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Adjustment of the composting process for mushroom cultivation based on initial substrate composition

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Abstract

The feasibility of adjusting individual composting processes to be able to produce the desired mass of compost of the required composition was evaluated. Data sets from experiments in tunnels were constructed and analyzed. Total mass and dry matter contents at the start and at the end of composting contained much statistical error. Error was propagated into the calculated central parameter of the process, the loss of dry matter. Water loss was estimated based on dry matter loss, heat generation and evaporation in a model. Estimated and actual losses from individual processes almost lacked correlation but the averages were rather similar. It is not the model but the error in input data that prevent the accurate prediction of the losses of water and of total matter. Moreover, error masked any correlation between the loss of dry matter and processing parameters. A model cannot be successfully applied to adjust an individual composting process. Compost producers should focus on getting the composition of the substrate constant at the start of processing. Adjusting an individual process is not a very reliable option.

Keywords: *Agaricus bisporus*; Lignocellulose degradation; Evaporation; Water loss

1. Introduction

Compost for the production of white button mushrooms, *Agaricus bisporus*, is produced from wheat straw, straw-bedded horse manure, chicken manure and gypsum. The substrate is made in two processes called Phase I and Phase II. Phase I includes mixing and moistening of the ingredients and a period of uncontrolled self-heating where temperatures will rise to 80°C. Phase II starts with a pasteurization period of 8 h at 56–60°C and continues with a conditioning period at 45°C for up to 7 days until volatile NH_3 has been cleared from the process air (Flegg et al., 1985; Van Griensven, 1988). After Phase II, the substrate is ready for growth of mushroom mycelium. Quality parameters of ready to spawn compost are: the absence of volatile NH_3 (Ross, 1976); the presence of the thermophilic fungus *Scytalidium thermophilum* (Straatsma et al., 1989, 1994); levels for dry matter of 0.25–0.30 (fraction of total matter), of nitrogen of 0.015–0.020 (fraction of dry matter) and of pH of 7–8; compost must have a high weight per volume rate to fill the cultivation area with a high amount of substrate but a relatively rigid texture must remain for gas and water exchange. The level of degradation of compost has no relation to the yield of mushrooms (Gerrits et al., 1997). However, degradation is relevant for the quantity of compost produced and, since the ratio of water and of dry matter is not constant, degradation plays a role in the final dry matter contents of the compost.

Processing in the Netherlands is done in solid-state fermentation rooms called tunnels with a floor area of about 100 m^2 to fill compost at 2 m height or 1 ton m^{-2} (Klaver and Van Gils, 1988). Air is forced upwards through the substrate using a fan supplying maximally 200 m^3 ton^{-1} h^{-1}. Most of the air is recirculated, only about 10% being discharged and replaced with ambient air. Circulation and ventilation in tunnels allow an adequate control of the process, better than the traditional Phase II process in a mushroom house, even if compost is layered at 2 m height. A secondary advantage of

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tunnels is the containment of process air and thus the opportunity to clean this air of ammonia and odour (Op den Camp et al., 1992). The latter has been reason to design special tunnels and adapt processes for Phase I composting as well.

Quality parameters for compost cannot be established directly. Moisture and nitrogen contents and pH can be adjusted at the start of Phase I, but the values will be affected during processing. The effects of processing and of the composition of the substrate before the process on the final composition are partially unknown and difficult to discriminate. The influence of the separate substrate and processing parameters on the final composition could possibly be analyzed using a mathematical model. Perhaps a model could also be used to adjust individual processes. A model requires that the relationships between the composition of the substrate, processing, degradation, heat production and heat removal by ventilation of evaporated water are known. What already has been modeled is the last part of this sequence, starting with heat production from a given amount of degraded dry matter (Randle, 1977; Arkenbout, 1984; Keener et al., 1993; Van Lier et al., 1994; Batista et al., 1995). To study the first part we collected and analyzed empirical data on Phase II processes in tunnel pilot plants from Gerrits (Mushroom Experimental Station, Horst, the Netherlands, trials from 1979–1994) and from Overstijns (Provincial Research and Advisory Centre for Agriculture and Horticulture, Roeselare–Rumbeke, Belgium, trials from 1977–1994). In these studies parameters were varied on purpose and therefore are more suited for analysis than data from commercial compost plants. Error, as 'repeatibility standard deviations', of some compost and calculated variables was analyzed. The relations between the losses of total mass, water and dry matter, and process and compost variables were investigated. The key parameters involved in the loss of matter and the usefulness of a model for processing are discussed.

2. Methods

2.1. Phase II process

The temperature of the air entering the compost is controlled by ventilating fresh air into the circulated air to the required temperature. After filling, a period of up to 10 h at 45°C equilibrates the compost temperature. This assures temperature homogeneity in the compost bulk during the rest of the process. Then, the air temperature is allowed to rise at 1.2°C h^{-1} to reach the pasteurization temperature of 56°C. After 8 h, cooling to 45°C occurs at 3°C h^{-1}. This conditioning temperature is maintained for the rest of the process time. By heat generation, the compost temperature in the top section may rise harmlessly 5–7°C higher than the entering air. At the end of the process the compost is cooled to 25°C in a few hours (Van Gils, 1988; outlines of automation by Hesen et al., 1988).

2.2. Data sets

Set G: Trials of the period 1979–1994 carried out in an experimental facility comprised of four small tunnels, of which each tunnel held four containers were described in several papers in Dutch and reviewed (Gerrits, 1981, 1985; Gerrits et al., 1995). Maximally four levels of one factor could be tested simultaneously. Containers were filled with ≈1000 kg of substrate. Containers and their contents were weighed before and after processing. Before filling and after emptying, samples were taken for analysis. We considered all processes: (i) in which some form of pasteurization and conditioning were combined, (ii) where the substrate remained untouched during processing (trials with mixing in between pasteurization and conditioning were not included), (iii) in which the four containers in the same tunnel contained the same substrate in the same amount, (iv) in which substrates consisted of mixed ingredients up until Phase I compost (substrates from experimental Phase I processes were not considered, nor were experiments on inoculation of pasteurized compost with accelerators or thermophilic fungi). The total number of trials considered was 105. In 77 trials, data from all four tunnels were used, in 3 trials three tunnels, in 1 trial two tunnels and in 24 trials one tunnel. Three trials were on the filling weight, 5 on the duration of pasteurization (3–24 h), 9 on the temperature of pasteurization (50–62°C), 6 on the duration of the whole process (4–11 d), 5 on the temperature of conditioning (40–52°C), 7 on circulation, 7 on ventilation, 16 on moisture levels and 10 on 'young' versus 'older' substrates. The number of standard processes is high: some experiments had another purpose than experimental Phase II (including the 24 trials with 1 tunnel only) and experiments on Phase II contained a standard process as a control. A total of 342 tunnels/processes was considered.

Set O: Results from 319 composting processes performed in the period 1976–1994 in small tunnels for 5 or 15 tonnes of compost were given by Overstijns and Bockstaele (1983), Overstijns et al. (1988), Overstijns and Lannoy (1992b) and Overstijns et al. (1995). Samples of 5 kg initial fresh weight were incubated in nylon bags in the centre of the compost and used for analyses. 136 processes were provided with data on weight loss; 18 of these processes were trials on conditioning temperature, these ranging from 25°C to 52°C.

Mass data were corrected to fit an initial total weight of 1000 kg. Dry matter (remaining after drying at 105°C) was expressed as a fraction of total weight, ash (remaining after incineration at 600°C), N–Kj (Kjeldahl nitrogen) and NH_4–N (ammonia–nitrogen) as fractions of dry matter.

The notation of variables and the formulas for calculations are given in Table 1.

2.3. Model calculation

Water losses were estimated using the rather simple model of Batista et al. (1995). The amount of degraded dry matter, L_{dm}, was an input variable; the production of heat and the evaporation of water were calculated subsequently. The model has an instantaneous nature (time is not accounted for): feed back of parameters changing in time (total mass, dry matter contents) is not considered. The model is operational in a spreadsheet (Microsoft–Excel). Some formulas were adapted, the most important adaptation relates to ventilation, here its amount is calculated, rather than taken as a constant. The spreadsheet is shown in Table 3.

2.4. Statistics

Most of the compost variables in set G were measured for each of four containers in a tunnel. From these measurements repeatability standard deviations, $S_{\text{repeat, container}}$, were calculated by analyses of variance with tunnel within trial as treatment structure. From the experiments in which the same process was carried out in more than one tunnel, the variance component between tunnel variation has been calculated, S^2_{tunnel}. With these variance components and the number of containers, n_c, the repeatability standard deviation of a tunnel, $S_{\text{repeat, tunnel}}$, is calculated:

Table 1
Notation and calculations (added scripts: i = initial value, f = final value; data are corrected for M.i = 1000 kg)

		Ranges applied[a]			
		Set G		Set O	
Measured process variables					
t	Process duration [d]	4	11	6	9
t_p	Pasteurization duration [h]	3	24	[b]	
T_p	Pasteurization temperature [°C] set value	50	62	[b]	
T_c	Conditioning temperature [°C] set value	40	52	25	52
T_{amb}	Ambient temperature [°C] value from climate table	0	18	2	18
Measured compost variables					
ash.i ash.f	Ash, fraction of DM	0.13	0.38	0.18	0.32
dm.i dm.f	Dry matter, fraction of M	0.18	0.32	0.22	0.31
M.i M.f	Mass total [kg]	500	1200	–	–
NH_4–N.i	N fraction of DM	0.10	0.71	0.21	0.79
N–Kjel.i	N fraction of DM	1.13	2.21	1.16	1.99
pH		7.0	8.7	6.9	8.8
Calculated compost variables					
ASH.i ASH.f	Mass of ash [kg]				
DM.i DM.f	Mass of dry matter [kg]				
L_{dm}	Loss of dry matter [kg]				
L_m	Loss of total mass [kg]				
L_w	Loss of water [kg]				
W.i W.f	Mass of water [kg]				
Calculations					
ASH.i = 1000∗dm.i∗ash.i					
ASH.f = M.f∗dm.f∗ash.f					
DM.i = 1000∗dm.i					
DM.f = M.f∗dm.f					
L_{dm} = DM.i – DM.f					
L_m = M.i – M.f = 1000 – M.f					
L_w = W.i – W.f					
M.f (ash) = 1000∗dm.i∗ash.i/(dm.f∗ash.f) from:					
ASH.i = 1000∗dm.i∗ash.i = ASH.f = M.f∗dm.f∗ash.f					
W.i = 1000 – DM.i					
W.f = M.f – DM.f					

[a] Ranges in initial values only: ash.i, dm.i, M.i, NH_4–N.i, N–Kjel.i, pH.i.
[b] Values not given in the original publications but assumed to be 8 h for t_p and 58°C for T_p.

$$S_{\text{repeat, tunnel}} = \sqrt{\left(S^2_{\text{tunnel}} + S^2_{\text{repeat,container}}/n_c\right)}.$$

In the calculations $n_c = 2$ was taken because in the regression of the losses, tunnel averages are calculated of two containers.

Simple linear regression and multiple linear regression analyses were performed to investigate the relations between the different variables. To eliminate intrinsic correlations between mass loss and water loss, one of the two losses has been calculated on two containers of each tunnel and the other loss on the other two containers.

To select best subsets of predictor variables in the regressions with total mass loss as response variable, procedure SELECT has been used. This procedure is contained in the library of the Centre for Biometry Wageningen, of the statistical package GENSTAT.

3. Results

3.1. Error and process analysis

Data variation was analyzed in set G (Table 2) where values for $S_{\text{repeat, tunnel}}$ are of particular importance. For the loss of dry matter, L_{dm}, the average of 41 kg has a value for $S_{\text{repeat, tunnel}}$ of 10.5. This means that, in a specific tunnel, the value for L_{dm} has a chance to be inside some range of twice 10.5 kg of only 68%. Since L_{dm} is calculated from fresh weights and dry matter contents before and after the process, error in these parameters accumulates in the error of L_{dm} (called error propagation). The error in L_{dm} prevents the establishment of relations between compost and process parameters and L_{dm}. This is a problem in an analysis where L_{dm} is thought to play a central role in heat generation and the evaporation and loss of water. As an alternative to L_{dm} we analyzed effects on the loss of total mass, L_m. The best subset of predictor variables for L_m in set G contained ash.i, the temperature of pasteurization, T_p, and time, t. The regression is formulated: $L_m = 316.4 - 670.1*\text{ash.i} - 0.9572*(T_p - 52.67)^2 + 24.42*t$; $R^2 = 0.65$, se = 32.0. The negative correlation of L_m with ash.i, the undegradable part of dry matter, means that L_m is positively correlated with the complement of ash.i, the degradable organic part (org.i = 1 − ash.i). 'Young' substrates, for instance gone through a short Phase I, are characterized by low ash.i values and high losses, but the ratio of water loss to dry matter loss seems unaffected. The square term with T_p means that L_m is maximum at about 53°C. The linear term with t indicates that L_m proceeds at a constant rate in time. This is unlikely if L_m is plotted against t, L_m seems to decline at increasing t values. A maximum lies beyond the maximum t value of 11 d. A more complicated regression model taking the decline into account did not result in a higher value of R^2. Therefore we maintained the linear term. For set O the best subset of predictor variables for

Table 2
Values and variation of important compost parameters in sets G and O (Parameters in lower case in fractions, in upper case in kg per 1000 kg of initial total mass)

	Set G				Set O
	Mean	$S_{\text{repeat, container}}$ [a]	S_{tunnel} [b]	$S_{\text{repeat, tunnel}}$ [c]	Mean
Measured					
ash.i	0.24	0.022	0.019	0.025	0.24
ash.f	0.29	0.018	0.007	0.015	0.27
dm.i	0.26	0.011	0.003	0.008	0.27
dm.f	0.31	0.012	0.004	0.010	0.32
M.f	697	12.6	16.5	18.8	748
Calculated					
ASH.i	60	6.8	5.8	7.5	66
ASH.f	64	4.9	2.9	4.5	66
DM.i	259	11.0	2.8	8.3	275
DM.f	218	8.3	4.3	7.3	242
L_{dm}	41	13.2	4.9	10.5	32
L_m	303	12.6	16.5	18.8	252
L_w	263	16.1	13.0	17.3	220
M.f(ash)	682	95.8	53.3	86.2	750
W.i	741	11.0	2.8	8.3	725
W.f	478	13.2	13.5	16.4	506

[a] $s_{\text{repeat, container}}$ standard deviation between containers of the same tunnel.
[b] s_{tunnel} square root of the variance component of between tunnel variation of the same process (i.e. $t = 7$, $T_c = 45$, $T_p = 56$, $t_p = 10$ of 18 trials with a total of 51 tunnels and 204 containers).
[c] $s_{\text{repeat, tunnel}}$ standard deviation between tunnel averages of the same process if the averages are calculated from two containers.

Table 3
Spreadsheet to calculate the mass of water loss and the requirement for ventilation to remove evaporated water. The input values are averages from set G (Table 2), literature data (List, 1951; Din, 1988; Ashrae, 1993) and estimates

	B column with input values and formulas	Parameter	Values
1	45.1	T_c, set point temperature of processing [°C]	45.1
2	0.26	dm.i, dry matter fraction of initial mass	0.26
3	41	L_{dm}, loss of dry matter [kg]	41
4	1000.00	M.i, initial mass [kg]	1000
5	9.7	T_{amb}, ambient temperature [°C]	9.7
6	70	Humidity of entering air [%]	70
7	2	Heat dissipated through walls and ducts [%]	2
8			
9	B26/(B24*(1000/B4))	Ventilated air [m^3 ton^{-1}]	3032
10	B15 + B27	L_w, loss of water [kg]	226.3
11			
12	B1 + 2	Processing temperature [°C]	47.1
13	B3*B29	Heat produced [kJ]	717 500
14	(B7/100)*B13	Heat dissipated through walls and ducts [kJ]	14 350
15	IF(0.379 – 1.425*B2 < 0,0,(0.379 – 1.425*B2)*B4)	Percolated water [kg]	8.5
16	5*B4*(B2*B31+(1 – B2 – B15/B4)*B30)	Energy for heating dry matter and water [kJ]	16 874
17	B13 – B14 – B16	Heat removed by ventilation [kJ]	686 276
18	B35*EXP((B36*B5)/(B37 + B5))	Saturation pressure of fresh air [mbar]	12.05
19	B6*B18/100	Partial pressure of water vapor [mbar]	8.43
20	B19*B32/(1015 – B19)	Water in dry air [kg/kg]	0.005
21	1.005*B5 + 2500*B20 + 1.93*B20*B5	Enthalpy of mixed perfect gases	22.87
22	B35*EXP((B36*B12)/(B37 + B12))	Saturation pressure of discharged air [mbar]	106.67
23	B22*B32/(1015 – B22)	Water in dry air [kg/kg]	0.073
24	B33*(1 + B23)/((B32 + B23)*(273 + B12))	Density of discharged air	1.06
25	1.005*B12 + 2500*B23 + 1.93*B23*B12	Enthalpy of mixed perfect gases	236.59
26	B17/(B25 – B21)	Mass flow discharged air [kg]	3211.2
27	(B23 – B20)*B26	Discharge of moisture [kg]	217.8
28			
29	17 500	Heat generated from cellulose [kJ kg^{-1}]	17 500
30	4.18	Heat capacity of water [kJ kg^{-1} C^{-1}]	4.18
31	1.22	Heat capacity of dry matter [kJ kg^{-1} C^{-1}]	1.22
32	0.622	Gas constant	0.622
33	219.60	Constant Mollier diagram	219.60
34	1.93	Specific heat of vapor [kJ/kg K]	1.93
35	6.108	Constant *C*1	6.108
36	17.081	Constant *C*2	17.081
37	234.175	Constant *C*3	234.175

L_m contained ash.i, the temperature of conditioning, T_c, NH_4–N.i and pH.i: $L_m = 541.0 - 319.3*\text{ash.i} - 0.2226*(T_c - 54.07)^2 + 105.0*NH_4\text{–N.i–}29.71*\text{pH.i}$; $R^2 = 0.59$, se = 30.0. The predictor variables are in part different from those for set G. T_p has no role because it was not varied in the trials in set O. On the other hand T_c is important; showing a maximum of L_m at 54°C. The range of T_c applied in set O was broader than in set G. Time, *t*, in set O was applied in a short range being insufficient to determine the time course of degradation. The temperatures found for maximal loss of matter in sets G and O agree with laboratory values (Derikx et al., 1990).

3.2. Water loss

Water loss by dry matter degradation, heat generation and evaporation was analyzed with a model, operational in a spreadsheet (Table 3). The water losses calculated in the spreadsheet are lower than the losses determined from weight and dry matter analyses data (Table 4a). The differences are 23 and 45 kg of water for sets G and O, respectively. Since the loss of dry matter is an input variable, its error is propagated in the model. Thus the value of water loss, as an output variable, shows much error. Consequently the calculated and measured values are poorly correlated, R^2 values being 0.24 and 0.09 in sets G and O, respectively.

The sensitivity of the spreadsheet output to some parameters was studied. Four of the input variables from set G (Table 2, and small variations) were studied and six variables that had been used as constants. The effects on water loss are given in Table 4b. The parameters: loss of dry matter, percolated water and heat generation from cellulose degradation have a significant effect on the output. Their input values may be questioned and must be reconsidered for adjustment.

The calculated amounts of ventilated air of about 15 m^3 ton^{-1} h^{-1} of compost (Table 4a) are similar to

Table 4
Results from spreadsheet calculations

	Set G, $n = 342$ tunnels		Set O		
	Average	sd	Average	sd	n
A. Calculated water loss and ventilation requirement. Primary data for containers of set G were averaged per tunnel to get 342 input sets of data (T_c, dm.i, L_{dm} and T_{amb})					
L_w [kg]	240	71	175	83	124
Percolated water [kg]	21	29	6	11	136
Ventilated air [m^3 ton^{-1}]	3105	992	2374	1560	124
Ventilated air per h	18	6	14	9	

B. Effect of input parameters on calculated water loss. The input values of Table 3 were taken as a reference, they were changed and their effect was calculated				
Parameter	Change	Value	L_w	Effect
1 T_c [°C]	1	46.1	227.5	1.2
2 dm.i (change = s-repeat tunnel) [fraction]	0.01	0.259	227.8 [a]	1.5
3 L_{dm} (change = s-repeat tunnel) [kg]	10.5	51.5	283.5	57.2
5 T_{amb} [°C]	1	10.7	227.1	0.8
6 Humidity of entering air [RH, %]	10	60	226.8	0.5
7 Heat loss through walls and ducts [%]	1	1	228.6	2.3
12 Processing temperature (set point + x) [°C]	1	48.1	227.5	1.2
15 Percolated water [kg]	1	9.5	227.3	1.0
16 Temperature difference of compost between filling and processing [°C]	1	4	227.4	1.1
29 Heat generated from cellulose [kJ kg^{-1}]	500	18 000	232.7	6.4

[a] Percolated water rising from 8.5 to 10.0.

estimated values in practice (Klaver and Van Gils, 1988).

3.3. Further observations

The fresh weights M.i and M.f can be estimated from data on dry matter and ash contents, assuming that the mass of ash during composting remains constant. The masses of ASH.i and ASH.f were almost the same (Table 2). Values of M.f (ash) estimated in this way show much variation (Table 2) and are only moderately correlated with weighed values; R^2 equals 0.47 and 0.23 in sets G and O, respectively. Therefore we decided not to use estimated M.f values in this paper. As a consequence we could only use data from 136 out of 319 experiments in set O. For the same reason, data from commercial composters will be difficult to use since individual tunnel loads are directly measured at filling only; weighed M.f values are difficult to obtain and only estimated values remain.

4. Discussion

4.1. Error in dry matter and water loss

The central parameter in this study, the loss of dry matter, L_{dm}, contained much error. L_{dm} is calculated from the basic parameters dm.i, dm.f and M.f (Table 1), the contribution of 'containers' to error being important (Table 2, set G). Processing error cannot be analyzed directly but is judged to be low. The data on dm.i relate to batches of 1000 kg of compost being filled into containers; the containers and processing having no impact. Error of dm.i is high and will be passed on to dm.f; indeed both errors are very similar (Table 2). The relative error of M.f is low. This leaves compost heterogenity and sampling technique as major sources of error; the analytical methods seem sound enough. Error could not be analyzed in set O but we expect it to be similar to error set G. Correlations of the losses of total and dry matter with processing parameters and of estimated with actual water losses were of the same magnitude as in set G.

The idea that the loss of water, L_w, can be calculated from dry matter loss, L_{dm}, is largely confirmed by the similarity of averaged values for measured and estimated water losses (Tables 2 and 4b, respectively; the relatively small difference is discussed below). In individual processes, measured and calculated values deviate strongly. Error in values for L_{dm} is propagated into calculated L_w values. This means that a model cannot yet be applied to adjust processes to an optimal outcome of weight and dry matter contents. Compost producers should focus on getting the composition constant at the start of composting. Adjusting an individual process is not a very reliable option.

4.2. Process analysis

The optimum temperature of pasteurization and conditioning of more than 50°C is higher than the commonly applied processing temperature of 45°C. An important objective of Phase II processing is ammonia clearance. From the data of Overstijns and Lannoy (1992a) we estimate that ammonia clearance is optimal just above 40°C. Almost the same low optimum can be estimated from a laboratory study (Ross, 1976; Ross and Harris, 1982). The different optimum temperatures for degradation and for ammonia clearance seem to conflict. However, pre-degradation of straw does not seem to be a prerequisite for the turnover of compost mass into mushroom fruit body biomass (Gerrits et al., 1997). Thus clearing of NH_3 and saving rather than degrading dry matter would be key factors to focus on, and a rather low processing temperature may be considered.

At prolonged processing, degradation is expected to come to a halt. The amount of organic matter, or the combined amounts of hemicellulose and cellulose, may become limiting. From Table 2 the amount of organic matter can be calculated as 199 and 209 kg, respectively for sets G and O (ORG.i = DM.i− ASH.i). For evaporation 741 and 725 kg of water are available. Using the spreadsheet (Table 3), these amounts of water can remove the heat produced from the degradation of 136 and 135 kg of dry matter. Of course degradation will stop earlier because of the biological requirement of water. Keener et al. (1996) found their composting process to be hampered at dm.i values over 0.55. Water might well be the limiting factor in degradation.

The general validity of the model confirms the physical concepts applied to composting. The model is useful to identify sensitive parameters (Table 4b). The model can be used to predict trends in losses if variables are consistently adapted. The actual water losses were systematically higher than the losses calculated in the model. The error and uncertainties in some important parameters in the model are high (Tables 2 and 4b). The heat loss through walls and ducts need to be measured rather than estimated. Percolation is assumed to have occurred in sets G and O in 181 and 47 out of 342 and 124 processes, respectively. This assumption was based on only one experiment with composts of different dry matter contents where percolation occurred below a dry matter fraction of 0.266 (Table 3, line 15). Percolation has previously been considered by Harper et al. (1992). They evaluated air pressure profiles under and above compost in tunnels, and found a hampered air circulation at a dry matter fraction below 0.22, probably due to percolation. Heat generation from microbial degradation of compost and cereal straw requires further evaluation despite studies already done (Ebeling and Jenkins, 1985; Marugg et al., 1993; Van Ginkel, 1996). We took 17.5 MJ per kg of degraded dry matter as the calculated free energy released by oxydation of cellulose. Values ranging from 15 to 25 MJ per kg are estimated or measured in the other studies. This parameter alone can account for the discrepancy in calculated and weighed water losses. Further, the transport of water in the exhaust air should be measured. Saturation of the exhaust air is inherent to the spreadsheet; this may be falsely assumed.

For further research we recommend that processing and compositional parameters are studied in wider ranges. The range for process duration should be between 1 and 15 days. This would allow for finding accurate values for the exponential rate of degradation and the amount of mass that can be maximally degraded, together describing the time progress of degradation (Keener et al., 1993; Marugg et al., 1993; refering to the rate of composting and the equilibrium mass). The effect of temperature should be studied in a range from 35°C to 60°C. Dm.i and ash.i have been tested at rather low values and thus testing at high values seems advisable.

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