

Carbon dioxide and ammonia emissions during composting of mixed paper, yard waste and food waste

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Accepted 8 December 2004

Available online 21 February 2005

Abstract

The objective of the work was to provide a method to predict CO₂ and NH₃ yields during composting of the biodegradable fraction of municipal solid wastes (MSW). The compostable portion of MSW was simulated using three principal biodegradable components, namely mixed paper wastes, yard wastes and food wastes. Twelve laboratory runs were carried out at thermophilic temperatures based on the principles of mixture experimental and full factorial designs. Seeded mixed paper (MXP), seeded yard waste (YW) and seeded food waste (FW), each composted individually, produced 150, 220 and 370 g CO₂-C, and 2.0, 4.4 and 34 g NH₃-N per dry kg of initial substrate, respectively. Several experimental runs were also carried out with different mixtures of these three substrates. The effect of seeding was insignificant during composting of food wastes and yard wastes, while seeding was necessary for composting of mixed paper. Polynomial equations were developed to predict CO₂ and NH₃ (in amounts of mass per dry kg of MSW) from mixtures of MSW. No interactions among components were found to be significant when predicting CO₂ yields, while the interaction of food wastes and mixed paper was found to be significant when predicting NH₃ yields.

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1. Introduction

Composting of municipal solid wastes (MSW) can be used to pretreat MSW prior to landfilling or to produce a soil amendment and landscaping material (Diaz et al., 1993). Two major biological products during MSW composting are carbon dioxide (CO₂) and ammonia (NH₃). CO₂ is a greenhouse gas, while ammonia is an air pollutant of malodorous and potentially toxic nature. Even though MSW consist of many types of organic and inorganic materials, paper wastes, yard wastes and food wastes are the principal biodegradable components, rendering them responsible for most of the CO₂ and NH₃ emitted during MSW composting.

Laboratory aerobic degradation studies of various solid organic wastes have been performed in the past.

Most laboratory studies have measured the reduction of the organic fraction during composting (Poincelot and Day, 1960; Inoko et al., 1979; Baca et al., 1992; Wang et al., 2003), while some studies have included a setup to capture and measure gases produced during composting. Michel et al. (1993) provided a laboratory setup to measure CO₂ emissions during composting of mixtures of grass and leaves in sealed laboratory digesters and also measured the reduction of certain chemical groups (cellulose, hemicellulose, lignin) during the process. Nakasaki et al. (1994) measured the degradation kinetics of grass clippings in laboratory reactors, providing a setup to capture and quantify the emitted CO₂. In addition, measurements of cellulose, hemicellulose and lignin in the grass were performed. Nakasaki et al. (1998a) measured NH₃ and other N gases emitted during dog food composting in thermophilic temperatures using a setup that also quantified CO₂ emissions. The same setup was also used in Nakasaki et al. (1998b).

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Laboratory-scale digesters to quantify CO₂ emissions during solid and agricultural waste composting experiments have been also described in Suler and Finstein (1977), Sikora et al. (1983), Bono et al. (1992), Palmisano et al. (1993), Schwab et al. (1994), Nakasaki et al. (1993), Magalhães et al. (1993), Cook et al. (1994) and Tseng et al. (1995). Different initial substrates were used in all composting experiments. Suler and Finstein (1977) used a mixture of food scraps, paper napkins, plastic tableware and shredded newspaper; Nakasaki et al. (1993) used garbage from a meal supply service industry; whilst Cook et al. (1994) used shredded newspaper, rabbit food, composted cow manure and corn cob piths to simulate organic waste. Magalhães et al. (1993) used a mixture of horse manure, alfalfa, newspaper and soil as the initial substrate, whilst Palmisano et al. (1993) used rabbit chow and shredded newspaper as initial substrates.

The objective of the study presented in this paper was to quantify the CO₂ and NH₃ emissions from the three major biodegradable components of MSW, as well as mixtures of these components, with the ultimate goal to develop a mathematical model to predict these emissions from such different mixtures. The mathematical model can aid in estimating the contribution of the biodegradable fraction of MSW from different sources or countries to global phenomena.

2. Materials and methods

The biodegradable fraction of MSW was assumed to comprise three substrates, namely mixed paper waste (MXP), food waste (FW) and yard waste (YW). Mixed paper waste (MXP) was prepared by mixing old corrugated cardboard (OCC), printed office paper (OFP) and old newsprint (ONP) at percentages of approximately 45%, 21% and 34%, respectively, on a wet weight basis, based on a typical composition for mixed paper in the US (Tchobanoglous et al., 1993). Yard wastes (YW) were prepared by mixing grass clippings and leaves at an arbitrary ratio of approximately 1.5:1 (dry content basis), respectively. Food wastes (FW) were simulated using milk, cooked pasta, hamburger, lettuce, raw potatoes and carrots, mixed in equal wet weight amounts. All food products were obtained from a local grocery store and prepared prior to each run.

The three MSW substrates (or components) were mixed according to the US typical MSW composition after recycling (Tchobanoglous et al., 1993). Twelve laboratory runs were carried out using five custom-made 25-l airtight stainless steel digesters constructed by HooperTM Corporation (Madison, Wisconsin, USA). All MSW substrates were mixed with #1.5 HyPak[®] aluminum packing material (4.5 cm thickness × 4.5 cm diameter) acquired by Norton Chemicals (Akron,

Ohio, USA) at a percentage of approximately 10% to 15% of the volume occupied by the substrate to facilitate air flow. A 4.5-cm air plenum was placed at the bottom of the digesters to provide uniform aeration. Initial moisture content was set to 55–60% (w.w.) for all substrates, unless the initial content was higher than that, such as in food wastes. Nitrogen was added to all substrates or mixtures to reach a C/N ratio of approximately 30, which is considered optimum for composting, unless the initial C/N ratio was lower than that, such as in food wastes. Nitrogen was added as NH₄NO₃ salt dissolved in the water used to increase the moisture content. Nitrogen was added to the mixed paper run (MXP) as well as to all mixtures of mixed paper, except the MSW_{1/3} run (see Table 1). The initial C/N ratios of all substrates are included in Table 1.

Laboratory ambient air was continuously pumped into the digesters using an air pump operating at a positive pressure. The air first passed through a 500-ml 5 N KOH solution to capture ambient CO₂ and then passed through 10 l of distilled water, kept at incubator temperature, to humidify the substrate.

A valve prior to each digester was used to regulate airflow to each digester so that oxygen content within the digester was kept higher than 15% by volume for all runs. Aluminum packing was mixed with all substrates to facilitate air flow. Moisture was added upon drying of a material during the course of a run. The digesters were operating concurrently in an incubator at a 52 ± 2 °C temperature (thermophilic range). Some runs were seeded with partially composted MSW, hereafter referred to as seed. Seed was collected from a nearby MSW composting facility located at Portage (Wisconsin, USA). Approximately 15 kg of seed (wet weight) were collected from the outlet of a 5-day retention time drum digester that receives raw MSW without any preprocessing. The seed was screened through a 12.7-mm screen to remove larger items, such as glass and plastic. Seeding was provided at a ratio of approximately 1:10 of dry seed to dry substrate. The above aerobic degradation conditions were considered close to optimal.

Carbon dioxide and ammonia yields and production rates were measured for all experimental runs. The air stream exiting a digester was bubbled through a 750-ml 5 N KOH solution to capture carbon dioxide and then through a 500-ml 1 N H₂SO₄ solution to capture ammonia. The cumulative mass of captured carbon dioxide (expressed in g CO₂-C) was measured periodically by titration. The alkaline trap was replenished when the CO₂-C concentration in the solution would exceed 10 g CO₂-C/l. In the case of ammonia, a sample of 1.5 ml of the NH₃ trap solution was periodically removed and mixed with 10 ml D.I. water. Dissolved ammonia was quantified using a preliminary distillation/titration

Table 1
Properties of experimental runs

No. of experiment	Name of run	Amount of seed (dry kg/digester)	MXP (dry kg/digester)	YW (dry kg/digester)	FW (dry kg/digester)	N content ^a (% dry weight)	C/N ^a	N addition (% dry weight)	Moisture (% wet weight)	Duration of run (days)
1	MXP	0.073	0.68	–	–	0.35%	120	1.5%	8.6%	198
2	MXP _{ns}	–	0.68	–	–	0.09%	506	–	8.6%	87
3	YW	0.059	–	0.39	–	2.1%	18	–	63%	77
4	YW _{ns}	–	–	0.39	–	1.9%	19	–	65%	69
5	FW	0.054	–	–	0.26	5.6%	8.4	–	76%	58
6	FW _{ns}	–	–	–	0.13	6.2%	7.9	–	79%	91
7	MXP/YW	0.11	0.65	0.13	–	0.72%	59	0.82%	24%	180
8	MXP/FW	0.086	0.82	–	0.037	0.58%	76	1.3%	19%	129
9	FW/YW	0.045	–	0.26	0.073	2.9%	14	–	65%	114
10	MXP/YW/FW	0.14	0.80	0.15	0.042	0.9%	47	0.77%	31%	170
11	MSW _{1/3}	–	0.14	0.15	0.12	2.6%	17	–	65%	47
12	Seed	0.17	–	–	–	2.8%	13	–	9.3%	62

^a Prior to NH₄NO₃ addition (values calculated include seed).

method (Komilis and Ham, 2000) and expressed in g NH₃-N.

The experimental runs were terminated when carbon dioxide production rates dropped below approximately 0.5 g CO₂-C/dry kg/day and after ensuring that this was not due to moisture limitation. Therefore, durations for each run varied, as shown in Table 1, depending on when a run approached complete degradation.

The materials and methods associated with the setup of the laboratory experiment, substrate selection and preparation, the analytical techniques and the quality assurance and quality control performed are presented in more detail in Komilis and Ham (2000). The properties of all experimental runs used are included in Table 1.

3. Statistical experimental designs

The statistical experimental designs were based on the principles of full factorial experimental design (Box et al., 1978) and mixture experimental design (Cornell, 1990). The full factorial design analysis was used to investigate the effect of seeding to the three MSW biodegradable components, while the mixture experimental design analysis was used to develop equations for predicting CO₂ and NH₃ yields from mixtures of mixed paper, yard waste and food waste.

3.1. Full factorial experimental design

To investigate the effect of seed in the overall emissions of unseeded MSW components, three factorial experiments with two factors and two levels were designed (Box et al., 1978). The two factors are the components and the seed. The two levels are the low level, representing the absence of a component or the seed from the digester and the high level, representing the presence of a component or the seed in the digester. The model for the 2² factorial design used to investigate component and seed interaction is shown in Eq. (1),

$$Y = n + \frac{X_C}{2}L_C + \frac{X_S}{2}L_S + \frac{X_{CS}}{2}L_CL_S + \varepsilon, \quad (1)$$

where

Y : carbon dioxide yield (Y_C in g C) or ammonia yield (Y_N in g N). These gaseous yields are used as the experimental responses to evaluate the effects and are the amounts of gas emitted by the amount of substrate placed in the digester, as shown in Table 2.

n : average yield or experimental mean (in g CO₂-C or g NH₃-N); this is the average response of the whole experiment and is calculated by the sum of all yields divided by 4 (Berthouex and Brown, 1994); the experimental mean is determined by the experiments.

X_C , X_S , X_{CS} : effects for each of the three MSW components (X_C), for the seed (X_S) and for the interaction of component/seed (X_{CS}); the effect of a factor (MSW component or seed) measures the average change in the response (gaseous yield) caused by changing that factor from its low level (absence of a component from the digester) to its high level (presence of a component in the digester) (Berthouex and Brown, 1994). these values are determined by the experiments.

L_C , L_S : either -1 (low level), representing the absence of a component or the seed from the digester, or $+1$ (high level) representing the presence of a component or the seed in the digester.

L_C : corresponds to the MSW biodegradable component – that is either mixed paper (MXP), yard waste (YW) or food waste (FW) – and L_S corresponds to the seed.

ε : errors (residuals) that are distributed normally with a zero mean and a constant variance.

The structures of the three 2^2 full factorial designs are included in Table 2. The n and the effects are calculated according to Box et al. (1978).

3.2. Mixture experimental design

To predict CO_2 and NH_3 yields from any MSW mixture on a per dry unit mass basis, a mixture experimental design was developed (Cornell, 1990). As part of the mixture experimental design analysis, the polynomial Eq. (2) was fit to the data:

$$Y_{\text{kg}} = b_P F_P + b_Y F_Y + b_F F_F + b_{PY} F_P F_Y + b_{PF} F_P F_F + b_{YF} F_Y F_F + b_{PYF} F_P F_Y F_F + \varepsilon, \quad (2)$$

where

Y_{kg} : is either the unit CO_2 yield (Y_{kgC}) or unit NH_3 yield (Y_{kgN}) of a MSW mixture expressed in g $\text{CO}_2\text{-C/dry kg}$ or g $\text{NH}_3\text{-N/dry kg}$ of individual component or mixture, respectively;

F_P , F_Y , F_F : are the dry fractions of mixed paper, yard waste and food waste, respectively, in the mixture, with each of the F_P , F_Y , F_F : values ranging from 0 (0%) to 1 (100%) and with $F_P + F_Y + F_F$ always being equal to 1 (100%);

b_P , b_Y , b_F , b_{PY} , b_{YF} , b_{PF} , b_{PYF} : are the model coefficients determined by the experiments using the method of least squares (Berthouex and Brown, 1994); and

ε : are the errors (residuals) that are distributed normally with a zero mean and a constant variance

The mixture experimental approach can indicate interactions among components, which are also known as synergisms or antagonisms (Cornell, 1990). These are indicated by the positive or negative sign, respectively, of the coefficient of the product of any of the F_i values in the equation (with i being either P, Y or F, as noted above).

4. Results and discussion

The CO_2 emissions from the control run (empty digester) were 0.64 g (as C), as measured over a period of 48 days. The $\text{CO}_2\text{-C}$ in the control run came from CO_2 in ambient air that was not captured by the initial alkaline filter. Most of the control $\text{CO}_2\text{-C}$ was captured

Table 2
 2^2 full factorial experimental runs to investigate interactions between individual MSW components and added seed

No. of experiment			Y_C^a (g $\text{CO}_2\text{-C}$)	Y_N^a (g $\text{NH}_3\text{-N}$)
1st 2^2 experiment	MXP _{ns} (0.68 dry kg)*	Seed (0.073 dry kg)		
Control (empty digester)	–	–	0	0
2	+	–	3.8	0
12	–	+	6.3	0.13
1	+	+	120	1.5
2nd 2^2 experiment	YW _{ns} (0.39 dry kg)	Seed (0.059 dry kg)		
Control (empty digester)	–	–	0	0
4	+	–	83	1.7
12	–	+	5.2	0.10
3	+	+	95	1.9
3rd 2^2 experiment	FW _{ns} (0.26 dry kg)	Seed (0.054 dry kg)		
Control (empty digester)	–	–	0	0
6	+	–	92	9.8
12	–	+	4.2	0.09
5	+	+	110	10

(+): high level, indicating presence of either an individual component or the seed in the digester; (–): low level, indicating absence of either an individual component or seed from the digester.

^a Total amount (yield) of $\text{CO}_2\text{-C}$ or $\text{NH}_3\text{-N}$ emitted (in g) from the amount of substrate placed in the digester during the course of a run.

* Values in parantheses indicate dry mass of substrate in digester.

during the first 5 days of the control run; therefore the amount of 0.64 g CO₂-C was simply subtracted from the total CO₂-C yields emitted from all other experimental runs. No significant amounts of ammonia were detected during the control run.

4.1. Gaseous yields

As illustrated in Fig. 1, FW_{ns} is the largest producer of CO₂ among all components, producing approximately 370 g CO₂-C/dry kg, within 91 days, as shown in Table 1. Based on Fig. 1(a), seeding appeared to affect CO₂ production rates, but not yields, for FW. FW_{ns} and FW had similar CO₂ production rates until day 5. After day 5, FW_{ns} had steadily lower CO₂ production rates compared to the corresponding rates of FW. It took 56 days for FW to approach complete degradation, as opposed to a period of 91 days for the FW_{ns} run. FW_{ns} was also the largest ammonia producer among all components, emitting up to 41 g NH₃-N/dry kg of starting

material (see Fig. 2(a)). FW_{ns} may have produced more NH₃ than FW, due to its longer duration.

YW emitted approximately 220 g CO₂-C and 4.5 g NH₃-N per dry kg of starting material, whilst no significant differences between the emissions of YW and YW_{ns} were observed.

MXP_{ns} produced the lowest CO₂ yield among all substrates (see Table 4). In addition, MXP produced some of the lowest ammonia amounts. MXP's ammonia emissions are mainly due to the added seed, since MXP contains no significant N. However, some ammonia from MXP might have partially originated from the initially added NH₄NO₃. Apparently, the chemical equilibrium attained between NH₄⁺ and NH₃ – which is a function of the fluctuating pH during the composting process – could have resulted in some nitrogen evaporating as NH₃ after the ammonium addition.

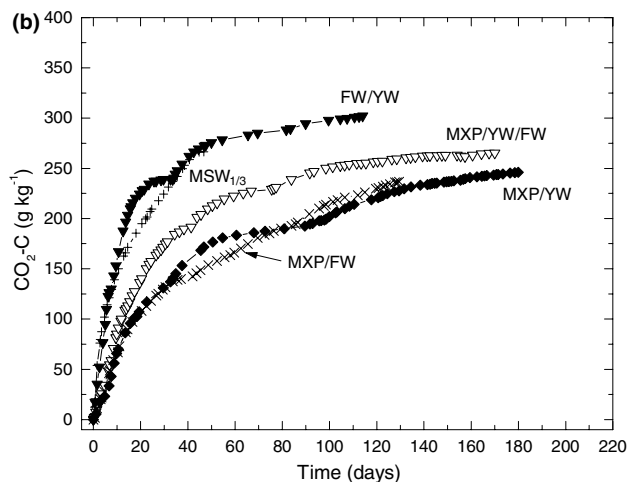
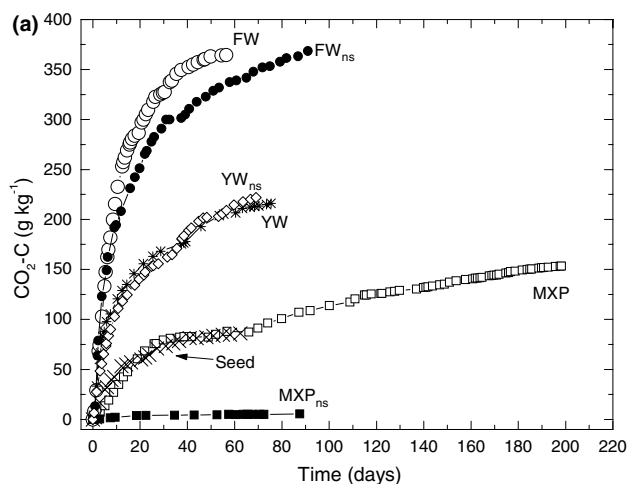


Fig. 1. (a) Cumulative CO₂-C production per dry kg of individual components (including seed). (b) Cumulative CO₂-C production per dry kg of mixtures (including seed).

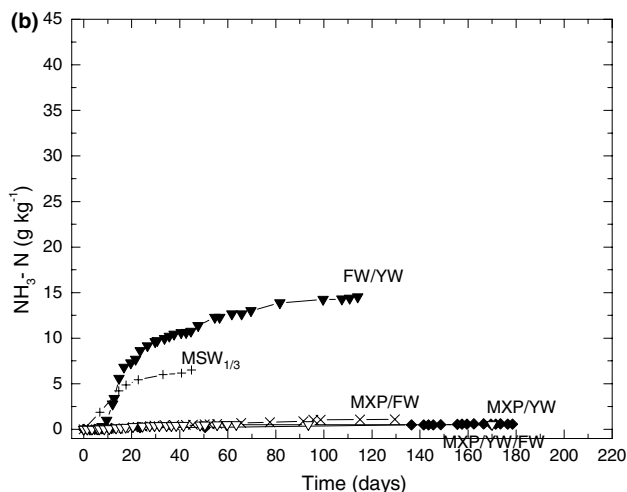
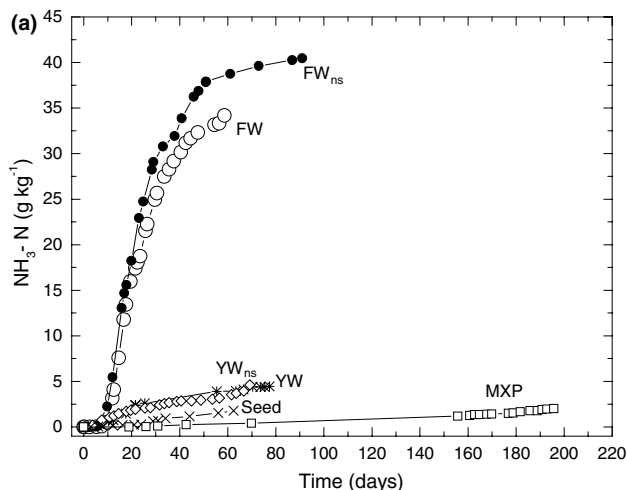


Fig. 2. (a) Cumulative NH₃-N production per dry kg of individual components (including seed); MXP_{ns} had zero NH₃ emitted. (b) Cumulative NH₃-N production per dry kg of mixtures (including seed).

Seed produced 86 g CO₂ (as g C/dry kg), during a period of 62 days, which was the lower CO₂ production after the MXP and MXP_{ns} runs. This indicates that seed was relatively stabilized compared to the other substrates.

From the mixtures, the FW/YW was the largest gas emitter, producing approximately 300 g CO₂-C and 15 g NH₃-N per dry kg. Interestingly, all mixtures had CO₂ emissions that ranged from 250 to 300 g CO₂-C/dry kg. Mixtures with paper percentages greater than 50% dry weight (MXP/YW, MXP/FW, MXP/YW/FW) had ammonia emissions lower than 1.5 g NH₃-N/dry kg. The FW/YW mixture was the mixture with the largest ammonia production, being approximately 15 g NH₃-N/dry kg.

4.2. Seed interaction

The model shown in Eq. (1) was fit to the CO₂-C and NH₃-N yield experimental data (*Y* values) included in Table 2. The effect of each component (*X_C*), the effect of the seed (*X_S*) and the interaction effects (*X_{CS}*) are included in Table 3. Based on Table 3, the seed main effects (*X_S*) are 10% and 11% of the YW and FW effects, respectively, when predicting CO₂ yields. The seed to component interaction effects (*X_{CS}*) are 4% and 7% of the component CO₂ yield effects for FW and YW, respectively. This indicates that the additional amounts of CO₂ produced due to the seed can be consid-

ered insignificant compared to the amounts produced by the components themselves. On the other hand, the interaction of the seed with MXP is almost equal to the effect of MXP alone when predicting both CO₂ and NH₃, indicating that this interaction is highly significant.

The relatively small component and seed interaction effects (based on the CO₂ response) for FW and YW (<7% of the component effect) are explained by the fact that these sole components are likely to contain an indigenous microbial population capable of initiating and maintaining the aerobic decomposition process (Gray et al., 1971). In the case of MXP, seeding was necessary to initiate decomposition, since negligible CO₂ was produced from the MXP_{ns} run.

In the case of ammonia, the seed effects are approximately 8% and 1.5% of the YW and FW effects, respectively. The component/seed interaction effects are approximately 3% and 0.6% of the YW and FW main effects, respectively. In a similar manner, it is likely that a microbial population capable of ammonification processes is originally present in the unseeded FW (FW_{ns}) and unseeded YW (YW_{ns}), as opposed to MXP.

According to the above, the amounts of CO₂ and NH₃ produced from the seed in the FW and YW runs are relatively low compared to the sole component emissions. Therefore, the CO₂ and NH₃ amounts given in Table 4 are expressed as g produced per dry kg of component plus the seed (for the seeded runs). Due to the

Table 3
Effects for the 3 2² factorial designs (based on Eq. (1))

	Mixed paper		Yard wastes		Food wastes	
	CO ₂ (g CO ₂ -C)	NH ₃ (g NH ₃ -N)	CO ₂ (g CO ₂ -C)	NH ₃ (g NH ₃ -N)	CO ₂ (g CO ₂ -C)	NH ₃ (g NH ₃ -N)
Component (<i>X_C</i>)	59	0.69	86	1.8	99	9.9
Seed (<i>X_S</i>)	61	0.82	8.6	0.15	11	0.15
Component/seed (<i>X_{CS}</i>)	55	0.69	3.4	0.05	6.9	0.06

Table 4
Fractions of components in mixtures (dry mass basis) and gaseous yields for 12 runs

Run title	MXP (<i>F_P</i>)	YW (<i>F_Y</i>)	FW (<i>F_F</i>)	Dry seed/dry component ratio	CO ₂ -C (g C/dry kg) ^a	NH ₃ -N (g N/dry kg) ^a	% of initial N (including added NH ₄ NO ₃) evaporated as NH ₃ -N
Seed	0	0	0	1	86	1.8	6.3%
MXP	1	0	0	1:9.4	150	2.0	11%
MXP _{ns}	1	0	0	0	5.5	0.0	0.0%
YW	0	1	0	1:6.5	220	4.4	22%
YW _{ns}	0	1	0	0	220	4.6	25%
FW	0	0	1	1:4.8	360	34	61%
FW _{ns}	0	0	1	0	370	41	65%
MXP/YW	0.83	0.17	0	1:7.2	250	0.6	3.9%
MXP/FW	0.96	0	0.04	1:9.9	240	1.1	5.9%
FW/YW	0	0.78	0.22	1:7.4	300	15	50%
MXP/YW/FW	0.80	0.155	0.045	1:7.4	270	0.5	3.0%
MSW _{1/3}	0.34	0.37	0.30	0	270	6.5	25%

^a Values represent cumulative mass of emitted gas per dry kg of initial substrate after the end of the test (component + seed for seeded runs).

relatively small amounts of CO₂ or NH₃ produced by the seed, the FW and FW_{ns} runs and the YW and YW_{ns} runs are treated as replicates.

Results for seed interaction effects are based on the specific seed to component ratios used. The use of different seed percentages might have led to different results. However, the addition of seed in a mixture was considered to be such so that to simply initiate biodegradation avoiding significant additional impact to the component's gaseous yields.

4.3. Mixture experiment

The results given in Table 4 were fit by least squares to Eq. (2). A parametric regression analysis was followed and the best reduced descriptive models for the CO₂ and NH₃ yields are given in Eqs. (3) and (4), respectively:

$$Y_{\text{kg}C} = 220(\pm 19)F_P + 240(\pm 21)F_Y + 370(\pm 24)F_F, \quad (3)$$

$$Y_{\text{kg}N} = 1.3(\pm 1.4)F_P + 5.2(\pm 1.4)F_Y + 38(\pm 1.6)F_F - 69(\pm 23)F_P F_F, \quad (4)$$

where

$Y_{\text{kg}C}$: unit yield (in g) of CO₂-C emitted per dry kg of component or mixture,

$Y_{\text{kg}N}$: unit yield (in g) of NH₃-N emitted per dry kg of component or mixture, and other parameters as defined previously.

Values in parentheses are the coefficients' standard errors.

The adjusted coefficient of determination (R^2) is higher than 98% for both aforementioned equations. In addition, residuals for Eqs. (3) and (4) are distributed normally with a mean of zero, indicating the adequacy of both models.

4.4. CO₂ emissions

According to Eq. (3), no component interactions are statistically significant during degradation of MSW components to carbon dioxide, since no second order terms are included. Eq. (3) is valid as long as components approach their "full" extent of decomposition, regardless of rates. Since MXP produced approximately 150 g CO₂-C/dry kg during the specific experiment presented here, Eq. (3) indicates that around 72% (150 g out of 220 g) of the ultimate MXP CO₂ emissions were actually released during the experimental course. This is likely due to inadequate seeding or simply because MXP requires a relatively long time to approximate its full extent of decomposition due to relatively slow solids

hydrolysis. Mixing of FW with MXP or YW with MXP, however, resulted in an apparently higher decomposition extent of MXP in the mixture, probably due to the seeding provided by the former two substrates.

The response surface described by Eq. (3) is illustrated in Fig. 3. Black dots in Fig. 3 indicate the "location" of the performed experimental runs. The "flat" response surface of Fig. 3 indicates that the predictive model is linear. It is worth noting that USA-based MSW, with a MXP content higher than 40%, is located at the upper part of the triangle of Fig. 3, while a typical Southeastern Europe MSW composition (such as in Greece) is located at the bottom right part of the triangle due to the FW content higher than 35%. Therefore, MSW in the former case are expected to produce less CO₂ (on a dry kg basis) compared to MSW in the latter case, when decomposed aerobically.

4.5. NH₃ emissions

According to Eq. (4), YW and FW are the only two statistically significant main effects, while only one two-component interaction (or antagonism) is significant. The MXP coefficient has a relatively large standard error rendering the corresponding main effect insignificant; however, the MXP term cannot be excluded from Eq. (4) since there is at least one interaction that includes MXP (Box et al., 1978). Therefore, according to Eq. (4), MXP is not a significant ammonia emitter despite its appearing in the equation. The negative 2nd order coefficient of Eq. (4) indicates that the mixing of MXP and FW significantly reduces overall NH₃ emis-

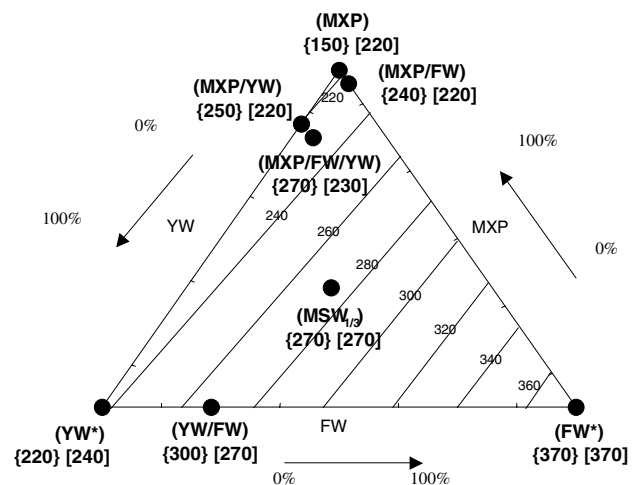


Fig. 3. Response surface for CO₂ based on Eq. (3) (dots indicate 'location' of experimental runs; contour lines represent locations of equal carbon dioxide yield expressed in g CO₂-C per dry kg of substrate). Note. {}: experimentally determined data, []: calculated data, *: indicates average experimental value from seeded and unseeded runs, which were considered as replicates for component shown.

sions. This is because by combining MXP and FW – at the percentages used during the experiment – nitrogen becomes limiting for the overall mixture, as opposed to when FW is composted individually.

Table 4 shows that the highest ammonia emissions are due to FW, which has the highest percentage of the initial N content emitted as NH_3 among all substrates, namely approximately 65%. YW follows with 25% of its initial total N emitted as NH_3 . Therefore, ammonia emissions appear to be a function of the initial N content of the MSW substrates. Ammonia emissions are expected to also depend strongly on the temperature and substrate pH, but this was not studied here, since temperature was kept similar to all digesters and the pH was let to follow its own course without any adjustments during a run.

The response surface described by Eq. (4) is illustrated in Fig. 4. The curved isopleths of Fig. 4 are due to Eq. (4) being non-linear. According to Fig. 4, a “dip” exists at approximately the top of the triangle indicating negligible NH_3 yields from MSW mixtures with a MXP content higher than approximately 80% (dry wt.). An “ascending slope” from the middle of the triangle towards high FW contents reflects the increases in NH_3 yields as FW content in MSW increase. The measured yield of 2.0 g NH_3 -N/dry kg of MXP represents a separate peak at the top of the triangle as a result of the initially added NH_4NO_3 to lower the initial C/N ratio. Similarly to the CO_2 emissions, South-Eastern European MSW, due to the relatively high FW contents, are expected to emit higher amounts of NH_3 on a dry kg basis compared to MSW from the USA.

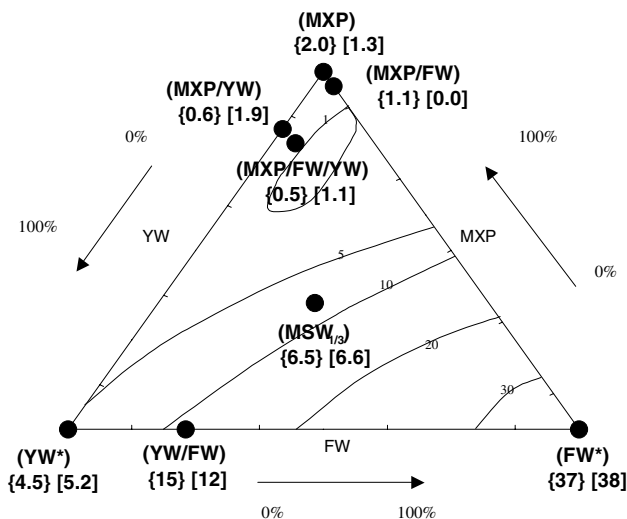


Fig. 4. Response surface for NH_3 based on Eq. (4) (dots indicate ‘location’ of experimental runs; contour lines represent locations of equal ammonia yield expressed in g NH_3 -N per dry kg of substrate). Note. {}: experimentally determined data, []: calculated data, *: indicates average experimental value from seeded and unseeded runs considered as replicates for component shown.

It is noted that the above equations were based on simulating the organic fraction of MSW with three biodegradable components, namely MXP, YW and FW. To express gaseous yields per unit mass of actual MSW, which contains inorganic (and other) components, the yields predicted in Eqs. (3) and (4) have to be reduced according to the percentage of inorganics (or other components) included in MSW. Figs. 3 and 4 can be used for rapid estimation of CO_2 and NH_3 yields, respectively, from MSW of various compositions.

5. Conclusions

1. Seeding of YW or FW does not significantly affect their decomposition, compared to when these components are composted without the addition of seed. Seeding is necessary for the aerobic decomposition of MXP.
2. CO_2 yields (in g C/dry kg) can be described by the additive model: $Y_{\text{kgC}} = 220F_P + 240F_Y + 370F_F$, with parameters as defined in the text, indicating that interactions among components are insignificant. The model indicates that MXP actually yielded 72% of its CO_2 ultimate yield during the experiment.
3. NH_3 yields (in g N/dry kg) can be described by the non-additive model: $Y_{\text{NH}_3} = 1.3F_P + 5.2F_Y + 38F_F - 69F_P F_F$, with parameters as defined in the text. Ammonia emissions are a function of the initial N content of the MSW substrates. Approximately 65% of the initial N of FW_{ns} was volatilized as ammonia.

Acknowledgements

The work presented in this paper was financially supported by USEPA from 1995 to 1999. The support of the USEPA project manager, Ms. Susan Thorneloe, is acknowledged. The authors also like to acknowledge Mr. Paul Fritschel, director of the Environmental Engineering Laboratory, for his assistance.

References

- Baca, M.T., Fornasier, F., Nobili de, M., 1992. Mineralization and humification pathways in two composting processes applied to cotton wastes. *J. Ferment. Bioeng.* 74 (3), 179–184.
- Berthouex, P.M., Brown, L.C., 1994. *Statistics for Environmental Engineers*. CRC Press Inc., FL, pp. 151–160 and 191–200.
- Bono, J.J., Chaloux, N., Chabbert, B., 1992. Bench-scale composting of two agricultural wastes. *Biores. Technol.* 40, 119–124.
- Box, G.E., Hunter, W.G., Hunter, J.S., 1978. *Statistics for Experimenters: an Introduction to Design, Data Analysis and Model Building*. Wiley, NY, pp. 306–351.
- Cook, B.D., Bloom, P.R., Halbach, T.R., 1994. A method for determining the ultimate fate of synthetic chemicals during composting. *Compost Sci. Util.* 2, 42–50.

- Cornell, J.A., 1990. Experiments with Mixtures: Designs, Models, and the Analysis of Mixture Data, second ed. Wiley, New York.
- Diaz, L., Savage, G., Eggerth, L., Golueke, C., 1993. Composting and Recycling Municipal Solid Waste. Lewis Publishers, Boca Raton.
- Gray, K.R., Sherman, K., Biddlestone, G., 1971. A review of composting – Part 1. *Process Biochem.* (June), 32–36.
- Inoko, A., Miyamatsu, K., Sugahara, K., Harada, Y., 1979. On some organic constituents of city refuse composts produced in Japan. *Soil Sci. Plant Nutr.* 25 (2), 225–234.
- Komilis, D.P., Ham, R.K., 2000. A laboratory method to investigate gaseous emissions and solids decomposition during composting of municipal solid wastes. *Compost Sci. Util.* 8 (3), 254–265.
- Magalhães, A.M.T., Shea, P.J., Jawson, M.D., Wicklund, E.A., Nelson, D.W., 1993. Practical simulation of composting in the laboratory. *Waste Manage. Res.* 11, 143–154.
- Michel Jr., F.C., Adinarayana, Reddy, C., Forney, L.J., 1993. Yard waste composting: studies using different mixes of leaves and grass in a laboratory scale system. *Compost Sci. Util.* 1 (3), 85–96.
- Nakasaki, K., Yaguchi, H., Sasaki, Y., Kubota, H., 1993. Effects of pH control on composting of garbage. *Waste Manage. Res.* 11, 117–125.
- Nakasaki, K., Aoki, Nobuto, Kubota, Hiroshi, 1994. Accelerated composting of grass clippings by controlling moisture level. *Waste Manage. Res.* 12 (1), 13–20.
- Nakasaki, K., Kuratomi, H., Wakizaka, H., Hiyama, R., Akakura, N., 1998a. Quantitative analysis of ammonia and odorous sulfur compounds evolved during thermophilic composting. *Waste Manage. Res.* 16 (6), 514–524.
- Nakasaki, K., Akakura, N., Atsumi, K., Takemoto, M., 1998b. Degradation patterns of organic material in batch and fed-batch composting operations. *Waste Manage. Res.* 16 (5), 484–489.
- Palmisano, A.C., Maruscik, D.A., Ritchie, C.J., Schwab, B.S., Harper, S.R., Rapaport, R.A., 1993. A novel bioreactor simulating composting of municipal solid waste. *J. Microbiol. Meth.* 18, 99–112.
- Poincelot, R.P., Day, P.R., 1960. Rates of cellulose decomposition during the composting of leaves combined with several municipal and industrial wastes and other additives. *Compost Sci.* 49, 3.
- Schwab, B.S., Ritchie, C.J., Kain, D.J., Dobrin, G.C., King, L.W., Palmisano, A.C., 1994. Characterization of compost from a pilot plant-scale composter utilizing simulated solid waste. *Waste Manage. Res.* 12, 289–303.
- Sikora, L.J., Ramirez, M.A., Troeschel, T.A., 1983. Laboratory composter for simulation studies. *J. Environ. Qual.* 12 (2), 219–224.
- Suler, D.J., Finstein, M.S., 1977. Effect of temperature, aeration and moisture on CO₂ formation in bench-scale, continuously thermophilic composting of solid waste. *Appl. Environ. Microbiol.* 33 (2), 345–350.
- Tchobanoglous, G., Theisen, H., Vigil, S.A., 1993. *Integrated Solid Waste Management: Engineering Principles and Management Issues*. McGraw Hill Inc., pp. 52–63.
- Tseng, D.Y., Chalmers, J.J., Tuovinen, O.H., Hoitink, A.J., 1995. Characterization of a bench-scale system for studying the biodegradation of organic solid wastes. *Biotechnol. Prog.* 11, 443–451.
- Wang, J.-Y., Stabnikova, O., Ivanov, V., Tay, S.T., Tay, J.-H., 2003. Intensive aerobic bioconversion of sewage sludge and food waste into fertilizer. *Waste Manage. Res.* 21, 405–415.