Bioaerosol in Composting Facilities: Occupational Health Risk Assessment

Olivier Schlosser[1]*, Alain Huyard[1], Keith Cartnick[2], Adela Yañez[3], Vicente Catalán[3], Zdravka Do Quang[1]

ABSTRACT: This research found evidence of an association between occupational exposure to bioaerosols in composting plants and health outcome occurrence in exposed workers. An occupational exposure assessment in six composting plants was performed to better characterize personal exposure levels and evaluate associated health risk in workers. Sampling results showed large ranges of concentrations of dust, bacteria, molds, and endotoxin in ambient air and in personal samples, both when driving a front-end loader and when cleaning, monitoring, and performing maintenance tasks. Mean personal exposure levels were high at 100 to more than 10 000 times higher than outdoor background levels and fully consistent with occurrence of inflammatory and allergic respiratory outcomes among workers. Engineering control, personal protection, and education and training programs for employees, health, and safety officials, and occupational physicians are being developed and implemented. *Water Environ. Res.*, **81,** 866 (2009).

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Introduction

Bioaerosols, or organic dust, are particulate matter of microbial, plant, or animal origin that contain live and dead microorganisms, constituents as fragments, toxins, and metabolites (American Conference of Industrial Hygienists [ACGIH], 1999). Scientists and health authorities have grown increasingly interested in bioaerosol exposure primarily because of the association between exposure to biological agents in occupational and residential environment and a wide range of adverse health effects including infections, immunoallergies, and toxic effects (Dutkiewicz, 1997; Douwes et al., 2003).

In occupational health, specific consideration is given to adverse effects of bioaerosol exposure on the respiratory tract and allergic and toxic inflammatory mechanisms. Industries associated with high potential exposure to bioaerosol, such as waste management, agriculture, farming, wood processing, and cotton textiles, are increasingly addressing this issue (Rylander, 2002). Scientific papers have been published on exposure assessment and risk evaluation in solid waste management and sewage treatment plants, and a dozen reports, technical notes, and research projects about composting have been produced at the request of public authorities in North America and European Union countries (Californian Department of Health Services, 1999; Cré-Composting Association of Ireland Teo, 2004; Deloraine et al., 2002; Enviros Consulting Ltd and University of Birmingham, 2004; Swan et al., 2003). The Water Environment Research Foundation (WERF) and IWA Publishing recently published a report addressing the question of airborne biological agents associated with land applied biosolids (WERF, 2007).

Composting activities generate emission and dispersion of organic dust. Highest dust emission is associated with indoor waste handling and extensive mechanical agitation, and emission and dispersion increase when weather is dry, warm, and windy. In addition, moisture content of compost affects the bioaerosol level (Wheeler et al., 2001). Sorting, shredding, turning, screening, piles breakdown, and unloading and cleaning activities are the main bioaerosol-generating activities (Epstein et al., 2001; Millner et al., 1994; Sanchez-Monedero et al., 2005; Spencer and Alix, 2006; ; Swan et al., 2003; Wouters et al., 2006). A few other mechanisms contribute to increases in bioaerosol air levels: mechanical agitation by wheels and tires of equipment, physical handling of materials, downdrafts onto dust-laden traffic surfaces, and front-end loaders moving stored wood chips (Millner et al., 1994). Vehicular movement across dust-covered surfaces generates dispersion that increases significantly when the bucket is lowered to scrape and clean the dusty floor. On the other hand, studies indicate that few of the aerosolized microorganisms originated as wind-blown losses from static piles of compost (Mullins et al., 1976; Millner et al., 1980).

From a qualitative point of view, airborne microorganisms in composting plants reflect the content of composting materials. Content results from microorganisms in the feedstock and of their fate according to changes in metabolic activity, temperature, and competitive mechanisms (Lacey et al., 1992; Lacey, 1997; Millner et al., 1994; Swan et al., 2003; Van der Werf, 1996). Mesophilic bacteria and fungi in feedstock are succeeded by thermophilic actinomycetes and fungi species as the temperature rises above 45°C. During the maturation phase, mesophilic and fungi predominate. Moving large quantities of composting materials leads to the release in air of large amounts of microorganisms and related components, such as microbial cell wall agents, that then may be inhaled and ingested by workers and deposited onto their skin and eyes.

Facing these hazards, compost companies are encouraged to perform a related occupational health risk evaluation and management program. Health risk evaluation for composting

[1] SUEZ ENVIRONNEMENT, CIRSEE.

[2] United Water, Haworth, New Jersey.

[3] LABAQUA, Alicante, Spain.

* SUEZ ENVIRONNEMENT, CIRSEE, 38 rue du President Wilson, 78230 Le Pecq, France; e-mail: olivier.schlosser@suez-env.com.

workers is hampered by limited published data on individual exposure assessment and by the lack of dose-response relationship for inhalation of most biological agents. Some authors have proposed guidelines. In Scandinavia, guidelines are 10^4 cfu/m^3 for total bacteria and 10^3 cfu/m^3 for Gram-negative bacteria (Malmros et al., 1992; Poulsen et al., 1995). In Poland, it is 10^5 cfu/m^3 for total bacteria, 5×10^4 cfu/m^3 for fungi, and 2×10^4 cfu/m^3 for Gram-negative bacteria and thermophilic actinomycetes (Dutkiewicz, 1997). No regulatory occupational exposure limit (OEL) is set for airborne biological agents. For endotoxin, the Netherlands adopted in 2003 a transitory legal OEL of 200 EU/m^3 over an eight-hour exposure; this limit, however, was withdrawn because of feasibility issues, mainly in agricultural industries (Douwes et al., 2003; Visser et al., 2006). In Poland, the authors proposed 2000 EU/m^3 as an OEL (Górny and Dutkiewicz, 2002).

Despite no existing regulatory OELs, operational and health and safety (H&S) managers need recommendations for bioaerosol-related health risk management. The main goal of this work was to provide a means to develop guidance for health risk management for bioaerosols in composting facilities. An appropriate methodology for occupational health risk evaluation for exposure to bioaerosols is suggested, and exposure associated with specific workplaces and tasks in operational composting facility was characterized on six sites.

Methodology

Two studies were conducted in parallel according to the objectives outlined above: (1) a qualitative health risk evaluation of bioaerosol occupational exposure in composting plants, and (2) an onsite exposure assessment.

Qualitative Health Risk Evaluation. A qualitative risk evaluation was achieved using a two-step analysis. In the first step, epidemiological studies and case reports of compost workers or handlers were researched in the literature. Because available data were limited, in the second step, the search was extended to other occupational fields where airborne biohazards are similar to those identified in composting plants ambient air. This approach resulted in a literature review of approximately 200 published scientific papers and 25 scientific reports and conference proceedings. When related exposure to bioaerosol was documented, these health outcome occurrence data were combined with exposure data in composting plants. This approach helped to determine whether or not measured/estimated exposure levels in composting plants are consistent with occurrence of a specific health outcome in exposed individuals. This combination of results may introduce potential bias and confounding because of transposing results from a specific occupational field to another. Results could, however, provide suggestive evidence of an association between occupational exposure to airborne agent in composting plants and health outcome occurrence in exposed workers. Most available exposure data, however, were from sampling of in site ambient air, and so did not provide a good assessment of real personal exposure of workers. Therefore, in a second phase, the risk evaluation approach was improved by including results from dedicated sampling campaigns. This double-sided approach allowed development of health risk evaluation that will support guidance proposals for risk management.

Onsite Exposure Evaluation. Six composting plants were investigated: three in France, two in the United Kingdom; and one in Spain (Table 1). All plants had been in operation for several years and all conduct fermentation and maturation to produce final compost compliant with the quality standards of that country. Both stationary sampling at static points and personal sampling were performed during summer 2007 and winter 2007 to 2008. Selected airborne agents included inhalable dust, aerobic heterotrophic bacteria, Gram-negative bacteria, mesophilic molds and yeasts, *Aspergillus fumigatus*, thermophilic actinomycetes, and endotoxin. Background levels were estimated from outdoor out-of-the-pad measurement results at 1 to 2 km from the site. Weather conditions (temperature, humidity, wind speed) were recorded at each outdoor and indoor sampling point.

Sampling Strategy. All air samples from both static and worker's points were collected with the CIP 10-M personal aerosol sampler (Arelco, France) using inhalable fraction selector. This device is based on the rotating cup system (Görner et al., 2006). To collect suspended particulate matter, the cup of the CIP 10 was equipped with a porous polyurethane foam filter. For the study of microorganisms and endotoxin, the appropriate rotating cup of the sampler (CIP 10-M) was filled with 2 mL of pyrogen-free sterile water (LAL Reagent Water ENDOSAFE®, Charles River Laboratories, Charleston, South Carolina) containing 0.05% Tween® 20 (polyoxyethylen sorbitan monolaurate; Merck KGgaA, Darmstadt, Germany) to increase the capture rate of hydrophobic fungi spores and mycelia. Bioaerosol sampling was conducted during normal working hours in each facility. Sampling duration was between 30 and 60 minutes for sampling ambient air (stationary sampling), and between 20 and 30 minutes for personal sampling based on the duration of the task performed by the worker. The flow rate of the CIP 10 was 10 L/min; the volume of sampled air ranged between 200 and 600 liters. Water samples were transported refrigerated to the laboratory within one to four days.

Sample Analysis. The mass of suspended particulate matter collected in the foams of CIP-10 was determined following the European Committee for Standardization EN 12341 standard. The difference in weight of the dried foam before and after sampling was determined, less the weight of the reference cups. Endotoxin was assayed with a quantitative kinetic chromogenic Limulus amebocyte lysate (LAL) method (Charles River Laboratories, Charleston) following manufacturer instructions. Aerobic heterotrophic bacteria (referred to as mesophilic bacteria in this text), Gram-negative bacteria, yeast and molds (mesophilic molds), thermophilic actinomycetes (actinomycetes), and *Aspergillus fumigatus* were identified and quantified in all cases by culture isolation. Mesophilic bacteria culture was carried out in Tryptone Soya Agar medium (TSA, Oxoid Ltd., Hampshire, United Kingdom) incubated at 22 ± 2°C for 72 hours following the ISO 6222. Gram-negative bacteria were determined from the TSA plates using Bactident® Aminopeptidase test strips (Merck KGaA). Mesophilic molds were recovered in Rose-Bengal 100 mg/L chloramphenicol (Oxoid Ltd.); plates were incubated at 22 ± 2°C for seven days. Thermophilic actinomycetes were incubated in Tryptone Soya Agar (TSA, Oxoid Ltd.) supplemented with 80 mg/L cycloheximide, and incubated at 55 ± 2°C for seven days. Finally, *Aspergillus fumigatus* was isolated in Rose-Bengal 100 mg/L Chloramphenicol (Oxoid Ltd.), incubated at 37 ± 1°C for seven days. Presumptive colonies were confirmed through microscopic and macroscopic morphology.

Statistical Analysis. Results were organized and analyzed to address the following questions, with and without regard to season:

Table 1—Composting plants description (WWTP = waste water treatment plant; GW = green waste; S = sludge; OFMSW = organic fraction of municipal solid waste).

Site	A	B	C	D	E	F
Type of plant	Intensive confined	Intensive confined	Intensive confined	Open-air	Open-air	Intensive confined
Real capacity (t/y)	S: 15 000	S: 20 000	S: 30 000	GW: 36 000 S: 15 000	GW: 25 000	OFMSW: 40 000
Substrate	Primary and secondary WWTP sludges	WWTP sludge	WWTP sludge	GW and WWTP sludge	GW	OFMSW (<50 mm, source selected)
Bulking agent	ground pallet	ground pallet and wood	ground wood	ground pallet and wood	no	no
Ratio substrate/bulking agent (vol/vol)	1/3	1/3	1/3	1/3		
Filling	front-end loader	front-end loader	front-end loader	front-end loader	front-end loader	front-end loader
Fermentation technology	open boxes	open boxes	tunnels	outdoor aerated windrows	outdoor turned windrows	tunnels (2 stages)
Fermentation duration (weeks)	3	3	2 to 3	3	>4	2 × 2
Aeration	negative	negative	positive	positive	1 turning per week	positive
Onsite shredding	no	no	no	outdoor	outdoor	no
Screening	indoor	outdoor, return of refuse indoor	indoor	outdoor	outdoor	under-shed
Maturation	indoor	outdoor	under-shed	outdoor	outdoor	under-shed
Air treatment	chemical +biofilter	chemical	chemical +biofilter	no	no	ozone

- Which ranges of bioaerosol concentration were measured onsite?
- Which were the processes and workplaces associated with the highest and lowest concentrations in ambient air?
- How high were personal exposure levels associated with the different tasks?
- What was the decrease in exposure levels associated with working in vehicle cabin?

As described in literature, concentration of air particles fits a log-normal, rather than a normal, distribution. Therefore, data were transformed into $\log_{10}$ units before analysis. Descriptive statistics of exposure levels were calculated as geometric means, geometric standard deviation, and ranges. To test for differences in variables means, Z-test, Student's t-test, and one-way analysis of variance (ANOVA) were performed. Data from stationary sampling and personal sampling were analyzed to determine correlation between variables, both in overall facilities and separately in open-air and confined/under-shed facilities. Tests of correlations were based on Spearman rank correlation coefficients and Pearson linear correlation coefficients. In all analysis, p values were considered significant at values less than 0.05.

Results

Case Reports. A dozen case reports of disease among individuals exposed to compost dust has been published since the 1980s. Six addressed allergic diseases to molds (hypersensitivity pneumonitis) and allergic bronchopulmonary aspergillosis (ABPA), because of *Aspergillus fumigatus* or actinomycetes (hypersensitivity pneumonitis) (Allmers et al., 2000; Brown et al., 1995; Bünger et al., 2007; Cobb et al., 1995; Kramer et al.,1989; Schappler-Scheele, 1999;). One case was organic dust toxic syndrome (ODTS), one case was insufficiently characterized (hypersensitivity pneumonitis or ODTS), one case was external otitis from *Aspergillus niger*, and three were invasive aspergillosis (Bünger et al., 2007; Clark et al., 1984; Weber et al., 1993). The latter cases concerned a worker in a green-waste composting plant, a professional gardener that probably handled compost, and a welder who spread rotting tree and plant mulch from a sack around his garden (Russell et al., 2008; Vincken and Roels, 1984; Zuk et al., 1989). The three cases of invasive aspergillosis did not represent typical characteristics for individual risk factors because the patients were not known to be immuno-compromised. These types of cases remain rare and are considered atypical cases of invasive aspergillosis, which prompted their submission for publication. On the other hand, both hypersensitivity pneumonitis reported cases and the few ABPA cases fit hypersensitivity pneumonitis and ABPA-related individual risk factors. In the three hypersensitivity pneumonitis cases with documented exposure levels, actinomycetes and/or total molds air concentrations were higher than 10^6 cfu/m^3, which is consistent with the known environmental risk factor in actinomycetes or mold-related hypersensitivity pneumonitis (Allmers et al., 2000; Bünger et al., 2007; Weber et al., 1993). In an ABPA case, the patient had an history of asthma (Kramer et al., 1989).

Epidemiological Studies. Twenty epidemiological studies have been published in this field, primarily in composting plants workers, and three in neighborhood residents. Most are cross-sectional studies based on questionnaires, and some are of poor quality. Most studies agree in indicating or suggesting an excess of upper airway (nose and throat) and eye irritation in exposed workers, which is the main finding from the review. The observation data support the hypothesis of an inflammatory effect

of bioaerosol exposure in compost workers, which is confirmed by the association between inflammatory upper airway symptoms and increases in inflammation cells and markers in nasal lavage samples (Douwes et al., 2000; Heldal et al., 2003; Wouters, 1999). Results pertaining to respiratory function decrease in exposed workers are conflicting, and most conclusions are limited by a weak statistical power related to the low number of included subjects.

On the other hand, available epidemiological data are not sufficient to determine whether or not the risk of allergic disease is increased in compost workers, even if some biological marks (IgG antibodies against mold species and actinomycetes) indicated high exposure levels (Beffa et al., 1998; Bünger et al., 2000; Clark et al., 1984; Cobb et al., 1995; Van den Bogart et al., 1993). The incidence rates of allergic disease in compost workers have not been estimated because no properly designed prospective studies have been conducted. Interestingly, a healthy worker effect is suggested by several authors to explain observed lower rates of atopy or asthma history in compost workers compared with non exposed control subjects (Bünger et al., 2000; Marth et al., 1997; Sigsgaard et al., 1994). In occupational epidemiology, the healthy worker effect is the potential bias caused by the phenomenon that sicker or more sensitive individuals may be excluded from employment or, once employed, may leave the job they do not tolerate. Such a phenomenon, which tends to underestimate true risk, also has been suggested for waste collectors (Hansen et al., 1997). There is no documented evidence of a significant excess of invasive aspergillosis in compost workers.

Published Exposure Data. Forty original studies were reviewed for this study. Aerodynamic diameters (D_{ae}) of dust in composting plants typically were less than 10 μm, and most were less than 2.5 μm and could be respirable, which means able to reach the alveolar area in the lungs. In most studies, total dust or inhalable dust were below 10 mg/m^3; however, a few peak concentrations reaching more than 100 mg/m^3 have been reported, usually with personal samplers and during feedstock unloading, pile screening, or breakdown activities (Darragh et al., 1997; Hryhrorczuk et al., 2001; Nersting et al., 1991; Van Tongeren et al., 1997; Wouters et al., 2006). Measurement values from the 40 reviewed studies were pooled and counted to estimate the number of times each order of magnitude of concentrations in air was indicated in all studies as a whole. In the same way, orders of magnitude of indicated background levels were counted. This approach, however, needs to be considered with caution because of differences between studies in sampling methods and in expressions of values dispersion. Total bacteria and total molds concentrations in air have been measured up to about 10^9 cfu/m^3, and maximum indicated log-unit value for Gram-negative bacteria, *A. fumigatus*, and actinomycetes was 7. Median value was 5 log-units for total bacteria, and 4 for Gram-negative bacteria, total molds, *A. fumigatus*, and actinomycetes. The interquartile range of indicated values was 4 to 6 log-units total bacteria, 3 to 5 log-units for Gram-negative bacteria and total molds, 2 to 5 log-units for *A. fumigatus*, and 2 to 6 log-units for actinomycetes. Background levels in outdoor air were 10 to 1000 times lower than concentrations in plants. For endotoxin, the median class of indicated values ranged from 200 to 500 endotoxin unit/m^3 (EU/m^3). Most (65%) of indicated measurement values were less than 1000 EU/m^3; however, 25% of the indicated values were greater than 2000 EU/m^3. The highest indicated value was 59 306 EU/m^3, which was measured during screening and sweeping in a sewage sludge composting facility (Darragh et al., 1997). In a recent study in background environments, median concentrations of airborne endotoxin levels in outdoor urban and industrial areas were less than 5 EU/m^3 (Madsen, 2006).

Health Risk Evaluation Results. Several conclusions emerged from results of the literature on occurrence of health effects in individuals exposed to bioaerosol and knowledge of related risk factors:

(1) Published exposure levels in composting plants are consistent with occurrence of inflammatory and allergic outcomes, primarily respiratory effects, as reported in case reports and workforce-based studies.
(2) The most prevalent health effect of exposure to bioaerosols in compost workers is an inflammatory response of the upper airways and eyes (mucous membrane irritation, MMI). Pro-inflammatory components in compost bioaerosol are a complex mixture of several microbial cell wall agents and toxins; endotoxin from Gram-negative bacteria, however, has been recognized as a major causal agent of MMI. Most reported concentrations of endotoxin in composting plant air exceeded the MMI-related dose thresholds (100 EU/m^3) (Rylander, 1997). Data are insufficient or inadequate to support sufficient evidence for a chronic decrease of respiratory function in compost workers.
(3) There is suggestive evidence of an association between exposure to bioaerosol in composting plant and ODTS supported by (1) the known exposure-response benchmarks for endotoxin and the reported endotoxin air measures in composting plants that exceeded the ODTS related dose threshold (2000 EU/m^3) (Rylander, 1997); and (2) ODTS cases reported in compost workers or compost handlers. There is insufficient incidence rate data, however, to address the risk level and strength of association. Although ODTS in compost workers can occur, level of risk is unknown.
(4) There is suggestive evidence of an association between exposure to bioaerosol in a composting plant and occurrence of mold- and actinomycetes-related hypersensitivity pneumonitis as indicated by the point-to-point data from case reports and exposure data reported from samplings in composting plant. This argument is supported by reported hypersensitivity pneumonitis cases in compost workers.
(5) There is insufficient evidence to determine whether or not an association exists between exposure to bioaerosol in a composting plant and allergic asthma and rhinitis. However, atopy, which is an individual risk factor for allergic asthma and rhinitis, is present in 20 to 25% of the population and may be present in compost workers and job applicants.
(6) There is insufficient evidence to determine whether or not an association exists between exposure to bioaerosol in a composting plant and ABPA or other allergic broncho pulmonary mycosis (ABPM). Allergic diseases linked to chronic colonization of respiratory mucous membranes by molds complicates atopic patients with asthma or cystic fibrosis. Atopic asthma occurs in approximately 11% of adults in the United States (Centers for Disease Control and Prevention, 2002). Compost workers and job applicants also can have an atopic asthma history. Published data pertaining

Table 2—Environmental conditions.

		Temperature (°C)		Humidity (%)		Wind speed (m/s)	
Site	**Season**	**Mean**	***SD***	**Mean**	***SD***	**Mean**	***SD***
A	Summer	27.8*	*1.1*	80.7**	*9.6*	0.18	*0.02*
A	Winter	17.2	*1.2*	94.8	*4.9*	0.13	*0.04*
B	Summer	28.5*	*2.3*	53.7	*9.6*	0.42	*0.43*
B	Winter	15.2	*3.0*	59.2	*19.6*	0.47	*0.23*
C	Summer	26.2*	*2.7*	47.7**	*9.2*	0.46	*0.27*
C	Winter	15.3	*2.6*	71.6	*5.6*	0.45	*0.42*
D	Summer	15.2*	*1.3*	76.6	*8.2*	1.41	*0.42*
D	Winter	6.9	*1.7*	81.0	*7.3*	1.60	*1.06*
E	Summer	19.8*	*2.6*	80.3	*7.1*	1.87**	*1.13*
E	Winter	9.8	*2.1*	92.9	*2.8*	3.49	*1.18*
F	Summer	19.8*	*1.4*	60.9*	*1.7*	0.57	*0.53*
F	Winter	8.3	*1.5*	94.2	*2.4*	0.81	*0.65*

*$p < 0.001$.
**$p < 0.05$; standard deviation (SD).

to waste bioaerosol exposure are limited to two case reports and do not provide sufficient evidence to estimate the association between bioaerosol in composting plants and ABPA or other ABPM. Similarly, there is insufficient evidence to determine whether or not an association exists between fungal allergic sinusitis and exposure to bioaerosol in composting plants.

(7) The risk of invasive aspergillosis in composting workers is very low because this disease is associated with severe immunodepression, which is usually not consistent with active employment. Invasive aspergillosis also is associated with severe chronic obstructive pulmonary disease treated by corticoids. These individuals often do not work, or, if they do, should be advised by their physician not work in waste management facilities. The three reported cases of invasive aspergillosis among compost workers/handlers do not provide strong evidence for a specific occupational health risk in immunocompetent compost workers.

(8) There is insufficient evidence to determine whether or not an association exists between exposure to bioaerosol in composting plants and aspergillal infections from colonization without an invasive mechanisms, like aspergillal fungus ball or aspergillal sinusitis. These infectious outcomes are the results of local risk factors that allow colonization by *Aspergillus* (e.g., healed cavitary tuberculosis or sarcoidosis in the lung) and might be present occasionally in compost workers. Occurrence of these infectious diseases in compost workers, however, is not documented.

Sampling Results

Data from environmental conditions measurements have been analyzed, considering only indoor measurements for confined facilities (Table 2). Mean temperature was consistently higher in summer than in winter ($p < 0.001$). Mean humidity was lower in summer than in winter in sites A, C, and F ($p < 0.05$) and not significantly different between seasons in sites B, D, and E. Mean wind speed was not different between seasons except in the open-air site E (higher in winter, $p < 0.05$).

A total of 173 samples were collected: 84 during summer, including 32 from static points and 52 personal; and 89 during winter campaign, including 36 from static points and 53 personal. Five to six static points were sampled in duplicates in each plant, including feedstock reception, shredding, mixing, fermentation, screening, maturation, and truck container loading areas, and one outdoor out-of-the pad point for background-level measurement. Regarding personal exposure, both loader driving and out-of-cabin tasks were investigated. Workers held two CIP 10 samplers, one for dust collection and one for biological agent collection. In each plant, one to three samples were collected during loader driving, mixer driving, turner driving, on-pile/process monitoring, municipal solid waste reception monitoring, handling, indoor ground cleaning, screen cleaning, maintenance, and miscellaneous tasks such as office tasks, plastic and metals collection, and cabin filter cleaning.

Overall Results of Stationary Sampling. Overall, data showed a large variation of variables in ambient air because ranges between nonoutlier smallest and highest observations of biological agents were between 4 to 5 log units, both in summer and winter sampling. Inhalable dust concentration reached 226 mg/m^3 in summer and 27.2 mg/m^3 in winter, with median concentration of 5.5 mg/m^3 and 1.8 mg/m^3, respectively. Endotoxin concentration in air was up to 1.5×10^6 EU/m^3, with a median value of 15 549 EU/m^3. Maximum and median values of microorganism concentration reached more than 10^9 cfu/m^3 and 10^8 cfu/m^3 for mesophilic bacteria and Gram-negative bacteria, respectively; 10^8 cfu/m^3 and 10^6 cfu/m^3 for mesophilic molds; 10^7 cfu/m^3 and 10^5 cfu/m^3 for *A. fumigatus*; and more than 10^8 cfu/m^3 and 10^6 cfu/m^3 for actinomycetes. When comparing mean values, onsite measurement results were two to more than three orders of magnitude higher (100 to 1000 times higher) than out-of-pad background levels. The highest onsite observations were from four to six orders of magnitude higher than the highest background level value, except for actinomycetes concentration, which was one order of magnitude higher in composting plants areas. A decrease in concentration levels between summer and winter seasons consistently was observed with all biological agents, from one to three orders of magnitude for median values (results not shown).

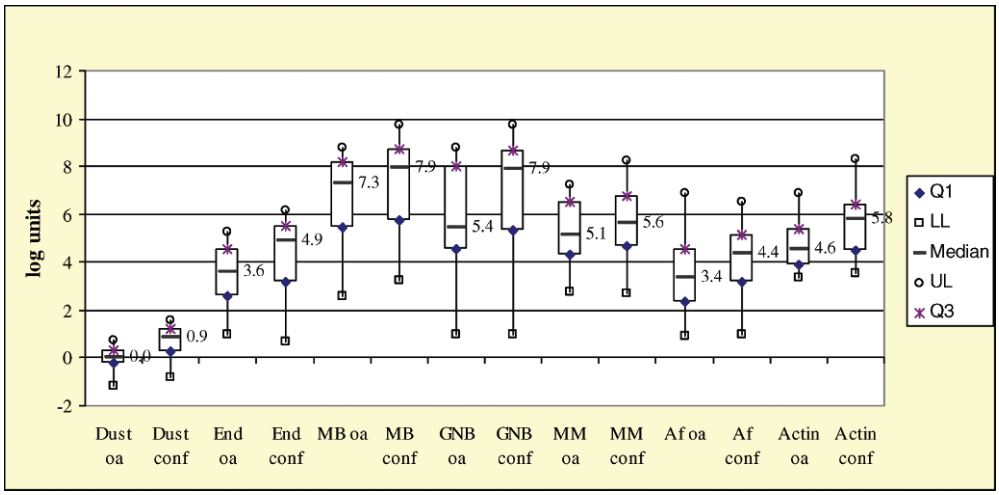

Figure 1—Dispersion of variables log concentration in air in open-air (n = 25) and confined and under-shed facilities (n = 34). Units are log-transformed mg/m^3 for dust, EU/m^3 for endotoxin, and cfu/m^3 for microorganisms (end = endotoxin; MB = mesophilic bacteria; GNB = Gram-negative bacteria; MM = mesophilic molds; Af = *A. fumigatus*; Actin = actinomycetes; oa = open-air; conf = confined; Q1 = first quarter; LL = nonoutlier, smallest value = [Q1 − 1.5(Q3–Q1)]; UL = nonoutlier, highest value = [Q3 + 1.5(Q3–Q1)]; Q3 = third quarter; n = number of measurements).

Comparison between Open-air and Confined Facilities. Overall, inhalable dust, endotoxin, and microorganisms concentrations in ambient air were lower in open-air facilities than in confined and under-shed facilities (Figure 1). Mean concentrations from stationary sampling in confined plants and in open-air facilities differed significantly for dust ($p < 10^{-4}$), endotoxin ($p < 0.01$) and actinomycetes ($p < 0.01$). For mesophilic bacteria, Gram-negative bacteria, mesophilic molds, and *A. fumigatus*, mean levels in open-air sites were not significantly lower than those in confined facilities.

Comparison within and between Process Areas. Dust and biological agent concentrations in air in processes areas from stationary sampling are indicated in Table 3. Within a process area, median values of inhalable dust and microorganism concentration were consistently lower in winter than summer (except for actinomycetes in shredding area; the number of

Table 3—Dust and biological agent concentrations in air in composting plant process areas and outdoor out-of-pad background levels.

Process area	Dust, mg/m^3	Endotoxin, EU/m^3	Mesophilic bacteria, cfu/m^3	Gram-negative bacteria, cfu/m^3	Mesophilic molds, cfu/m^3	*A. fumigates*, cfu/m^3	Actinomyc., cfu/m^3
	GM[1] *(GSD[2])* Min–Max	GM *(GSD)* Min–Max	GM *(GSD)* Min–Max	GM *(GSD)* Min–Max	GM *(GSD)* Min–Max	GM *(GSD)* Min–Max	GM *(GSD)* Min–Max
Mixing-fermentation (n* = 10)	3.6 *(4.9)* <0.2–17.9	1.2×10^5 *(10)* 4.8×10^3 –6.8×10^5	1.0×10^7 *(150)* 1.7×10^3 –1.6×10^9	4.4×10^6 *(620)* <18–1.6×10^9	4.1×10^5 *(40)* 1.2×10^3 –1.2×10^8	1.8×10^4 *(44)* <21–1.4×10^6	2.4×10^5 *(10)* 8.0×10^3 –5.2×10^6
Screening (n = 17)	7.5[A] *(4.8)* 1.0–226.0	1.3×10^5 *(10)* 486–3.2×10^6	2.7×10^7 *(75)* 5.4×10^3 –5.5×10^9	1.3×10^7 *(96)* 3.1×10^3 –5.5×10^9	3.2×10^5 *(28)* 1.6×10^3 –1.7×10^8	8.0×10^3 *(80)* <18–3.5×10^6	5.5×10^5 *(16)* 5.3×10^3 –2.0×10^8
Maturation (n = 13)	1.1[A] *(6.9)* <0.1–35.9	2.3×10^4 *(18)* 213–1.5×10^6	3.3×10^6 *(150)* 1.9×10^3 –3.1×10^9	4.0×10^5 *(440)* 10–3.1×10^9	1.2×10^5 *(21)* 490–19×10^6	4.0×10^3 *(74)* <18–7.1×10^6	1.4×10^5 *(14)* 3.4×10^3 –7.1×10^6
Shredding (n = 5)	1.2 *(4.0)* 0.1–5.5	5.2×10^4 *(3)* 1.6×10^4 –3.6×10^5	7.2×10^6 *(100)* 1.1×10^4 –1.6×10^9	1.4×10^6 *(160)* 1.9×10^3 –2.7×10^8	8.6×10^5 *(24)* 6.2×10^3 –1.1×10^7	1.5×10^3 *(31)* <20–1.8×10^5	4.0×10^4 *(4)* 6.1×10^3 –3.6×10^5
Out-of-pad background level (n = 6)	0.3 *(2.8)* 0.1–1.3	76 *(6)* 10–930	2.8×10^3 *(3)* 6.5×10^2 –9.5×10^3	170 *(14)* 10–5.4×10^3	650 *(11)* <19–6.2×10^3	16 *(5)* <12–460	2.9×10^3 *(4)* 650–2.5×10^4

[1] GM = geometric mean.
[2] GSD = geometric standard deviation.
* n = number of measurements.
[A] $p < 0.01$.

Table 4—Dust and biological agents concentrations in personal sampling; means comparison between seasons.

Season	Dust, mg/m^3	Endotoxin, EU/m^3	Mesophilic bacteria, cfu/m^3	Gram-negative bacteria, cfu/m^3	Mesophilic molds, cfu/m^3	*A. fumigatus*, cfu/m^3	Actinomyc., cfu/m^3
	GM[1] *(GSD[2])* Min–Max	GM *(GSD)* Min–Max	GM *(GSD)* Min–Max	GM *(GSD)* Min–Max	GM *(GSD)* Min–Max	GM *(GSD)* Min–Max	GM *(GSD)* Min–Max
Summer (n* = 52)	1.7 *(4.1)* 0.1–100.8	1.9×10^4 *(20)* <200–1.3×10^7	3.2×10^7 *(38)* 1.1×10^4–4.8×10^9	6.0×10^6 *(83)* 1,350–4.3×10^9	2.6×10^5 *(13)* 190–3.5×10^7	1.8×10^4 *(11)* <16–3.2×10^6	1.1×10^5 *(8)* 1.8×10^3–5.3×10^7
Winter (n = 53)	0.9 *(4.5)* <0.2–49.5	680 *(10)* <20–4.3×10^4	2.1×10^5 *(101)* <20–3.9×10^8	2.3×10^3 *(460)* <12–3.0×10^8	2.7×10^4 *(34)* 44–5.0×10^8	174 *(27)* <12–2.2×10^5	4.5×10^4 *(9)* 350–9.6×10^6
p	<0.05	$<10^{-5}$	$<10^{-5}$	$<10^{-5}$	$<10^{-3}$	$<10^{-5}$	NS[3]

[1] GM = geometric mean.
[2] GSD = geometric standard deviation.
[3] not significant ($p > 0.05$).
* n = number of measurements.

measurements, however, was low) (results not shown). On the other hand, summer- and winter-related median concentrations of endotoxin were similar, within 1 log unit of difference. For dust measurement, the highest results were associated with the screening area in summer. The lowest stationary dust sampling results were associated with static maturation area in winter. The data indicate high concentrations of microorganisms in ambient air of the various process areas and workplaces on the sites (mixing-fermentation areas, screening areas, including refuse side and compost side, maturation areas and green waste, and wood shredding areas). Between-process areas differences in median values were from less than 1 to 2.5 orders of magnitude according to the microorganism variable, both in summer and winter. The screening area was associated with the highest mean concentration level for inhalable dust, endotoxin, Gram-negative bacteria, and actinomycetes. The shredding area was associated with the lowest concentrations of thermophilic microorganisms, actinomycetes, and *A. fumigatus*; for all other variables, the lowest mean concentrations were observed in the maturation area. Comparison of means (ANOVA), however, did not show significant differences between process areas, except for dust concentration.

Comparison between Sites. Between sites, differences in summer results varied from less than 1 to 2 log units for the same type of process area, with the exception of maturation in sludge composting plants (more than 3 log units for mesophilic bacteria). When samples were collected in winter, results indicated larger differences between facilities, up to 5 log units for mesophilic bacteria in fermentation and screening areas in sludge composting plants. Ranking of sludge composting plants according to the bioaerosol level for each process area was consistently similar. In green waste composting plants, microorganisms results from summer sampling in screening and shredding areas were not significantly different between the two sites (within 1 log unit of difference), but between-sites differences were larger in winter, both in screening and shredding areas, from 2 (mesophilic molds) to more than 3 log units (mesophilic bacteria). In the windrow turning area, summer samplings indicated higher levels of microorganism concentrations in the organic fraction of municipal solid waste (OFMSW) composting plant than in green waste composting plants, 10 to 100 times higher. This difference was lower in winter sampling, showing less than 1 order of magnitude.

Results from Personal Sampling. Ranges of biological agent concentration in personal samples were large at between 4 and 7 log units (Table 4). In summer, inhalable dust concentration reached 100.8 mg/m^3; this result, however, was an extreme outlier. The dispersion of dust concentration variable showed that 90% of values were less than or equal to 5.7 mg/m^3, and that median concentration was 2.3 mg/m^3. In winter, dust concentration reached a maximum level of 49.5 mg/m^3, and 90% of values were less than or equal to 10.5 mg/m^3. The inhalable dust median concentration in winter personal samples was less than 1 mg/m^3 (0.9 mg/m^3). Median personal exposure to endotoxin was 50 119 EU/m^3 in summer, and 513 EU/m^3 in winter. A significant decrease in concentration between summer and winter seasons was observed consistently with all biological agents, except actinomycetes. Microorganism median concentrations in air were from one to three orders of magnitude lower in winter than in summer.

Comparison between Tasks. Regardless of season, maintenance and ground cleaning were the tasks associated with the highest mean exposure levels to dust, endotoxin, and mesophilic bacteria (Table 5). Regarding mesophilic molds and actinomycetes, differences in task-related exposure levels were not as large, with means within a range of one order of magnitude.

In most cases, driving a vehicle did not provide less exposure than tasks performed outside the vehicle cabin. Statistical significance (p) of means comparison Student's t-test between inside cabin measurement and maintenance, ground cleaning and monitoring ones, respectively, are provided in Table 6.

The ANOVA did not show differences between variables means when comparing tasks performed outside of the vehicle cabin. Nearly all results showed higher personal exposure level to airborne biological agents in summer than in winter. When winter results were higher than summer ones, the difference was low, less than 1 log unit. Results of personal sampling inside the vehicle cabin indicate statistically significant lower exposure levels in winter than in summer for dust (geometric means 0.59 mg/m^3 and 1.43 mg/m^3, respectively; $p < 0/05$) and for all biological agents (Figure 2).

In summer and winter sampling campaigns, loader driving was associated with the highest and the lowest variables concentrations. This observation was made between sites and within the same site. Driving a loader in open-air facilities did not demonstrate a statistically significant difference in personal exposure to inhalable dust when compared with confined facilities, regardless of season. On the other hand, personal mean

Table 5—Task-related personal exposure to dust and biological agents.

Task	Dust mg/m^3	Endotoxin EU/m^3	Mesophilic Bacteria cfu/m^3	Mesophilic Molds cfu/m^3	Actinomyc. cfu/m^3
	GM[1] *(GSD[2])* Min–Max	GM *(GSD)* Min–Max	GM *(GSD)* Min–Max	GM *(GSD)* Min–Max	GM *(GSD)* Min–Max
Inside cabin (n* = 67)	0.9 *(4.0)* 0.1–100.8	2.1×10^3 *(22)* 6–8.3×10^5	1.5×10^6 *(140)* <20–4.8×10^9	7.9×10^4 *(27)* 190–5.0×10^8	5.4×10^4 *(7)* 980–5.3×10^7
Maintenance (n = 9)	3.6 *(3.4)* 0.3–13.7	5.7×10^4 *(17)* 1.2×10^3–1.3×10^7	3.2×10^7 *(17)* 40×10^3–2.8×10^8	7.5×10^4 *(7)* 1.6×10^3–7.1×10^5	1.2×10^5 *(6)* 3.8×10^3–3.0×10^6
Ground cleaning (n = 6)	2.5 *(4.9)* 0.5–48.9	2.4×10^4 *(24)* 213–2.1×10^6	1.0×10^8 *(28)* 2.7×10^5–3.2×10^9	2.6×10^5 *(21)* 1.8×10^4–3.2×10^6	3.0×10^5 *(6)* 1.4×10^4–3.2×10^6
Monitoring (n = 11)	2.1 *(4.8)* 0.2–49.5	8.0×10^3 *(28)* 95–8.1×10^5	4.5×10^6 *(95)* 1.3×10^3–3.3×10^8	7.3×10^4 *(25)* 860–1.8×10^7	1.3×10^5 *(6)* 1.0×10^4–1.8×10^6

[1] GM = geometric mean.
[2] GSD = geometric standard deviation.
* n = number of measurements.

Table 6—Statistical significance (*p*) of means comparison Student's t-test between inside cabin driving task and maintenance, ground cleaning, and monitoring.

Means comparison between inside cabin plus:	Dust	Endotoxin	Mesophilic bacteria	Mesophilic molds	Actinomyc.
Maintenance	<0.01	<0.01	NA	NS	NS
Ground cleaning	NS	NS	NS	NS	<0.05
Monitoring	NS	NS	NS	NS	NS

NS = not significant ($p > 0.05$); NA = not applicable because of differences in variances.

exposure to mesophilic and Gram-negative bacteria, mesophilic molds, and endotoxin was significantly higher when a vehicle was driven in open-air facilities compared to confined facilities when considering total sampling ($p < 0.05$). Exposure levels to *A. fumigatus* and actinomycetes inside cabins were not different between open-air and confined facilities for both total and season-related results.

Comparison between Personal Exposure Inside Cabin and Stationary Sampling. Mean exposure levels inside the vehicle cabin and concentration in related ambient air were compared with regard to dust, endotoxin, and mesophilic and Gram-negative bacteria, and spores (molds and actinomycetes). Comparison was made by subtracting log-transformed values. This yielded a positive result when there was a decrease in exposure and a negative result with an increase in exposure inside the vehicle cabin. Results indicated differences between sites and within sites and that driving a vehicle may have been associated with an increase of exposure to bioaerosol compared to related workplace ambient air (Table 7). The most significant decreases in concentration were for mesophilic and Gram-negative bacteria and were observed in a confined sludge composting plant (site B). The most significant increase in exposure level when a vehicle was driven was observed in the reception hall in the organic fraction municipal solid waste composting plant (site F).

Correlations between Variables Log Concentrations. Coefficients from Spearman rank correlation analysis and Pearson linear correlation analysis of all data were quite similar. This suggests a log-linear relationship between variables. Correlation coefficients indicate low ($0.2 \leq r < 0.5$) to moderate ($0.5 \leq r < 0.8$) association between inhalable dust level and microorganisms or endotoxin levels, with a high degree of significance (all $p < 0.0001$) (Figure 3). Changes in dust concentration can explain 15 to 25% of changes in microorganism levels. Changes in Gram negative bacteria concentration may explain up to 64% of changes in endotoxin concentration, and changes in

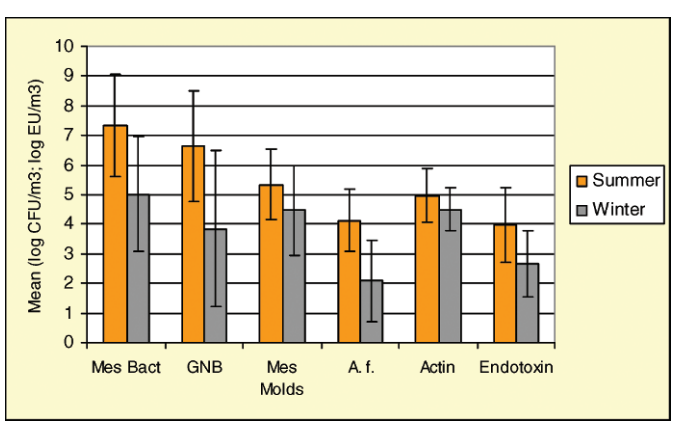

Figure 2—Inside vehicle cabin personal exposure in summer (n = 33) and winter (n = 34) campaigns. Error bars are standard deviations (Mes Bact = mesophilic bacteria; GNB = Gram-negative bacteria; Mes = mesophilic; Af = *A.fumigatus*; Actin = actinomycetes).

Table 7—Exposure decrease when working in vehicle cabin (GW = green waste; OFMSW = organic fraction of municipal solid waste).

Sites	Activity	Dust	Endotoxin	Mes. and Gram-neg bacteria	Spores (molds + actin)
A	Mixing	0.7	−0.1	0.4	0.1
A	Screening	0.7	0.9	0.5	0.2
B	Mixing and Fermentation	0.9	3.1	5.8	1.0
B	Screening	1.2	2.0	4.3	1.2
C	Fermentation	0.2	2.2	1.9	−0.3
D	Mixing	0.3	0.5	1.0	1.9
D	GW shredding	0.1	0.3	1.6	0.3
D	Screening	−0.1	−0.5	0.5	0.1
E	GW reception	−0.1	−0.1	0.0	−0.6
E	Screening	0.1	0.4	4.2	−0.2
E	GW shredding	0.2	0.0	0.0	0.1
F	Maturation	0.0	−0.6	−1.1	0.6
F	OFMSW reception	0.0	−1.5	−1.3	0.8
F	Screening	1.5	2.0	3.9	3.3

mesophilic molds concentration explained up to 44% of changes in *A. fumigatus* concentration. Associations between variables concentrations were significantly stronger in confined and under-shed facilities than in open-air facilities. In open-air sites, analysis did not demonstrate a significant correlation between dust and Gram-negative bacteria, mesophilic molds, *A. fumigatus*, and actinomycetes.

Discussion

This paper reviews concentrations in air of inhalable dust, endotoxin, and mesophilic and thermophilic microorganisms in composting plants. Suspected differences of bioaerosol concentration between summer and winter season and between open-air and confined sites were considered when developing the sampling plan. In addition, the sampling plan was designed to estimate variables concentrations both in ambient air and in personal samples. The same sampling device, the CIP 10, was used to collect dust, endotoxin, and microorganisms in air in stationary and personal samplings. This strategy avoided potential biases that would have been associated with the use of different types of sampler. Moreover, the configuration of the CIP 10-M air flow caused minimal stress to the microorganisms (Görner et al., 2006). The CIP 10-M was developed in 2003 from the CIP 10 dust sampler to collect bioaerosols. It has not, however, been included in the European Standards for workplaces atmospheres, nor in the 2006-reapproved E 884-82 Standard Practice for Sampling Airborne Micro-organisms at Municipal Solid-Waste Processing Facilities (ASTM International, 2006; Comité Européen de Normalisation [CEN], 2000; CEN, 2003). Particle size CIP 10-selector for inhalable aerosol fraction was designed to satisfy the sampling requirements for health-related aerosol fractions in accordance with the CEN, American Conference of Governmental Industrial Hygienists (ACGIH), and International Organization for Standardization (ISO) sampling criteria (Görner et al., 2006). The CIP 10 exhibited acceptable inhalable fraction efficiency versus aerosol diameter (Bartley, 1998). For the CIP 10-M version, sampling efficiency tested in laboratory and field trials demonstrated fair microbiological efficiency compared to existing microbiological sampling devices (Görner et al., 2006). Because most bioaerosol collection devices used in published works were impactors, filters, and impingers, a comparison of CIP 10-M-related results with published studies is limited.

Results for maximum values of variables concentrations were roughly similar to published data with differences within 1 log-unit. Median values of molds and actinomycetes concentrations were slightly higher (1 to 2 log-units). On the other hand, differences in medians for mesophilic and Gram-negative bacteria were larger, at 3 and 4 log-units, respectively. This difference may be explained by decreased inactivation of vegetative bacteria, especially Gram-negative bacteria, when collected into liquid than on to a cassette. Methods were consistent with the recommendation by ASTM International (2006) to use an all-glass impinger for fecal coliforms sampling and for determination of total plate count.

Endotoxin measurements were high compared to published results, which, in most cases, are from collection by filters. Additional samples were taken at plants B and C to identify potential interactions and to determine the effect of collection into liquid. Results (not shown) did not support the hypothesis of a significant amplification/interaction with the tensio-active added to the liquid, nor an interaction with glucan from molds. The hypothesis of a relationship between high values of CIP 10-M-related endotoxin measurements and long transport duration of samples (ranged between one and four days) was not supported by Gram-negative bacteria-endotoxin correlation slopes analysis (results not shown). Parallel collection with CIP 10-M and 25 mm cassette IOM filtering device (SKC Inc.) was performed at plants B, E, and F. Results were 10 to 100 times lower when endotoxin was collected and analyzed from cassette compared to liquid. Correlation between CIP 10-M-related and IOM-related results was statistically significant ($p < 0.01$), but the strength of the association was moderate ($r = 0.78$). High observed endotoxin results may be associated with high recovery efficiency of sampling with CIP 10-M device; a potential bias, however, cannot be excluded.

Sampling in composting plants indicated high concentrations of dust endotoxin, bacteria, molds, and actinomycetes in ambient air and in personal samples, both when workers were driving a vehicle and when working outside the vehicle cleaning, monitoring, and performing maintenance tasks. Many onsite

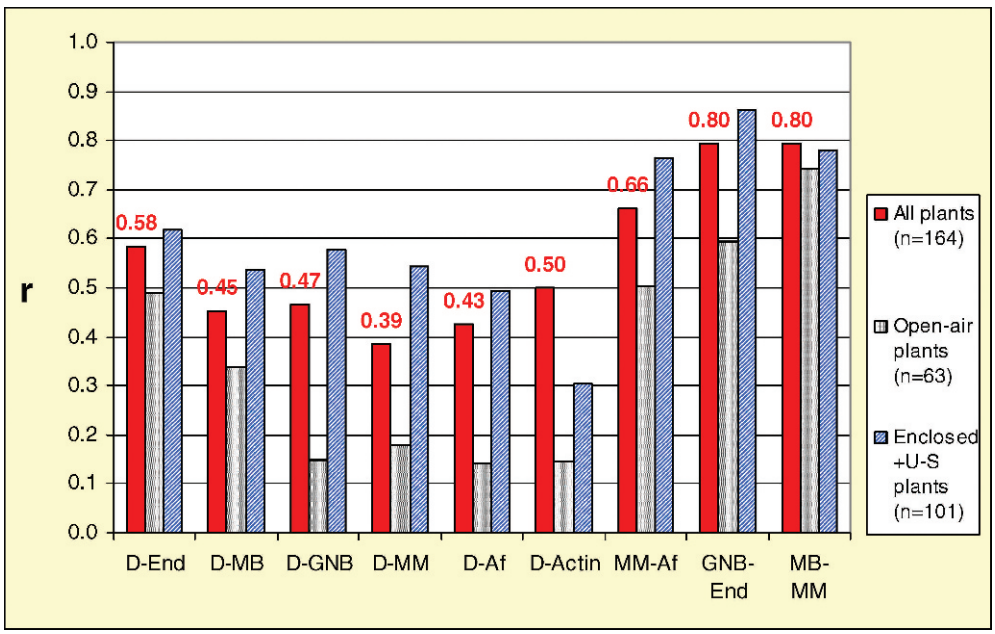

Figure 3—Correlation coefficients of associations between variables log concentrations (D = dust; end = endotoxin; MB = mesophilic bacteria; GNB = Gram-negative bacteria; MM = mesophilic molds; Af = *A.fumigatus*; Actin = actinomycetes; U-S = under-shed).

activities extensively agitate composting materials, spreading into ambient air microorganisms in materials. Cleaning, maintenance tasks, and vehicle movement across dust covered surfaces also generate dust dispersion. In these latter situations, environmental conditions such as air temperature and dryness will affect dust deposited on the ground and on surfaces, which can partly explain observed differences between summer and winter sampling results. Statistical analysis of stationary sampling results did not consistently support the hypothesis of higher exposure levels in closed buildings because of confinement compared with open-air facilities.

Regarding personal sampling, the highest mean exposure levels were associated with maintenance, cleaning, on pile monitoring, handling, and some vehicle driving, both in confined/under-shed and in open-air facilities. Some tasks, such as loader driving, maintenance tasks, and monitoring, were associated with both the highest and lowest personal exposure level. High personal exposure levels in composting plants were not clearly associated with similar tasks between sites. The task associated with the highest personal exposure level varied between seasons, which is consistent with observations by Wouters et al. (2006) of a greater within-worker than between worker variance of exposure to inhalable dust and endotoxin. Interestingly, vehicle driving was both associated with the highest and the lowest variables concentrations, within site and when comparing sites. This also may be explained by

- Sampling fluctuation effect because of low number of samples for each task on each site;
- Differences between vehicles regarding the fitting and efficiency of the cabin protection system (overpressure and filtration system), as was indicated by comparison of molds and actinomycetes concentrations measured in cabins of shovel loaders with and without filtered air (Bünger et al., 2007);
- Accumulation of dust and associated biological agents inside the cabin if it was not regularly cleaned;
- Movement of the worker into and out of the cabin during the sampling time; and
- To a lesser extent, the portion of the sampling time (less than 1/10) that was related to the holding of the sampler from the onsite laboratory to the workplace (moving with the CIP 10-M needs it to be operational in order not to spill the liquid).

Even if some measurement results were significantly different between tasks within site, mean personal exposure levels in composting plants were high, 100 to more than 10 000 times higher than outdoor background levels. Comparison with published exposure data in case reports and epidemiological studies shows that these personal exposure levels are fully consistent with occurrence of allergic and inflammatory outcomes among exposed workers. Probability calculation shows that when driving a vehicle eight hours per day, personal exposure level to actinomycetes had 0.5% of chance to exceed published hypersensitivity pneumonitis-related threshold; exposure to mold spores had 47% of chance to exceed benchmark dose associated with a decrease in respiratory flow rate; and exposure to endotoxin had 43% and 0.2% of chance to exceed MMI-and ODTS-related thresholds, respectively. Highest OELs that have been proposed had 0.2% of chance to be exceeded for endotoxin, 56% for molds, and 70% for actinomycetes.

Obviously, these latter findings should be considered with caution because of different sampling and analysis methods. Nevertheless, the findings emphasize the need to develop appropriate means of protection through facility design, operational changes, and personal protective equipment. In addition, education and training program for employees, health and safety officials, and occupational physicians is important.

Conclusion

Sampling campaigns in composting plants indicated that mean personal exposure levels to airborne biological agents were high, both when workers were driving front-end loaders and working outside the loader cabin. Comparison with results from medical literature pertaining to occupational exposure to bioaerosol suggests that personal exposure levels were consistent with occurrence of allergic and inflammatory health effects among workers. However, incidence rates of these health outcomes in compost workers are poorly documented. Long-term evaluation of respiratory function and additional prospective cohort epidemiological studies are required. High personal exposure levels in this study emphasize the need for source and pathway control and personal protection, including preemployment medical screening, routine medical surveillance, and education and training programs.

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