Monitoring Mushroom Compost Quality During Production and Cropping

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Abstract: The objective of the investigation was to establish a range with target values of parameters, for monitoring quality at phase I, II & III. Additional aims were to compare changes in parameters during production and cropping with spectral and thermal results, determined by near infrared spectroscopy and thermogravimetry and also to review industry protocols and published literature for collating suitable intervention steps. Samples were obtained from composters for analyses. Cropping trials were carried out to monitor differences in key parameters and the productivity of substrates. The thermal technique was able to show gradual breakdown of the fibre components, formation and subsequent degradation of lignin-humus complex and an increase in ash. The spectra of samples identified shifts in specific spectral segments, indicating changes in dry matter, nitrogen dry matter, fibre and lignin-humus content of substrates during production and cropping. Intervention steps for improving quality during production, management of environmental conditions in tunnels and crop are also discussed.

Key words: Phase I, II and III compost, spectroscopy, thermal analysis, quality assessment, production and cropping

1 Introduction

A typical commercial formulation of raw materials, used by composters in Northern Ireland, consists of straw blended with a mixture of chicken litter and gypsum (1000:25 kg) at a ratio of 1000:450 kg respectively, with a target C:N ratio of 20:1 at the start of the production. Chicken litter is regularly evaluated for nitrogen dry matter (NDM) content before a batch formulation is finalised yet, in contrast, straw is rarely assessed for NDM or the degree of breakdown. Previous research carried out in Europe has shown that straw can be variable in NDM, fibre fractions and microbial degradability depending on the soil fertility, the variety, crop management and protection protocols.[1] The gypsum used in the industry is typically agricultural grade although other commercial sources of gypsum from the food and glass crystal industries are available but should not be used unless the materials are analysed for toxicity to compost microorganisms, possibly due to chemical residues. The preparation of compost is a balance between allowing the synthesis of nutrients for *Agaricus bisporus* that confers selectivity to the substrate and minimising the loss of carbon.[2] The basic principles of heat, mass transfer and biological constraints of the mesophilic and thermophilic microorganisms[3] govern the process of composting. Compost moisture control is critical in optimising the decomposition process,[4] as it not only directly effects the microbial processes *per se* but also aeration and gaseous exchange within the compost stacks. Thus, in phase I, the general trend for straw wetting has been away from pre-wet lagoons and boom watering gantries to a process of whole-bale dunking that increases the efficiency of moisture penetration of the bales from the outset. In phase I, raw materials are first wetted, followed by blending and left as a loose pile for 1-3 days before forming a windrow or transferring into a bunker for a duration of 7-11 days. This is followed by a phase II stage, consisting of pasteurisation and conditioning periods for 5 to 7 days in a bulk tunnel.[5] The most significant compositional change of composting is the formation of a nitrogen-rich lignin-humus complex

from the microbial biomass and de-polymerised lignin.[6] Several researchers have investigated compositional changes in compost for NDM, DM, pH, conductivity, carbon, ash, lignin, phenolic acids and fibre fractions of substrates.[2, 6, 7, 8] The factors affecting the productivity of phase II substrate are many, including differences in the availability of key nutrients,[9] the type of spawn used, the management of crop and environmental conditions in the mushroom house and watering regime adopted during case-run and cropping. During the phase III/ spawn-run and cropping stages, changes in the concentration of NDM, the dormant biomass, fibre fractions and enzymes, including endo-cellulases, polyphenol oxidase and laccase, have been monitored to study the depletion rate of specific nutrients.[10, 11] The changes in enzyme concentration during cropping are linked to nutrient requirements of rapidly developing primordia.[12]

After the initiation of phase I, protocols employed by composters in the UK and Ireland have limited options for manipulating the process, apart from turning the windrow or blending the substrate for bunker composting or an additional input of water to optimise moisture content or altering bunker aeration. Previous research projects were focused on developing rapid techniques, such as visible and near infrared spectroscopy (NIRS) and thermogravimetry (TG), which could be used for monitoring changes in the key quality parameters of substrates. The current investigation was aimed at the application of instrumental techniques to identify key changes in the substrate during the production and cropping stages. An associated objective was to review industry protocols and published reports on all aspects for developing a decision support system, which could be adopted by the industry.

1.1 Phase I

The objective of Phase I stage is to minimise wasteful decomposition of straw, whilst utilizing self-heating properties of the substrate to produce a stable material for pasteurization and conditioning stages of phase II. The formulation of raw materials needs to be carefully calculated to match the composting protocol, as different types of lignocellulosic waste have been used successfully throughout the world.[2, 13] The protocols for batch size, the duration, and turning cycles are usually adapted by individual composters, to suit available machinery for handling raw materials and a target volume of phase II or III substrate. During this period, pH, temperature, dry matter (DM), NDM, and ammonia content of the substrate need to be monitored by composters and if necessary, modification of the production steps, such as turning cycle, shortening or extending the duration of the first phase, should take place based on the analytical results of the substrate. Composters in N. Ireland regularly monitor substrate for temperature and moisture content, and a few test for ammonia. The phase I stage is the most critical period of production, as the degree of microbial breakdown of a substrate in the first 10 days will largely determine pH, DM, NDM, and ash content of compost at the end of phase II.[2, 6] The generation of ammonia, as a result of protein breakdown is driven by heat generated during rapid microbial oxidation of the organic substrate. Since the material acts as an insulator, much of the heat is retained and temperature zones are formed in a stack.[2] or a bunker.[1] The core temperature can rise to 65 - 80°C leading to a reduction in the microbial activities, while the outer layer remains at near 10°C. In order to maintain uniform microbial degradation of the substrate, windrows are turned regularly and for a bunker system, the aerobic condition is sustained by injecting fresh air,[1] followed by transfer of the substrate mass after supplementing with water to an adjacent bunker. Several research groups in Europe and elsewhere in the world[14-19] have examined different rates of aeration, the nutritional and physical factors for sustaining microbial activity inside a windrow or a bunker. The biological and physical factors are interdependent to the extent that required turning schedules and moisture content in the substrate must be optimised for a production batch size. The distribution of bulk density and porosity in a compost pile has been investigated by Van Ginkel et al.[20] and they concluded that bulk density/air-filled volume and the height of windrow were negatively related. Comparative studies on the physical, chemical and microbiological changes, taking place during the windrow and bunker composting, have been carried out by Sharma et al.[21]mThey reported that key parameters, such as straw length,

population of *Scytalidium thermophilum*, DM, conductivity, ammonia, fibre fractions and ash content of phase I composts were significantly different for the two production systems, due to many factors including high bunker core temperature (80°C) which could retard the microbial degradation process. Variations in the key parameters at the end of phase I are shown in Table 1.

Table 1. Changes in key parameters including, total soluble carbohydrate (TSC), total soluble polyphenol (TSP), acid detergent fibre (ADF) and neutral detergent fibre (NDF) phase I, II, III, flush 1, 3 and end of cropping showing range and target values; the results for cropping are based on limited samples

Parameters	Range Phase I	Target Phase 1	Range Phase II	Target Phase II	Target Phase III	Range Flush 1	Range Flush 3	Range End of crop
Ammonia (%)	0.10-0.35	0.24	0.001-0.062	0.005	0.001	-	-	-
pH	7.8-8.5	8.2	7.3-8.7	7.3-7.5	6.6-7.0	5.6-5.9	5.8-6.0	5.9-6.04
Conductivity S/cm	2.2-3.5	3.0	2.9-4.0	3.2-3.4	4.0	4.99-5.59	5.92-6.60	6.7-7.1
Nitrogen dry matter (%)	1.4-2.3	2.0	1.8-2.5	2.3-2.4	2.4- 2.5	2.4-2.5	2.5-2.6	2.46-2.67
Dry matter (%)	25.8-31.0	28.0	30.9-37.0	31-33	33-35	36.3- 37.8	40.9-42.5	41.2-43.4
Carbon (%)	35.5-40.0	38.5	35.0-41.3	34.0-36.0	33.0-35.0	32.2-33.6	30.7-32.8	31.0-33.3
C:N ratio	15-20	17.0-18.0	9.5-17.0	14.0-15.0	12-13	13.7-13.7	12.1-12.9	11.7-12.4
Ash (%)	14.7-19.0	18.0	17.9-29.3	22.0-24.0	24-26	25.5-26.3	28.0-30.2	29.82 -30.78
S. *thermophilum* (lc/g^{-1})	-	-	3.5-7.5	6.0-7.5	-	-	-	-
TSC (g/kg DM)	4.91-19.36	16.0-17.0	1.44-16.75	12.0	19.18	-	-	-
TSP (g/kg DM)	5.06-15.19	7 .0-8.0	0.94-6.1	3.5	4.60	-	-	-
ADF (%)	47.0-54.0	49.0-50.0	40.1-49.21	46.0-47.0	-	-	-	-
NDF (%)	55.5-67.9	64.5	41.98-55.27	48.0-50.0	-	-	-	-
Lignin (%)	16.0-20.3	17.6	15.0-22.0	19.5-20.0	-	-	-	-
Fibre-weight loss Peak 1 (%)	49.5-61.5	56.2	45.5-56.6	52.5	45.1	38.8-41.9	34.9-37.9	33.8-37.4
Temperature- Peak 1(°C)	296.1-320.6	308.5	293.1-302.1	297.6	295.0	292.7-297.1	294.5-298.6	294.1-297.1
Fibre- weight loss Peak 2 (%)	14.0-23.8	18.8	15.9-24.8	20.5	23.3	23.6-24.9	24.4-25.3	24.1-26.0
Temperature - Peak 2 (°C)	397.1-491.5	487.1	460.8-502.7	478.3	473.5	470.2-479.6	464.5-474.6	464.8-479.4
Ash as measured by DTG (%)	13.6-27.6	19.2	15.6-26.8	22.6	23.7	24.9-28.8	28.3-31.6	28.4-32.3

During commercial production, not all parameters listed above are monitored and the protocols for production are usually based on in-house database of temperature, moisture, ammonia, pH and NDM content collected during winter and summer months. As long as the measured values of the five quality parameters are within expected ranges, the intervention of a production protocol does not take place. This approach is risky, if the previous results are not accurate, due to systematic error in the sampling procedures and protocols employed to measure parameters or the problem is caused by other unidentified factors, such as variation in the quality of input raw materials. A summarised key, based on industry protocols and previous reports for monitoring temperature, moisture, ammonia, NDM and pH, is shown in Table 2.

1.2 Phase II

At the end of phase I, the substrate is relatively more homogeneous and contains thermophilic population consisting of *Thermoactinomyces vulgaris, Streptomyces* spp, *S. thermophilum* and *Rizomucor pusilus* and *Aspergillus fumigatus*,[22, 23] and residual extra-cellular enzymes, such as cellulases, xylanases and proteases. An extensive work on the diversity of thermophilic fungi and actinomycetes has been reported, including roles played by thermophiles in converting a non-selective substrate to a selective compost for *Agaricus bisporus*.[22, 24] The objectives of phase II are to pasteurize the substrate by eliminating weed mould fungi and pests in a controlled environment, and complete the fermentation process initiated in the first phase. Both steps are

Table 2. Summarised monitoring steps for temperature, moisture, NDM, ammonia and pH during phase I to implement actions to optimise the parameters; windrow/bunker - 2-4 days in phase I

Parameter	Likely outcome at the end of phase I if no action is taken.	Suggested action to optimise key parameters	Likely outcome as a result of the action at the end of phase I
Core Temperature			
80°C	Lower thermophilic population with minimal substrate breakdown	Turning/transfer of substrate to an adjacent bunker after blending and moisture supplementation	More homogeneous breakdown of substrate
56°C	Optimum conditions for thermophiles and substrate degradation	Intervention not required	Homogenous substrate breakdown,
40°C	Poor microbial activity, low pH & NDM	Need to supplement nitrogen and moisture content & increase aeration rate	Microbial activity enhanced leading to higher core temperature.
Moisture content			
79 %	High moisture content, could lead to anaerobic condition & poor substrate quality	Turning/transfer of substrate to an adjacent bunker after blending, increase aeration rate & core temperature	Moisture content likely to be reduced due to increased evaporation rate & core temperature
75 %	Optimum moisture content	Intervention not required	Homogeneous substrate breakdown substrate quality target achieved
70 %	Low moisture content - needs to increase moisture content	Turning/ transfer of substrate to adjacent bunker after blending and moisture supplementation	More homogeneous breakdown of substrate
Ammonia			
0.35 (%)	High ammonia content, high NDM	Ammonia content high, increase aeration rate to drive out excess ammonia	Homogenous substrate breakdown, substrate parameters within target
0.24 (%)	Optimum ammonia and NDM content	Intervention not required	
0.10 (%)	Low ammonia concentration & likely to be lower than optimum NDM content	Need to supplement the substrate to increase ammonia content	Key parameters within target
NDM			
2.2 %	High NDM associated with high core temperature & high ammonia	Increase aeration/turning to reduce ammonia & Control degradation process	Ammonia concentration reduced
1.8 %	Optimum NDM content, ammonia and pH	Intervention not required	Substrate quality target achieved
1.4 %	Poor microbial activity, low ammonia & pH	Nitrogen supplementation required	NDM content near target
pH			
9.0	High pH, likely to be high in ammonia	Same intervention protocol for high nitrogen substrate	Lower pH and ammonia
8.0	Optimum pH	Intervention not required	Target pH achieved
7.5	Low pH, poor NDM content & ammonia	Same intervention protocol for low NDM & ammonia	pH below target

important for imparting selectivity to the substrate, due to controlled microbiological and chemical changes taking place during conditioning. The microbial activities are driven by the utilization of readily available carbohydrates, followed by the volatilization and incorporation of ammonia to form microbial protein complex, thereby con-

serving nitrogen.[25] This change resulted in reducing pH of compost to near neutral (pH 7.2 -7.6). Three main factors: compost temperature in the tunnel, the initial level of ammonia and the rate of aeration, determine the duration of phase II ranging from 5 to 7 days.

During the mechanical transfer of phase I substrate into a bulk tunnel, due care needs to be taken to distribute the compost evenly to maintain an optimum bulk density (550 kg m^{-3}), air-filled volume (57% porosity) and height *ca* 2.0 - 2.2 m. In contrast, overfilling a tunnel will increase the substrate mass/height in the tunnel, leading to a reduction in porosity and increasing the bulk density, due to compression by its own mass.[20] This is an important factor, but composters do not always estimate optimum fill volume of a tunnel, after assessing bulk density of a substrate at the end of phase I.[26] reported benefits of using a compact instrument for measuring bulk density of composts and subsequently, a composter from N. Ireland used the device successfully for estimating the bulk density of substrate at the end of phase I. The two factors listed above determine the rate of aeration through the substrate mass and phase II tunnel conditions cannot be controlled effectively without an optimum porosity and bulk density. The biochemical and physical changes in the substrate are influenced by the composition, the degree of microbial degradation, the pasteurisation temperature, heat removed by the ventilation of evaporated water and aeration.[14, 27-29] Researchers in the Netherlands have attempted to model the phase II composting process by correlating loss of DM, generated heat and the evaporation rate of water from a series of experimental trials carried out during a 30 year (1970s to 1990s) period.[30] They were unsuccessful in their objective but recommended that major problems in phase II stage could be minimised by reducing variations in the composition of raw materials.

The bulk tunnels used by a majority of composters for Phase II/III are equipped to continuously monitor various parameters - most notable air and compost temperature, oxygen or CO_2 levels, fan and damper positions, air-flow rate and back pressure. Control programmes generally regulate recursively - taking into account the values of the immediate preceding period - thereby attenuating reactions and avoiding sudden changes. Regulation of temperature and ventilation are the most important factors and by evaluating differences between air and compost temperatures a measure of the microbial activity of the compost is taken into account. To identify key changes during phase II the operators rely on their knowledge and experience from the database of parameters to manipulate the factors to maximise efficiency of nitrogen conversion. The computerised monitoring system for tunnels is thus generally programmed to follow a set of instructions to complete the process without intervention. Alternatively the system can be used as a decision support system by adjusting process timings, temperature, damper and fan speed ranges to achieve target parameters, such as ammonia and CO_2/O_2 concentrations. A summary of intervention steps is listed in Table 3 for maintaining target parameters at the end of phase II. A substrate quality is determined by a number of factors including, residual ammonia, DM, pH, conductivity, NDM, carbon, ash and *S. thermophilum* population and the parameters can be used to estimate potential productivity of compost.[31] Target values with a range for parameters are shown in Table 1.

1.3 Phase III

The main aim of Phase III is to promote rapid colonisation of mushroom mycelium while limiting the growth of microorganisms inhibitory to its growth. While it is generally assumed that chemically balanced compost exhibiting these properties will be productive there is as yet limited published data to support this.[32] Compost selectivity remains a frequently used but as yet not fully understood term. Composts with high populations of thermophilic fungi i.e. *Scytalidium thermophilum* at spawning allow rapid colonisation of mycelium, yet it is not clear if the thermophilic fungi indicate a suitable chemical status of the compost, or if their presence actually stimulates mycelial growth.[33] By the end of Phase II thermogenesis has declined and compost microflora exist at a temperature near their minimum for growth. Biomass in this "static condition" (intact cell structure with nutrients "locked" within the microorganisms) protect the compost from attack by contaminating weed moulds[34] until the mushroom becomes the dominant organism. This microbial biomass can comprise up to 2%

Table 3. Summarised monitoring steps for key parameters, temperature, airflow and CO_2 during phase II to implement actions for optimising the parameters

Parameter	Likely outcome/consequence at the end of phase II if no action is taken.	Suggested action to optimise key parameters	Likely outcome as a result of the action at the end of phase II
Temperature at pasteurisation			
65°C	High compost temperature, could eliminate beneficial thermophiles, selectivity will be retarded	Need to reduce temperature to 58°C	Population of beneficial thermophiles should increase
58 °C	Optimum substrate temperature	Intervention not necessary	Optimum population of beneficial thermophiles
50 ° C	Low pasteurisation temperature, weed mould & pests present in substrate	Need to increase temperature to eliminate weed mould and pests	Population of beneficial thermophiles should increase to optimum level
At conditioning			
55°C	High temperature for conditioning stage, will reduce microbial activity, high residual ammonia	Need to reduce temperature to optimise conversion of ammonia to microbial protein	Enhanced microbial fixation of ammonia to form protein
45°C	Optimum temperature for activity of thermophiles optimum conversion of ammonia to microbial protein	Intervention not necessary	Optimum nitrogen content, low residual ammonia
30° C	Low temperature leading to poor microbial conversion of ammonia to protein	Need to increase temperature to optimise conversion rate	Nitrogen content near target value
Airflow - Levelling*			
ca 50 m^3/T / hr	Longer time to achieve uniform compost temperatures in active, uneven temperatured compost	Increase air flow to 150 - 200 m^3/T/ hr	Improved control of compost temperature, optimum levelling period.
150-200 m^3/ T/hr	Compost temperature differentials resolved faster	Intervention not necessary	Shorter levelling period, conserved ammonia
Airflow- Conditioning*			
ca 50 - 100 m^3/T/hr	Optimum air flow rate during conditioning	Intervention not necessary	Enhanced microbial fixation of ammonia to form protein
150-200 m^3/ T/hr	Loss of useful moisture with excessive air movement through less active compost	Reduce air flow rate to *ca* 50 - 100 m^3/T/hr	Retained compost moisture levels
CO_2 levels * At pasteurisation			
ca 1-2 %	Low CO_2, difficult to achieve target temperature, selectivity retarded, useful moisture loss	Reduce fresh air to minimum necessary	Effective pasteurisation with minimal useful substrate moisture loss
ca 6-10 %	High CO_2 necessary, but with sufficient O_2 for survival of microorganisms	Intervention not necessary	Effective kill achieved with optimum microflora maintained
At conditioning			
ca 1-2 %	Optimum level for active microbial phase, effective compost temperature control	Intervention not necessary	Optimum population of beneficial thermophiles
ca 6-10 %	Insufficient O_2, low water vapour removal, temperature control restricted & reduced microbial activity	Increase proportion of fresh air.	Effective temperature control and optimum microbial conversion restored

*Dependent on tunnel emptying system (net or bobcat system), compost structure, moisture content and activity.

of the dry matter of the compost and while not an important carbon source may represent a concentrated reserve of nitrogen, lipids and other minerals[35] for the initial colonisation of compost by mushroom mycelium. A wealth of literature is available on the degradation and utilisation of compost by *A. bisporus*.[6, 36, 37] There is general agreement that both cellulose and non-cellulose polysaccharides of straw are substrates for mushroom growth, but the situation is less clear for lignin. Rapid lignin utilisation during mycelial growth was indicated by Gerrits et al.[6] when measured as an acid insoluble fraction. Wood and co-workers[11, 36] and Durrant et al.[38] used radio-respirometric studies to show that mushroom mycelium respired the labelled lignin to CO_2, confirming rapid lignin utilisation during mycelial growth. However, further chemical analysis of degradation using the reagent acetyl bromide [37] challenged this hypothesis and showed that lignin accumulates during both composting and mushroom production, suggesting lignin is not used to any significant extent. Their studies further showed that the structure of the lignin fraction had changed with evidence of oxidation and condensation products in the lignin polymer. Other factors that have been shown to affect the rate of mycelial colonisation of compost include moisture content, pH, ammonium N, salinity, temperature and CO_2.[32] However, these studies of mycelial extension rates through compost using both "race tube" techniques and fungal biomass estimated by measurement of the extracellular enzyme laccase, indicated that the rate of mycelial growth does not necessarily correlate with improved mushroom yield. In practice, three main factors: compost temperature, rate of aeration and CO_2/O_2 levels control the duration of phase III that generally proceeds for 12 to 16 days.

As in Phase II, good tunnel design and construction are essential prerequisites for optimum process control. Fan capacity is calculated based on the phase II process with high specification spore filters operating at 99.5% efficiency within predefined volumes of air. Tunnel filling weights (optimum 1250kg m^{-3}) and evenness of fill are critical in phase III. While the aeration requirement at the start of spawnrun may be as low as 50-80m^3 air per tonne of compost per hour, this can increase to 150 - 175m^3 air per tonne when compost activity is greatest, 8-10 days after spawning.[39] Specifications for mechanical cooling capacity depend on filling weights and outside climatic conditions but must be sufficient to prevent the excessive use of fresh air as a means of cooling. Conversely, when compost moisture is above optimum, the tunnel computerised control system can be manipulated to facilitate a higher level of fresh air intake to allow some adjustment in compost moisture. Optimum CO_2 levels during spawn run are between 0.5 - 1.5%; any lower will slow down the spawnrun and dry out the compost unnecessarily. Higher levels have been shown to be toxic to the mushroom mycelium.[40] As mycelium colonises the compost, organic matter continues to be broken down and the heat produced discharged slowly from the compost layer in the form of water vapour with temperature gradients similar to those found in Phase I windrows occurring. Efficient temperature control during Phase III is paramount; with optimum temperatures of 24 - 25°C particularly during the first 7-8 days when the compost is most vulnerable to weed moulds. As mushroom growth progresses so too will compost activity, with the temperature difference in the layer increasing to a peak 8-12 days after spawning. By day 16, compost activity starts to decrease indicating that the compost is ready to be emptied from the tunnel. As before, a summary of intervention steps is listed in Table 4 for maintaining target parameters during Phase III/cropping with target values for a range of key parameters shown in Table 1.

1.4 Cropping

There are two commonly used methods to investigate *A. bisporus* compost utilisation during mycelial growth and cropping. The first is by direct analytical comparison of compost at spawning and end of crop. Unfortunately, the complex mixture of substances is not always amenable to simple chemical analysis and it is often impossible to differentiate components of mushroom mycelium and substances in the compost matrix.[41] A more successful approach has been to study extracellular enzyme activity during growth and fruiting of *Agaricus* on compost.[11, 36, 42] Activities including oxidases, peroxidases and various hydrolases indicate the likely substrates for these enzymes comprise many of the plant and microbial polymers in compost. Continual laccase activity

evident during mycelial growth rapidly declines after fruit bodies develop and continues to rise and fall with each successive flush in a cyclical regulation pattern. Cellulase (endoglucanase) activity operates in a similar manner; the regulation of activity indicating that the fungus controls the supply of carbon to the mycelium. As fruitbodies are formed the increased carbon demand is met by translocating carbon metabolites from the mycelium, that in turn increases production of extracellular cellulase in the compost thus replenishing its carbon levels. It is estimated that although about 15% of the compost plant cell wall polysaccharides are used during the colonisation of substrate and fruiting, a considerable quantity (17-31%) remain unused at the end of cropping.[43] By comparison, a two-fold increase in protease activity occurs as fruiting starts but there is no cyclical regulation evident in flush cycles. This protease may be involved in increasing the nitrogen supply to

Table 4. Summarised monitoring steps for key parameters, temperature, CO_2 and airflow during phase III to implement actions for optimising the parameters

Parameter	Likely consequence at the end of phase III/ during cropping if no action is taken.	Suggested action to optimise key parameters	Likely outcome as a result of the action at the end of phase III/during cropping
Compost Temperature, Days 1 - 8			
27 - 30 ° C	Encourages mould growth, loss of moisture leading to high activity in case run/cropping.	Need to reduce temperature to mean of 25° C maximum	Reduced risk of mould growth, moisture retained in the compost, improved control during cropping.
24 - 25 °C	Optimum substrate temperature	Intervention not required	Optimum caserun in optimum time, pH target achieved.
22 - 23 ° C	Slower initial mycelial growth, may need longer spawnrunning time.	Need to increase to mean of 25° C	Mycelial colonisation improves to allow optimum spawn run within normal time limits.
Days 9 - 16			
27 - 30 ° C	Loss of useful compost moisture leading to active compost during caserun/cropping period;	Need to reduce to 25° C, risk of mould growth reduced.	Retained moisture levels in the compost, improved temperature control in crop cycle.
24 - 25 ° C	Optimum substrate temperature	Intervention not required	Substrate parameters within target range.
22 - 23 °C	Low temperature for spawnrunning with slower mycelial colonisation	Need to increase to 25° C	Mycelial colonisation should increase to allow spawn run within normal time limits.
CO_2 Levels			
< 0.5 %	Slow mycelial growth, unnecessary drying out of the compost, could reduce crop yield.	Need to reduce ventilation to increase levels to 0.5 - 1. 5 %.	Mycelial growth rate should increase, excessive drying out of compost prevented.
2. 5 - 1.5 %	Optimum CO_2 levels	Intervention not required	Optimum substrate colonisation with *Agaricus* mycelium and retained moisture levels.
>1.5 %	Slowed and/or retarded mycelial growth rate	Increase ventilation to reduce levels to 5.0 - 1.5 %.	Mycelial growth rate increases, improved utilisation of compost nutrients for crop yield.
Airflow Days 1 - 3			
50 - 80 m^3/ T/hr	Small temperature differentials achieved in the bulk compost tunnel.	Intervention not required	Optimum airflow achieved during relatively inactive phase of spawnrun.
150 - 175 m^3/ T/hr	Loss of useful moisture; active compost during caserun and cropping.	Reduce air flow rate to 50 - 80 m^3/T/hr	Retained compost moisture levels, improved control of compost temperature post casing.
Airflow Days 8 - 12			
50 - 80 m^3/T/ hr	Insufficient airflow through compost, difficult to control temperature	Increase air flow rate to ca 150 - 175 m^3/T/hr	Decrease compost temperature differentials, regain control to within optimum range.
150 - 175 m^3/ T/hr	Effective control of compost temperature.	Intervention not required	Optimum airflow for active mycelial growth and effective compost utilisation.

the mycelium and thus the developing mushrooms but not in a cyclical flush regulation pattern. Mycelial growth and mushroom production of *Agaricus bisporus* use 20-25% of the compost dry matter.[30] Productivity decreases with successive flushes until a point where the economic viability of the cropping cycle is untenable. With fragmented data available on chemical changes in compost as cropping progresses, factors limiting productivity are not fully understood. They may include shortages of one or more nutrients, adverse accumulation of toxic substances,[41] changes in ratios between water, dry matter and air space in compost resulting in alterations in the mushroom growing environment[30] and build up of pests and disease.

Cultural system, environmental and crop management protocols also play a highly significant role in compost productivity. Cropping factors known to impact on yield include: spawn strain, casing formulation/management, watering regimes, harvesting protocols, air/compost temperature, relative humidity and CO_2 levels.[12, 40, 44] Composts of disparate characteristics need to be treated appropriately to achieve the maximum practical yield.[45] Accurate compost production and analytical data are essential if cropping procedures are to be adapted to most appropriately fit the substrate and successful intervention steps can only be applied if this information is made available by the compost manufacturer to the grower. In the satellite system in Ireland, protocols for mushroom crop production are generally not based on such information. This is a precarious situation that too often culminates in cropping problems that are at least limitable, if not preventable. Better growers however, strictly monitor compost structure and temperature on arrival and develop a more exacting relationship with the compost manufacturer being provided with compost analysis and forewarned of composting difficulties. In such cases, early intervention is essential. If substrate is, for example, above or below optimum temperature (or NDM) the crop manager will start pre-emptive measures, cooling or heating the receiving tunnel appropriately. High ammonia (or over-wet) compost, particularly in bags, can be managed through increased tunnel ventilation (and lower relative humidities) and loosely folded polythene to permit increased air diffusion; the converse is equally appropriate. With overactive composts, dropping the filling rate by 5-10%, spacing bag layouts, compressing compost at fill to calm activity and using lower rates of supplementation if applicable, may minimise potential cropping problems. Further, given that mycelial growth into the casing is likely to be faster in overactive Phase III compost, experienced growers prepare to initiate the watering regime earlier in case run. During cropping, environmental conditions (CO_2, air and compost temperatures, relative humidity, fan speed and proportions fresh to re-circulated air) and water application rates and timing are continuously adjusted to optimise pin set/outgrowth for individual compost types.

Unlike the relatively standard phases of compost production, crop procedures are highly dependent on the diversity of cultural systems used (bags, blocks or bulk) and specific produce market requirements (buttons, cups or flats). Thus detailing prescriptive crop intervention procedures is inadvisable. While, all environmental parameters are monitored/recorded, the protocols for crop production are by-in-large based on the grower's expertise and experience within their individual production system. To ensure maximum productivity from compost more open co-operation between composters and growers is necessary.

2 Results and Discussion

2.1 Instrumental analyses of phase I, II, III substrate and cropping stages

Thermal analysis: Previous studies have shown that the microbial breakdown of straw during phase I and II stages can be identified by thermogravimetry, as changes in thermal profiles of the fibre fractions and increase in the inorganic content, detected as residual ash left in the crucible.[7, 46] An overlay of thermograms of straw and phase I composts is shown in Figure 1, to show changes in the peak temperatures and changes in the derivative weight loss curves at both the primary (210-420°C) and secondary (420-500°C) decomposition bands (Table 1). Similarly an overlay of thermograms of poor, medium and high yielding phase II composts (Figure 2) is shown to indicate significant differences in the profiles.

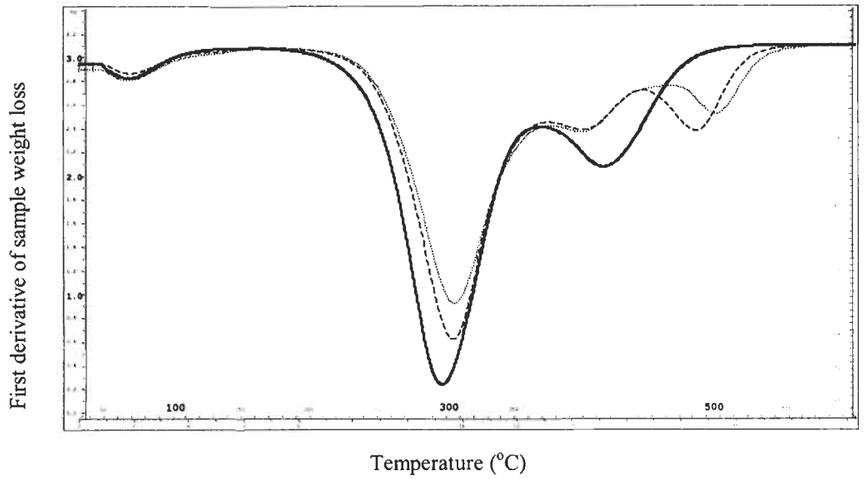

Figure 1. An overlay of thermograms of undegraded straw (–), poor (.....), medium (–) and good (---)quality phase I composts showing differences in hollocellulose and lignin/humus complex and peak decomposition temperatures; lipid fraction detected as a small decomposition peak in the 100-150˚C temperature band

The breakdown of hollocellulose (cellulose and hemicellulose) fraction, in the primary decomposition band at phase I can range between 55.80-64.84 % for windrow and 62.09-66.63 % for bunker substrates.[21] The peak decomposition temperature was reduced from 313˚C at phase I to 290 ˚C at the end of phase II, indicating extensive degradation of the amorphous hemicellulose and partial breakdown of cellulose fraction during composting (Figures 1 & 2). In addition, the structural hemicellulose represented by a minor peak at 410 ˚C of straw (Figure 1) was degraded, as shown by a shift to lower peak temperature of 395 ˚C at the end of phase I. The conservation of residual structural hemicellulose is necessary for maintaining bulk density of substrates and gradual reduction of this fraction during production can be seen in Figure 3. The accumulation of thermal stable lignin-humus fraction during composting was observed, as an increase in the weight loss of the secondary peak ranging from 11.0-14.0 % at phase I, to 14.0-23.5 % at the end of phase II (Table 1). The change was also associated with a reduction in the peak decomposition temperature from 480-490 ˚C at phase I to 470 - 486 ˚C at the end of phase II indicating a decline in thermal stability, due to the re-polymerisation of lignin/ phenolic fractions with the microbial biomass (Figures 1 & 2). The extent of reduction in the peak temperature could be linked to the effectiveness of phase II conditioning stage, especially the formation of lignin-humus complex. The presence of a peak in the 100-150 ˚C temperature band, representing lipid fraction can be detected in well prepared phase I and II substrates (Figures 1 and 2) and the peak height and area are likely to be proportional to the total population of thermophilic population present in the compost. This type of information will be valuable to composters to confirm affects of unfavourable conditions during phase I and II stages. The inorganic fraction increased from 16.26-17.34 % at phase I to 17.23-19.06 % at the end of phase II as determined by thermal analysis.

The accumulation of the lipid fraction during cropping contributed by the mushroom mycelium was detected in the peak near 100-150 ˚C decomposition band (Figure 3). The depletion of holocellulose during phase III/ spawn-run and cropping, distinguished by reductions in peak height and weight loss of the primary peak, is presented in Figure 3 and Table 1. The utilisation of the lignin-humus fraction during cropping coincided with a fall in the decomposition temperature of the secondary peak from 480 ˚C at phase III to 464 ˚C at the beginning of 3rd flush (Figure 4). In addition, a shoulder to the secondary peak appeared at the same time indicating the presence of residual thermal stable fractions, possibly degradation by-products of lignin-humus complex by *Agaricus* mycelium (Figure 3). The residual inorganic fraction left in the crucible increased in concentration to near 32.3 % at the end of cropping (Table 1). During the past 10 years, phase I and II (300) samples have been

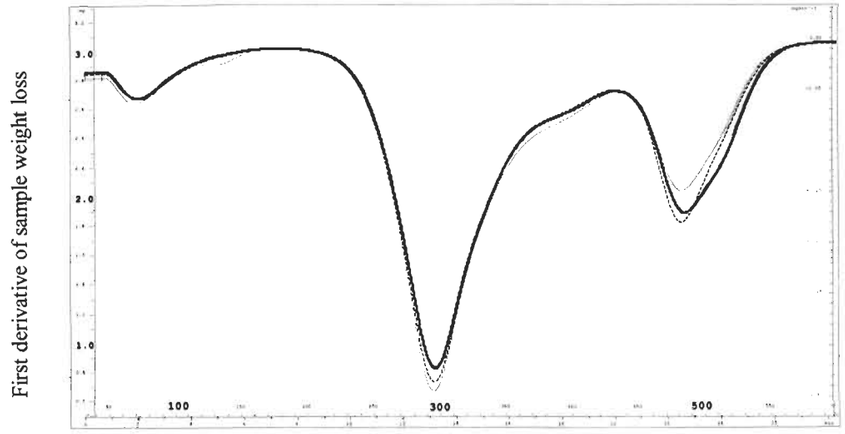

Figure 2. An overlay of thermograms of poor (190 kg/tonne, –) medium (250 kg/tonne, ...) and high (300 kg/tonne, –) yielding phase II composts showing differences in decomposition profile and peak decomposition temperatures; lipid fraction detected as a small peak in the 100-150˚C temperature band

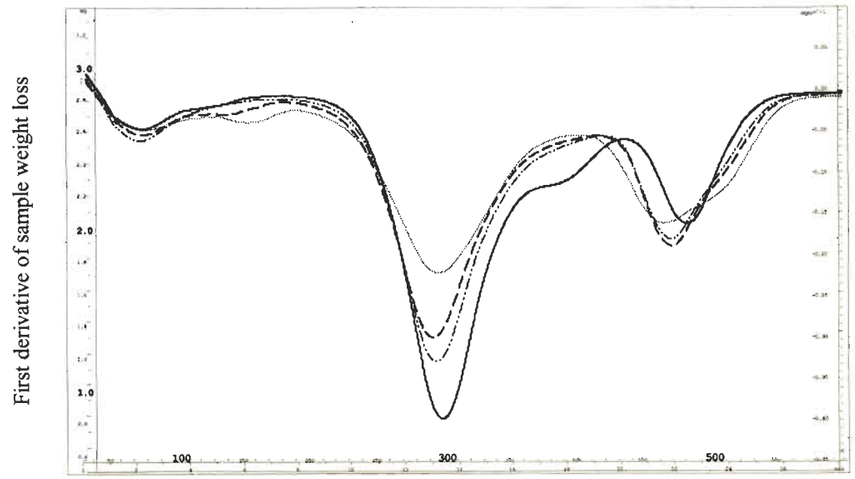

Figure 3. An overlay of thermograms of phase I (–), II (–..–), III (- - -), flush 1 (–) and flush 3 (-----) samples showing gradual breakdown of cellulose in the primary (285- 300˚C) and thermal stable lignin-humus fractions in the secondary (465-485˚C) peaks; increase in lipid fraction during flush 1 and 3 compared to phase I and II shown in the 100-150˚C decomposition band

evaluated to determine the feasibility of assessing phase II substrate quality by thermal analysis and preliminary results suggest that thermal profiles of poor, medium and high yielding composts are distinctly different (Unpublished data). In addition, thermograms could provide a reliable trace on process history of a substrate by comparing with results of known samples in the database, as the expected rate of decomposition, the formation of lignin-humus complex and the accumulation of inorganic fractions could be identified.[21, 46]

Vis-NIR spectroscopy: The use of Vis-NIR spectroscopy, as a rapid tool for quality assessment of compost during production, has been widely reported in the past 5 years.[31, 47-49] In the past 3 years, the use of spectroscopy for quality assessment of chicken litter and wheat straw has been investigated in Northern Ireland using

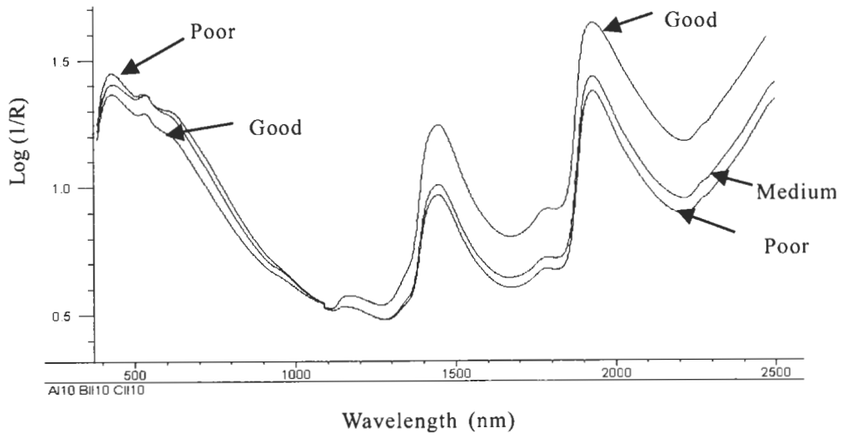

Figure 4. An overlay of visible and near infrared spectra of poor, medium and good quality composts at the phase I stage showing differences in the spectral segments

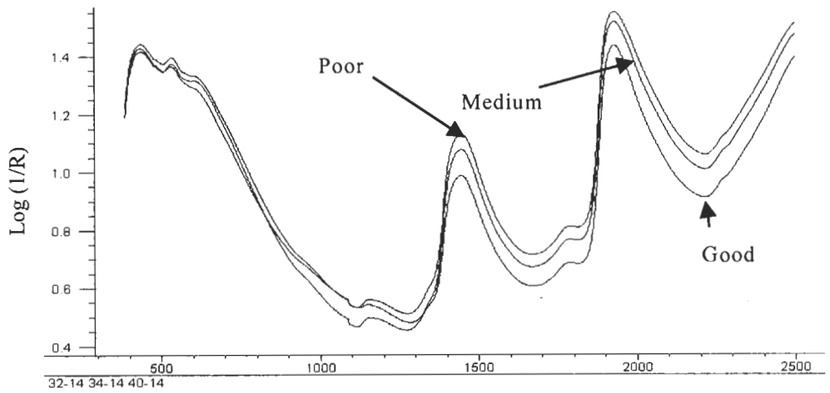

Figure 5. An overlay of spectra of poor, medium and good quality composts at the phase II stage showing differences in the spectral segments

industry samples. Preliminary vis-NIR calibrations for NDM and DM content of the raw materials have been developed with a view to introducing the models for industrial evaluation in the next 12 months (unpublished data). The calibrations could make a significant improvement to the efficiency of production protocols, enabling yard mangers to evaluate variations in the quality parameters of input raw materials. Since microbial activity drives the breakdown of the substrate, changes in fibre fractions, moisture, pH, ammonia and lignin-humus formation can be monitored by vis-NIR spectroscopy. Examples of Phase I samples with different key parameters are presented in Figure 4. The important differences are in the following wavelengths: 500 -550, 635 - 760, 810 - 900, 1100 - 1200, 1350 - 1400, 1460 - 1500, 1720 - 1800, 2000 - 2100, 2230 - 2400 nm indicating variations in the C-H, C-O-H, O-H, C=O, N-H and C-N-C stretching and bending. These bands are assigned to water, cellulose, protein and aromatic structures. Similarly, an overlay of poor, medium and high yielding phase II composts is presented in Figure 5, showing significant differences at the following spectral bands: 522 - 540, 588 - 678, 796 - 1234, 1248 - 1360, 1248 - 1360, 1472 - 1528, 1870 - 1920, 1942 - 2128, 2248 - 2258 and 2294 - 2494 nm.

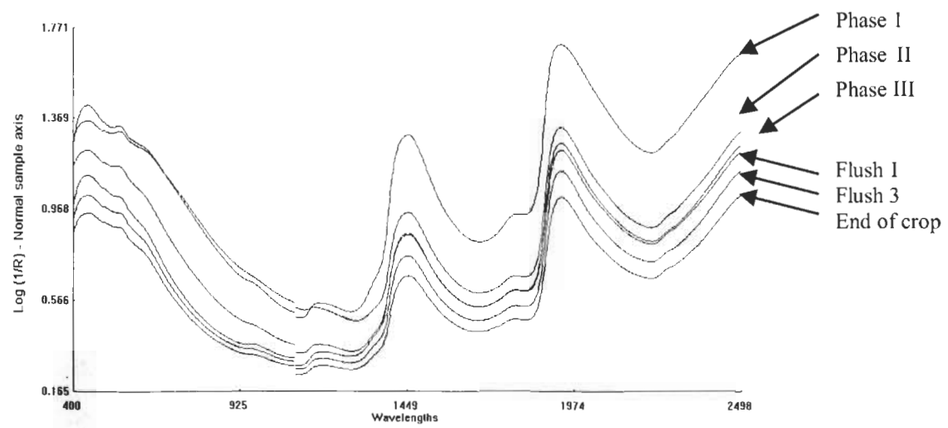

Figure 6. An overlay of visible and near infrared spectra of compost at phase I, II, III and flush 1, 3 and end of crop showing reductions in spectral reflectance values from the top (phase I) to the bottom (end of crop)

The utilisation of nutrients during phase III and cropping by the mushroom mycelium can be observed, as reduction in spectral intensity of spectral bands listed above (Figure 6). During the past 5 years, fresh phase I and II samples from 6 commercial composters have been assessed by spectroscopy, to develop Vis-NIR calibrations for DM, NDM, ammonia, pH, conductivity, thermophilic fungi, ash and potential mushroom yield (unpublished data). The majority of the calibrations, including potential yield have been validated with additional samples from the industry and the models are being transferred to a new spectrometer based at Loughgall, where the instrument will provide an analytical service for composters and growers.[49]

The two instrumental techniques have significant advantages over wet chemical methods, as substrates can be evaluated rapidly for key parameters including fibre fractions, compared to wet chemical methods for NDM, ammonia and fibre fractions. Spectroscopy can provide results within 30 minutes of presenting a sample to the instrument, whereas thermal analysis will require 2 hrs of sample preparation time, consisting of drying in an oven followed by milling of the dried material. The thermal test of a sample in triplicate would require an additional 3 hrs to analyse and report the results. In terms of speed of sample evaluation, NIRS is faster than thermal analysis. However, the advantage of thermal analysis over NIRS is the ability to show process history of a sample from the changes in peak temperatures, weight losses of fibre fractions and the inorganic content. The two techniques are complementary and results of the tests could significantly improve the ability of a yard manger to intervene a production protocol by introducing remedial measures to optimise substrate quality.

3 Conclusion

The compost producers regularly analyse chicken litter for NDM content, but wheat straw is rarely assessed for NDM or the degree of breakdown, apart from the visual evaluation of colour, which indicates breakdown during storage, caused by the sun, rain and microorganisms. The protocols for quality assessment of compost during production need to include all raw materials, including gypsum. Regular monitoring of substrate for key parameters is feasible, if NIRS can be employed to provide accurate predictions of factors rapidly and also thermal analysis can show changes in the rate of fibre breakdown. The results need to be carefully interpreted to provide a decision support system for determining, whether an intervention of the standard protocol is necessary to rectify a specific problem. In practice, this is not going to be an easy decision, as many factors can influence an alteration in one parameter and unless all constituents contributing to a change are taken into account, overall substrate quality may not improve. With regard to the crop management, protocols are de

signed to be flexible in order to maximise yield and the quality of harvested mushrooms by modifying environmental conditions in the mushroom tunnel and watering regime to suit a range of substrate quality, including high or low NDM and high or low DM compost. The suggested intervention steps could be used as a decision support system by composters and growers in the UK and Ireland. However, further modification of the monitoring and intervention steps will be necessary for use by industry in Europe or elsewhere in the world, due to significant differences in the raw material quality, batch size and other production protocols. The development of a decision support system is an important area of strategic research, which in the longer term could provide valuable support to the industry for the production of consistent substrate quality. Inputs from composters, growers, microbial ecologists, organic chemists, spectroscopists and computer programmers will be necessary to collate all relevant information to show the necessary intervention steps based on a set of input information.

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