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Monitoring of Changes in Substrate Characteristics during Mushroom Compost Production

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Substrates from three mushroom compost facilities in Northern Ireland, employing similar production technologies, were examined to assess the quality of the compost produced. Biochemical investigation highlighted changes in substrates through each step of the production cycle. Thermogravimetric analysis (TGA) provided useful information on fiber fraction content and extent of substrate breakdown. A comparison of productivity, chemical, and thermal data permitted assessment of the degree of bioconversion that had occurred in the decomposition from raw materials to finished substrate for each composter. One of the composters consistently produced substrate of inferior quality compared to the other two, indicating production inefficiencies during composting. Results demonstrated that allied to chemical analyses, TGA is a useful tool, providing valuable information on substrate quality and, in particular, for studying the bioconversion of lignocellulosic materials in mushroom compost.

KEYWORDS: ***Agaricus bisporus*; mushroom compost; substrate bioconversion; thermogravimetry; compost biochemistry**

INTRODUCTION

The production of mushroom compost is a two-phase process (*1*) involving the bioconversion of raw materials (wheat straw, poultry litter, and gypsum) into a substrate capable of supporting the growth of *Agaricus bisporus*. Wheat straw provides both nutrition for the growing mushroom mycelium and physical structure which ensures that when water and other nutrients are added, air spaces form in the substrate to allow aerobic conditions to fuel biodegradation. Poultry litter is added to both activate fermentation and act as a slow-release nitrogen and carbohydrate source, which influences the final bulk density of the substrate (*2*). Gypsum is added as a mineral source and provides a secondary function in that it precipitates suspended colloids and makes the compost less greasy.

The immobilization of nutrients into both thermophilic biomass and humus-like compounds and the conservation of less available parts of straw correspond to the objectives of composting to produce a selective substrate that will preferentially support the growth of mushroom mycelium (*3*). During composting, dry matter, in the form of nutrients, is lost as volatile metabolites of microbial growth. The compromise between loss of potential nutrients and the production of a selective substrate is the key factor in composting that determines yield (*4*). Control of heat, aeration, and moisture content ensures that chemical and microbial developments are regulated, leading to the formation of a substrate lignin−humus complex (*5*, *6*). The main factors governing successful substrate production are the quality of raw materials and effective process control during both phases of compost production to maximize bioconversion.

Studies on biochemical and thermal analyses of mushroom compost have been reported previously (*6*, *7*); however, these dealt specifically with the older stack/windrow production method, which was superseded in the mid to late 1990s in Northern Ireland by the introduction of in-vessel (bunker) phase I composting (*8*). This study aims to examine the use of thermal analysis in tandem with chemical techniques as tools to allow assessment of substrate quality.

MATERIALS AND METHODS

Compost Production. Three mushroom composting facilities were selected from different locations in Northern Ireland on the basis of similar substrate production methods. All of the composters followed a system of prewetting the straw with recycled yard leachate or "goody water", blending the raw materials with gypsum, and rough stacking, followed by phase I in a bunker/windrow regime (**Figure 1**). All had a similar indoor phase II system of pasteurization and conditioning in tunnels. Fresh samples were returned to the laboratory immediately, where they were subsampled for analysis.

Sampling. Wheat straw samples were taken from unbroken or broken bales (before wetting) by taking 50 handfuls of material from around the straw mass. Poultry litter was sampled using a garden trowel by moving around the pile and taking 50 small samples from the bottom,

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PI Stage	Composter 1	Composter 2	Composter 3
Pre-wet straw	Gantry	Lagoon & mechanically braised	Gantry / Hoses
Straw blended with poultry litter & gypsum	Mechanical blending line	Mixed by mechanical loader	Mixed by mechanical loader
Rough stack	4 d with 1 turn	8-10 d & turned every 2 d	12 d & turned every 3 d
Fill into aerated bunker	4 d	3-4 d	5 d
Moved to second bunker and adjusted for moisture	4 d	3-4 d	4 d
Final PI stage	Formed into windrows for 8 d (turned every 2 d)	Moved to third bunker for 2d. Moisture added. Emptied into covered shed overnight to cool	Emptied & left in yard overnight to cool
Filled into PII tunnels for	6-7 d	7-8 d	6 d

Figure 1. Substrate production schemes for the three composters studied.

sides, and top, digging in ≈10 cm each time. Phase I compost was sampled at filling of phase II tunnels. Phase II samples were taken from the bagging conveyor belt before spawn had been added.

pH and Electrical Conductivity (EC) (*6*). Straw samples (12.5 g) were cut into 5 cm lengths and macerated (Waring Commercial Blendor) in distilled water (DW) (500 mL) for two 30 s bursts with a 10 s rest between each. From the resulting slurry, pH was determined using a Mettler Toledo MP230 pH-meter with a temperature-compensated Inlab 410 electrode, and EC was measured by a Mettler Toledo MC226 conductivity meter with an Inlab 730 electrode. For poultry litter and phase I and II compost samples, 50 g of each of these was blended in 500 mL of DW. The slurry was filtered (Whatman no. 1), and 20 mL of the water-soluble extract was frozen and retained for further analyses.

Total Soluble Carbohydrate (TSC) and Polyphenol (TSP). TSC was estimated colorimetrically using the improved anthrone method outlined by Loewus (*9*). Sample color changes were read on a UV−vis spectrophotometer (Unicam Helios α) at 620 nm. TSP was measured using the method of Folin and Denis (*10*). Sample color changes were read on a UV−vis spectrophotometer at 720 nm. Soluble carbohydrate and polyphenol were estimated as grams per kilogram of dry matter. All chemicals used were of AR grade (Sigma Chemical Co., St. Louis, MO). D-(+)-Glucose was supplied by Prolabo (Fontenay, France). TSP and TSC were measured using water-soluble extracts.

Dry Matter (DM). A portion of each sample (100 g in triplicate) was oven-dried (Sanyo OMT fan oven) at 85 °C overnight to determine DM content. The dried samples were milled (Foss Tecator Cyclotec mill) to pass through a 0.5 mm screen for further analyses.

Ash Content (Ash). Dried, milled samples were weighed accurately (1 g) in triplicate, placed in a ceramic crucible, and heated in a muffle furnace (Carbolite OAF) at 600 °C overnight. The samples were cooled in a desiccator and weighed accurately to constant weight to determine inorganic ash content.

Nitrogen Content (NDM). Organic nitrogen content of wheat straw, poultry litter, and phase I and II composts was measured on dried milled samples using the Kjeldahl method (*11*). All samples were measured in triplicate and corrected for DM content.

Carbon Content (Elemental Analysis, C) (*7*). Organic carbon in straw and phase I and II compost samples was measured by elemental analysis (Perkin-Elmer 2400 series II CHNS analyzer) of dried milled samples in triplicate.

Ammonia (NH_3) Content of Phase I and II Samples. Fresh compost was analyzed on a Kjeltec 2200 Auto Distillation Unit (Foss Analytical AB) using program 1. The concentration of ammonia was determined by comparison with an ammonia standard. All samples were analyzed in triplicate.

Thermogravimetric Analysis (TGA). TGA was undertaken on a Mettler Toledo TGA/SDTA851 Thermal Analysis System, equipped with an autosampler and a TSO801RO sample robot. Three replicates were analyzed for each sample. Dried milled samples (3−3.2 mg) were heated in alumina crucibles in a furnace from 32 to 600 °C at a heating rate of 20 °C min^{-1} under compressed air at a flow rate of 20 mL min^{-1}. Data collected for each sample consisted of the measurement of sample weight loss (Wl), peak height (Ph), peak width (Pw), peak temperature (Pt), peak area (Pa), and inorganic residue. Data were measured using the thermogravimetric curve and also its first derivative (dw/dt). The latter technique is referred to as derivative thermogravimetry (DTG).

Phase II Productivity Assessment. The potential yield of phase II composts was assessed by vis−NIR spectroscopy using the sample scanning protocols and regression equations reported by Sharma, Kilpatrick, and Lyons (*12*). An experimental cropping trial to measure mushroom yield was undertaken using corresponding phase II samples from one batch for each composter. Experimental design and crop management conditions were described previously (*12*).

Data Analysis. All chemical, thermal, and yield data were submitted to spreadsheets and analyzed using the Microsoft Excel Descriptive Statistics and ANOVA tools to calculate minimum, maximum, mean, and standard deviation (SD) of samples for each of the composters materials. This facilitated assessment of substrate variation from batch to batch for individuals. Standard errors of means (SEM) with significance levels were calculated to evaluate differences between composters, on the basis of mean values. TGA data from the straw and phase I and phase II samples were also analyzed by principal component analysis (PCA) using The Unscrambler (Camo, Oslo, Norway) multivariate statistical software package to examine possible relationships between the sample sets.

Table 1. pH, Electrical Conductivity (EC), Dry Matter (DM), Ash, and Ammonia (NH_3) Measurements for Straw, Poultry Litter, Phase I, and Phase II Samples Taken from Three Compost Producers (1–3)[a]

		pH			EC (mS/cm)			DM (%)			ash (%)			NH_3 (% DM)		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
straw	mean	7.6	7.5	7.6	0.54	0.38	0.50	86.6	80.1	86.0	4.6	4.4	4.9			
	SD	0.38	0.43	0.38	0.12	0.13	0.13	6.92	13.11	9.32	0.68	0.77	0.72			
	min	7.0	6.7	6.9	0.35	0.19	0.26	63.9	45.8	57.3	3.2	3.0	2.9			
	max	8.6	8.8	8.2	0.82	0.69	0.79	94.1	97.5	95.8	6.4	6.1	6.1			
	SEM		0.10[ns]			0.04			2.72			0.15				
poultry	mean	7.4	7.0	7.7	5.98	5.99	5.57	65.1	51.7	54.5	14.1	15.9	14.8			
	SD	0.63	0.56	0.97	7.71	9.68	8.15	4.86	8.89	8.22	0.83	1.08	1.13			
	min	6.5	5.9	6.2	0.46	4.42	3.60	54.5	36.2	36.6	11.9	12.5	12.8			
	max	8.5	8.2	9.0	0.75	8.09	7.11	73.0	69.6	70.2	15.7	18.8	17.0			
	SEM		0.19			0.23			2.06			0.25				
phase I	mean	8.1	8.1	8.4	2.90	2.95	2.70	27.0	27.0	28.5	15.7	18.4	18.4	0.49	0.57	0.56
	SD	0.27	0.20	0.29	0.45	0.32	0.29	1.26	1.47	1.58	1.54	2.36	0.89	0.13	0.07	0.18
	min	7.5	7.8	7.7	2.18	1.23	2.15	24.6	24.5	24.8	12.5	13.5	16.8	0.28	0.45	0.31
	max	8.6	8.6	8.9	3.97	2.42	3.34	29.3	29.9	31.5	18.8	29.4	20.9	0.71	0.67	0.87
	SEM		0.07			0.10			0.37			0.41			0.009	
phase II	mean	7.7	7.6	8.1	3.47	3.32	3.13	33.3	33.9	33.5	21.7	23.1	22.8	0.010	0.032	0.035
	SD	0.20	0.20	0.38	0.40	0.32	0.41	2.24	4.43	2.50	1.96	1.98	1.68	0.005	0.020	0.053
	min	7.4	7.3	7.2	2.70	1.31	2.16	30.2	29.2	30.7	18.6	16.9	19.6	0.005	0.010	0.004
	max	8.2	8.1	8.7	4.11	4.03	3.92	38.2	46.5	38.4	27.1	26.0	27.3	0.020	0.069	0.197
	SEM		0.08			0.11			0.91			0.57			0.004	

[a] Mean, standard deviation (SD), and minimum and maximum values are shown for each composter. Standard error of means (SEM) are presented for comparison of mean results between composters. All SEMs were significant at $P < 0.05$ except those marked [ns], for which no significant difference was found.

Table 2. Nitrogen in the Dry Matter (NDM), Carbon (C), Carbon/Nitrogen Ratio (C/N), Total Soluble Carbohydrate (TSC), and Total Soluble Polyphenol (TSP) Measurements for Straw, Poultry Litter, Phase I, and Phase II Samples Taken from Three Compost Producers (1–3)[a]

		NDM (%)			C (%)			C/N ratio			TSC (g/kg)			TSP (g/kg)		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
straw	mean	0.52	0.51	0.55	41.7	42.3	42.0	78.7	83.0	76.4	11.0	10.7	11.8	3.05	2.31	2.78
	SD	0.08	0.09	0.09	0.41	0.59	0.53				3.21	4.53	2.96	0.89	0.71	0.69
	min	0.39	0.35	0.39	40.7	41.1	41.2				7.2	6.1	6.4	1.98	1.22	0.43
	max	0.68	0.72	0.71	42.8	43.6	43.5				21.9	30.6	18.7	6.89	3.86	4.26
	SEM		0.02[ns]			0.09						0.38			0.08	
poultry	mean	3.93	3.98	3.79							43.9	36.6	37.0	14.29	17.01	15.24
	SD	0.35	0.41	0.36							7.69	6.01	10.0	1.28	1.67	2.09
	min	3.12	3.18	2.74							31.3	24.1	16.3	12.25	14.73	11.18
	max	4.61	4.69	4.34							57.9	48.0	64.0	18.14	21.57	22.30
	SEM		0.10									1.00			0.21	
phase I	mean	1.65	1.55	1.65	37.7	36.9	37.3	22.8	23.8	22.6	12.9	8.6	10.0	8.04	7.84	9.54
	SD	0.16	0.19	0.14	1.08	1.38	0.80				3.15	2.11	3.01	0.88	1.24	2.20
	min	1.38	1.32	1.47	36.1	33.2	35.2				6.9	4.9	6.4	6.22	5.06	6.25
	max	1.98	1.82	1.90	39.6	39.5	39.0				19.4	12.6	16.2	9.47	10.32	15.19
	SEM		0.04			0.26						0.36			0.20	
phase II	mean	2.27	2.26	2.17	36.2	35.2	36.0	17.5	15.6	16.6	11.4	8.5	11.5	3.52	2.54	5.01
	SD	0.18	0.18	0.14	1.42	1.20	0.90				3.39	2.40	6.50	1.19	0.72	3.07
	min	2.14	1.95	1.16	33.0	33.1	34.3				6.4	4.2	4.8	1.76	1.37	1.30
	max	2.45	3.40	2.48	38.9	38.2	37.9				18.9	13.1	25.7	6.87	3.88	12.76
	SEM		0.08			0.31						0.59			0.24	

[a] Mean, standard deviation (SD), and minimum and maximum values are shown for each composter. Standard error of means (SEM) are presented for comparison of mean results between composters. All SEMs were significant at $P < 0.05$ except those marked [ns], for which no significant difference was found.

RESULTS

Chemical Parameters. *Wheat Straw and Poultry Litter.* Mean chemical data for measurements made on wheat straw, poultry litter, and phase I and phase II substrates for the three compost yards are displayed in **Tables 1** and **2**. There were significant differences ($P < 0.05$) in the chemical composition of straw between each sample period for composters 2 and 3 for all parameters measured. However, straw from composter 1 was more uniform, with only EC, NDM, and TSC displaying significantly different values ($P < 0.01$). Examination of the SEM results indicated that there was significant ($P < 0.05$) intercomposter variation in DM, ash, C, TSC, TSP, and EC, but this was not the case for NDM and pH. Data measured on the poultry litter showed that significant variation ($P < 0.001$) existed in all of the parameters measured for the three composters (**Tables 1** and **2**). Comparison of SEM values also indicated significant ($P < 0.05$) intercomposter variation for poultry litter.

Phase I and II Compost. Phase I samples from composter 1 demonstrated a large amount of variation in chemical composition. Significant differences ($P < 0.05$) were noted for all chemical parameters measured (**Tables 1** and **2**). Similar trends

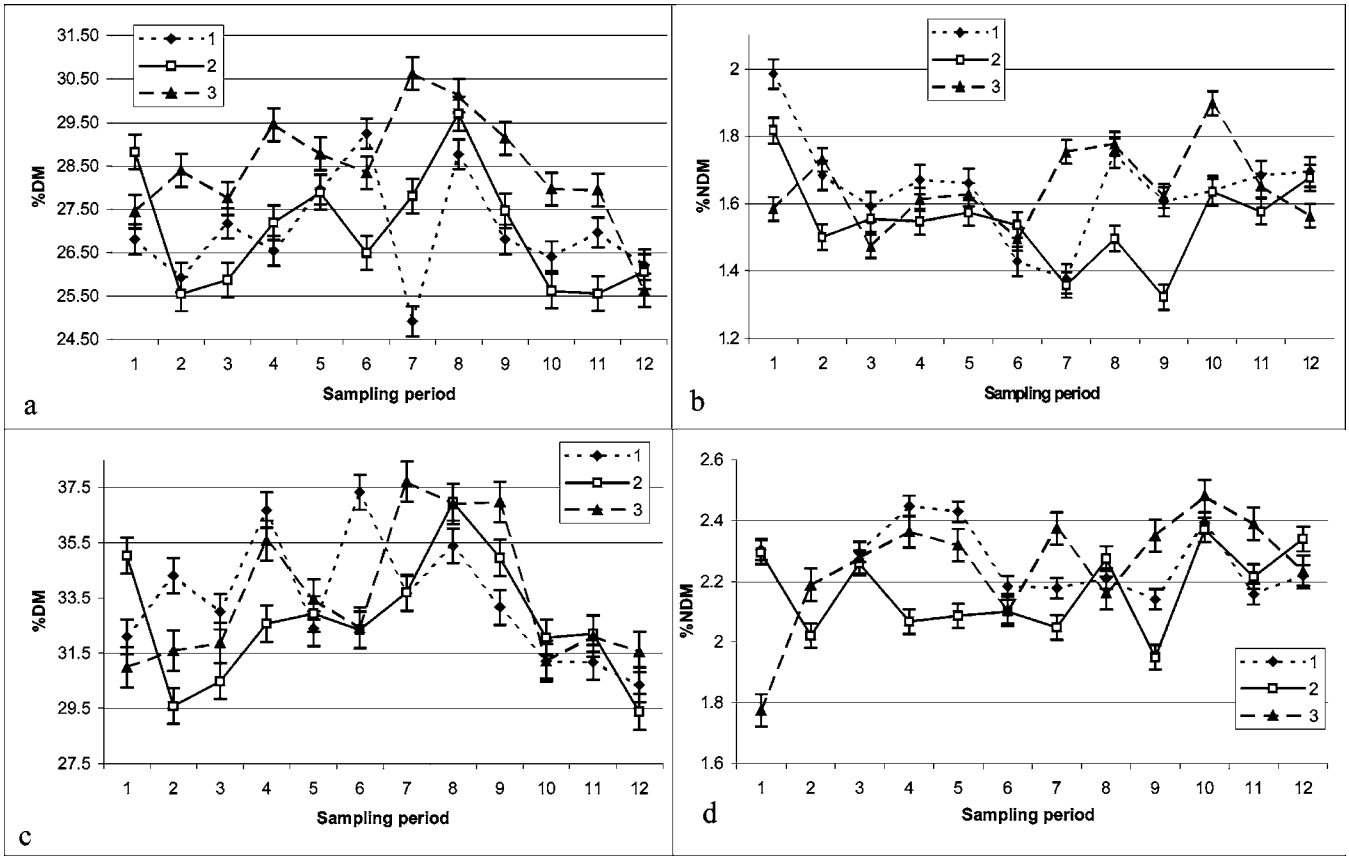

Figure 2. Variation in (**a**) DM and (**b**) NDM values of phase I substrate and (**c**) DM and (**d**) NDM values of phase II substrate for the three composters. Error bars indicate standard error for each measurement.

were observed for composters 2 and 3, except there were no significant differences in the phase I NDM levels for composter 2 or in the ash and NDM contents for composter 3. Panels **a** and **b** of **Figure 2** indicate the level of variability in DM and NDM for each composter, and SEM data again suggested that there was significant ($P < 0.05$) intercomposter variation for all measured phase I parameters. Phase II samples showed significant differences ($P < 0.001$) in all measured parameters, with the exception of NDM level for composter 1 (**Tables 1** and **2**). An indication of the variation in data measured for each compost producer is shown for DM (**Figure 2c**) and NDM (**Figure 2d**). SEM values for phase II data suggested significant ($P < 0.05$) intercomposter variation.

Thermogravimetry. *Reference Materials.* Thermal analyses of reference materials representing the major cell wall (plant and fungal) and lignocellulose components of mushroom compost were undertaken. Selected results are shown in **Figure 3**. Compounds analyzed and their maximum combustion rate temperatures were as follows: α-cellulose (Sigma C-8002), 340 °C; xylan (Sigma X-0502), 250 °C; araban (Koch-Light 0444-00), 290 °C; alkali lignin (Sigma I-6384), 450 °C; hydrolytic lignin (Aldrich 371076), 410 °C; phase II compost humus (extracted by sonication), 300 and 450 °C; chitin (Sigma C-3641), 320 °C; melanin (Sigma M-2649), 450 °C; fungal (*Scytalidium thermophilum*), biomass 280−310 and 420−460 °C. By studying the thermal decomposition of these materials it was possible to characterize the combustion profiles of various compost fractions during production.

Wheat Straw and Poultry Litter. Thermograms of straw and phase I and II samples from the same composter (**Figure 4**), overlaid on one combustion profile, illustrate how the shape of the thermogravimetric and first-derivative curves changed as substrate production progressed. Two significant areas of weight loss were produced as the uncomposted straw was heated to 600 °C. The first, weight loss band 1 (Wl 1), occurred between 200 and 360 °C, and the second, weight loss band 2 (Wl 2), occurred between 360 and 580 °C. On the derivative (DTG) curve (**Figure 4**), the major weight losses are represented as peaks on the thermogram. Combustion of cellulose and amorphous hemicellulose was observed between 200 and 360 °C (Wl 1). Thermal stable fractions (structural hemicellulose and lignin) displayed higher combustion temperatures and were characterized as major products evolving between 360 and 580 °C (Wl 2). Structural hemicellulose was observed as a shoulder on the second peak (**Figure 4**). The mean thermogravimentric data for wheat straw, poultry litter, phase I, and phase II for the three yards are shown in **Table 3**. The results indicated that for most of the parameters measured, wheat straw showed significant differences ($P < 0.05$) in fiber fraction content for each composter. Notable exceptions, with no significant differences, were Pt 1 for composter 1, residue for composter 2, and Pt 2 for composter 3 (**Table 3**). Significant ($P < 0.05$) intercomposter differences for the straw samples were noted for Pa 1, Ph 2, Pw 2, and residue values.

TGA on poultry litter (**Table 3**) again indicated that there were significant differences ($P < 0.001$) in the parameters measured for all three composters throughout the sample period. The only exception was Wl 1 for composter 1, for which no significant difference was noted. Thermograms consisted of two major weight loss bands: Wl 1 ranged from 45.2 to 46.6%, with a combustion temperature of 278−282 °C, and Wl 2 exhibited a weight loss of 25.4−26.1% and a mean combustion temperature of 480 °C. Inorganic residue levels varied between 17.7 and 19.0%. A number of TGA parameters indicated that

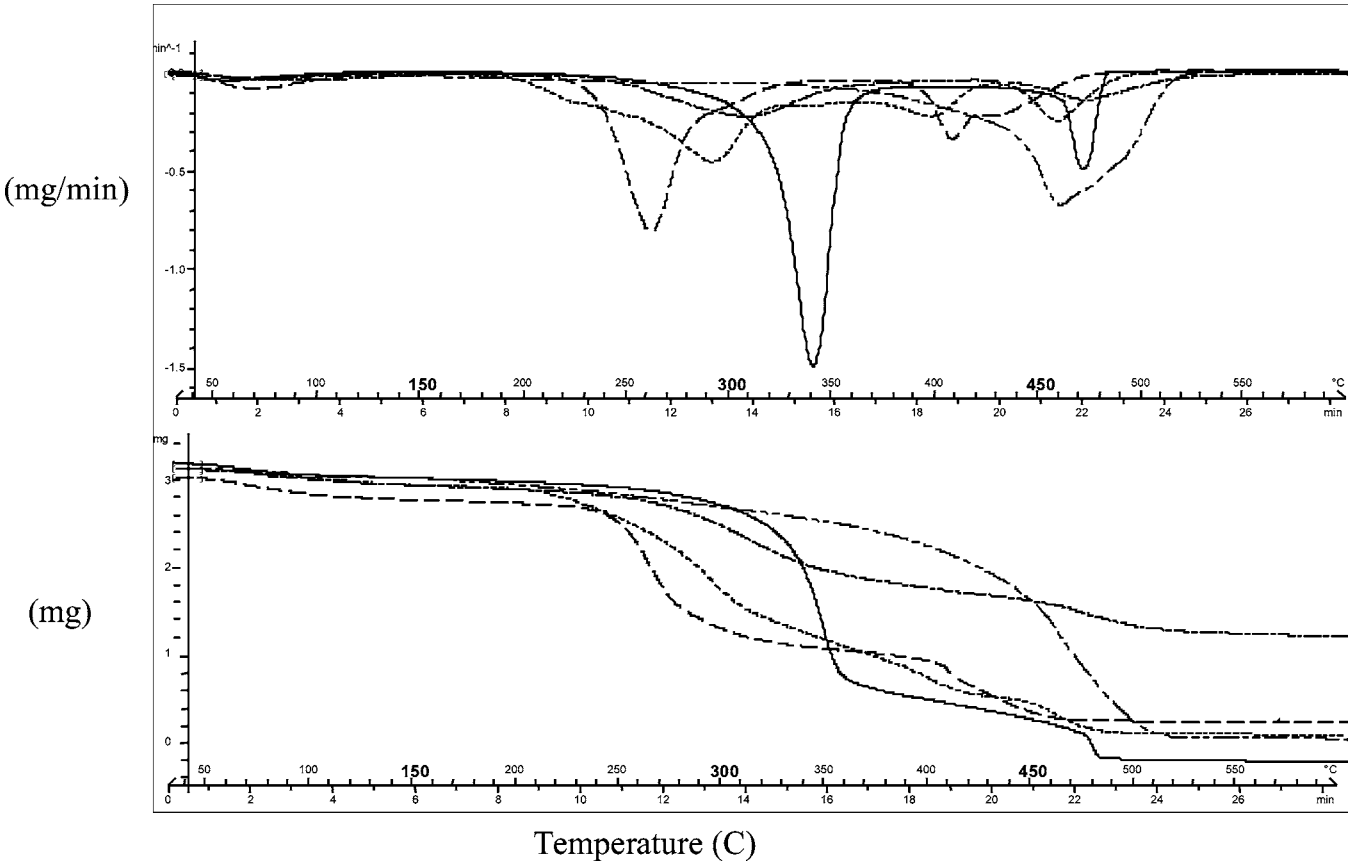

Figure 3. Derivative thermogravimetric (top) and thermogravimetric (bottom) weight loss characteristics of reference compounds: cellulose (—); xylan (- -); araban (···); alkali lignin (— ··); compost humus fraction (— · —).

significant ($P < 0.05$) intercomposter variation existed, namely, Wl 1, Pt 1, Pw 1, Wl 2, and residue.

Phase I and II Compost. Two major combustion products were noted in the same temperature bands previously highlighted for uncomposted straw. The observed transformations in combustion profiles were due to the well-documented chemical and microbial degradation processes that occur during composting (*13*). There was a decrease in peak height from straw to phase I, with an increase from phase I to phase II. Peak area and width for this fraction increased during substrate transformation, and combustion temperature increased dramatically from straw to phase I and decreased from phase I to phase II. Comparison of the phase I TGA data (**Table 3**) for the three composters indicated that there were significant differences ($P < 0.05$) in the fiber fractions between each sample period, with the exception of Pw 2 for composter 1, Pt 2 for composter 2, and Ph 1 for composter 3. Structural hemicellulose and lignin levels were on average elevated by 1.5−2.0%, and combustion temperature was 35−45 °C higher than that for straw. Inorganic residue had increased by 10−12% of sample weight (**Table 3**). SEM values showed that there were significant ($P < 0.05$) intercomposter differences in the fiber fractions of phase I samples.

Figure 5 shows three overlaid derivative thermograms representing a phase II substrate sample from each of the three composters. As before, there were two main weight loss bands present. Clear differences were evident in the combustion profiles beyond 360 °C, particularly in the shoulder representing structural hemicellulose between 260 and 440 °C, and obvious variations in peak height, width, area, and combustion temperature for the lignin−humus fraction between 440 and 540 °C were noted. Analysis of phase II data (**Table 3**) suggested that significant differences ($P < 0.05$) existed in the TGA measurements between sample periods for all three composters. Amorphous hemicellulose and cellulose fractions were 5−6% lower than phase I, and combustion temperatures for this fraction were also lower by 3−6 °C. The thermally stable lignin−humus fraction in phase II had increased by 2−3% and the combustion temperature had fallen slightly, in comparison to phase I compost. Inorganic residue had increased by 2−4% from phase I. Intercomposter variation was significant ($P < 0.05$) for all TGA parameters except Pt 2.

PCA of TGA Results. Sample population sizes for straw and phase I were 108, whereas 105 samples made up the phase II population (3 samples from composter 1 were missing). PCA of the straw results revealed two distinct groups among the population (**Figure 6a**). The PCA described 52% of the variation within the population using two principal components. In contrast, analysis of phase I composts by PCA (**Figure 6b**) indicated that samples from composters 1 and 2 formed two groups with a large degree of overlap. Approximately 65% of samples from composter 3 were also distributed within the two groups, whereas the remaining 35% formed a completely separate cluster. The PCA explained 72% of the variation within the population using two principal components. Two outliers, one each from composters 2 and 3, were also present. PCA of phase II TGA data (**Figure 6c**) produced two sample populations containing all of the composter 1 population and 33 of the 36 samples from composter 2, with less overlap than the phase I composts. Again, 26 of the 36 samples from composter 3 were distributed between the two populations, with the other 10 samples forming a separate group. Three of the samples from

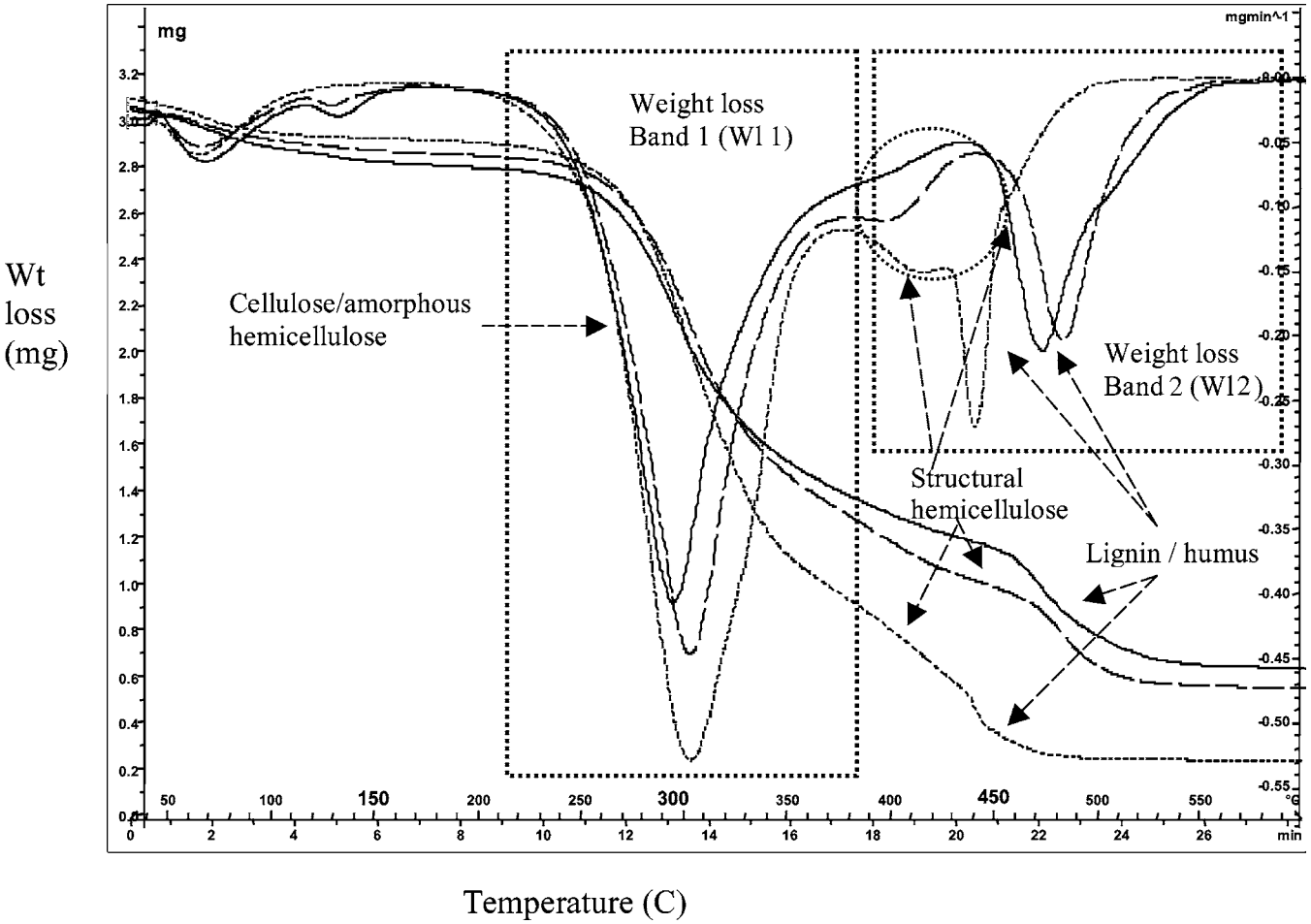

Figure 4. Straw (···), phase I (- -), and II (—) substrate thermograms (thermogravimetric weight loss and first-derivative curves) showing reductions in peak height and width and changes in combustion temperatures of the major fiber fractions as bioconversion proceeded for composter 1.

Table 3. Mean Thermal Analysis Parameters for Straw, Poultry Litter, Phase I, and Phase II Samples Taken from Three Compost Producers (1–3)[a]

composter	sample	Wl 1 (%)	Pt 1 (°C)	Pa 1 (%)	Ph 1 (mg/min)	Pw 1 (°C)	Wl 2 (%)	Pt 2 (°C)	Pa 2 (%)	Ph 2 (mg/min)	Pw 2 (°C)	residue (%)
1	straw	69.7	302	45.6	0.49	56.9	16.6	444	9.0	0.40	21.0	7.3
2	straw	70.7	302	45.4	0.49	56.2	16.2	443	8.5	0.21	37.1	6.4
3	straw	69.4	302	44.9	0.49	56.2	16.5	444	8.5	0.27	30.7	6.8
	SEM	0.78[ns]	0.65[ns]	0.28	0.01[ns]	1.08[ns]	1.06[ns]	2.56[ns]	0.36[ns]	0.05	4.53	0.22
1	poultry	46.5	280	33.5	0.23	81.9	26.1	479	17.0	0.33	28.9	17.7
2	poultry	45.2	278	32.4	0.20	88.4	25.4	480	16.8	0.31	29.7	18.7
3	poultry	46.6	282	32.9	0.22	83.0	26.1	479	17.2	0.33	29.8	19.0
	SEM	0.42	0.84	0.69[ns]	0.01[ns]	1.33	0.28	1.42[ns]	0.24[ns]	0.01[ns]	0.93[ns]	0.43
1	phase I	57.4	301	48.7	0.44	52.2	17.9	481	7.7	0.15	27.5	17.7
2	phase I	57.8	307	49.8	0.42	58.2	16.4	489	6.2	0.12	27.0	18.7
3	phase I	55.6	301	45.8	0.42	52.9	18.6	478	8.7	0.19	25.2	19.0
	SEM	0.51	0.88	0.58	0.01	0.72	0.42	2.66	0.54	0.01	0.63	0.43
1	phase II	51.4	297	43.3	0.41	50.6	20.1	476	11.6	0.20	32.9	21.2
2	phase II	51.1	299	43.6	0.40	52.1	18.7	481	10.2	0.15	40.8	22.7
3	phase II	49.7	297	41.0	0.38	54.1	20.6	481	11.9	0.20	33.8	22.6
	SEM	0.64	0.40	0.70	0.01	0.67	0.42	2.20[ns]	0.49	0.02	2.22	0.60

[a] Standard error of means (SEM) are presented for comparison of mean results between composters. All SEMs were significant at $P < 0.05$ except those marked ns, for which no significant difference was found.

composter 2 formed a distinct group. The PCA explained 81% of the variation within the population using two principal components.

Productivity of Phase II Substrate. Productivity of phase II composts (mushroom yield) is directly related to substrate quality (*14*). The mushroom cropping trial data (**Table 4**) indicated that composters 1 and 2 produced a similar phase II yield when their substrates were analyzed (309 and 308 kg/tonne respectively); however, the yield measured for composter 3 was considerably lower (274 kg/tonne). The vis−NIR model

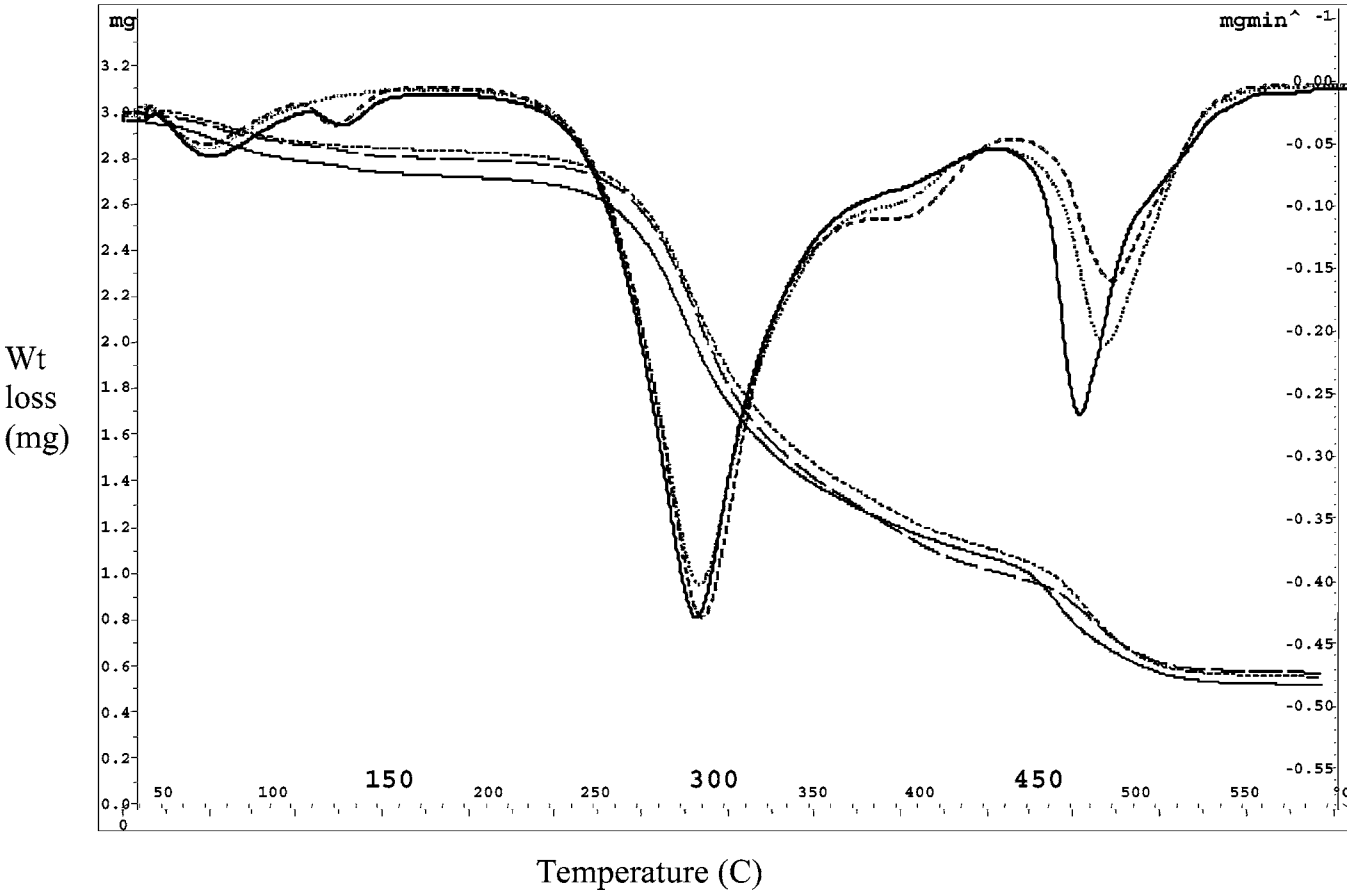

Figure 5. Representative thermograms of typical phase II composts indicating fiber fraction differences, highlighted by thermogravimetric analysis data, for composters 1 (—), 2 (- -), and 3 (···). Greatest variation is observed between 350 and 550 °C, representing structural hemicellulose and lignin–humus fractions.

Table 4. Mushroom Yield Prediction Values for Phase II Samples from the Three Composters during Each of the Sample Periods, Derived from a Vis–NIR Yield Prediction Model[a]

sample period	predicted yield, composter 1 (kg/tonne)	predicted yield, composter 2 (kg/tonne)	predicted yield, composter 3 (kg/tonne)
1	316	322	273
2		299	326
3	312	314	307
4	322	332	295
5	312	319	315
6	304	312	291
7	317	318	298
8	307	300	298
9	295	315	292
10	298	279	268
11	310	278	270
12	277	292	284
min	277	278	268
max	322	332	326
SEM	3.78	4.92	5.15
mean (predicted)	306	307	293
mean (measured)	308	309	274
difference	−2	−2	+19

[a] Yields are expressed as kg of mushrooms per tonne of compost. Standard error of mean (SEM) values are indicated for each composter. Measured yields from a compost cropping trial are indicated at the bottom of the table along with the difference between predicted and measured values

used to predict the yield of all of the phase II substrates proved to be an effective indicator of compost quality. Mean predicted yields (**Table 4**) were highest for composters 1 and 2 (306 and 307 kg/tonne, respectively), whereas the value for composter 3 was lower (293 kg/tonne). The SEM of predicted yield was lowest for composter 1 (3.78).

DISCUSSION

Compost chemistry has been the traditional method of studying substrate quality, with emphasis on pH, DM, NDM, C, ash, and C/N ratio as key indicators of bioconversion (*5*, *13*, *15*). With the chemical factors previously listed, TSC, TSP, and EC are also important markers of substrate breakdown and quality (*6*, *14*). Chemical analyses (**Tables 1** and **2**) indicated that significant variation existed in different batches of wheat straw and poultry litter for each composter. The only exception was more uniform wheat straw from composter 1, the largest producer of the three studied, who was able to buy straw in bulk quantities from large contract suppliers. This could explain the apparent consistency in the straw results.

Straatsma et al. (*16*) reported that a selective degradation of straw components took place during composting with the production of microbial biomass through the bioconversion of raw materials into phase II compost. Chemical data gave a direct indication of the efficiency of conversion. Reduction in DM between raw material mixing and end of phase I was caused by microorganisms breaking down the substrate (*17*). Increasing ash content and EC levels, along with a fall in TSC and TSP, indicated that microbial bioconversion had occurred. However, some anomalies were noted; composter 2 had a higher ash content in phase II; composter 3 displayed increased TSC levels

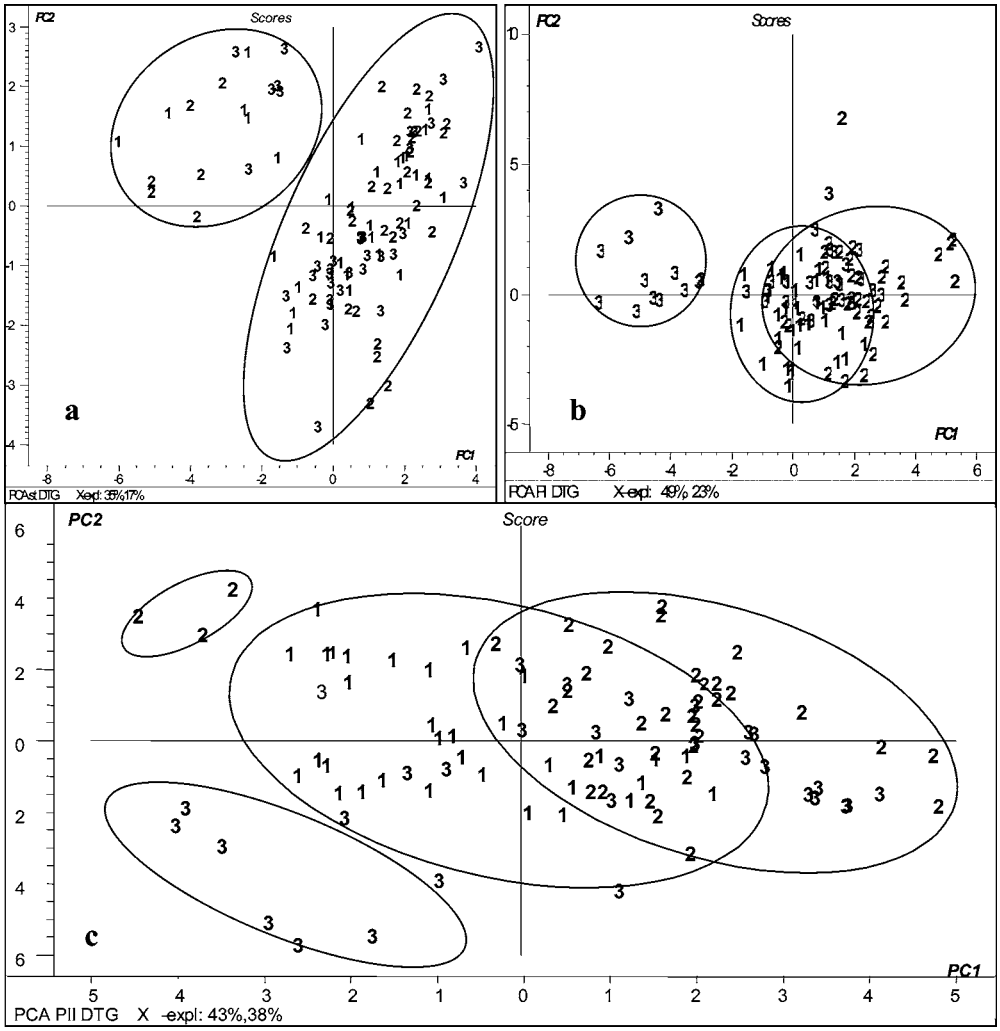

Figure 6. PCA of (**a**) wheat straw, (**b**) phase I, and (**c**) phase II samples from the three composters based on TGA results of fiber fraction content, indicating sample population clusters for the first two principal components.

between phases I and II instead of a reduction, indicating anaerobic conditions; composter 3 maintained a much higher level of TSP in phases I and II. It appeared that composter 3 had process control problems. Increasing TSC through phase II and higher levels of TSP suggested that aerobic decomposition of substrate was not optimized, causing inefficient breakdown of holocellulose and less effective repolymerization of water-soluble polyphenols with microbial biomass and lignin during humus formation.

pH levels changed as conversion progressed (*18*). Composter 3 exhibited a high pH in phases I and II, indicating that both of these phases were incomplete and contained abnormally high ammonia levels. A pH of 8.07 (**Table 1**) at phase II could result in poor selectivity for *A. bisporus* growth (*19*). A falling C/N ratio is a positive indicator of bioconversion, and composter 1 displayed maximum mean C and N contents in phases I and II and highest C/N ratio in phase II. Composters 1 and 2 kept ammonia levels within a tighter range than composter 3 at the end of phase II, indicating that the latter experienced problems during substrate conditioning.

TGA had been reported previously as an effective method of studying fiber fractions in lignocellulosic materials (*20*, *21*) and growth substrates associated with edible fungi (*22*). Combustion data (**Table 3**) indicated that two major areas of weight loss were present (**Figures 4** and **5**), which could be related to substrate quality. During bioconversion, amorphous hemicellulose and cellulose were degraded, with lignin remaining substantially undegraded (*5*). The structure of lignin was, however, altered as formation of the lignin−humus complex progressed during phase II (*23*). The TGA results indicated that ≈20% of cellulose and amorphous hemicellulose was lost between the start of phase I and the end of phase II. Composters 1 and 2 had similar holocellulose contents for phases I and II, whereas composter 3 had consistently lower levels, suggesting excessive degradation had occurred, impairing compost aeration and making the substrate more susceptible to attack by fungal pathogens and pests (nematodes). Reduction in combustion temperature between phases I and II for all composters indicated that significant microbial breakdown of the thermal stable fractions had taken place.

The degradation of structural hemicellulose must be controlled in composting as this fraction is important for maintaining bulk density in the substrate. Reduction in this fraction was apparent, and there was considerable intercomposter variation. Composter 1 generally produced substrates with greater lignin−humus content, as evidenced by a lower combustion temperature for the second weight loss fraction of phase II. An elevated combustion temperature from straw to phase I was further indication of bioconversion, and this was followed by a reduction in thermal stability in the transition from phase I to II for composters 1 and 2, due to repolymerization of humic and lignin fractions with microbial biomass (*6*). Substrate

samples from composter 3, conversely, displayed an increase in thermal stability between phases I and II, suggesting processing problems in phase I leading to incomplete repolymerization of humic/lignin fractions with microbial material, as indicated by the high TSP levels reported.

Composter 2 produced a thermally stable fraction in phases I and II that had lower weight loss characteristics than composters 1 and 3. The phase II results indicated that the lignin−humus fraction had a smaller peak area and height, but increased peak width compared with the other two composters, suggesting greater degradation of structural hemicellulose. TGA data, higher ash content, and lower C/N ratio in phase II, with lower TSC and TSP, all indicated that composter 2 may have overcomposted the substrate, with some loss of nutritive value. PCA of the TGA results clearly separated individual samples on the basis of differences in fiber fractions in the straw and phase I and phase II populations from each of the composters. The PCA data showed a clear indication of the greater variation in fiber fraction content of samples from composter 3 compared to the less variable substrates produced by composters 1 and 2.

Predicted yield data using near-infrared spectroscopy indicated that highest average yields were produced by composters 1 and 2. The difference in substrate productivity was even greater in the compost cropping trial, during which true yield was measured. Composter 3 yielded 15% less mushrooms than the other two. The trial was undertaken at a time when all three composters had white plaster mold (WPM) infection (*Scopulariopsis* sp.), with substrate from composter 3 the most heavily infected. Nematodes were also found in samples from composter 3. The presence of nematodes and a heavy WPM infection are indicators of inferior substrate structure (particularly with overwetted compost) and high ammonia level, due to poor aeration during phase I.

Comparison of phase II compost productivity data with chemical and thermogravimteric results indicated that composters 1 and 2 produced better quality substrate than composter 3, by optimizing conditions for bioconversion to produce more uniform phase II substrates. Composter 1 produced lower SD values for a number of the key quality parameters measured, indicating a higher degree of substrate homogeneity. The lower variability of the straw samples from composter 1 would have been a key contributory factor in determining substrate uniformity. Data for composter 3 indicated inferior substrate quality due to inefficient process control and less than optimal bioconversion of raw materials into phase II compost.

Results demonstrated that allied to chemical analyses, TGA has proved to be a useful tool in providing valuable information on substrate quality, more specifically in understanding the bioconversion of lignocellulosic materials in mushroom compost. In this study, production inefficiencies were highlighted when substrates from three individual compost manufacturers operating similar production technologies were compared. TGA allowed rapid and accurate assessment of the biotransformation of substrates at each stage of composting, based on changes in weight loss and combustion temperature characteristics. The technique is a useful quality analysis tool for those involved in compost research and production.

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