Microbial disinfection capacity of municipal solid waste (MSW) composting

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I. DÉPORTES, J.-L. BENOIT-GUYOD, D. ZMIROU AND M.-C. BOUVIER. 1998. The disinfection capacity of a municipal solid waste (MSW) composting plant (Siloda[®]) has been evaluated. In spring and summer, MSW was followed during the composting process from raw material to mature compost and long-term storage (1 year). *Ascaris* eggs, *Salmonella*, *Shigella*, total streptococci, faecal streptococci, total coliforms, faecal coliforms and *Escherichia coli* were studied. Disinfection was successful in terms of a decrease in faecal contamination indicators and disappearance of faecal pathogens. Faecal coliform concentrations in raw waste reached 2.1×10^8 cfu g⁻¹ dry weight in spring (CI 95%: 5.2×10^7 – 3.4×10^8) and 7.2×10^8 cfu g⁻¹ dry weight (1×10^8 – 1.7×10^9) in summer, and fell to less than 100 cfu g⁻¹ dry weight within 20 d. Faecal streptococci concentrations reached 8.7×10^8 cfu g⁻¹ dry weight (3.7×10^8 – 1.3×10^9) in spring and 2.0×10^9 cfu g⁻¹ dry weight (5.6×10^8 – 3.4×10^9) in summer, and fell to 8.7×10^4 cfu g⁻¹ dry weight (6.9×10^4 – 1.0×10^5). No seasonal pattern of contamination, mainly of animal origin, was observed. Microbiological quality of finished compost depends on the storage conditions. Therefore, the storage stage should be viewed as part of the composting process. Monitoring disinfection capacity of MSW composting needs to combine several microbial populations.

INTRODUCTION

Composting transforms organic matter into a stable product consisting of a humus-like substance. The end product is available for agricultural use. Composted raw matter is of various origins including yard waste, manure and sewage sludge (SS). The composting process is also used to treat municipal solid waste (MSW).

Microbial contamination is mainly of faecal origin, especially for SS or MSW. For example, 1–4% of the dry weight of MSW consists of soiled disposable diapers (Pahren and Clark 1987; Gerba *et al.* 1995). As most of the contaminating micro-organisms are heat-sensitive, they disappear during composting, leading to a faecal pathogen-free end product. This disappearance is defined as disinfection or sanitization. Sanitization through the composting process has already been studied for SS (Clark *et al.* 1984; Epstein and Epstein 1985, 1989; Schwartzbrod *et al.* 1990). Several authors have quantified the pathogens of concern in SS

(Schwartzbrod *et al.* 1986; Goldstein *et al.* 1988; Strauch *et al.* 1991; Straub *et al.* 1993) and their evolution during composting (Nell *et al.* 1983; De Bertoldi 1988; Schwartzbrod *et al.* 1990; Strauch 1991). In contrast, MSW composting has received little attention. Pathogens found in MSW, as in SS, can be viruses, bacteria, protozoa or helminths (Table 1). As they are heat-sensitive, the heat increase occurring during the composting process should eliminate them. Several parameters (e.g. humidity and oxygen) have an influence on the heat increase. For this reason, sanitization efficiency depends on the composting method used (Pereira-Neto *et al.* 1986, 1987).

To evaluate hygienization, the evolution of micro-organisms during composting has been studied. These micro-organisms were chosen either because of their pathogenicity or because they are indicators of faecal contamination. The study was conducted at a new composting plant (Siloda[®], OTVD, France) treating sorted MSW of a metropolitan area of 400 000 inhabitants (Grenoble, France) since February 1994. In March and July 1995, samples were collected from the composting chain to assess sanitization of the end product.

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Table 1 Pathogens in sewage sludge and in municipal solid wastes (adapted from Nell *et al.* 1983; Zucconi and De Bertoldi 1987; De Bertoldi *et al.* 1988; Strauch 1991; Straub *et al.* 1993)

Virus	Bacteria	Fungi
Enteric virus	<i>Arizona hinshawii</i>	<i>Aspergillus fumigatus</i>
Poliovirus	<i>Aeromonas</i> spp.	<i>Candida albicans</i>
Coxsachivirus	<i>Bacillus cereus</i>	<i>C. guilliermondii</i>
Echovirus	<i>B. anthracis</i>	<i>C. krusei</i>
Respiratory virus	<i>Brucella</i> sp.	<i>C. tropicalis</i>
influenza	<i>Campylobacter jejuni</i>	<i>Cryptococcus neoformans</i>
Adenovirus	<i>Citrobacter</i> spp.	<i>Epidermophyton</i> sp.
Astrovirus	<i>Clostridium botulinum</i>	<i>Geotrichum candidum</i>
Calicivirus	<i>Cl. perfringens</i>	<i>Microsporum</i> sp.
Coronavirus	Enterobacteriaceae	<i>Phiolophora richardsii</i>
Enterovirus	<i>Escherichia coli</i>	<i>Trichosporon cutaneum</i>
Parovirus	<i>Klebsiella</i> sp.	<i>Tricophyton</i> sp.
Reovirus	<i>Leptospira</i>	
Rotavirus	<i>icterohaemorrhagiae</i>	
Norwalk virus	<i>Listeria monocytogenes</i>	Helminths
Hepatitis A virus	<i>Mycobacterium tuberculosis</i>	<i>Ankylostoma duodenale</i>
Hepatitis E virus	<i>Pasteurella pseudotuberculosis</i>	<i>Ascaris lumbricoides</i>
	<i>Proteus</i> sp.	<i>Echinococcus granulosus</i>
Protozoa	<i>Providencia</i> sp.	<i>Echinococcus multilocularis</i>
	<i>Pseudomonas aeruginosa</i>	<i>Enterobium vermicularis</i>
<i>Acanthamoeba</i>	<i>Salmonella</i> spp.	<i>Hymenolepsis nana</i>
<i>Dientamoeba fragilis</i>	<i>Serratia</i> sp.	<i>Necator americanus</i>
<i>Entamoeba histolytica</i>	<i>Shigellae</i> spp.	<i>Strongyloides stercoralis</i>
<i>Giardia lamblia</i>	<i>Staphylococcus aureus</i>	<i>Taenia saginata</i>
<i>G. intestinalis</i>	<i>Streptococcus</i> spp.	<i>T. solium</i>
<i>Isospora belli</i>	<i>Vibrio parahaemolyticus</i>	<i>Toxocara cati</i>
<i>Naegleria fowleri</i>	<i>Vibrio cholerae</i>	<i>T. canis</i>
<i>Palantidium coli</i>	<i>Yersinia enterocolitica</i>	<i>Trichuris trichura</i>
<i>Sarcocystis</i> spp.		
<i>Toxoplasma gondii</i>		

Samples were taken at different stages of the chain; long-term storage was also studied.

This paper deals with the quality of the composting process in terms of disinfection, and with the suitability of traditional faecal indicators for monitoring MSW sanitization by composting.

MATERIALS AND METHODS

Incoming waste is sorted before it is delivered to the composting plant. This facility received the fermentable part of MSW which is sorted a second time to remove most of the inert particles and sent on to the composting process. Degradation occurs in longitudinal windrows placed side by side. Ambient air is sucked through the piles.

Municipal solid waste is forwarded through two series of windrows (Fig. 1). At first, the digestion phase takes place in four windrows. After this digestion phase, waste is refined by mechanical sorting of the inert matter (mostly plastics and

glasses). Then, the product passes through a second series of four windrows for the maturation phase. In view of the seasonal pattern of the compost market most of the end product is stored for several months in a roofed hall. There are two parallel rows of degradation windrows (W_1 to W_4 , W_5 to W_8). W_1 and W_5 are filled alternately. Only one series of windrows was studied because both series are similar in terms of MSW origin and composting process. There is only one series of maturation windrows, W_9 – W_{12} , which lumps together W_4 and W_8 material.

Windrows are turned by the Siloda® wheel and compost is forwarded from one windrow to the next every 2–5 d. Finally, the end product is sent to the storage area after 3–4 weeks of processing.

Sampling method

Samples were collected when the windrows were turned. The Siloda® wheel was stopped for a few minutes and driven

Fig. 1 Composting plant and sampling strategy

backwards. In the cross-section, samples were collected at four locations in order to account for heterogeneity of the material (Fig. 1). The temperature was recorded with a thermic probe plunged 50 cm deep into the heap. This operation was repeated three times in the windrow, every 8–9 m. Samples were collected in freezer bags designed for food use and thus presumed to be sterile. At each collection point, 500 g of material was collected and manually blended at the laboratory to obtain a mean sample (about 5 kg) representative of the windrow. Sub-samples for analysis were taken from the mean sample.

The study was performed in spring and in summer in order to take into account seasonal variations of contamination and hygienization efficiency.

Waste falling into W_1 was followed through the composting chain. Days of collection were different for each period (Table 2) because of the plant processing constraints. Both runs started on the same weekday (Thursday) to account for weekly variation of MSW content.

The study also dealt with long-term compost storage. A 100 ton fraction of the end product of the spring run was stored in a covered area of the plant and 1 ton was stored in the open at the University. Both heaps were sampled after storage time at D_{43} , D_{57} , D_{91} , D_{174} and D_{142} (D = day).

Physico-chemical analyses

Temperature was recorded at the plant when samples were collected. For pH, 40 g of MSW or compost were placed in an Erlenmeyer flask and 2 l of distilled water added. The suspension was stirred for 3–5 min. The mixture was allowed

Table 2 Time of sampling along the composting chain (days)

Spring run (March 1995)	Summer run (July 1995)
D_0 : when the first windrow (W_1) was filled	D_0 : when the first windrow (W_1) was filled
D_5 : when W_1 was turned	D_4 : when W_1 was turned
D_{13} : when W_2 was turned	D_6 : when W_2 was turned
D_{21} : when W_4 was turned	D_8 : when W_3 was turned
D_{27} : when W_{11} was turned	D_{12} : when W_4 was turned
	D_{14} : when W_{10} was turned
	D_{21} : when W_{12} was turned

to settle for 5 min and the pH was measured (Carnes and Lossin 1970). For dry weight, 400 g of fresh MSW was dried at 105 °C until the weight remained stable.

Microbiological analyses

Two microbial populations were studied: pathogenic and indicator micro-organisms. An indicator is a bacterium normally present in the digestive tract, relatively resistant, and for which routine analysis methods are available (Epstein and Epstein 1989). Indicators were successfully used to assess drinking water quality and the same micro-organisms have been used for hygienic evaluation of sewage sludge compost (Nell *et al.* 1983; Pereira-Neto 1987; De Bertoldi *et al.* 1988). Faecal streptococci and Enterobacteriaceae are most often used for this purpose. Faecal coliforms and faecal streptococci

are good candidates for assessing MSW compost hygienization (Zucconi and De Bertoldi 1987). They have been used previously for SS/MSW mixture compost (Gaby 1975; Pereira-Neto *et al.* 1986). In this study, total coliforms, faecal coliforms, *E. coli*, total streptococci and faecal streptococci were tested as indicators of pathogen inactivation.

Three pathogenic micro-organisms were chosen. *Salmonella* and *Shigella* enterobacteria have often been studied because they are occasionally present after faecal contamination (Goldstein *et al.* 1988; De Bertoldi *et al.* 1988). *Ascaris* eggs were chosen because they are among the most abundant parasites, resistant, and easily recognized. They can also be considered as both pathogens and indicators for other parasitic populations (Strauch 1987; Little 1994).

For *Salmonella* and *Shigella* recovery, 100 g of material was mixed in 1 l sulphate brilliant green (SBG) enrichment broth (Difco) (24 h, 37 °C). Then, 30 plates of *Salmonella* and *Shigella* modified agar (Oxoid) were inoculated with 0.2 ml of broth (24 h, 37 °C). Identification of *Salmonella* and *Shigella*-like colonies on this medium was confirmed with an API gallery (API 20 E, BioMérieux, Marcy l'Etoile, France).

Ascaris eggs were recovered by serial centrifugation at specific gravity, according to EPA recommendations (EPA 1992).

For other micro-organisms, 400 g of MSW were placed in a 5 l Erlenmeyer flask with 4 l of sterile distilled water (0.05% Tween-80) to obtain a 10^{-1} suspension, and manually shaken for 10 min. Three 2 ml samples (A, B and C) of the 10^{-1} suspension were placed in 18 ml of sterile distilled water to obtain a 10^{-2} suspension. Hence, three serial suspensions up to 10^{-8} strength were obtained. Depending on the micro-organisms and the composting stage at which the sample was taken, four of the eight dilutions were spread onto agar plates. For each sample (A, B and C) and each dilution level, two Petri plates were inoculated. For each bacterium, 0.1 ml of the suspension was used.

Most micro-organisms were recovered by membrane filtration methods (APHA 1971). The membrane was then inoculated onto a suitable medium. For total coliforms, filters were placed on triphenyl tetrazolium 2-3-5 chloride (TTC) agar (Pasteur) (24 h, 37 °C); for faecal coliforms, TTC agar (Pasteur) (24 h, 45 °C was used).

For *E. coli*, faecal coliforms were submitted to several tests: oxidase activity (Bactident® Oxidase, Merck), urease (24 h, 37 °C) in urea-indole broth (L-tryptophane, 3 g; KH_2PO_4 , 1 g; KH_2PO_4 , 1 g; NaCl, 5 g; urea, 20 g; ethyl alcohol 95%, 10 ml; phenol red, 25 mg; 1 l distilled water, filter-sterilized) and the indole test (Kovacs reagent added to the urea-indole broth). Micro-organisms O^- , U^- , I^+ were presumed to be *E. coli*. For total streptococci, Slanetz and Bartley agar (Pasteur) (48 h, 37 °C) was used and for faecal streptococci (D group), streptococci were inoculated onto esculin azide agar (Oxoid) (48 h, 37 °C). For staphylococci, Chapman agar (Pasteur) (24 h, 37 °C) was used. Colonies were inoculated

into brain heart broth and tested for coagulation with rabbit plasma (Bio Mérieux).

Total bacteria were recovered in nutrient broth (Difco). In order to facilitate enumeration of bacteria, 5 ml l^{-1} cycloheximide was added to the medium to eliminate fungi. The suspension was placed on the plate (0.1 ml) and the medium was then poured and allowed to cool. Total bacteria were recovered at 37 °C (24 h), 20 °C (72 h) and 30 °C (30 h) for the spring run. During the first run, values for bacterial concentrations at 30 °C were found to be equal to the mean of the results at 20 and 37 °C. Therefore, in the second run and in some storage analyses, bacterial concentrations were determined only at 30 °C.

A Student *t*-test was used to assess differences in average microbial concentrations across the composting chain. The critical *P*-value was set at 0.05.

Recovery rate

To assess recovery rates of the extraction method, 50 g of compost was sterilized (autoclaved for 20 min at 120 °C) and artificially contaminated with 10 ml of a 1.1×10^8 streptococci ml^{-1} solution, leading to a theoretical concentration of 2.2×10^7 micro-organisms g^{-1} . The contaminated compost remained at 4 °C overnight. Serial suspensions were made and 0.1 ml of the appropriate dilutions was collected by membrane filtration on Slanetz and Bartley agar (Pasteur) and left for 48 h at 37 °C. Faecal streptococci were counted and the recovery rate was calculated ($\text{Rr} = \text{experimental concentration/theoretical concentration} \times 100$).

RESULTS

Physico-chemical parameters (Tables 3 and 4)

In both runs, pH and temperature rose during the composting process. The temperature reached 70–80 °C. Due to seasonal variations, the starting temperature was not the same in each period. After processing, the smaller heap was stored outside (at the university) and the temperature was lower. The temperature remained quite steady during the hotter month (D_{57} – D_{91}) and decreased in November (D_{242}). However, the temperature of compost stored under a shed remained high. During storage, pH rose in the heap stored outside but remained stable in the heap stored under a shed.

Micro-organisms (Tables 5 and 6)

During both runs, micro-organism concentrations evolved in a similar way. Faecal coliform concentrations were drastically reduced during the first stage of composting and, in the end, were below the threshold for detection. Total coliforms, faecal coliforms and *E. coli* were strongly correlated (Fig. 2). Most

Table 3 Physico-chemical parameters during composting and storage in the first run (March 1995) according to the conditions of storage

	Time															
	D ₀	D ₅	D ₁₃	D ₂₁	D ₂₇	D ₄₃	D ₄₃	D ₅₇	D ₅₇	D ₉₁	D ₉₁	D ₁₇₄	D ₁₇₄	D ₂₄₂	D ₂₄₂	
						C	UnC	C	UnC	C	UnC	C	UnC	C	UnC	
Minimum temperature (°C)	16.7	41	68.3	68.2	35	50	35	56	27.5	55	28	47	20	47.8	10	
Mean temperature (°C)	16.7	54	58	66	40.3	56.1	45.7	60.5	28.3	58.8	28.7	49.8	22.3	51.8	13.2	
Maximum temperature (°C)	16.7	57.8	77.7	82	44	64.3	54	67.4	30	62	30	54	25	56	15	
H ₂ O (%)	46	47	41.8	36.3	31	27	13	24	22	25	14.6	18.4	10.4	12.6	16	
pH	5.6	6.2	6.4	7.1	7.6	7.5	8.2	7.6	8.9	7.8	9.1	7.7	9.4	7.4	9.27	

C, Covered storage; UnC, uncovered storage.

Table 4 Physico-chemical parameters during composting and storage in the second run (July 1995)

	Time						
	D ₀	D ₄	D ₆	D ₈	D ₁₂	D ₁₄	D ₂₁
Lower temperature (°C)	31.5	54	36	47.7	54.7	40.7	30
Mean temperature (°C)	31.5	60.6	51.1	59.8	62.6	54.4	39.2
Higher temperature (°C)	31.5	70	63.7	68.7	69.9	65.6	55.5
H ₂ O (%)	50.5	59.6	41.3	39.6	39.2	34.3	25.8
pH	6.3	6.2	6.7	7	7.1	7	7.8

total coliforms were faecal coliforms, specifically *E. coli*. Therefore, in order to simplify the analysis, only faecal coliforms were studied during the summer run. Streptococci were essentially faecal streptococci (78.5–100%) and concentration decreased during composting. Staphylococci were abundant, but no pathogenic strain was found (Tables 5 and 6). Two pathogens out of three were present in MSW (*Salmonella* and *Ascaris* eggs) collected during the first run but disappeared during composting before 27 d (Tables 5 and 6). *Ascaris* eggs were not recovered during the second run (Table 6). *Shigella* was never observed.

During storage, indicators and pathogens remained either undetectable or at a low level. However, streptococci, coliforms and *Salmonella* had risen at D₅₇ in the uncovered heap. In both stored heaps, coliforms were observed again at D₁₇₄ and D₂₄₂.

Salmonella specification by API gallery did not allow identification beyond *Salmonella* sp.; the SS modified med-

Fig. 2 Pathogenic and indicator micro-organisms; average concentrations during the spring run (March 1995). Δ , Total coliforms; $\square$, faecal coliforms; $\blacktriangle$, *E. coli*; $\bullet$, total streptococci; $\circ$, faecal streptococci; $\blacksquare$, *Ascaris* eggs (10^2 eggs g^{-1})

ium appeared to lack selectivity for compost studies. Only 48% of the 54 black strains isolated as *Salmonella* sp. on the SS medium were actually shown to be *Salmonella* with the API gallery. The other 52% were mainly *Proteus mirabilis*.

DISCUSSION

Physico-chemical parameters (Tables 3 and 4)

During the composting process and storage, heat rose as expected (Gaby 1975). During storage, a paradoxical situation

Table 5 Indicators and pathogenic micro-organisms in MSW and MSW compost during composting and storage in the spring run (March 1995) (arithmetic mean, log cfu g⁻¹ dry weight)

Time ^a	Storage ^b	Bacteria (20 °C)	Bacteria (37 °C)	Bacteria (30 °C)	Total coliform	Faecal coliform	Presumed <i>E. coli</i> ^d	Total streptococci	Faecal streptococci ^e	<i>Salmonella</i> ^f	Total staphylococci	<i>Ascaris</i> (eggs g ⁻¹)
D ₀		9.74 [9.56–9.87]	9.38 [9.11–9.55]	NT ^e	9.7 [8.88–10.4]	8.96 [8–9.23]	70%	9.39 [8.83–9.62]	83.3	+	8.96 [8.35–9.20]	0.05
D ₅		8.43 [6–8.73]	8.77 [7.46–9.06]	NT	6.67 [6.37–6.85]	6.59 [6.59–6.59]	77%	6.7 [5–7]	78.5	+	8.17 [7.08–8.46]	0.01
D ₁₃		6.92 [6.88–6.95]	6.35 [6.16–6.49]	NT	2.41 [2.41–2.41]	2.24 [2.24–2.24]	100%	4.29 [4.11–4.41]	84.8	+	5.51 [5.27–5.67]	0.02
D ₂₁		7.89 [7.76–7.99]	7.73 [7.59–7.84]	NT	<2	<2		5.37 [5.21–5.48]	98.1	–	7.61 [7.45–7.72]	0.006
D ₂₇		7.52 [7.21–7.69]	7.7 [7.2–7.93]	NT	<2	<2		5.52 [5.36–5.64]	92.4	–	7.87 [7.7–7.99]	0
D ₄₃	C	7.90 [6–8.20]	7.53 [7.53–7.53]	NT	NT	<2		5.7 [4–6]	93.4	–	7.96 [6–8.26]	0
D ₄₃	UnC	8.17 [8.14–8.20]	7.15 [7.35–6.75]	NT	NT	<2		5.87 [5.56–6.05]	80.6	–	6.95 [6.67–7.12]	0
D ₅₇	C	7.29 [6.74–7.52]	7.37 [7.06–7.54]	NT	NT	<2		5.45 [3–5.75]	94	–	7.65 [7–7.9]	0
D ₅₇	UnC	7.91 [7.06–8.18]	8.39 [7.98–8.6]	NT	NT	2.18 [2.18–2.18]		7.01 [6.56–7.23]	90	+	9.19 [8.11–9.47]	0
D ₉₁	C	OC ^g	6.86 [4.30–7.16]	NT	NT	<2		5.45 [3.95–5.74]	100	–	NT	0
D ₉₁	UnC	OC	8.23 [8.20–8.25]	NT	NT	<2		5.21 [5.18–5.25]	100	–	NT	0
D ₁₇₄	C	NT	NT	NT	NT	4.78 [4.36–4.99]		4.82 [4.39–5.03]	100	–	NT	0
D ₁₇₄	UnC	NT	NT	NT	NT	5.34 [5.47–5.16]		4.79 [3.3–5.09]	100	–	NT	0
D ₂₄₂	C	NT	NT	7.36 [6.96–7.57]	NT	2.07 [2.07–2.07]		3.84 [3.37–4.06]	100	–	7.9 [5.17–7.26]	0
D ₂₄₂	UnC	NT	NT	8.22 [7.96–8.38]	NT	4.32 [4.0–4.5]		4.71 [4.15–4.95]	100	–	8.84 [8.78–8.89]	0

^a D₀–D₂₇, active composting process and D₄₃–D₂₄₂, storage; ^b C, covered storage; UnC, uncovered storage; ^c NT, not tested; ^d % faecal coliform; ^e % total streptococci; ^f – = absent; + = present; ^g OC, overcrowned by fungi *Neurospora* sp., no count available.

[], Confidence interval, 95%.

Table 6 Indicators and pathogenic micro-organisms in MSW and MSW compost during composting in the summer run (July 1995) (arithmetic mean, log cfu g⁻¹ dry weight)

Time	Bacteria (30 °C)	Faecal coliform	Total streptococci	Faecal streptococci ^a (%)	<i>Salmonella</i> ^b	<i>Ascaris</i> eggs (eggs g ⁻¹ dw)
D ₀	9.62 [9.18–9.83]	8.32 [7.72–8.56]	8.94 [8.57–9.14]	100	+	0
D ₄	7.87 [7.64–8.02]	6.39 [6.39–6.39]	7.30 [5.95–7.59]	100	+	0
D ₆	7.26 [7.07–7.39]	4.95	7.74 [5.6–8.04]	100	+	0
D ₈	7.94 [8.05–7.8]	3.87	7.09 [6.79–7.26]	100	+	0
D ₁₂	8.37 [8.5–8.19]	<2	6.5 [6.21–6.67]	100	–	0
D ₁₄	8.42 [8.21–8.87]	<2	4.96 [2.48–5.26]	100	–	0
D ₂₁	7.44 [7.26–7.57]	<2	4.94 [4.84–5.02]	100	–	0

^aTotal streptococci; ^b – = absent; + = present.
[], Confidence interval, 95%.

was observed. The physico-chemical parameters showed a faster maturity for the uncovered compost than for the covered heap. The covered compost did not exhibit a great variation of temperature during storage (Fig. 3), indicating a lasting microbial activity, while the temperature in the uncovered compost decreased faster because of exposure to the external environment temperatures and the lower volume of the heap. During storage, pH of the uncovered compost rose while that of the covered compost remained stable (Table 3). This could be explained by a faster evolution towards maturity in the uncovered compost heap (Mustin 1987).

Fig. 3 Evolution of the lowest (●) and highest (○) temperature recorded during covered and uncovered storage

Maturity is the final stage of the composting process. Mature compost is defined as a stable stage at which mineralization and humification have resumed. At this stage, compost is safe for agricultural use (Zucconi *et al.* 1985).

Micro-organisms (Tables 5 and 6)

There were no seasonal variations in the MSW microbial population between the spring and the summer run at D₀ (*t*-test). Seasonal variation in the microbiological composition of human faeces has already been described (MacGowan *et al.* 1994). However, faecal contamination of MSW seemed to be mainly of non-human origin. The faecal coliform/faecal streptococci ratio (FC/FS) is thought to be an index of the faecal contamination origin (Pahren and Clark 1987); an FC/FS above 4 may characterize human faeces while a value below 0.6 is characteristic of other warm-blooded animals (i.e. about 0.3 for dogs and 0.02 for cats) (Pahren and Clark 1987). In this study, the ratios were 0.4 and 0.23 according to the run, suggesting that human faecal contamination was relatively low. However, this result must be considered carefully, as the FC/FS ratio is more suitable in fresh waste because die-off rates are different in both groups. In this study, the time between waste being collected and being sent to the composting chain could reach 5 d. A low human faecal contamination is also supported by other microbial analyses. No *Shigella* were found in this study because they are linked to human and higher monkeys' digestive tracts and are only occasionally found in other mammalian species (e.g. dogs)

(Krieg and Holt 1984). *Ascaris* eggs were not recovered during the second run even though they were detected in the first one (Table 6). However, Schwartzbrod *et al.* (1990) have shown that there are few *Ascaris* eggs in MSW.

Using the API gallery, it has been shown that SS media was not sufficiently selective. This should be taken into account when *Salmonella* is recovered from MSW or compost for environmental or occupational health risk assessment.

It has been stated that composting material should reach 55–65 °C, covering a time-span ranging from 24 h to 3 d, in order to achieve hygienization (De Bertoldi *et al.* 1988). However, it was shown in a laboratory-scale composting process (i.e. 55 °C for 3 d, in-vessel composting) that temperature was not the only factor to be taken into account (Droffner and Brinton 1995). In both runs, MSW stayed at a temperature higher than 50 °C for 10 d (Tables 3 and 4), and remained at over 60 °C for 5 d. Under these conditions, pathogens disappeared (Tables 5 and 6). In both runs, pathogen disappearance and indicator decrease occurred before 21 d. At D₂₁ in the spring run, the compost cohort was set in W₄, whereas in the summer run it was set in W₁₂, clearly indicating that the governing factors are time and temperature and not the type of windrow.

In this study, indicator bacteria population assessment proved a reliable method for following sanitization. Pathogen removal was linked with faecal indicator decline. Some bacterial limit values for disinfected compost have been suggested as 5×10^3 faecal streptococci g⁻¹ dry weight, 5×10^2 total coliforms g⁻¹ dry weight and 0 *Salmonella* in 100 g, but more investigations are needed to confirm this observation (Zuconni and De Bertoldi 1987). In our study, we observed the disappearance of *Salmonella* and *Ascaris* eggs at higher faecal streptococci concentrations than those proposed by Zuconni and De Bertoldi (1987). However, these results are difficult to compare as microbiological analysis methods were not standardized. For example, in this study, the recovery rate for faecal streptococci was 21% when distilled water was used for the compost suspension. When the other solution (water, phosphate buffer) or sonication was tested for suspension of the compost before serial dilution, bacterial counts varied five or 10-fold (unpublished data). It is also important to note that the recovery rate was assessed for a single bacterial population and it is not known what it would be in a heterogeneous bacterial environment. However, the recovery rate observed was not unexpected (EPA 1992).

At D₅₇ faecal coliform contamination of the heap showed a higher rate of streptococci and *Salmonella*, possibly due to a dog as traces were found on the heap. At D₁₇₄ and D₂₄₂, the situation was different, as in both heaps there was a rise in coliforms only. This bacterial regrowth was smaller in covered compost, probably because of the higher temperature and lower humidity (Pepper *et al.* 1993). Only coliforms showed regrowth, emphasizing the need to combine several

indicators or pathogens in order to assess sanitization. Had coliforms been measured alone, this regrowth could have been misinterpreted as an external contamination; streptococci are unlikely to regrow in compost (EPA 1992) while *Salmonella* and coliforms are able to do so (Hussong *et al.* 1985). This observation suggests that sanitization should be monitored by following *Salmonella* and faecal streptococci during composting and storage. Coliform monitoring would be unnecessary with regard to hygiene but could be of interest for monitoring compost stability (Soares *et al.* 1995).

It is concluded that, as composting drastically reduced faecal microbial indicators and pathogens during both study periods, the composting process is efficient for disinfection. Although temperature monitoring is the simplest and most usually recommended method for monitoring hygienization, this study suggests that it is also important to assess hygienization by microbial analysis. Microbial analysis should concern every stage of the composting process, starting from the thermophilic phase and including the storage of the end product. In order to fully assess sanitation, it is important to combine monitoring of both indicators and pathogens because of the risk of confusion between natural regrowth and accidental contamination liable to occur mainly during storage.

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