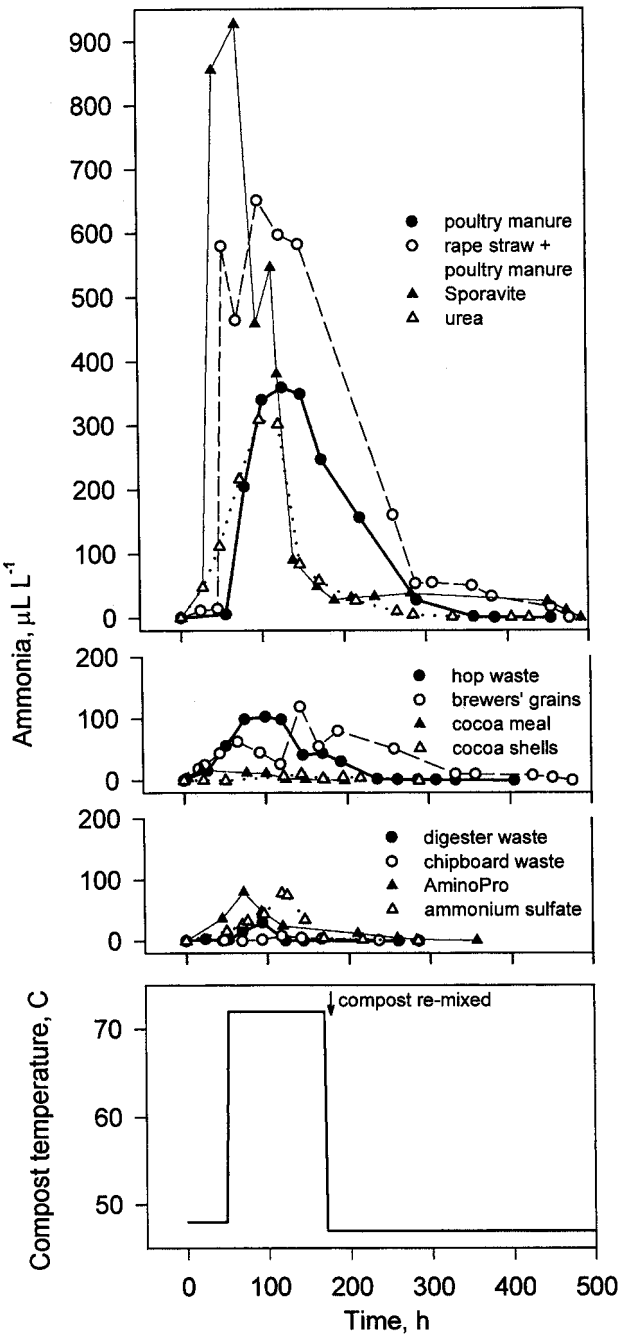

Figure 1 Flask headspace ammonia concentrations and compost temperature during experiment 1. N sources were composted with wheat straw except where stated. Mean of three N rates and three replicates.

Experiment 2: composting different straw types and N sources in aerated tunnels

Six aerated bulk composting tunnels were used for the experiments. Compost was filled on to a slatted base in the tunnels, mounted above an air plenum through which a controlled flow of fresh and/or recirculated air could be blown. Two of the tunnels consisted of

modified insulated cargo containers. Both of these tunnels had a vertical partition, which did not extend into the air plenum below, to enable two different composts to be filled into each tunnel (type A). The other four tunnels consisted of insulated polythene tunnels, inside which were two parallel walls, joined by a wall at one end (type B). The compost was enclosed by a removable end wall, which fitted across the sidewalls. Details of the tunnels, temperature, O_2, NH_3 and airflow measurement, recirculation and control, and methods for filling and emptying compost are given in Noble and Gaze [18,20].

Bales of new season straw were wetted and formed into stacks using a compost turning machine (revolving drum type). Further water was added to the straw in a separate turn to achieve a moisture content of 70% wt/wt. After 3 days, 50% of the required N source was mixed into the stack; the remaining N source and gypsum at 30 kg ton^{-1} fresh compost ingredients were mixed into the stack after a further 2 days. The prepared ingredients were wetted to 76% wt/wt moisture content [11,19,20] and filled into tunnels on the following day (6-day preparation period). The tunnel composting regime had three stages, designated Phases 0, I, and II. The tunnels were filled with 4-ton batches (two batches in the type A tunnels) of blended compost ingredients to a height of 1.5 m. The airflow was set at 9 m^3 h^{-1}, unless the O_2 concentration in the compost fell below 7% vol/vol, in which case the airflow was increased to 13 m^3 h^{-1} until the O_2 concentration was above 7% vol/vol to prevent anaerobic odors [19]. After 5 days (Phase 0), the compost was emptied from the tunnels, mixed, and, if necessary, rewetted to achieve a moisture content of 77% wt/wt, and then refilled. The subsequent 6-day Phase I was similar to the Phase 0 regime. For the Phase II pasteurisation regime, which was used for all the composts prepared in aerated tunnels or in windrows, the tunnels were filled with 2.5 tons of material from the Phase I stage to a height of 0.9–1.1 m, depending on the ingredients. Following a 20-h equalization of compost temperature at 45–48°C, the composts were pasteurised at 58–60°C for 6 h. Compost temperatures were then reduced to 46–49°C (conditioning). A minimum O_2 concentration of 16% was maintained during Phase II. Composting was completed when compost temperature was within 1°C of air temperature, and NH_3 could not be detected in the compost.

Substrates were prepared from wheat or oilseed rape straw, which were both used with poultry manure. Wheat straw was also used with cocoa meal, hop waste, ammonium sulfate, and urea. Blended ingredients of the formulations were prepared with N rates of 1.8% and 2.3% of DM.

The experiment was conducted as a series of three runs and each treatment combination (compost ingredient and N rate) was replicated twice, once in each tunnel type. The six compost ingredient treatments were allocated to runs and tunnel types in an incomplete Trojan square design. Four of the six compost ingredient treatments appeared in each run. Each compost ingredient treatment appeared with both N rate treatments in each of the two runs in which it occurred.

Experiment 3: composting different straw types and N sources in windrows

Blended ingredients were prepared as for aerated tunnel composts during the initial 6 days. Windrow Phase I composts continued to be turned on alternate days (16-day composting period). Compost prepared from linseed (flax) straw was composted for 40 days due to a slow rate of degradation. Moisture content at the end of windrow composting was 76% wt/wt [8]. Stack temperatures were monitored with platinum resistance sensors and a data logger. Initial stack dimensions were *ca.* 5×2×1.6 (high) m.

Substrates were prepared from wheat, oilseed rape, bean (*Vicea faba*), and linseed (flax) (*Linum usitatissimum*) straws (Table 1). The latter treatment was composted separately and not repeated or included in the experimental design or analysis. All the straw types were used with broiler poultry manure, with wheat straw+poultry manure as the control treatment. Wheat straw was also used with three other N sources, AminoPro, cocoa meal, and hop waste (Table 1), in combination with urea which provided 50% of the supplemented N. Two further wheat straw+poultry manure treatments were used in which 50% of the poultry manure in the control treatment was substituted with cocoa meal or urea. The nine combinations of straw types, organic, and inorganic N sources are shown in Table 6. Compost formulations were prepared with an initial N content of 2% of DM. The experiment was conducted in a series of three runs in four pairs of tunnels, two of each type (A and B), with each of the eight compost formulation treatments replicated three times. Compost treatments were allocated to tunnels following an incomplete Trojan square, with each treatment occurring once in each run, and in three of the four pairs of tunnels (and hence at least once in each tunnel type).

Analysis of odor and gaseous emissions and composts

Odor samples (two replicates) were collected in 20-l nalophane bags (Adtech, Gloucester, UK), 0.2 m downwind of the compost during the emptying of the Phase 0 stage of aerated tunnel composts, or from windrow composts, during turning on day 11 after the stacks were formed. The odor samples were then transported to IGER North Wyke and analysed within 24 h. Odor concentration (OC) was determined by an odor panel using dilution olfactometry and volatile organic compounds quantified by gas chromatography mass spectrometry (GC-MS) [22]. A Dräger Accuro bellows pump with appropriate detector tubes [22] was used to quantify NH_3. Losses of NH_3 from compost were calculated from the NH_3 concentration and exhaust airflow in flask or aerated tunnels. Losses of NH_3 from windrows were assumed to occur mainly from the air volume between the turner drum and the face of the stack (0.6 m^3) during turning. Losses were calculated from the NH_3 concentration, wind speed during sampling, and turning time of *ca.* 20 min. Wind speed, 2 m above the ground at the position of odor sampling, was measured with a vane anemometer (Type 949079; Airflow Developments, High Wycombe, UK).

Analyses of DM, N, S, ammonium (NH_4^+) and ash contents, and pH were determined on straw and N sources, and on substrates before and after composting, as described previously [1,18]. Compost bulk density was measured after compression in trays [18].

Mushroom cropping procedure

After composting in the bench-scale facilities, the material in each flask was weighed. After samples were taken for analysis, 2 kg of the material was inoculated with mushroom spawn ("spawned") at 2% wt/wt with *A. bisporus* strain Sylvan A15 (Sylvan Spawn, Peterborough, UK) and filled into plastic pots, 230 mm diameter × 220 mm depth. The pots were placed in polythene bags in an incubator at 25°C and when the substrate was fully colonised with mushroom mycelium, about 15 days after spawning, the containers

were covered (cased) with a moist 4:1 vol/vol mixture of peat and sugar beet lime (900 g). When mushroom mycelium was visible on the casing surface, the containers were transferred to a controlled environment chamber with an air temperature of 18°C, relative humidity of 90%, and a CO_2 concentration of 0.1% vol/vol to induce fruiting. Mushrooms from three "flushes" were harvested daily with caps closed, diameter 30 mm, over a 24-day period.

Composts from experiments 2 and 3 were cropped in trays in a controlled environment room [20]. Compost spawned with strains Sylvan A15 and 2100 (Amycel-UK, Burton-on-Trent, Staffs., UK) at 0.5% wt/wt was filled into trays at 50 kg tray^{-1}. Half the compost was supplemented with the soya meal-based supplement Betamyl 1000 (Sylvan Spawn) at a rate of 1% wt/wt. Other cultural conditions were the same as those used for pots. Percentage DM content of 20 mushrooms from the first and second flushes from each batch of compost (strain A15, unsupplemented compost) was determined [1]. The N and NH_4^+ contents of mushrooms from the first and second flush were determined on freeze-dried samples of 20 mushrooms from each batch of compost [18].

At the cropping stage for each run, each of the six or eight compost treatments was assessed with two strains, with and without supplementation, in all combinations. Each of the 24 or 32 treatment combinations was replicated four times. Cropping trays were stacked four stacks high in a cropping room, with four stacks across the width of the house and six or eight stacks along the length. Within each run, the compost treatments were allocated to blocks of four trays following a Trojan square design, allowing for differences between the four layers, the four stacks across the width of the house, and the front and back of the house. The combinations of supplement and strain treatments were randomly allocated to trays within these blocks, as in a split-plot design.

Statistical analysis

An initial analysis of data from experiment 1 using the Residual Maximum Likelihood (REML) approach indicated little variation between blocks within replicates. To simplify presentation and interpretation, therefore, the presented results are from analysis of variance (ANOVA) of the data, ignoring blocks within replicates. Presented least significant differences (LSDs) are not adjusted for missing values and therefore give a slightly inflated indication of the significance of comparisons between means including the missing high N rate treatment combinations. Data from the cropping stages of each of the runs of experiments 2 and 3 were initially analyzed by ANOVA to obtain adjusted treatments means. For each experiment, these treatment means were then included in a combined analysis, taking account of the design at the composting stage, but including the combinations of strain and supplement as subplot treatments. In all the experiments, certain compost, mushroom cropping, and emission parameters showed evidence of a mean–variance relationship, notably those with a wide range of observed values, with minimum values approaching zero. These variables (maximum NH_3 concentration, NH_3 and N losses, OC, and concentrations of NH_3, acetone, butanol, ethanol, and sulfides) were subjected to a logarithmic transformation prior to analysis. Back-transformed means are shown alongside the transformed values in each of the tables. The remaining compost, emission, and mushroom cropping variables were analyzed without prior transformation. Sulfide concentrations in experiment 2 were not analyzed by ANOVA due to large number of zeros. All differences in the Results section were significant at $P<0.05$ or, if stated, $P<0.01$ or 0.001.

Results

Analysis of straw types and N sources

The DM contents of the four straw types were similar, but rape straw had a higher N content (Table 1). Wheat and rape straw had higher ash contents than the bean and linseed straws. Digester waste and brewers' grains had much lower DM contents than the other N sources. AminoPro had a DM content only slightly lower than poultry manure (Table 1). Sporavite and AminoPro had N contents above 6% of DM due to inclusion of N-containing compounds (urea, amines, or ammonium chloride). Of the organic materials, poultry manure had the highest N content on a DM basis, followed by cocoa meal. The other organic materials had N contents of about 3% of DM or lower. With the exception of ammonium sulfate, the highest NH_4^+ contents on a DM basis were found in AminoPro, Sporavite, poultry manure, and digester waste. The other materials had low NH_4^+ contents. Poultry manure, digester waste, and Sporavite had higher ash contents than the other materials.

Experiment 1: bench-scale composting different straw types and N sources

Compost analysis: Compost DM at spawning was 27.0±1.1%. Increasing the N rate in the compost increased the maximum NH_3 concentration, and NH_3 and N losses from compost ($P<0.001$, Table 2). Increasing the N rate of the compost from 1.6% to 2.6% of DM also increased the duration required to clear NH_3 from the composts from an average of 205–312 h. Compost N and NH_4^+ contents at spawning increased with initial compost N rate ($P<0.001$). NH_3 was evolved from hop waste, brewers' grains, urea, Sporavite, and AminoPro composts within 24 h of filling the flasks. With other formulations, there was delay in the evolution of

Table 2 Effect of initial compost N content on NH_3 and N losses during flask composting and compost analysis at spawning in experiment 1

Initial compost N content, % of DM	During composting						Compost at spawning (% of DM)		
	Maximum NH_3 concentration (μl l^{-1})		NH_3 loss (mg kg^{-1})		N loss (mg kg^{-1})		N	Ash	NH_4^+
1.6	29	[3.39][a]	124	[4.82][a]	69	[4.24][a]	1.72	11.8	0.14
2.1	85	[4.45]	592	[6.38]	536	[6.28]	2.36	14.1	0.17
2.6	267	[5.59]	1203	[7.09]	785	[6.67]	2.70	13.7	0.52
LSD, $P=0.05$		[0.59]		[0.62]		[1.09]	0.13	1.8	0.06

Values for compost parameters are the means of 12 N sources and three replicate composts.
[a]Figures in square parentheses are $\log_e$ transformations, shown next to back-transformed values.

Table 3 Losses of NH_3 and N during flask composting, compost analysis at spawning, and mushroom yield in experiment 1

Straw type and N source in compost	During composting						Compost at spawning				Mushroom yield[a] (g kg^{-1})	
	Maximum NH_3 concentration (μl l^{-1})		NH_3 loss (mg kg^{-1})		N loss (mg kg^{-1})		% of DM			pH	1.6%N	2.1%N
							N	NH_4^+	Ash			
Wheat straw+												
Poultry manure	339	[5.83][b]	689	[6.54][b]	385	[5.95][b]	2.28	0.15	16	8.1	126	138
Digester waste	30	[3.42]	170	[5.14]	18	[2.93]	2.32	0.15	22	7.8	79	60
Chipboard waste	8	[2.08]	135	[4.91]	151	[5.02]	2.36	0.18	12	7.8	55	55
Brewers' grains	119	[4.78]	516	[6.25]	148	[5.00]	2.22	0.39	12	7.4	93	97
Cocoa meal	17	[2.87]	67	[4.21]	77	[4.35]	2.42	0.07	10	8.4	199	94
Cocoa shells	10	[2.33]	53	[3.97]	78	[4.36]	2.54	0.17	11	8.5	10	0
Hop waste	103	[4.63]	544	[6.30]	403	[6.00]	2.16	0.19	13	8.1	89	132
Sporavite	927	[6.83]	4538	[8.42]	2490	[7.82]	2.09	0.62	14	8.3	168	0
AminoPro	80	[4.39]	897	[6.80]	698	[6.55]	2.72	0.56	13	7.8	118	97
Urea	309	[5.73]	1740	[7.46]	1315	[7.18]	1.85	0.17	12	7.9	89	108
Ammonium sulfate	78	[4.36]	428	[6.06]	444	[6.10]	2.41	0.50	9	6.9	74	98
Rape straw+												
Poultry manure	651	[6.48]	1261	[7.14]	1812	[7.50]	2.18	0.14	15	8.0	82	177
LSD, P=0.05		[1.18]		[1.24]		[2.18]	0.26	0.12	4	0.3	46	46

Values for compost parameters are the means of three N rates (1.6%, 2.1%, and 2.6% of DM) and three replicate composts.
[a]Yield expressed as gram of mushrooms per kilogram of spawned compost, in composts with initial N content of 1.6% and 2.1% of DM.
[b]Figures in square parentheses are $\log_e$ transformations, shown next to back-transformed values.

NH_3 until the compost temperature had been increased to 72°C (Figure 1). Maximum NH_3 concentrations were greatest from Sporavite composts and were higher from poultry manure, brewers' grains, hop waste, and urea composts than from the remaining formulations (Table 3; Figure 1). Losses of NH_3 and N from poultry manure, Sporavite, hop waste, AminoPro, brewers' grains, urea, and ammonium sulfate composts were higher than from other formulations. Maximum NH_3 concentrations, and NH_3 and N losses during composting were all closely correlated with each other (r=0.80–0.93, P<0.001). Ammonium sulfate, brewers' grains, Sporavite, and AminoPro composts had higher NH_4^+ contents at spawning than composts prepared from the other materials (P<0.001, Table 3).

Ash contents at spawning of digester waste composts were higher than those of other formulations (Table 3). The pH of cocoa meal or shells and Sporavite composts (8.2–8.5) was higher than that of digester and chipboard wastes, brewers' grains, AminoPro, and ammonium sulfate composts (6.9–7.8), with other formulations intermediate in pH (7.9–8.1). Increasing compost N rate from 1.6% to 2.1% or 2.6% of DM resulted in a higher ash content at spawning (Table 2) but did not affect pH (mean 7.9).

Mushroom cropping: Mushroom mycelium grew on all the composts produced, although mycelial growth on all the cocoa shells composts and 2.6% N rate Sporavite compost was poor. The

Table 4 Compost temperatures, NH_3 and N losses during aerated tunnel composting (Phases 0, I, and II), compost analysis at spawning, and mushroom yield in experiment 2

Compost formulation		During composting								Compost at spawning			Mushroom yield[a] (kg ton^{-1})
Straw type and N source	N rate[b] (% of DM)	Maximum temperature (°C)	Maximum NH_3 concentration (μl l^{-1})		NH_3 loss (mg kg^{-1})		N loss (mg kg^{-1})		S loss (mg kg^{-1})	% of DM		BD[c] (kg m^{-3})	
										N	Ash		
Wheat straw+	1.8	76.8	358	[5.88][d]	460	[6.13][d]	816	[6.70][d]	43	2.41	18	446	268
Poultry manure	2.3	76.8	881	[6.78]	3069	[8.03]	1204	[7.09]	145	2.66	23	458	273
Rape straw+	1.8	78.3	299	[5.70]	1299	[7.17]	832	[6.72]	85	2.12	20	496	207
Poultry manure	2.3	78.3	876	[6.78]	3495	[8.16]	1268	[7.15]	48	2.35	19	508	206
Wheat straw+	1.8	80.9	14	[2.68]	6	[1.81]	4	[1.43]	21	3.01	16	445	108
Cocoa meal	2.3	77.9	77	[4.35]	120	[4.79]	134	[4.90]	19	3.15	12	470	107
Wheat straw+	1.8	76.9	29	[3.36]	265	[5.58]	887	[6.79]	17	2.60	17	507	241
Hop waste	2.3	81.4	104	[4.65]	514	[6.24]	1273	[7.15]	0	3.20	11	520	159
Wheat straw+	1.8	70.8	31	[3.45]	558	[6.38]	86	[4.46]	155	2.56	14	347	135
Ammonium sulfate	2.3	67.8	176	[5.18]	996	[6.90]	251	[5.53]	169	2.79	15	359	85
Wheat straw+	1.8	70.3	191	[5.25]	3429	[8.14]	1962	[7.58]	49	1.61	15	397	122
Urea	2.3	74.3	322	[5.78]	7137	[8.87]	2275	[7.93]	36	2.20	11	397	120
LSD, P=0.05		8.1		[1.77]		[2.60]		[3.38]	38	0.66	9	81	16

[a]Mushroom yield expressed as kilogram of mushrooms per ton of spawned compost, mean of strains A15 and 2100, supplemented and unsupplemented composts.
[b]N content of blended compost ingredients before Phase 0 tunnel composting.
[c]Bulk density.
[d]Figures in square parentheses are $\log_e$ transformations, shown next to back-transformed values.

Table 5 Odor and gas (GC-MS) concentrations of bag air samples from different aerated tunnel compost formulations in experiment 2 at emptying of Phase 0

Compost formulation	N rate[a]	OC (OU m^{-3})		Concentration (mg m^{-3})											
				H_2S	DMS	MeSH[b]	NH_3		Acetone		Ethanol		Butanol[d]	
Wheat straw+	1.8	2216	[7.70][b]	0.09	0.26	0.07	7	[1.97][c]	0.74	[0.11][c]	3.05	[1.23][c]	2.58	[1.08][c]
Poultry manure	2.3	6342	[8.76]	0.73	2.06	0.46	80	[4.38]	1.38	[0.56]	10.26	[2.36]	13.60	[2.64]
Rape straw+	1.8	2619	[7.87]	0.07	0.34	0.15	41	[3.73]	0.29	[−0.41]	2.92	[1.19]	1.94	[0.84]
Poultry manure	2.3	3584	[8.18]	0.49	0.52	0.33	107	[4.68]	1.25	[0.49]	12.65	[2.57]	13.52	[2.63]
Wheat straw+	1.8	488	[6.19]	0	0	0	9	[2.24]	0.21	[−0.53]	0.86	[0.21]	1.08	[0.38]
Cocoa meal	2.3	977	[6.89]	0	0	0	23	[3.16]	0.63	[0.01]	0.08	[−0.79]	0.83	[0.19]
Wheat straw+	1.8	854	[6.70]	0	0	0	2	[0.91]	1.07	[0.37]	2.07	[0.90]	0.23	[−0.51]
Hop waste	2.3	2970	[8.00]	0.05	0.13	0.09	50	[3.93]	1.60	[0.68]	1.66	[0.71]	8.16	[2.14]
Wheat straw+	1.8	699	[6.55]	0	0	0.12	12	[2.49]	0.34	[−0.34]	3.28	[1.30]	2.44	[1.04]
Ammonium sulfate	2.3	1045	[6.95]	0.02	0.12	0.27	20	[3.00]	1.44	[0.59]	6.04	[1.86]	1.89	[0.82]
Wheat straw+	1.8	670	[6.51]	0	0	0	5	[1.71]	0.65	[0.03]	1.16	[0.43]	1.18	[0.44]
Urea	2.3	843	[6.74]	0	0.02	0	41	[3.71]	0.70	[0.07]	0.55	[−0.07]	0.88	[0.23]
LSD, $P=0.05$			[1.50]					[3.11]		[0.99]		[2.49]		[1.77]
Olfactory detection threshold [6]				0.03	0.006	0.002	4		34.67		54.95		1.51	

Values are the means of two replicate composts and two bag samples per compost.
[a]N content of DM of blended compost ingredients before Phase 0 tunnel composting.
[b]Methanethiol.
[c]Figures in square parentheses are $\log_e$ transformations, shown next to back-transformed values.
[d]Other odorants identified with GC-MS but not significantly different between treatments were (range in concentrations, mg m^{-3}): acetic acid (0.37–1.043), butanoic acid (0.70–2.68), dimethyl disulfide (0.10–0.19), 4-ethyl phenol (0.06–0.35), isopropyl alcohol (0.28–0.79), 3-methyl butanoic acid (0.66–4.92), methyl ethyl ketone (1.76–4.68), 4-methyl phenol (0.14–0.33), methyl propanoic acid (0.33–1.07), pentanoic acid (0.63–2.48), phenol (0.29–0.51), propanol (0.05–1.49), propanoic acid (0.14–0.74). NH_3 was measured with detector tubes.

latter compost also produced fruit bodies of *Coprinus* spp., indicative of composts with high NH_4^+ contents [18], but there were no other obvious mould or disease problems in the composts. There was an interaction between the effects of N rate and N source on mushroom yield ($P<0.001$, Table 3). Cocoa meal and Sporavite composts produced the best yields at the 1.6% N rate, and also better yields than at the higher N rates, whereas hop waste and rape straw composts produced higher yields at the 2.1% rate than at the 1.6% rate (Table 3). At the 2.1% and 2.6% N rates, rape straw+poultry manure compost produced the best yield. At all N rates, yields from digester and chipboard wastes, and ammonium sulfate composts were lower than from the wheat straw+poultry manure composts. Cocoa shells compost produced only one mushroom per pot. The 2.6% N rate produced either a lower yield than the 1.6% and 2.1% rates or no mushrooms (cocoa meal and Sporavite composts), with the exception of rape straw+poultry manure compost, where there was no significant difference in yield between the 2.1% and 2.6% rates. Mushroom yield results for the 2.6% N rate are therefore not shown. There were no significant correlations between any of the measured composting or compost analysis parameters in Table 3 and mushroom yield.

Experiment 2: composting different straw types and N sources in aerated tunnels

Composting process and compost analysis: During composting, composts with organic N sources generally reached higher temperatures than those with inorganic N sources (ammonium sulfate or urea) (Table 4). Losses of S during composting were greater from ammonium sulfate composts than from poultry manure composts, which in turn lost more S than the other formulations ($P<0.001$, Table 4). Compost N rate did not affect S losses, except for poultry manure composts, where a higher inclusion increased S losses. Initial S contents of treatments followed a similar pattern to S losses (Table 4), with poultry manure composts (1.0–1.1% S of DM) intermediate between those of ammonium sulfate composts (1.8% S of DM) and the other formulations (0.8–0.9% S of DM). Of this S, about 0.8% of DM could be attributed to the inclusion of gypsum.

The duration required to clear NH_3 from the compost was greater for the 1.8% N rate composts (mean 315 h) than for the 2.3% N rate composts (mean 359 h). Maximum NH_3 concentrations and NH_3 losses were greater from the 2.3% N rate than from the 1.8% N rate composts (Table 4). Maximum NH_3 concentrations and losses were also higher from the urea composts than from the cocoa meal, hop waste, and ammonium sulfate formulations. This corresponded to higher N contents at spawning in the latter composts ($P<0.01$). Compost DM and NH_4^+ contents at spawning were not significantly different between treatments (26.9±1.4% and 0.06±0.03% of DM, respectively).

Ash contents of poultry manure composts were higher than those of urea composts ($P<0.001$, Table 4). The pH of hop waste composts (8.0–8.2) was higher, and that of ammonium sulfate composts (6.4–6.7) lower than those of other composts (7.6–7.8) ($P<0.001$). There was no significant effect of N rate on compost ash content, pH, or bulk density at spawning. However, composts prepared with organic N sources had greater bulk densities at spawning than those prepared with the inorganic N sources, (urea or ammonium sulfate) ($P<0.001$, Table 4).

Mushroom cropping: Mushroom yield was higher from the wheat straw+poultry manure composts than from the rape straw+poultry manure and 1.8% N hop waste composts, which produced higher yields than the remaining formulations ($P<0.01$, Table 4). N rate only affected the yield of ammonium sulfate and hop waste composts (negatively). There was no difference in mushroom yield between the strains A15 and 2100, or between supplemented and unsupplemented composts. Mushroom DM (mean 8.2±0.4%), N (5.8±1.0% of DM), and NH_4^+

Table 6 Odor and sulfide concentrations of bag air samples, NH_3 concentrations, and NH_3 and N losses during Phase I windrow and Phase II aerated tunnel composting, compost analysis at spawning, and mushroom yields and DM content from different windrow compost formulations in experiment 3

Compost formulation inclusion rate (% wt/wt)[a]		Bag air sample concentration						During composting						Compost at spawning			Mushroom yield[b] (kg ton^{-1})
Straw	N source	OC (OU m^{-3})		H_2S (mg m^{-3})		DMS (mg m^{-3})		Maximum NH_3 concentration (μl l^{-1})		NH_3 loss (mg kg^{-1})		N loss (mg kg^{-1})		% of DM		BD[c] (kg m^{-3})	
														N	Ash		
Wheat (63)	Poultry manure (37)	11,950	[9.39][d]	2.45	[1.04][d]	4.94	[1.67][d]	141	[4.95][d]	548	[6.31][d]	452	[6.11][d]	2.85	25	463	283
Rape (67)	Poultry manure (33)	5729	[8.65]	1.69	[0.72]	1.70	[0.73]	242	[5.49]	1107	[7.01]	1247	[7.13]	2.34	24	496	226
Bean (72)	Poultry manure (28)	4189	[8.34]	0.96	[0.29]	1.53	[0.65]	141	[4.96]	1781	[7.49]	605	[6.41]	2.77	20	452	210
Linseed (68)	Poultry manure (32)	–	–	–	–	–	–	94	[4.54]	584	[6.37]	829	[6.72]	2.49	16	400	91
Wheat (78)	Poultry manure (21) +urea (1)	4458	[8.40]	0.37	[−0.30]	0.04	[−0.87]	50	[3.92]	482	[6.17]	56	[4.03]	2.73	24	488	224
Wheat (64)	Poultry manure (18) +cocoa meal (18)	7320	[8.90]	0.52	[−0.11]	0.10	[−0.75]	8	[2.16]	356	[5.88]	71	[4.27]	3.53	22	489	205
Wheat (78)	Cocoa meal (21) +urea (1)	1716	[7.45]	0.20	[−0.55]	0.23	[−0.50]	27	[3.31]	62	[4.14]	220	[5.39]	3.23	22	480	202
Wheat (77)	Hop waste (22) +urea (1)	1609	[7.38]	0.19	[−0.58]	0.11	[−0.72]	23	[3.14]	34	[3.55]	276	[5.62]	2.67	20	444	234
Wheat (84)	AminoPro (15) +urea (1)	1406	[7.25]	0.01	[−0.96]	0.03	[−0.89]	13	[2.62]	44	[3.80]	352	[5.86]	2.79	15	423	179
LSD (P=0.05)			[0.94]		[0.66]		[0.47]		[1.61]		[1.22]		[0.93]	0.65	4	39	46

Values are the means of three replicate composts, except the linseed straw compost, which was not repeated or included in the statistical analysis.
[a]Figures in parentheses are percentage wt/wt inclusion rates, before the addition of water and gypsum.
[b]Mushroom yield expressed as kilogram of mushrooms per ton of spawned compost, mean of strains A15 and 2100 and supplemented and unsupplemented composts.
[c]Bulk density.
[d]Figures in square parentheses are $\log_e$ transformations, shown next to back-transformed values.

(0.6±0.2% of DM) contents were unaffected by the compost treatments.

Odor and gaseous emissions: Generally, with all the N sources, the 2.3% N rate produced a higher OC than the 1.8% N rate. The bag sample OC of wheat straw+poultry manure compost (2.3% N rate) was higher than that of the other composts (Table 5). The other poultry manure composts and hop waste compost (2.3% N rate) had higher OCs than the remaining formulations.

Odorants in the odor samples that exceeded their olfactory detection thresholds [6] were NH_3, butanol, and those containing S (Table 5). Several other compounds (mainly organic acids) were found at concentrations just greater than their olfactory detection threshold, but were not significantly different between treatments (footnote to Table 5). The S-containing compound mainly responsible for exceeding its olfactory detection threshold in compost air was dimethyl sulfide (DMS), followed by H_2S, except in ammonium sulfate composts where methanethiol (MeSH) predominated. Little or no S-containing compounds were detected in the air from cocoa meal, hop waste, or urea composts. In the other formulations, increasing the rate of the N source increased the emission of S-containing compounds. The concentrations of NH_3 and acetone were higher from all the 2.3% N rate composts than from the 1.8% N rate composts. Butanol concentration was higher from the 2.3% N rate composts prepared with poultry manure or hop waste than from the other treatments. Ethanol concentration was also highest from composts prepared with poultry manure at 2.3% N (Table 5).

In agreement with previous work [22], there was a close correlation between the combined concentration of H_2S+DMS and the OC of emissions from the compost. The linear regression equation, with $\log_e$-transformed data, was:

$$\log_e OC = 8.291 + 1.513 \log_e(H_2S + DMS + 0.375); \quad r = 0.87,\ P < 0.001 \qquad (1)$$

where H_2S and DMS were concentrations in $\mu l\ l^{-1}$ and OC was measured in OU m^{-3}. Including the concentration of MeSH, the other main S-containing compound emitted from compost did not significantly improve the goodness-of-fit. The above correlation coefficient was better than for individual S-containing compounds (r=0.79, 0.76, and 0.75 for correlations between $\log_e$ OC and the concentrations of H_2S, DMS, and MeSH, respectively). There was no correlation between OC and total losses of S during composting (Tables 4 and 5).

There was also a close correlation between $\log_e$ OC and $\log_e$ concentration of butanol (r=0.83, P<0.001), and significant correlations between $\log_e$ OC and $\log_e$ concentrations of NH_3, ethanol, and propanol (r=0.70, 0.63, and 0.64, respectively).

Experiment 3: windrow composting different straw types and N sources

Composting process and compost analysis: Compost prepared from linseed straw was slow to degrade and maximum compost temperature was only 55°C. Subsequent compost bulk density and mushroom yield were very low (Table 6) and the treatment was therefore not repeated. Maximum temperatures during composting were not significantly different between the other treatments (mean 73±3°C). Maximum NH_3 concentrations from poultry manure composts (wheat, rape, or bean straws) were higher than from the other wheat straw formulations (P<0.01, Table 6). Maximum NH_3 concentration during composting was correlated positively with NH_3 and N losses (r=0.79 and 0.72, P<0.01), and negatively with compost N content at spawning (r=0.68, P<0.05). Composts prepared with cocoa meal had higher N contents at spawning than the other formulations. Calculated N losses during composting of equivalent formulations in windrows (Table 6) and aerated tunnels (Table 4) were similar. However, maximum NH_3 concentrations and calculated losses were lower for windrow composts with equivalent formulations, possibly due to dilution of emissions during sampling. At spawning, all composts in experiment 3 had NH_4^+ contents in the range 0.03–0.11% of DM.

Compost DM content at spawning was 27.1±1.2% and was not significantly different between treatments. The ash content (Table 4) and pH (7.5) of the AminoPro+urea compost were lower than those of the other composts (pH 7.8–8.0), except for the pH of rape straw+poultry manure compost (7.7). Compost bulk densities of hop waste+urea and AminoPro+urea composts were lower than those of poultry manure+cocoa meal or urea, and rape straw+poultry manure composts. Composts prepared from wheat or bean straw+poultry manure were intermediate in bulk density.

Mushroom cropping: In all the experiments, mushroom mycelial growth on the casing layer over urea-based composts was more vigorous than on the other treatments. In experiment 3, mushroom yield from wheat straw+poultry manure compost was significantly greater than that from other compost formulations (Table 6). AminoPro+urea produced a significantly lower mushroom yield than rape straw+poultry manure or hop waste+urea. There were two indirect relationships between composting parameters and mushroom yield resulting from the higher yields from poultry manure-based composts. In both experiments 2 and 3, there was a correlation between the compost OC or ash content and mushroom yield obtained from different compost formulations (r=0.64–0.74, P<0.05). This was at least partly due to stronger odors during composting and higher ash content of poultry manure compared with the other N sources. There were no other significant correlations between any of the composting or composting analysis parameters and mushroom yield.

There were no significant differences in mushroom yield between supplemented and unsupplemented composts, but strain A15 produced a higher yield than strain 2100 (mean values 227 and 213 kg ton^{-1}). Mushroom DM content was not significantly different between treatments or different from that in experiment 2 (mean 8.3±0.5%).

Odor and gaseous emissions: The bag sample OCs of poultry manure composts was significantly higher than those of compost formulations that did not include poultry manure (Table 6). The H_2S and DMS concentrations of the wheat straw+poultry manure compost were significantly higher than those of the rape or bean straw+poultry manure composts, which in turn were higher than the concentrations from other treatments. As in experiment 2, there was a correlation between the combined concentration of H_2S+DMS and the OC of compost air in bag

samples. The linear regression equation, with $\log_e$-transformed data, was:

$$\log_e OC = 8.134 + 0.368\log_e(H_2S + DMS + 0.375); \quad r = 0.76,\ P < 0.01 \qquad (2)$$

where H_2S and DMS were concentrations in $\mu l\ l^{-1}$ and OC was measured in OU m^{-3}. Sulfide concentrations and OCs from aerated tunnels (Table 5) were lower than from windrow composts (Table 6) using similar ingredients. There was no significant correlation between OC and NH_3 concentration in experiment 3.

Discussion

Losses and emissions of N- and S-containing compounds

Losses of N and NH_3 during aerated tunnel and windrow composting (experiments 2 and 3) were lower than those reported by Gerrits [8] for straw/horse manure/poultry manure composts (1.7 g and 2.1 g kg^{-1} compost, respectively). Losses during aerated tunnel Phases 0, I, and II composting in experiment 2 were similar to those found in previous experiments for straw/poultry manure composts [18,19] (0.74 g and 0.1–0.6 g kg^{-1} compost for N and NH_3, respectively). However, N losses were higher than those reported by Gerrits *et al* [12] for wheat straw/horse manure/poultry manure composts in aerated tunnels (269 mg kg^{-1} compost). The differences in N losses may have been due to the materials used, as well as to the composting conditions such as temperature, aeration, and time.

Only a small proportion of compost S (or S losses) was emitted as volatile compound. The compost S losses found here were higher than those reported by Derikx *et al* [4] of 8.3 mg kg^{-1} compost fresh weight for emission of volatile S-containing compounds. They could not observe any S loss on the basis of compost analysis, due to high standard deviations in analysis. Here, the higher emission of volatile S-containing compounds from poultry manure-based composts, compared with other formulations, was due to the protein S in cystine and methionine [15]. Miller and McCauley [16] found that odors increased with increasing initial N content and available nutrients used in compost on mushroom farms. This was attributed to rapid oxygen depletion due to reduced compost porosity and increased production of odoriferous compounds from anaerobic zones. The effect of compost aeration on reducing the emission of S-containing compounds and odors from compost in the present work confirms earlier results [5,22]. Although gypsum is a significant source of S in mushroom compost, no effect of gypsum rate in compost on odor or sulfides in anaerobic flasks was found (unpublished data). Gerrits [9] found that omission of gypsum from compost had a detrimental effect on mushroom yield, particularly if the compost NH_4^+ content was high.

Noble *et al* [22] found the following regression equation between concentrations of H_2S and DMS on mushroom composting sites and bag sample OCs measured 24 h later:

$$\log_e OC = 7.601 + 0.934\log_e(H_2S + DMS + 0.375); \quad r = 0.95,\ P < 0.001 \qquad (3)$$

where H_2S and DMS were concentrations in $\mu l\ l^{-1}$ and OC was measured in OU m^{-3}. Due to a decay of H_2S in the bags at a rate of 48% day^{-1}, the combined DMS+H_2S concentrations 24 h after sampling were estimated as DMS+0.52 H_2S. Regressing OC on this sum, again using $\log_e$-transformed data, produced the following relationship:

$$\log_e OC = 7.702 + 0.999\log_e([0.52H_2S] + DMS + 0.375); \quad r = 0.941,\ P < 0.001. \qquad (4)$$

The regression coefficients in Eqs. (3) and (4), obtained from four aerated tunnel and seven turned windrow sites, are intermediate between those found here for aerated tunnels Eq. (1) and turned windrows Eq. (2).

In agreement with previous measurements on emissions from poultry manure-based composts [22], NH_3 and butanol were detected at concentrations exceeding their olfactory detection thresholds. However, unlike the earlier work, NH_3 concentration was correlated with OC in experiment 2, but not in experiment 3. This may have been an indirect effect of adding more of the N sources (in particular, poultry manure or hop waste) to compost, which increased OC. Correlations between OC and ethanol or propanol concentrations were probably indirect effects since both compounds were only detected by GC-MS at concentrations below their olfactory detection thresholds (Table 5), although they may have had additive or modifying effects on other odorants.

Mushroom cropping

There were some differences in the relative mushroom yields produced by different compost N sources in flask-scale and large-scale composting systems (aerated tunnels and windrows). Wheat straw+poultry manure, cocoa meal, or hop waste and rape straw+poultry manure were similar in performance in flask composts, but wheat straw+poultry manure was significantly better in the large-scale systems. This may have been due to flasks being heated externally, whereas large-scale systems relied on metabolic heat, except for the initial part of Phase II pasteurization. However, in both the flask-scale and large-scale composting systems, the above organic N sources produced better mushroom yields than composts prepared from wheat straw with inorganic N sources, ammonium sulfate, or urea. Where similar compost ingredients were used, mushroom yields were better from aerated tunnels than from flask composts, and better from windrow than from aerated tunnel composts. Compost ash contents at spawning followed a similar order. This indicates that greater C losses and compost degradation in the composting systems were related to higher mushroom yields. This may partly explain the correlations between compost ash content and mushroom yield in experiments 2 and 3, although this would also be influenced by the high ash content of poultry manure, as previously described. Earlier work has shown either no difference in mushroom yields from composts prepared in windrows or aerated tunnels [17] or better mushroom yields from windrow composts [18–20]. In these experiments, windrow and aerated tunnel composts had similar bulk densities, although previous work has shown that bulk density is usually greater in windrow composts [17] and this depends on compost moisture [11]. The influence of C losses and compost degradation on mushroom yield would need to be confirmed by elemental analysis of C in compost.

There was no difference in mushroom yield between composts with N contents at the start of Phase II of 1.6% and 2.1% of DM (flasks) or 1.8% and 2.3% of DM (aerated tunnels). Gerrits [8,9] showed that the optimum N content for straw/horse manure/poultry manure composts prepared in windrows or aerated tunnels was about 2% of DM at the start of Phase II. Noble and Gaze [18,19] found that the optimum initial N content for poultry manure-based compost prepared in aerated tunnels was 2.2–2.5% of DM.

The more vigorous mycelial growth on the casing layer over urea-based composts indicates that culture using such composts needs to be modified. In particular, an earlier induction of fruiting may be necessary, since too vigorous mycelial growth can affect cropping adversely.

Replacement of poultry manure with other N sources at 50–100% or wheat with rape straw in aerated tunnels or windrow compost reduced composting OC and emission of odorous S-containing compounds, but also reduced mushroom yield. Gerrits [7] showed that replacement of 38% of the poultry manure in a straw/horse manure/poultry manure compost with an equivalent amount of N in the form of malt sprouts, urea, or ammonium nitrate did not significantly affect yield. Noble and Gaze [19] found that replacing 40% of the poultry manure N with an equivalent quantity of N using Sporavite had no effect on mushroom yield, but a similar replacement with ammonium sulfate significantly reduced yield. Gerrits and Amsing [10] showed that adding supplementary ammonium sulfate to a straw/horse manure/poultry manure compost increased compost NH_4^+ content by 0.06–0.35% of DM, but had no overall effect on mushroom yield. Chalk has been added to compost containing ammonium sulfate to increase dissociation of ammonium ions as well as producing gypsum [2]. Separate flasks composting tests (unpublished) showed that ammonium chloride performed similarly to ammonium sulfate during composting and subsequent mushroom cropping. This indicates that the NH_3 losses from AminoPro, and subsequent mushroom yield, were mainly due to the amine rather than ammonium chloride content. Pecchia *et al* [23] found that substituting poultry manure with an equivalent amount of N in the form of brewers' grains, in a horse manure/hay/cotton seed hull compost, reduced odor intensity and unpleasantness, but did not affect subsequent mushroom yield.

Conclusions

The results here showed that substitution of 50% or more of the poultry manure in compost significantly reduced odorous emissions, but also reduced mushroom yield. Differences in N availability, in terms of NH_3 and N losses during composting, were found. Sources in which the N was less available (chipboard and digester wastes, cocoa shells, ammonium sulfate) produced lower mushroom yields than materials in which N was more readily available (poultry manure, urea, hop waste, cocoa meal, brewers' grains, AminoPro, Sporavite). The latter materials may be suitable for "low odor" prewetting of straw, with addition of poultry manure immediately before aerated tunnel composting. Of these materials, urea and cocoa meal were the cheapest sources of N. Wheat straw compost produced a better mushroom yield than rape straw compost. However, as well as being cheaper than wheat straw (Table 1), a proportion of rape straw in compost will assist in reducing the formation of anaerobic zones and resulting odorous emissions, since it maintains its structure and porosity better than wheat straw.

Acknowledgements

This work was funded by the Department for Environment, Food and Rural Affairs, the Horticultural Development Council, and other members of the consortium of Horticulture LINK Project 180.

References

1 Anonymous. 1986. The Analysis of Agricultural Materials. Ministry of Agriculture, Fisheries and Food/Agricultural Development and Advisory Service Reference Book 427. HMSO, London, pp. 219–221.
2 Bech K and C Rasmussen. 1968. Further investigations in organic and inorganic supplementation of mushroom compost. *Mushroom Sci* VII: 329–342.
3 Delmas J and J Laborde. 1968. Influence de la forme d'azote utilisee an cours de la fermentation des composts sur l'effect d'une supplementation proteinique apportee au moment du gobertage, et sur le rendement. *Mushroom Sci* VII: 309–328.
4 Derikx PJL, HJM Op den Camp, C van der Drift, LJLD van Griensven and GD Vogels. 1990. Odorous sulfur compounds emitted during production of compost used as a substrate in mushroom cultivation. *Appl Environ Microbiol* 56: 176–180.
5 Derikx PJL, FHM Simons, HJM Op den Camp, C van der Drift, LJLD van Griensven and GD Vogels. 1991. Evolution of volatile sulfur compounds during laboratory-scale incubations and indoor preparation of compost used as a substrate in mushroom cultivation. *Appl Environ Microbiol* 57: 563–567.
6 Devos M, F Patte, J Rouault, P Lafffort and LJ van Gemert. 1990. Standardized Human Olfactory Thresholds. Oxford Univ. Press, Oxford, UK.
7 Gerrits JPG. 1974. Development of a synthetic compost for mushroom growing based on wheat straw and chicken manure. *Neth J Agric Sci* 22: 175–194.
8 Gerrits JPG. 1988. Nutrition and compost. In: van Griensven LJLD (Ed), The Cultivation of Mushrooms. Darlington Mushroom Laboratories, Sussex, UK, pp. 29–72.
9 Gerrits JPG. 1992. Bijvoeden van conventionele en indoor compost. *Champignoncultuur* 36: 31–37.
10 Gerrits JPG and JGM Amsing. 1997. Ammoniumsulfaat als aanvullende stikstofbron in indoor compost bij gebruik van water uit luchtwassers. *Champignoncultuur* 41: 243–251.
11 Gerrits JPG, JGM Amsing, G Straatsma and LJLD van Griensven. 1994. Indoor compost: Fase I. Processen van 5 dagen in tunnels. *Champignoncultuur* 38: 338–345.
12 Gerrits JPG, JGM Amsing and G Straatsma. 1997. Vochtgehalte en volumengewicht van indoor compost. *Champignoncultuur* 41: 179–183.
13 Grabbe K. 1974. Versuche zur Biotechnologischen Aufbereitung von Rinderflüsigmist zu Kultursubstraten für höhre Pilze. *Mushroom Sci* IX: 99–108.
14 MacCanna C. 1968. Nitrogen supplementation of composts. *Mushroom Sci* VII: 294–307.
15 Miller FC and BJ Macauley. 1988. Odours arising from mushroom composting: a review. *Aust J Exp Agric* 28: 553–560.
16 Miller FC and BJ McCauley. 1989. Substrate usage and odours in mushroom composting. *Aust J Exp Agric* 29: 119–124.
17 Miller FC, ER Harper, BJ Macauley and A Guliver. 1990. Composting based on moderately thermophilic and aerobic conditions for the production of commercial mushroom growing compost. *Aust J Exp Agric* 30: 287–296.
18 Noble R and RH Gaze. 1994. Controlled environment composting for mushroom cultivation: substrates based on wheat and barley straw and deep litter poultry manure. *J Agric Sci (Cambridge)* 123: 71–79.
19 Noble R and RH Gaze. 1996. Preparation of mushroom (*Agaricus bisporus*) composts in controlled environments: factors influencing compost bulk density and productivity. *Int Biodeterior Biodegrad* 37: 93–100.

20 Noble R and RH Gaze. 1998. Composting in aerated tunnels for mushroom cultivation: influences of process temperature and substrate formulation on compost bulk density and productivity. *Acta Hortic* 469: 417–427.
21 Noble R, TR Fermor, CE Evered and PT Atkey. 1997. Bench-scale preparation of mushroom substrates in controlled environments. *Compost Sci Util* 5: 32–43.
22 Noble R, PJ Hobbs, A Dobrovin-Pennington, TH Misselbrook and A Mead. 2001. Olfactory response to mushroom composting emissions as a function of chemical concentration. *J Environ Qual* 30: 760–767.
23 Pecchia JA, DM Beyer and PJ Wuest. 2000. The effects of poultry manure based formulations on odor generation in phase I mushroom composting. In: van Griensven LJLD (Ed), Science and Cultivation of Edible Mushrooms. Balkema, Rotterdam, the Netherlands, pp. 335–339.
24 Poppe J. 2000. Use of agricultural waste materials in the cultivation of mushrooms. In: van Griensven LJLD (Ed), Science and Cultivation of Edible Mushrooms. Balkema, Rotterdam, the Netherlands, pp. 3–23.
25 Riethus H. 1962. Versuchsergebenisse für Stickstoffbilanz in Champignonsubstraat. *Mushroom* V: 10–18.
26 Ross RC. 1968. Experiments on the use of farm waste products in mushroom composting. *Mushroom Sci* VII: 365–371.
27 Smith JF and DM Spencer. 1977. The use of high energy carbon sources in rapidly prepared mushroom composts. *Sci Hortic* 19: 65–78.