Los Angeles, London, New Delhi
and Singapore
http://www.sagepub.com

ISSN 0734–242X
Waste Management & Research
2008: 26: 47–60

Green house gas emissions from composting and mechanical biological treatment

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In order to carry out life-cycle assessments as a basis for far-reaching decisions about environmentally sustainable waste treatment, it is important that the input data be reliable and sound. A comparison of the potential greenhouse gas (GHG) emissions associated with each solid waste treatment option is essential. This paper addresses GHG emissions from controlled composting processes. Some important methodological prerequisites for proper measurement and data interpretation are described, and a common scale and dimension of emission data are proposed so that data from different studies can be compared. A range of emission factors associated with home composting, open windrow composting, encapsulated composting systems with waste air treatment and mechanical biological waste treatment (MBT) are presented from our own investigations as well as from the literature. The composition of source materials along with process management issues such as aeration, mechanical agitation, moisture control and temperature regime are the most important factors controlling methane (CH_4), nitrous oxide (N_2O) and ammoniac (NH_3) emissions. If ammoniac is not stripped during the initial rotting phase or eliminated by acid scrubber systems, biofiltration of waste air provides only limited GHG mitigation, since additional N_2O may be synthesized during the oxidation of NH_3, and only a small amount of CH_4 degradation occurs in the biofilter. It is estimated that composting contributes very little to national GHG inventories generating only 0.01–0.06% of global emissions. This analysis does not include emissions from preceding or post-treatment activities (such as collection, transport, energy consumption during processing and land spreading), so that for a full emissions account, emissions from these activities would need to be added to an analysis.

Keywords: Greenhouse gas (GHG) emissions, open composting, in vessel composting, home composting, mechanical biological waste treatment (MBT), biofilter, wmr 1318–2

Introduction

The life-cycle framework is advocated as a modern tool for assessing the best, namely the most environmentally friendly, option for the collection, treatment, disposal or use of a specific waste stream (COM 2005). The potential environmental impacts of biological waste treatment systems (e.g. aerobic in-vessel or windrow systems with and without forced aeration; anaerobic digestion), including their pollution potential and contributions to climate change have been under consideration for about a decade. (e.g. Wintzer *et al*. 1996, Raninger 1999, Edelmann & Schleiss 1999). To achieve comparable and trustworthy emission data, measurements must respect minimum standards in order to avoid major errors and misinterpretations. The demand for closed composting systems and purification of gaseous emissions must be assessed by considering the likely effectiveness of such systems in reducing pollution and greenhouse gas (GHG).emissions. The purpose of this paper is to consider some GHG emission data from controlled composting processes, discuss some important methodological prerequisites for proper measurement and data interpretation, and propose a common scale and dimension of emission data for a better comparison of gained data. The emission data presented is from our own investigations as well as from the literature. Methodological concerns are discussed in the context of our own methods of

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DOI: 10.1177/0734242X07088432
Received 22 August 2007; accepted 18 December 2007
Figures 5, 8 appear in color online: http://wmr.sagepub.com

measuring emissions from open windrow composting and backyard composting (Amlinger & Peyr 2002, 2003).

Materials and methods applied for the full-scale emission trials on backyard and windrow composting

- Backyard composting (BYC-1 and BYC-2): Two series of backyard composting measurements were conducted over 12 (BYC-1) and 52 (BYC-2) weeks, respectively. Simple wooden composters (100 cm × 100 cm × 80 cm) were used. The gaseous emissions (CO_2, CH_4, NH_3 and N_2O) were measured throughout the composting and maturation period using an open static or dynamic (BYC-2) emission chamber that contained all of the composters tested in a given series (Figure 1). Separated organic household waste (biowaste) taken from a suburban multi-storey borough was added weekly in amounts of 6–50 kg per composter. Each biowaste addition was covered with a thin layer (3–6 kg) of chopped woody yard waste and a synthetic textile fleece. Temperature was measured by sensors in the centre (approximately 30 cm below the surface) and in the peripheral zone, and a data logger recorded the results. Further details of the experimental design of the experiments are summarized in Table 1.
- Windrow composting (WR): Composting trials with three different feedstocks were tested in open windrows and the results compared. Each feedstock was tested in duplicate, and the windrows were operated without forced aeration but with regular mechanical turning. The feedstocks tested were: (1) biowaste compost (WR-BW/1; WR-BW/2), (2i) green waste (WR-GW/1; WR-GW/2), and (3) sewage sludge (WR-SS/1; WR-SS/2). Details about the materials are summarized in Table 2. In each case, homogenized feedstock was configured in windrows with a triangular cross s… (approximately 2.2 m × 8.2 m × 1.1–12 m) i… …ion chamber. The windrows w… …twice weekly.

For both the backyard and windrow composting systems, gaseous emission of total volatile C, CH_4, CO_2, NH_3, N_2O was measured over a period of approximately 12 h every 2 to 4 days. The gas samples were continuously extracted from the waste gas duct using a heated sampling probe and routed via a heated sample gas line to a flame ionization detector (FID) for total volatile organic carbon determination. To determine the other gas concentrations (NH_3, N_2O, CH_4, CO_2), the sample gas stream was passed through a cooler for moisture removal and then to a Fourier transform infrared spectrometer (Boxberger *et al*. 1997). The measured pollutant concentrations (collected every 3 min) as well as the reference variables (temperature, pressure, flow rate) were transmitted to a computer-based registration system that performed the necessary calculations and averaged results to generate half-hour and daily mean values. To evaluate cumulative emission factors, the emission rates between the measurement periods were estimated by linear interpolation.

Volatile organic compounds (VOC) were measured in three of the windrow variants (WR-BW/1; WR-GW1; WR-SS/2). Two methods were used: (1) active sampling with sampling tubes and (2) passive sampling with activated carbon tubes. In the first case, measurements were carried out at the air outlet and inlet stream at an air rate of approximately 500 mL min^{-1}. Samples were taken after the windrows were first configured and again after 2 weeks of composting and two turnings. For passive sampling, activated carbon tubes were placed at the two sampling locations over a period of 2 weeks after the windrow were configured. Alkanes, terpenes, aromatic compounds, chlorbenzene, chlorinated hydrocarbons, phenoles, kresole, acetates, ketones, alcohols, polycyclic compounds, sulphuric compounds were eluted with solvents (carbon disulphide and methanol) and …sed with capillary gas-chromatography and a mass-sele… …or or a flame ionization detector. Aldehyde was … …atonitrile and detected by high-pressure li… …ith a UV detector.

Table 1: Experimental data of backyard composting trials BYC-1 and BYC-2.

	BYC-1	BYC-2
Period of weekly biowaste input	3.9.1999–25.11.1999 (12 weeks)	20.4.2000–12.4.2001 (51 weeks)
Period of emission measurements	12.9.1999–23. 3. 2000 (30 weeks)	22.4.2000–1.7.2001 (64 weeks)
Total biowaste input	1775.3 kg	2930.8 kg
Biowaste input week^{-1}	161.4 (eight composters)	57.5 kg (two composters)
Biowaste input day^{-1}	21.1 kg	8.2 kg
Biowaste input year^{-1}	7714.1 kg	2996.4 kg
Biowaste input week^{-1} & composter	min 3.1 kg–max. 46.8 kg	min. 5.7 kg–max. 52.7 kg
Inhabitants served depending on specific biowaste production		
260 kg Inh^{-1} *a	30 Inh	12 Inh
170 kg Inh^{-1} *a	45 Inh	18 Inh
100 kg Inh^{-1} *a	77 Inh	30 Inh
85 kg Inh^{-1}*a	91 Inh	35 Inh
Loss of fresh matter		
Phase 1 (first turning)		34%
Phase 2 (extraction)	30%	41%
Total (after maturation)	57% (m/m)	59%
Leachate water / composter	3.4 l	29–56 l
Leachate water / week & composter	0.3 l	1.5 – 2.1 l

Since input materials were taken every week from source separated organic household waste from a nearby settlement, the raw material was not analysed. Rather, it was important in this experiment to simulate a composting system that is very close to a full-scale typical composting system.

Table 2: Experimental data of windrow composting trials.

	WR-BW/1	WR-BW/2	WR-GW/1	WR-GW/2	WR-SS/1	WR-SS/2
Period of measurements	9 weeks (July–Aug)	11 weeks (Oct–Dec)	4 weeks (Sept–Oct)	21 weeks (May–Oct)	4 weeks (March)	7 weeks (Apr–May)
Days	67	76	29	133	31	49
Material input	5835 kg	5300 kg	4140 kg	3310 kg	4980 kg	6300 kg
Essential quality parameter of input mixture						
C_{org} (% DM)	29.3	33.2	37.3	27.3	22.7	12.5
N_{tot} (%DM)	1.52	2.02	1.35	1.71	2.33*	10.91*
C/N	19.3	16.5	27.6	15.9	9.7*	1.1*
N-soluble (mg per 100 g)			0.1	7.2		52.6
Bulk density (g L^{-1})						
Mass loss during rotting	45%	53%	4%	26%	10%	0%
Water addition	302 L t^{-1}	65 L t^{-1}	394 L t^{-1}	911 L t^{-1}	12 L t^{-1}	101 L t^{-1}

The raw sludge compost mixture was received from two different sewage sludge composting plants. We had no influence on the composition. Both had high and unfavourable N-concentrations leading to very low C/N ratios. This was the main reason why decomposition was considerably inhibited and high N_2O emissions occurred

An emissions measurement protocol

General

In order to ensure that measurement data are representative and comparable from trial-to-trial and also from one experiment to another, a protocol including relevant material handling and technology of processing is essential. The protocol described below was developed based on our own experience and a review of the literature, including VDI 3475 Part 1 (2003). Emission data are reported in units of mass flow rate, e.g kg h^{-1}. The results should be reported after they have been normalized for temperature and pressure conditions, i.e. 0 °C and 1013 hPa, dry basis. The emission factor from a

given source can be calculated as the mass ratio of gas emitted to initial fresh matter mass (kg Mg^{-1}), although sometimes the feedstock is reported in units of dry mass.

Measurement planning

Before commencing emission measurements, a measurement plan that accounts for all influencing parameters of relevance to the emissions should be prepared. If the aim is to evaluate all aspects of the composting process, the plan must include measurements that reflect contributions from material delivery, mechanical sorting, and biological treatment. It should also include plans for measurement of emissions associated with interim storage, packaging, and disposal of stabilized ripe compost product. Each step should be monitored continuously, at least for some small recurring time unit. The calculation for balancing the emissions must consider all parts of the process when reporting the treatment times. However, emissions during application of compost, i.e. as fertilizer, do not belong to the composting treatment process.

Sampling locations

Measuring the gas composition inside a windrow or in an open curing stage is useful for monitoring the aerobic milieu and the treatment conditions, but it is not a good means to estimate air emissions. Appropriate sampling locations are those that are easily inspected and preferably contained, such as stacks. The sampling locations must be representative of all areas of the active and passive source exhibiting different types of emission behaviour. Consequently, the number of required sampling locations is governed by the composition of the material and treatment conditions rather than the size of the area source. Suitable sampling locations should be provided in every plant, and area sources also need to be investigated because they are frequently in use. Thorough sampling plans to collect reliable data can require significant expenditure.

a. Point sources: the sampling location must be permanently installed, meet occupational health and safety standards and be readily accessible for carrying out the measurements. They are to be selected in accordance with the requirements of guidelines VDI 4200 (2000) and VDI 2066 Part 1 (2006).
b. Active area (non-point) sources: in order to collect reliable emission data from non-enclosed wide surface biofilters or active aerated windrows with fans, these units need to be covered temporarily with a wide thin foil sealed against disturbing ambient air. The emission concentration of the waste gas can then be measured within the covering. The waste gas flow rate can be measured in the pipes serving the aerating fan.
c. Passive area (non-point) sources: passive aerated windrows and compost storage piles similarly need to be temporarily covered by a wide thin foil tunnel sealed against ambient air if good emission data are to be collected. They would also need to be aerated with clean air by a suitable fan. The emission concentration of the waste gas could be measured within the exhaust gas of the foil tunnel. The waste gas flow rate can then be determined in the pipes that belong to the aerating fan. Emissions would be calculated as a flux (mass flow per m^2 surface area) from the tunnel-covered passive area source. Turning activities from windrows is an example of a process from which emissions are particularly difficult to measure.
d. Fugitive sources: composting facilities typically have a variety of fugitive emission sources, such as open buildings and open transportation and loading areas, where it is difficult to collect good emission data. Such areas require temporary encapsulation and a source of controlled air flow to measure. An alternate solution is to use a dilution tracer gas method (e.g. SF_6) to calculate the source strength.

Measured parameters and measurement methods

Continuous measurements are appropriate for point sources and for area sources whereas emissions are temporarily capsulated. The monitoring and registration systems also must be adequate. Parameters to be continuously monitored include total organic carbon (TOC), N_2O and CH_4. A manual discontinuous analysis of N_2O and CH_4 with gas chromatography from single gas samples is acceptable for measurements over short-term durations.

The CO_2 from composting is not fossil derived, and therefore, it is not counted as a greenhouse gas emission. A suitable method for NH_3 analyses is to extract it from the waste gas stream by absorbing it in sulfuric acid and then measuring the resulting solution photometrically. To ensure valid emission monitoring data, such testing is subject to various standards and guidelines that regulate the minimum requirements for measuring instruments, function tests and calibrations (DIN EN, VDI). Our measurement protocol described above meets all of these requirements.

In summary, gas samples collected with probes inserted into a compost pile are not acceptable. The environmental performance of the systems can only be judged by coverage of the entire emission source (compost pile or windrow) and the waste air flow from it. Furthermore, emissions from all relevant phases of the process must be considered over the entire process duration.

Results and discussion

General overview of emission factors

Data here are limited to emissions from the composting operation only. Peripheral associated activities would need to be added for a complete accounting of system-wide GHG emissions. Table 3 shows the CO_2, NH_3 and GHG (CH_4, N_2O) emission factors for biowaste, green waste, sewage sludge and manure composting derived from our own and other research studies. All emission factors are given in kg or g per Mg fresh matter (FM) input material. We consider this to be the dimension that should be used for general comparison of

Table 3: Emission factors of GHG and ammoniac per Mg fresh matter input material; own investigations and data from literature.

	CO_2 (kg Mg^{-1} FM)	CH_4 (g Mg^{-1} FM)	NH_3	N_2O	CO_2-equ (kg Mg^{-1} FM)	Experimental rotting time
Windrow BW-1: own trials	43	293	52	27	14.4	9 weeks
Windrow BW-2: own trials	115	243	576	116	41.2	12/21 weeks
Windrow GW-1: own trials	118	49	25	25	8.6	4 weeks
Windrow GW-2: own trials	194	604	354	178	67.9	21 weeks
Windrow SS-1: own trials	10	37	25	266	83.3	4 weeks
Windrow SS-2: own trials	25	45	19	165	52.0	7 weeks
Manure composting : Amon *et al*. (1998)	–	142	643	34	13.8	11 weeks summer, dry
	–	692	303	47	36.4	11 weeks, spring (cooler, humid)
Stocked manure: Amon *et al*. (1998)	–	1354	163	52	60.9	11 weeks, summer
	–	512	46	80	38.6	11 weeks, spring (cooler, humid)
Backyard/BYC-1: own trials	215	2185	972	454	186.7	12 weeks mat. input
Backyard/BYC-2: own trials	139	788	474	192	76.1	51 weeks mat. input
Biowaste aerated table heap,	173	1840	670	120	75.6	54 measurements.
in hall; raw gas (Gronauer et al., 1997)						height: 1.8 m
Biowaste windrows (Hellmann, 1995)	150–230	880–1400	–	150–180	65.0–85.2	min.-max. values: height: 1.2–1.5 m
Trials with turning frequency:						
Daily (BioW : GW = 40 : 60)	383	266	–	195	66	7.5 weeks
Every 3 days (BioW : GW = 40 : 60)	378	628	–	232	85.2	
Once per week (BioW : GW = 40 : 60)	373	863	–	158	67.2	
Every 3 days (BioW : GW = 40 : 60)	317	360	–	120	44.8	11.5 weeks
Once per 3 weeks (BioW : GW = 40 : 60)	277	933	–	78	43.7	
Every 3 days (BioW : GW = 100 : 0)	256	237	–	150	51.5	12.5 weeks
Every 3 days (BioW : GW = 80 : 20)	134	514	–	67	31.5	
Every 3 days (BioW : GW = 60 : 40)	168	146	–	78	27.2	
Every 3 days (BioW : GW = 40 : 60)	235	63	–	172	54.6	
Every 3 days (BioW : GW = 20 : 80)	212	129	–	22	9.5	
Bio and green waste (own measurements): raw gas; aerated table heap		1517		252	50–100	12 weeks
Tunnel reactor (own measurements)						2–3 weeks
raw gas winter	–	816	–	21	23.6	high temperatures
raw gas summer	–	1132	–	29	32.8	
10 m^3 tunnel reactor (Leinemann, 1998): raw gas	–	683	–	62	33.6	
MBT mean (own measurements): raw gas	120–185	110–1200	400–1600	50–200	17.8–87.2	Varying rotting periods

BW, biowaste including kitchen waste; GW, green waste (garden and park waste); SS, sewage sludge.

treatment systems and processes. Using other scales such as dry matter basis or area (m^2) introduces additional uncertainty factors, since this information is very often not known or documented.

The data show that despite varying process conditions and the lack of complete information in some cases, it is possible to identify reliable ranges of emission factors. From the total emission of CH_4 and N_2O and (CO_2 as produced here and NH_3 emissions are not counted toward GHG emissions) we can estimate a CO_2 equivalent emission factor of 20–65 kg Mg^{-1} FM resulting from the entire composting process of biowaste or green waste materials. Values in excess of this probably indicate some kind of system mismanagement, such as use of an unbalanced initial mixture of source materials (high available N sources and low C/N ratio, low structure and air-filled pore space, respectively, excessive moisture) or insufficient aeration and mechanical turning of the material. Values below this range are hardly achievable and would suggest

Table 4: Methane in percentage of total C emissions and CH_4-C/kg CO_2-C.

		Emitted CH_4 in percentage of total C emissions	G CH_4-C/kg CO_2-C
Own investigations			
Windrow composting	Biowaste	0.77–2.46	5.83–18.77
Turning: 1–2 × per week	Green waste	0.15–1.13	1.13–8.58
	Sewage sludge	0.64–1.33	4.84–10.08
Backyard composting	Composters: 0.8 m^3	2.05–3.62	15.59–27.94
Results from literature			
Hellmann (1995)	Biowaste / several proportions of structure materials and turning frequencies		0.37–10.56
Marb *et al*. (1997)	Biowaste/green waste mixture;	Mean: 2.4; median: 2.1	
	1 m^3-reactors with 400–500 kg	Range: 1.0–10.3	
Gronauer *et al*. (1997)	Biowaste / closed reactor with aerated table heap during maturation	3	
Wintzer *et al*. (1996)	Estimation; no measurement carried out	Up to 10	
Edelmann & Schleiss (1999)	Biowaste / Compaq box + trapezoid heaps during maturation	5.12	

that either incorrect measurements or calculations were to blame, or extreme and atypical conditions existed, such as too short composting duration, incomplete decomposition, or a very high C/N ratio existed.

Our own measurements showed that the highest emission rates (76 kg CO_2-equ Mg^{-1}) tended to be from home composting of treated kitchen and garden waste that was mechanically turned every 12 weeks (BYC-2). We consider the results from this experiment to be highly representative, since they represent a full year of regular measurements that covered typical continental seasonal variations. On the other hand, results from the first experiment (BYC-1), in which 186 kg CO_2-equ Mg^{-1} were generated, might be questionable, since due to calibration problems, no measurements could be performed for more than 2 months, and in order to report the cumulative emissions, data from this period had to be interpolated.

The fact that the waste was not turned for at least 12 weeks and contained comparatively high proportions of kitchen waste may explain the higher emission factors for CH_4 and N_2O, even though the waste was contained in less than 0.8 m^3 composters. CH_4 emission factors of 788 g CH_4 Mg^{-1} are in the range of wet manure composting (Amon 1998). With regard to other literature CH_4 emission rates reported relative to total emitted C, we believe that values greater than 2.5% CH_4 of C_{tot} may be overestimates (Table 4).

To relate GHG emissions to the efficiency of aerobic decomposition and organic matter transformation, we propose that the ratio of a GHG emission factor [kg CO_2-equ Mg^{-1} treated material = (kg CH_4 $Mg^{-1} \times 21$) + (kg N_2O $Mg^{-1} \times 310$)] to the CO_2 produced be used. Ratio values exceeding 0.3 to 0.5 would indicate undesirable decomposition conditions.

In our own experiments, windrow composting achieved ratios of 0.34 and 0.36 for the biowaste variants and 0.07 and 0.35 for green waste, respectively (Table 5). The sewage sludge composts, with very low decomposition rates and high N_2O production, yielded extreme ratios of 2.05 and 8.29. For the second backyard composting trial that was monitored over more than 52 weeks, the process yielded an acceptable ratio of 0.55.

Some specific findings in open and closed composting systems

Typical dynamics of GHG and ammoniac emission

The appearance of CH_4, N_2O and NH_3 shows a typical pattern during intensive rotting and maturation (Figure 2). When the mean GHG emission rate is expressed as a percentage of CO_2 production, a clear pattern of temperature dependency emerges. CH_4 and NH_3 concentrations are highest at temperatures above 40–50 °C, whereas N_2O only appears when the temperature falls below 45 °C. This finding is consistent with previous reports (Hellmann 1995, Schießl 1995, Tollknäpper 1996, Hao *et al*. 2001). Thus, CH_4 and N_2O have inverse relationships with respect to decomposition. Cuhls (2001) found that high CH_4 concentrations in windrow zones always corresponded to low N_2O concentrations. During maturation at temperatures of 35 °C and below, there was a certain baseline amount of N_2O and CH_4

Table 5: Greenhouse gas emissions (methane + nitrous oxide as CO_2-equ) in relation to natural CO_2 formation of own backyard and windrow composting experiments.

	BYC-1	BYC-2	WR-BW/1	WR-BW/2	WR-GW/1	WR-GW/2	WR-SS/1	WR-SS/2
CO_2-equ kg CO_2^{-1} t^{-1} DM	0.87	0.55	0.34	0.36	0.07	0.35	8.29	2.05

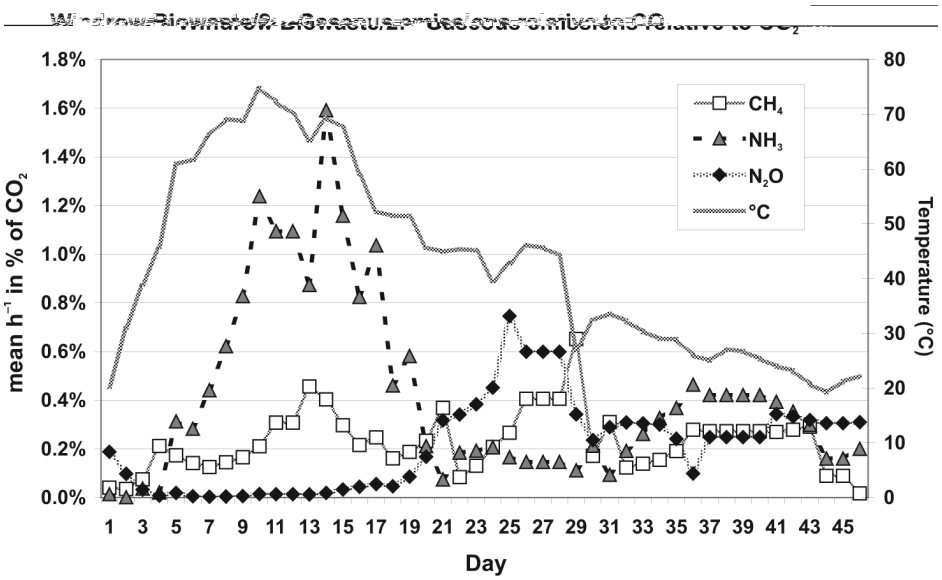


Fig. 2: Gaseous emissions relative to CO_2 production during composting of biowaste (WR-BW/2).

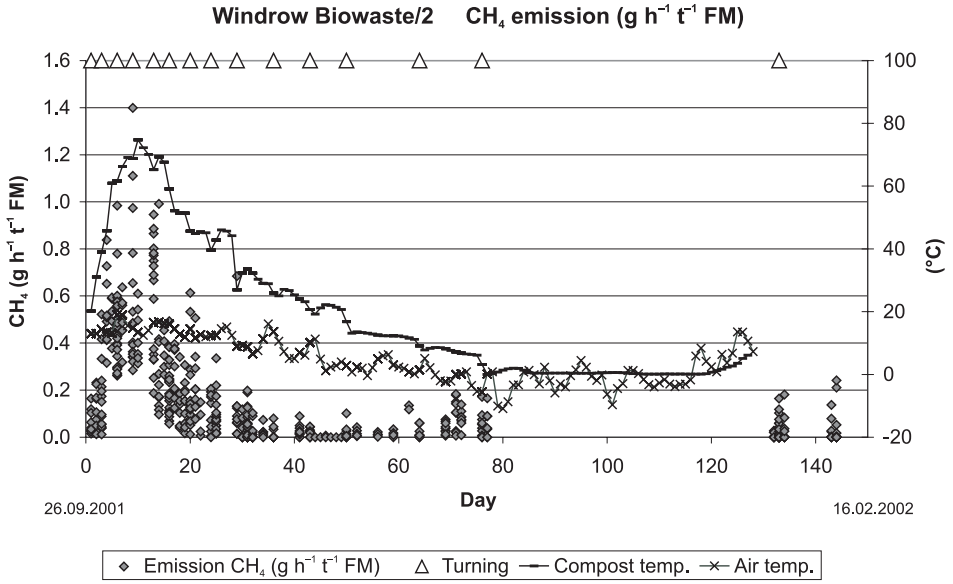
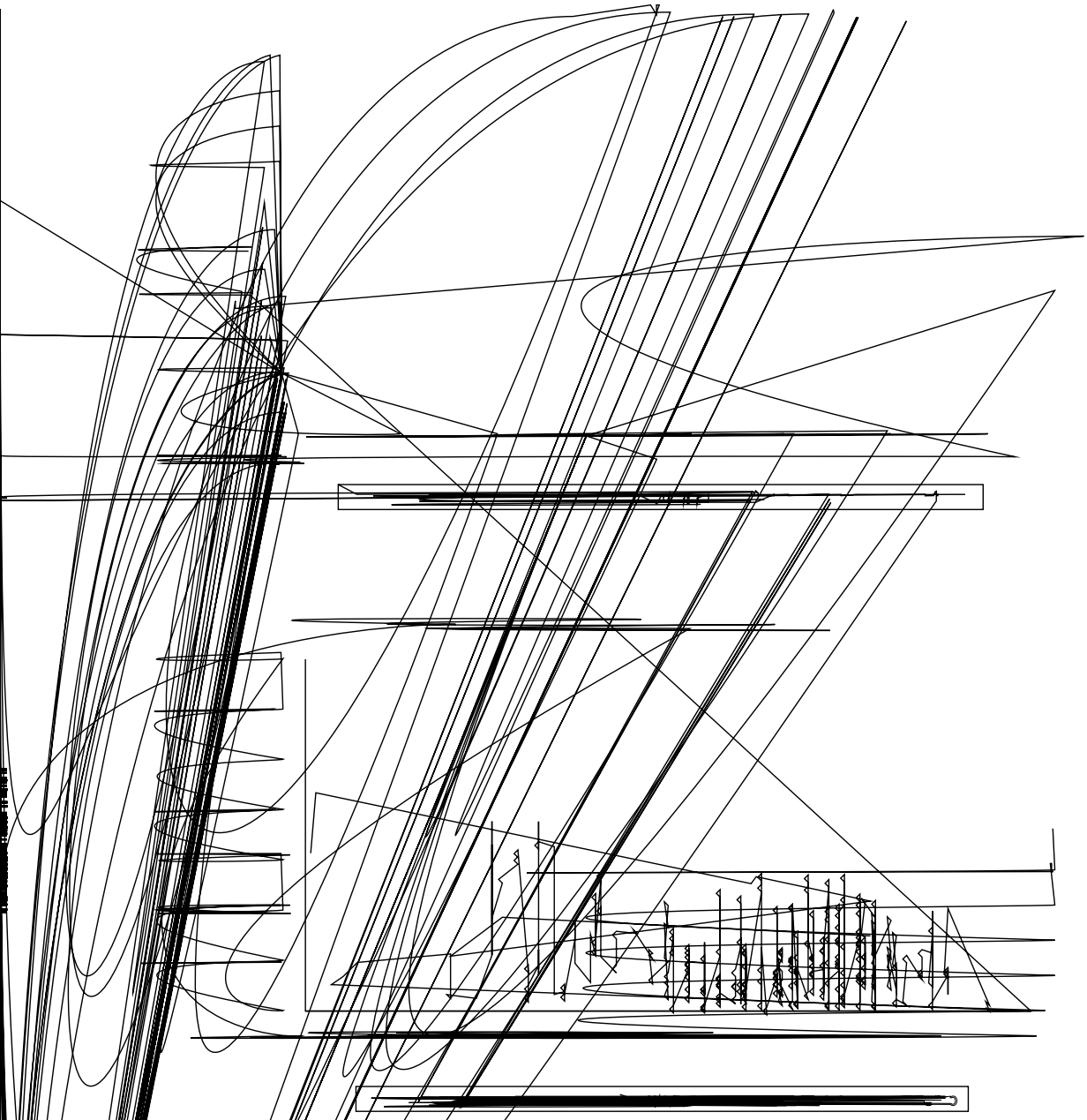


Fig. 3: CH_4 emission rates during biowaste windrow composting [WR-BW/2].

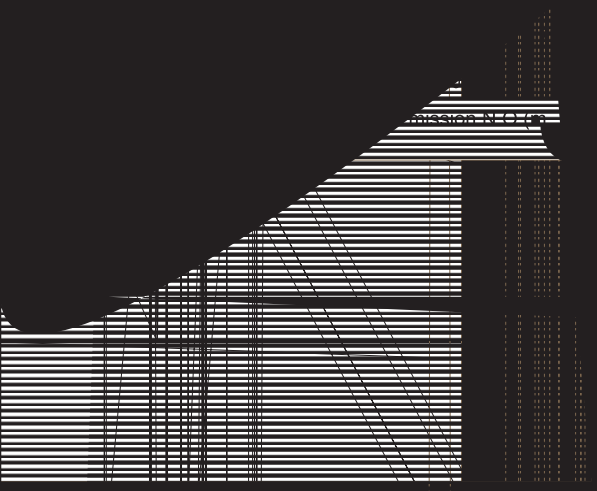
produced that reflects available N and C sources, which has also been documented by others (Hellmann 1995, Hellebrand & Kalk 2000).

Methane and N_2O emission measurements over the duration of composting showed that there were differences among the three feedstocks: biowaste, green waste windrow and backyard composting (Figures 3–8). Biowaste, which contains a considerable amount of easily degradable kitchen waste, shows a typical decomposition dynamic (indicated by the temperature curve). CH_4 peaks were found during thermophilic degradation, whereas N_2O emission rates rose mainly in the mesophilic rotting stages. After 12 weeks, both sets of gas emission data mirror what would be expected of well stabilized compost. Sustained stabilization was confirmed with a control measurement in week 21, in which gas emissions were found to remain at the same low level.

In contrast, green waste, with a high proportion of ligneous and bulky constituents, showed a more even and slow degradation pattern with constant gas emission levels over the entire test period. Extreme values for short periods were missing. Even after 21 weeks, CH_4 and N_2O emission rates were only slightly reduced. Reviewing emission patterns from backyard composting, in which weekly input of material occurred, two main observations can be made: (1) despite a clear seasonal dependency of the temperature profile, after each material addition of 5–50 kg waste per composter, the temperature rose in nearly each case to 50–65 °C and remained greater than 50 °C for at least 2 to 3 days; (2) the weekly material addition resulted in a continuous and constant emission of CO_2 and



c[illegible] effluent were higher than those in the i[illegible] own). This phenomenon predominantly [illegible] ammonium/ammoniac concentration in the [illegible] monthly parallel waste gas measurements [illegible] biofiltration at the MBT plant in Bassum com[illegible] N_2O concentrations increased two- to 10-old after [illegible]ration. Trimborn *et al*. (2003) suggested that ndepend[illegible] from the level of NH_3 load in the raw waste gas, about 2[illegible] nd 9% of the NH_3 that enters the biofilter is trans-forme[illegible] nd released as N_2O and NO, respectively. Continuous a[illegible]obic conditions in the biofilter probably support the mic[illegible]bial oxidation of NH_4^+ to NO_2^-, and then high concentra[illegible]ons of NH_3 and NO_2^- inhibit further oxidation to NO_3^- ([illegible]ector 1998a, b). NO_2



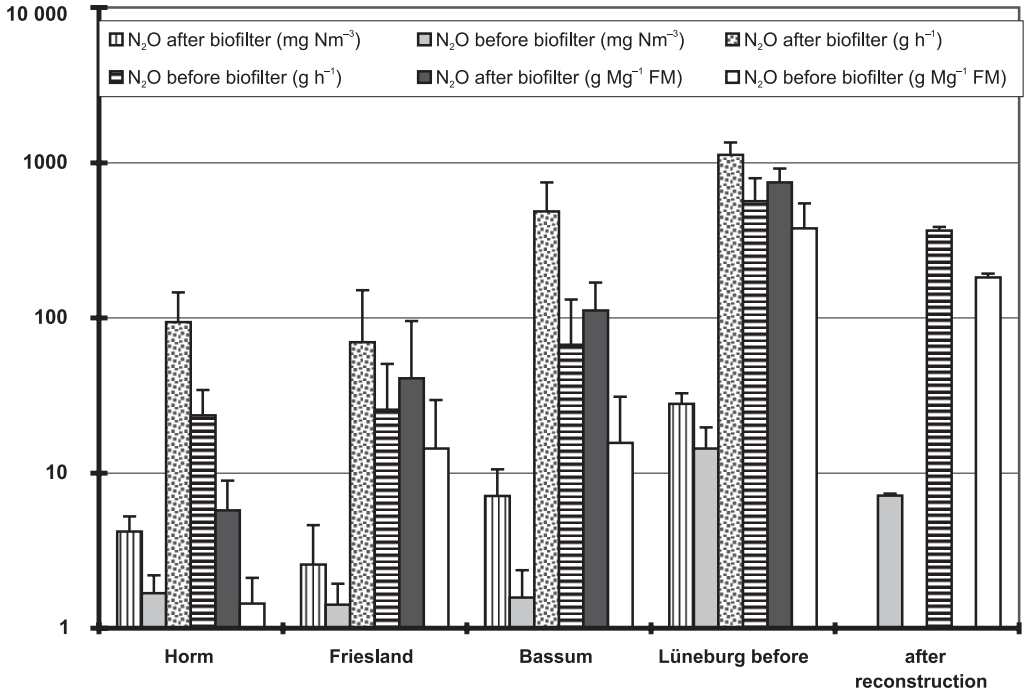


Fig. 10: N_2O emission concentration (mg N^{-1} m^{-3}); emission mass flow (g h^{-1}), emission factor (g Mg^{-1} FM); with standard deviation in four compost and MBT plants respectively with forced aeration and waste air treatment.

Table 6: Emission of GHG and ammoniac in Austria and Germany.

Gas	Germany (Mg)[a]		Austria (Mg)[b]	
	Individual gases	CO_2-equivalent	Individual gases	CO_2-equivalent
CO_2 (without LUCF)[c]	857 907 000	857 907 000	65 778 000	65 778 000
CH_4	2 885 000	60 583 000	454 000	9 541 000
N_2O	194 000	60 079 000	7350	2 279 000
Sum GHG		978 569 000		77 598 000
NH_3	598 000		98 600[d]	

[a]GHG monitoring report 2001, Environment Agency Germany; values from 2000.
[b]Ritter (2000): values from 1999.
[c]Data from national CO_2 inventories; Land-Use Change and Forestry (LUCF) is not included.
[d]Amon *et al*. (1998) this figure consists of the following components: life stock: 67.3 kt; mineral N fertilizer: 10.4 kt; stationary combustion: 0.4 kt; industries: 4.7 kt; traffic: 1.0 kt; households, waste, waste water: 7.1 kt; natural sources: 7.7 kt.

Table 7: Basic data used for the estimation of GHG and NH_3 emissions of the compostings process in Austria and Germany.

Gases	Emission factor (kg Mg^{-1} FM)		Yearly emission from composting (Mg $year^{-1}$)		CO_2 equivalent (Mg $year^{-1}$)		CO_2 equivalent (% of national emissions)	
	Austria	Germany	Austria[a]	Germany[b]	Austria	Germany	Austria	Germany
CH_4	0.05–0.49	0.5–1.0	39–484	3400–6800	817–10 160	71 400–143 000	0.01–0.11	0.12–0.24
NH_3	0.025–0.576	0.1–0.6[c]	20–462	680–4100	–	–	(0.02–0.47)[d]	(0.11–0.69)[e]
N_2O	0.025–0.178	0.02–0.18	20–143	136–1200	6083–44 169	42 200–372 000	0.27–1.94	0.070–0.62

[a]800 680 Mg $year^{-1}$ FM biowaste and green waste treatment (Amlinger *et al*. 2001).
[b]6.8 Mt $year^{-1}$ input FM (4.1 Mt biowaste and 2.7 Mt green waste).
[c]After biofilter (for the proportion of enclosed facilities).
[d]In percentage relative to national NH_3 emissions of 98 600 Mg.
[e]In percentage relative to national NH_3 emissions of 598 000 Mg.

Table 8: Relative contribution of biowaste and green waste composting to the national GHG inventory in Austria and Germany: unit is percentage of national GHG inventory.

	CO_2	CH_4	NH_3	N_2O	CO_2-equ
Austria					
Total potential biowaste and green waste composting: 800 680 Mg	0.06–0.25	0.01–0.11	0.03–0.47	0.87–2.71	0.01–0.06
Germany					
Biowaste and green waste treated in compost facilities: 6 800 000 Mg	0.12–0.20	0.12–0.24	0.11–0.69	0.070–0.62	0.01–0.05

Requirements for the initial material mix for composting with the aim to minimize GHG emissions

From our own investigations and other reports, we conclude that in order to minimize GHG and NH_3 emissions from composting, the following recommendations can be followed.

- C/N-ratio: a low C/N ratio feedstock will yield high NH_3 emissions, particularly when it is well aerated and a high temperature is maintained. Therefore a C/N ratio > 25 will help to minimize NH_3 and N_2O emissions. However, a C/N ratio > 35 may result in the available nitrogen pool limiting the proper decomposition and humification process. Materials rich in N (sewage or industrial sludge, digestion residues from anaerobic digestion, specific residues from food processing, kitchen waste, poultry manure, etc.) must be mixed and homogenized with sufficient cellulose and ligneous materials.
- Humidity: initial humidity should be 65/70% (w/w), and a humidity of 50 to 60% should be maintained in subsequent stages.
- Structure/bulking material: bulking material should be added to constitute 40–60% of the mix by volume. This supplement is needed to provide the necessary air-filled pore space throughout the composting process. However, a consistent general relation between proportion of bulking agents and GHG formation has not been described because too many accompanying parameters (height and cross-section of windrow, particle size and structure of shredded wood, C/N ratio, turning frequency and technique as well as aeration system, structure and water retention capacity of mixing partners, etc.) are interfering factors.
- Additives: although this has not been specifically investigated in the experiments practical experience indicates that the addition of up to 10 % (v/v) mature compost will ensure the early formation of humic substances and effective binding of soluble and volatile carbon and nitrogen sources.

Key recommendations for process management practices that will minimize GHG and NH_3 emissions are shown in Table 9. Many of these are the same basic rules of compost quality management used to reduce odours and optimize decomposition and humidification.

Our recommendations to reduce N_2O emissions in a closed composting system with waste air treatment are:

1. High aeration and effective stripping of NH_3 during early stages of the thermophilic decomposition phase will reduce N_2O formation. It will widen the C/N ratio during the subsequent maturation at lower temperatures.
2. Maintaining a temperature range of > 40 to 55/60 °C as long as possible will suppress N_2O formation.
3. High NH_3 concentrations in the raw gas should be removed by pre-treatment with acid scrubbers.

Table 9: Specific measures and their effects on GHG and ammoniac emissions in open and closed composting systems.

Measure	CH_4	NH_3[a]	N_2O
Open windrow systems without waste air treatment			
Increased proportion of structure material; increased turning frequency	Positive, enhances O_2-supply suppresses CH_4 formation	Higher aeration (turning) may slightly increase NH_3 formation. This is also supported by: • the rise in pH • increased evaporation.	potentially negative, optimized O_2 supply at temperatures < 45 °C may enhance N_2O formation as intermediate product of nitrification and denitrification.
Optimized humidity by controlled water addition Coverage by fleece (geo-textile) or roof in order to drain rain water off Closed/encapsulated composting systems with waste air treatment (box, tunnel, hall, etc.)	Positive, prevention of water logging and the creation of anaerobic zones	Excess of water may induce deoxidizing conditions (denitrification) and an accumulation of NH_4^+, drying may result in increased NH_3 emission.	Excess water may result in considerable O_2 deficiency during maturation; this induces denitrification and formation of N_2O.

Table 9: Specific measures and their effects on GHG and ammoniac emissions in open and closed composting systems. *(Continued)*

Measure	CH_4	NH_3[a]	N_2O
Enhancing turning frequency or aeration rate	Positive, enhances O_2-supply suppresses CH_4 formation	Higher aeration (eventually turning) may slightly increase. This is also supported by: • increased NH_3 stripping • increased evaporation • increased evaporation	Potentially negative, optimized O_2 supply at temperatures < 45 °C may enhance N_2O formation as intermediate product of nitrification and denitrification
Temperature control: < 45–65 °C after sufficient sanitization	Positive the maximum CH_4 production takes place during the first intensive decomposition phase at high temperatures because of a facultative O_2 deficiency. CH_4 formation is clearly minimized below 45/50 °C	Positive the maximum of NH_3 formation during the thermophilic phase parallel to the CH_4 dynamic	The maximum of N_2O formation < 40/45 to 30 °C; minimum at higher temperatures
Humidity control: should be maintained at 50–60% (w/w)	Positive, prevention of water logging and the creation of a aerobic zones	Excess of water may induce deoxidizing conditions (denitrification) and an accumulation of NH_4^+, drying may result in increased NH_3 emission	Excess of water may result in a considerable O_2 deficiency also during maturation; this induces denitrification of NO_2^- and NO_3^- by forming N_2O
Biofilter	Neutral, only limited degradation (ca. 15%)	Positive, partly to complete degradation	Negative, considerable formation of as intermediate product from NH_3 degradation
Biofilter with preceding acid scrubber	Neutral, only limited degradation (ca. 15%)	Positive, effective elimination by acid scrubber systems	Neutral to slightly negative, limited N_2O formation from NH_3 that was not captured

[a]At early stages emitted NH_3 would not be available anymore for a later N_2O-formation at lower temperatures.

References

Amlinger, F. & Peyr, S. (2002) Environmental impacts of backyard composting – Greenhouse gas emissions, liquid emissions, mass balance, hygienisation potential. Forschungsprojekt im Auftrag von NÖ LReg., OÖ LReg., Tiroler LReg., Stm. LReg., Wiener LReg., Szb. LReg., BMLFUW. http://www.biowaste.at/fileadmin/download/tpq_Klimarelevanz_Hausgartenkompostierung_de.pdf (accessed 6 January 2008).

Amlinger, F. & Peyr, S. (2003) Environmental impacts of decentralized windrow composting – Greenhouse gas emissions, liquid emissions, mass balance, hygienisation potential. Forschungsprojekt im Auftrag von NÖ LReg., OÖ LReg., Tiroler LReg., Stm. LReg., Wiener LReg., Szb. LReg., BMLFUW. http://www.biowaste.at/fileadmin/download/tpq_Klimarelevanz-Mietenkompostierung_de.pdf (accessed 6 January 2008).

Amlinger, F., Peyr, S. & Geszti, J. (2001) Compost management in Austria – quantities and qualities. In: proc. Biowaste Conference, 15–17 May 2001, St. Pölten-Vienna. Edt.: Lower Austria Government, St. Poelten. http://www.biowaste.at/fileadmin/download/bwc_amlinger.pdf (accessed 6 January 2008).

Amon, B. (1998) NH_3-, N_2O- und CH_4-emissions from stable manure management in dairy farm systems: stable – storage – manure spreading. Diss. University of Natural Resources and Applied Life Sciences, Vienna.

Amon, B., Amon T. & Boxberger, J. (1998) Evaluation of Ammoniac emissions caused by Austrian agriculture. Assessment of reduction potentials and options, Forschungsprojekt Nr. L883/94 Im Auftrag des Bundesministeriums für Land- und Forstwirtschaft, 1998

Bartels, P. (2002) Composting – Measurements and toxicological evaluation of volatile organic compounds (VOC) in exhaust air of composting facilities, Dissertation, Christian-Albrechts-Universität zu Kiel

Boxberger, J., Amon, B. & Pöllinger, A. (1997) Liquid and gaseous emissions during solid manure storage and composting. In: 7. Gumpensteiner Lysimetertagung „Lysimeter und nachhaltige Landnutzung; BAL Gumpenstein, 7–9 April 1997; edt: Bundesanstalt für alpenländische Landwirtschaft, Gumpenstein, Irdning.

COM (2005) 666 final: Taking sustainable use of resources forward: A Thematic Strategy on the prevention and recycling of waste Communication from the commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions. http://ec.europa.eu/environment/waste/strategy.html Accessed 6 January 2008.

Cuhls, C. (2001) Balance of volatile pollutants and emission reduction in mechanical-biological waste treatment. Heft 114 der Veröffentlichungen des Institutes für Siedlungswasserwirtschaft und Abfalltechnik der Uni-versität Hannover.

Edelmann, W. & Schleiss, K. (1999) Ecologic, energetic and economic comparison of digestion, composting and incineration of solid organic waste materials. Abfallstoffe Studie im Auftrag von BFE, Bundesamt für Energie und BUWAL, Bundesamt für Umwelt, Wald und Landschaft

Gronauer, A., Claassen, N., Ebertseder, T., Fischer, P., Gutser, R., Helm, M., Popp, L. & Schön, H. (1997) Biowaste composting: techniques and recycling. Bayerisches Landesamt für Umweltschutz; Schriftenreihe Heft 139; München

Gudladt, U. (2001) Potentials of emission reductions by process related measures in composting of biowaste. Dissertation, Kiel

Hao, X., Chang, C., Larney, F.J. & Travis, G.R. (2001) Greenhouse gas emissions during cattle feedlot manure. *Journal of Environmental Quality*, **30**, 376–386.

Hellebrand, H.J. & Kalk, W.D. (2000) Emissions in solid manure composting. *Landtechnik*, **2/2000**, 184–185.

Hellmann, B. (1995) Occurrence of greenhouse gases from biomass aggregations. Abschlussbericht zum Förderprojekt der Deutschen Bundesstiftung Umwelt, Zeller Verlag, Osnabrück

Leinemann, B. (1998) The formation of greenhouse gases during composting as a result of process management and input materials. Dissertation an der Gemeinsamen Naturwissenschaftlichen Fakultät der Technischen Universität Braunschweig.

Marb, C., Dietrich, G., Köbernik, M. & Neuchl, C. (1997) Comparative investigations on composting of biowaste in closed reactors and open windrows: emissions, quality and pollutants. in Müll und Abfall 10/97

Payne, W.J. (1981) *Denitrification*. John Wiley & Sons, Inc., New York.

Raninger, B. (1999) Preferred recovery options for organic waste in Austria. Studie im Auftrag des Bundesministeriums für Umwelt, Jugend und Familie; Wien; 220 S

Ritter, M. (2000) GHG Emission inventory for Austria 1990 to 1999; Reporting within Council Decission 1999/296/EC. von 1990 bis 1999; Berichterstattung gemäß Entscheidung des Rates 1999/296/EG; Interne Berichte, UBA Wien, Dezember 2000

Schießl, K. (1995) N_2O-emissions from open windrow composting. Diplomarbeit in der Abteilung Agraröko-logie der Universität Bayreuth.

Spector M. (1998a) Production and decomposition of nitrous oxide during biological denitrification. *Water Environment Research*, **70**, 1096–1098.

Spector, M. (1998b) Cocurrent biological nitrification and denitrification in wastewater treatment. *Water Environment Research*, **70**, 1242–1247.

Tollknäpper, K. (1996) Investigations on the rotting process of biowaste composting with varying proportions of biowaste (kitchen waste). Diplomarbeit in der Abteilung Agrarökologie der Universität Bayreuth.

Trimborn, M., Goldbach, H., Clemens, J., Cuhls, C. & Breeger, A. (2003) Reduction of greenhouse gases in the exhaust air of biofilters at biowaste treatment plants. Band 14 der Bonner Agrikulturchemischen Reihe, Abschlußbericht zum Forschungsvorhaben AZ.: 15052 der Deutschen Bundesstiftung Umwelt (Osnabrück).

VDI 2066 Part 1 (2006) Technische Regel: Messen von Partikeln – Staubmessungen in strömenden Gasen – Gravimetrische Bestimmung der Staubbeladung; (Particulate matter measurement – Dust measurement in flowing gases – Gravimetric determination of dust load) edt: Kommission Reinhaltung der Luft (KRdL) im VDI und DIN – Normenausschuss

VDI 3475 Part 1 (2003) Emissionsminderung – Biologische Abfallbehandlungsanlagen – Kompostierung und Vergärung; Anlagenkapazität mehr als ca. 6000 Mg/a; Emission control – Biological waste treatment facilities – Composting and anaerobic digestion; Plant capacities more than approx. 6000 Mg/a

VDI 4200 (2000) Technische Regel: Durchführung von Emissionsmessungen an geführten Quellen; (Realization of stationary source emission measurements) edt: Kommission Reinhaltung der Luft (KRdL) im VDI und DIN – Normenausschuss

Wintzer, D., Leible, L., Rösch, Ch., Bräutigam, R., Fürniß, B. & Sardemann, G. (1996) Ways towards an environmentally sound recycling of organic waste. *Abfallwirtschaft in Forschung und Praxis*, Band 97. Erich Schmidt Verlag, Berlin; 373 S.