

1 **Morphological Classification of Bioaerosols from Composting using Scanning**  
2 **Electron Microscopy**

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9  
10 **Abstract:**

11 This research classifies the physical morphology (form and structure) of bioaerosols  
12 emitted from open windrow composting. Aggregation state, shape and size of the  
13 particles captured are reported alongside the implications for bioaerosol dispersal  
14 after release. Bioaerosol sampling took place at a composting facility using personal  
15 air filter samplers. Samples were analysed using scanning electron microscopy.  
16 Particles were released mainly as small (< 1 µm) single, spherical cells, followed by  
17 larger (>1 µm) single cells, with aggregates occurring in smaller proportions. Most  
18 aggregates consisted of clusters of 2-3 particles as opposed to chains, and were  
19 <10 µm in size. No cells were attached to soil debris or wood particles. These small  
20 single cells or small aggregates are more likely to disperse further downwind from  
21 source, and cell viability may be reduced due to increased exposure to  
22 environmental factors.

23  
24 **Keywords:** Bioaerosols, dispersion, SEM, particle size, aggregation

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25

## 26 **1. Introduction**

27 Bioaerosols are airborne particles of biological origin (Cox and Wathes, 1995),  
28 ranging from 0.02 to 100  $\mu\text{m}$  in size (Dowd and Maier, 2000; Ariya and Amyot,  
29 2004), including living microorganisms such as bacteria, fungi, yeasts and  
30 protozoans, or fragments and constituents of microorganisms (ADAS/SWICEB,  
31 2005). Bioaerosols are released as a consequence of compost agitation activities  
32 (shredding, turning and screening), but do also occur naturally in the environment  
33 and exposure to bioaerosols is not limited to composting facilities (Dutkiewicz, 1997;  
34 Lacey, 1997; Nielsen et al., 1997; Reponen et al., 1998; Sánchez-Monedero and  
35 Stentiford, 2003; Seedorf et al., 1998; Swan et al., 2003). Under prolonged or acute  
36 exposure conditions, bioaerosols have the potential to pose health risks to immune-  
37 compromised or vulnerable humans, particularly where high concentrations are  
38 emitted close to residences, schools, hospitals and other public facilities  
39 (Environment Agency, 2007).

40

41 The physical and morphological characteristics of bioaerosols are central to  
42 understanding emissions and downwind dispersal from composting facilities. The  
43 behaviour of bioaerosols after release is governed by physical factors, including  
44 gravitational forces and Brownian motion, as well as environmental factors, such as  
45 wind speed, relative humidity and temperature (Pillai and Ricke, 2002). Bioaerosol  
46 properties such as size, shape, aspect ratio, surface characteristics and their affinity  
47 for aggregation, also affect their behaviour and are important factors in predicting  
48 their dispersal (Levetin, 1995; Madelin and Johnson, 1992; McCartney, 1994;  
49 McCartney et al., 1997). For example, a larger particle or aggregate might be subject

50 to higher deposition velocities than a smaller one (Wheeler et al., 2001; Swan et al.,  
51 2003), with implications for the distance and time particles remain airborne (Pillai and  
52 Ricke, 2002).

53

54 Research examining bioaerosol size distribution and aggregation from composting  
55 emissions is limited. Kanaani et al. (2008) found that deposition rates for bioaerosols  
56 and non-biological particles were a function of particle size, not the nature of the  
57 particle. Byeon et al. (2008) found that aerodynamic diameters of microorganisms  
58 were larger than expected and attributed this to the possibility that they were  
59 suspended as aggregates with other bioaerosols and/or with dust particles. Feng et  
60 al. (2011) claim that size and shape of bioaerosols can be clarified in real-time  
61 environmental monitoring by means of analysing the special distribution of scattered  
62 light, although their research is still requires further development.

63

64 Our research attempts to improve understanding of bioaerosol transport from source  
65 to sensitive receptor. In an attempt to improve characterisation of aggregation and  
66 size distribution of compost bioaerosols, experiments were undertaken to:

- 67 a) determine the size distribution of particulates released from compost and  
68 composting facilities, and
- 69 b) examine and characterise the nature of bioaerosol aggregates released from  
70 compost and composting facilities.

71

72 Images of microorganisms and their aggregates have been published before using  
73 Scanning Electron Microscopy (SEM) from either pure cultures or from substrates  
74 other than composts (Heikkilä et al., 1988; Klich, 2002; Kormendy and Wayman,

75 1972; Karlsson and Malmberg, 1989; Prescott et al., 1999a, b; Wittmaack et al.,  
76 2005). SEM has also been previously used as a technique for characterising  
77 morphological properties of small particles and bioaerosols (Friedbacher and  
78 Grasserbauer, 1995; Hiranuma *et al.*, 2008; Pasanen *et al.*, 1989; Skujins *et al.*,  
79 1971; Williams, 1970). SEM was therefore chosen as the method to study  
80 bioaerosols emitted from compost.

81

## 82 **2. Materials and Methods**

83 Bioaerosols were initially sampled under controlled experimental conditions, with  
84 samples being analysed using SEM and through traditional culture techniques.

85 These results confirmed the suitability of SEM as an analysis method and the  
86 presence of bioaerosols typically sampled from composting facilities, notably  
87 *Aspergillus fumigatus* (for further details see Tamer Vestlund, 2009).

88

### 89 **2.1. Site sampling techniques**

90 Samples were collected from a composting facility from a windrow (static source)  
91 using a wind tunnel and from agitation activities as described below (Jiang and Kaye,  
92 2001; Taha et al., 2005). Particles were sampled in triplicate at a height of 1.8 m for  
93 a period of 30 minutes at ten locations around the windrows and screening area (one  
94 upwind; three at 10, 50 and 100 m downwind of the windrows respectively; two by  
95 the screening area, and two at source). Calibrated (with an SKC Ltd. rotameter)  
96 personal SKC (Universal dust and vapour) air filter samplers were connected to IOM  
97 sampling heads by a 10 mm internal diameter Tygon tube (Taha et al., 2006; 2007).  
98 Particles were collected on polycarbonate filters (SKC Ltd.) with 0.8 µm pore size  
99 and 25 mm diameter. Air was drawn through the sampling heads at a flow rate of 2 ±

100 0.2 L min<sup>-1</sup> (SKC, 2002). After sampling the cassettes and filters were placed in a  
101 sterile 30 mL Nalgene vial (121 °C, 15 min) and stored in an ice-box at 4 °C for  
102 transport. The filters had an effective exposed diameter of 15 mm.

103

## 104 **2.2. Scanning electron microscopy protocol**

105 The filters were mounted onto a 25.3 mm (diameter) SEM stub prior to gold coating  
106 within 24 hours of sample collection (Polaron Equipment Ltd., SEM gold coating unit  
107 ES100). The coated filters were examined with a high-resolution SEM (XL30SFEG,  
108 Phillips; 10-12 kV beam size, 3-4 spot size) according to standard SEM practices.  
109 Nine pairs of coordinates were selected for analysis (Figure 1) using a systematic  
110 sampling design. Initial focus of the microscope was on the upper right edge  
111 (x=6000, y=6000) of the filter at a magnification of x30 and then increased to x2000  
112 when particles of interest (0.5 - 10 µm in size) were found. New viewing fields were  
113 selected at each of the nine pairs of coordinates until ten fields containing at least  
114 one particle were found for each pair of coordinates with 20 viewing fields around the  
115 central set of coordinates to account for 100 viewing fields in total (Heikkilä et al.,  
116 1988). The magnification was adjusted to ensure the visual properties of the particles  
117 were sufficiently clear to analyse and record their number, size, shape, type of  
118 particle, and aggregation status. Blank viewing fields, defined as fields with no  
119 particles of interest, were also considered and recorded to calculate the total area  
120 examined per filter. Blank viewing fields were scanned at magnifications of x500,  
121 x1000 and x2000.

122

123 **Figure 1 here**

124

125 **2.3. Statistical analysis**

126 Description of the data was performed by arithmetic mean values and standard error  
127 to measure variability, and a correlation analysis where required. One-factor ANOVA  
128 and, where applicable, Fisher tests were used to analyse the differences between  
129 independent data groups, using STATISTICA 8 (StatSoft Ltd.).

130

131 **3. Results and Discussion**

132 All SEM results shown correspond to the total area of 100 viewing fields (0.252 mm<sup>2</sup>)  
133 plus blanks scanned per filter as explained above. Filters (total area 490.8 mm<sup>2</sup>  
134 each) with low numbers of particles had a larger area analysed than those heavily  
135 populated, resulting in an average of 0.19% of the filter being analysed.

136

137 **3.1. Particle size distribution and characterisation**

138 In this study, particles observed were classified as small (0.5 - 1 µm) and large cells  
139 (2 - 3 µm). These were further classified into 8 different small cells and two major  
140 large cell types according to their physical appearance (Table 1). Particles such as  
141 filamentous and pollen-like particles (>10 µm), or those with no structure, were  
142 considered to result from structural defects of the filters according to additional  
143 analyses of filters that were not exposed to composting emissions (Tamer Vestlund,  
144 2009).

145

146 **Table 1 here**

147

148 A wide variety of microorganisms is present in and released from compost. Michel et  
149 al. (2002) identified over 94 species of microorganisms in green waste compost.

150 Similarly, Epstein (1997) listed 16 species of bacteria, 16 of actinomycetes and 35  
151 species of fungi derived from compost. Although the presence of the bioaerosols  
152 typically associated with composting (e.g. *Aspergillus fumigatus*) was confirmed by  
153 culture (see Tamer Vestlund, 2009), difficulties in identifying particular species could  
154 arise as sample preparation for SEM analysis results in the dehydration of the  
155 sample that causes collapse and distortion of the image (Heikkilä et al., 1988).  
156 Therefore, this research focused on the observable properties of bioaerosols (size,  
157 shape and aggregation status), irrespective of the bioaerosol species.

158

159 Figure 2 shows the dominant cell types according to sampling position at the  
160 composting facility. Cell type A was the most commonly occurring at all distances,  
161 with types B and D also found in the samples taken at source. Cell type G was also  
162 found in high proportions at 100m downwind of the composting facility. The overall  
163 tendency was for small cells to occur in higher frequencies than the large cells in all  
164 experiments, with the majority of particles present in the 100 viewing fields examined  
165 from compost samples are in the 0.5-1 µm size range. The dominance of smaller  
166 particles reflects previous research from compost facilities using Andersen 6 stage  
167 samples. Reinthaler et al. (1997) found that 56-73% of all particles were smaller than  
168 3.4 µm. Kamilaki and Stentiford (2001) found that 80% of all the *A. fumigatus*  
169 captured on stages 3, 4 and 5 of an Andersen sampler were in the size range of 1.1  
170 to 3.3 µm. Byeon et al. (2008) examined bioaerosols in a municipal composting  
171 facility and reported concentrations of 10<sup>8</sup> CFU/m<sup>3</sup> total airborne particles sized 0.3  
172 µm, which drastically decreased as the particle diameter increased. While not  
173 directly comparable, these studies provide the only other published indications of the  
174 size range of bioaerosols emitted from composting.

175

176 **Figure 2 here**

177

### 178 **3.2. Aggregate size distribution and characterisation**

179 Airborne microorganisms have been found in aggregates consisting of 2-6 spores in  
180 various environments (Bell et al., 2000; Karlsson and Malmberg, 1989; Lacey, 1991;  
181 Lacey and Dutkiewicz, 1976a, b; Levetin, 1995; Madelin and Johnson, 1992; Trunov  
182 et al., 2001). However, Figure 3 demonstrates that in all cases, single cells  
183 dominated over aggregates. The majority of cells observed for all sampling locations  
184 were small cells (66-99%); while their aggregates accounted for 1.4-30%. The  
185 proportion of single large cells and their aggregates are 1.3-6 % and 0.7-1.4 %,  
186 respectively. In addition, no aggregate structures were observed at 100 m downwind  
187 from the compost source, suggesting that aggregates drop out from the pollutant  
188 plume. Although, with a sampling height of 1.8 m, there is the possibility that the full  
189 pollutant plume was not sampled and aggregates may have disintegrated during the  
190 sampling process.

191

192 Bioaerosol survival rates within aggregates exceed that of single cells due to the  
193 protective effect of the outer layer for the inner cells (Carrera et al., 2005; Duncan  
194 and Ho, 2008; Lighthart and Schaffer, 1994; Marthi et al., 1990; Thomas et al., 2008;  
195 Tong and Lighthart, 1997). As most of the particles studied here consisted of single  
196 cells, it is conceivable that even if the particles were dispersed further downwind due  
197 to their small size, they will be less protected from environmental factors, and  
198 therefore cell viability could be reduced. This suggests that traditional culture

199 techniques often used for sampling downwind of composting facilities may  
200 underestimate the actual concentration of particles in the plume.

201

202 Bioaerosols have various release mechanisms. Filamentous structures or mycelia  
203 that extend above the growth substrate can become airborne as short chains, single  
204 spores or as fractions of mycelium (Gregory, 1973; Jankowska et al., 2000; Kanaani  
205 et al. 2008; Lacey, 1997; Madelin and Madelin, 1995; Pillai and Ricke, 2002). These  
206 can disintegrate into smaller sections and single spores, either due to release  
207 mechanisms or during sampling (Madelin and Johnson, 1992; Trunov et al., 2001).  
208 Single particles could also aggregate once airborne to make larger units (Calleja,  
209 1984).

210

211 Based on the results, aggregates of cells were classified into clusters and chain-like  
212 structures, depending on either width or length. The vast majority of aggregates were  
213 clusters indicating that either a larger proportion of non-filamentous microorganism  
214 aggregates become airborne, or that cells are clustering into aggregates subsequent  
215 to release (Figure 4). Furthermore, small aggregates dominated over large ones  
216 regardless of their shape. Approximately 50% of the small aggregates had a  
217 diameter of  $< 2 \mu\text{m}$  in size, equating to aggregates of 2-3 cells based on the  
218 assumption that single cells ranged from 0.5 to 1  $\mu\text{m}$ . Agitation produced more  
219 aggregates than static windrows ( $p=0.005$ ; Figure 4). Aggregates of three or more  
220 cells were more abundant in samples from the source than in any downwind sample  
221 (Figure 4). No aggregates were identified in upwind samples, suggesting that the  
222 composting activities may have an impact on the formation of aggregates. It is also

223 possible that the sampling technique has impacted on the number and formation of  
224 aggregates.

225

226 Several studies suggest that particles can be released as single cells, aggregates  
227 and as cells attached to other particles such as dust or wood fibres (Swan et al.,  
228 2003; ADAS/SWICEB 2005; Wittmaack et al., 2005). The results here do not  
229 suggest that the release of bioaerosols is dependent on the release of matter such  
230 as dust or wood fibres. However, only a small portion of each filter (maximum of  
231 1.1%) was examined. There is therefore the possibility that these particles could  
232 have existed in areas that were not examined or that the filters did not effectively  
233 sample or retain wood fibres.

234

### 235 **3.3. Particle morphology**

236 The majority of the particles, both single and aggregated cells, were spherical in  
237 nature with an aspect ratio of 1 (Figure 5). Gregory (1973) showed that the falling  
238 rate of a particle due to gravitational forces is proportional to the square of its radius.  
239 Furthermore, non-spherically shaped particles might fall more slowly due to an  
240 increased surface drag that would result in a delay in deposition (Lacey, 1991;  
241 McCartney, 1994; Levetin, 1995). Therefore, as the majority of particles observed in  
242 this study were spherical or almost spherical (aspect ratio 1 to 1.5), the effects of  
243 surface drag on bioaerosols is proposed to be minimal.

244

245 **Figure 5 here**

246

### 247 **3.4. Limitations of methodology**

248 SEM is able to provide accurate and detailed information on particle surface and physical  
249 particle size; however the samples are prepared and scanned under vacuum conditions,  
250 which causes dehydration, collapse and distortion of particles that might bias the actual size  
251 and surface characteristics of the particle (Heywood, 1969; Skujiņš *et al.*, 1971; Gwaze *et al.*,  
252 2007). Furthermore, due to the fact that only a very small percentage of the overall filter was  
253 analysed, the results here are only a representation rather than absolute values of the overall  
254 bioaerosol concentrations. The classification of the shape and nature of particles of interest  
255 was based on subjective assessment. Similar limitations have been reported due to the  
256 tendency of the operator to focus on more interesting particle features (Gwaze *et al.*, 2007;  
257 Shekunov *et al.*, 2007)

258

### 259 **3.5. Implications**

260 Bioaerosol dispersion modelling could be an invaluable tool to estimate downwind  
261 concentrations, particularly for regulatory compliance and in the design of control strategies.  
262 Knowledge on the physical attributes of bioaerosols is thus crucial to provide confidence in  
263 model outputs for composting facilities. A key decision for modellers is whether to model as a  
264 particle or as a gas (Drew *et al.*, 2007). However, there is currently insufficient information  
265 available to fully define the particle properties within dispersion models. The results here  
266 suggest that modelling as a gas would suffice, as the majority of particles found were small  
267 enough for this to be a suitable option.

268

269 Studies on the health impact of airborne pollutants have shown that smaller particles  
270 (<2.5  $\mu\text{m}$ ) are more likely to negatively affect sensitive receptors as they can  
271 penetrate deeper into the lungs (Dockery *et al.*, 1993; Levy *et al.*, 2000; Schwartz *et*  
272 *al.*, 1996; Spengler and Wilson, 1996; Sturm, 2011). Thomas *et al.* (2008) argued

273 that a lower dose of aggregate particulates is required to initiate an adverse health  
274 impact compared to non-aggregate particles, because aggregates contain higher  
275 number of individual cells. This has important implications in determining a dose-  
276 response relationship for bioaerosols.

277

#### 278 **4. Conclusions**

279 To the authors' knowledge, this is the first study that has classified bioaerosols  
280 emitted from compost according to shape and size. The results suggest the following  
281 conclusions regarding bioaerosols from composting sites:

- 282 • The majority of bioaerosols released in this study were single cells, shaped  
283 spherically or almost spherically, suggesting that they may disperse further than  
284 heavier aggregate structures.
- 285 • Eight types of small (0.5-1  $\mu\text{m}$ ) cells and 2 types of large (1-2  $\mu\text{m}$ ) cells and their  
286 aggregates were released from both static (i.e. compost windrow) and active (i.e.  
287 agitation) compost sources.
- 288 • The majority of all aggregates consisted of 2-3 cells and were smaller than 10  
289  $\mu\text{m}$ . Again, these are more likely to disperse further downwind, but would not  
290 benefit from the protection that larger aggregates would provide from  
291 environmental factors.
- 292 • Aggregate structures were primarily released in clusters as opposed to chains.
- 293 • There were no aggregate structures observed at 100 m downwind from compost  
294 source, or upwind, suggesting that composting facilities impact on the formation  
295 of aggregates.

296

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# Morphological classification of bioaerosols from composting using scanning electron microscopy

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