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Exposure to dust and bioaerosols at GB municipal waste handling sites

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Abstract

Background

Municipal waste in Britain contains organic matter. Handling this material can risk exposure to substances, including airborne dust and bioaerosol (airborne fungi, bacteria and their cellular components) that can impair human respiratory health. This paper combines the main findings of a series of studies conducted by the Health and Safety Executive in Great Britain to assess exposure to bioaerosols in various facilities processing municipal waste.

Methods

Site visits were conducted by a team of occupational hygienists and microbiologists. The key aims of the site visits were to quantify exposures to airborne dust and bioaerosol, to assess how waste processing methods and working practices contributed to worker exposure and to assess the effectiveness of exposure controls. Exposure measurement visits were conducted at materials recovery facilities (MRFs), waste transfer stations (WTS) and mechanical and biological treatment plants (MBTs).

Findings

High bioaerosol exposures, including endotoxin and *Aspergillus fumigatus*, both of which are associated with specific respiratory health conditions, were measured for several work activities. Higher risk tasks included work around unenclosed, high energy mechanical waste processing plant, cleaning operations using compressed air and high-pressure water jetting and hand sorting of waste at MRFs.

Conclusions

The higher exposures measured during this work could be reduced by increased sorting of waste at source to separate out food waste, a significant source of contamination in unsorted waste, improved plant design to provide greater containment of automated processes, targeted use of well-designed and suitably maintained LEV systems where practical and the adoption of low dust cleaning techniques.

Introduction

Around the world, and particularly in more developed countries, in recent decades there has been a shift to increasing recycling rates and reducing the amount of landfill associated with the disposal of municipal waste. Typically, such waste arises from kerbside collections from domestic and commercial premises or is deposited by consumers at collection points and local recycling facilities. Collection arrangements vary regionally, dependant on local policies. From here, the waste is usually taken to larger facilities for sorting, separating and onward processing. The handling of this material at such facilities brings workers into close proximity with the waste. Energetic handling and processing methods can generate airborne contamination, including particulate which, in addition to fragments of the waste material itself, can also contain micro-organisms. These bioaerosols, predominantly composed of fungi and bacteria, and the breakdown products thereof, represent a health risk if inhaled by workers operating these processes.

The extent to which municipal waste is colonised by micro-organisms is dependent upon a number of factors, including the composition of the waste itself, and in particular the extent of organic contamination, the length of time which it has been stored and environmental conditions, most notably temperature and moisture content (Madsen et al 2021). These factors will be influenced by the local waste collection policy and will have a significant bearing on the potential for bioaerosol exposure associated with processing the waste.

Inhalation exposure to bioaerosol can lead to serious respiratory disease (Walser et al 2015) including occupational asthma (sensitisation) and extrinsic allergic alveolitis. Fungi associated with the breakdown of organic waste include *Aspergillus fumigatus*. This is ubiquitous in the environment and its spores are almost always in the air and therefore being inhaled by most of the population (Latge and Chamilos, 2019). However, it is particularly associated with degrading/composting of organic material where the metabolic heat of degradation elevates the temperature to its optimum for growth and spore production. As a consequence, workers in close association with such material, and especially its manual handling, are likely to be exposed to large concentration of *Aspergillus fumigatus* spores and this puts them at risk of respiratory sensitisation (Sánchez-Monedero and Stentiford, 2003). Other microbial components of waste include bacteria and also their cellular components. Endotoxin is a cellular component of Gram negative bacteria, and inhalation of large concentrations can cause 'flu like' symptoms also known as "organic toxic dust syndrome" (Simpson et al, 1999; Seifert et al, 2003; Liebers et al, 2008). This cumulative evidence emphasises the need to control exposure to these bioaerosols adequately, and thus to protect the health of workers.

There are few established occupational exposure limits for bioaerosols. For the purposes of the studies described in this paper, for fungi and bacteria, results greater than $1x10^6$ colony forming units (CFU)/m^3 are considered high and those above $1x10^4$ CFU/m^3 medium. For *Aspergillus fumigatus*, a known respiratory sensitiser, results greater than $1x10^5$ CFU/m^3 are considered high and those above $1x10^3$ CFU/m^3 medium. This banding of results is based on the consensus view of bioaerosol experts and published data from Europe and the USA, although limited data exists on dose-response relationships (Pearson et al, 2015, WISH 2023). For endotoxin, the Dutch Expert Committee on Occupational Standards (DECOS), a committee of the Health Council of the Netherlands, has recommended a health based occupational exposure limit of 90 endotoxin units (EU/m^3) 8-hour time weighted averaged (8-hour TWA), for endotoxin in the inhalable fraction, and this can serve as one benchmark when conducting risk assessment. (DECOS 2010).

This paper combines the main findings of a series of studies conducted by the Health and Safety Executive (HSE) in Great Britain (GB), to assess exposure to bioaerosols in various municipal waste processing facilities. The site visits were completed as two separate research projects, the first looking at materials recycling facilities (MRFs) (HSE 2013) where pre-sorted recyclable waste is handled, the second looking at a range of other sites handling mixed municipal waste (HSE 2019). Clearly, as the work was conducted in GB, then the extent that findings and conclusions may be valid in other countries is dependent upon the similarity of work processes and exposure controls being applied. Also, the site visits for the MRF project were conducted in 2011-12 and the visits for the mixed municipal waste project were conducted in 2015-17. It is likely that developments in waste processing methods, such as better separation of food waste at source to provide cleaner recycling waste streams and technology, including the use of picking robots, have occurred since these visits were conducted which will influence the bioaerosol exposure profile in these industries.

Methods

Site visits were conducted to a number of waste processing facilities to observe working practices, assess exposure controls and, at some sites, to conduct measurements to assess workers' inhalation exposure to bioaerosols. Site selection, and recruitment to the studies, was supported by the Waste Industry Safety and Health forum (WISH), a group whose composition includes representatives from HSE, trade and professional associations, trade unions, recycling organisations and national and local government bodies involved in waste management and recycling. The sites visited were typically operated directly by local authorities or by large waste treatment companies on behalf of local authorities. Participation in the study, at both a site and individual worker level, was voluntary. All participating sites were provided with written feedback from the visits, which included commentary on the adequacy of exposure controls and, where measurements were taken, all exposure monitoring results.

Site visits were conducted by a team of occupational hygienists and microbiologists from HSE's Science and Research Centre.

Observational visits

The main aim of these visits was to make observational records of work tasks, potential health hazards and the exposure controls in place. The knowledge gained allowed subsequent measurement visits to be targeted efficiently (ie, where exposure risk was considered highest). Observational visits were only conducted as part of the project studying the handling of mixed, general waste. For this project, observational visits were carried out at two energy-from-waste (EfW) plants, two waste transfer stations (WTS) and two mechanical and biological treatment (MBT) plants.

Measurement visits

Measurement visits were conducted over one or two days and inhalation exposures to dust and bioaerosol were measured. Personal samples for inhalable dust were taken on all personnel at smaller sites, or selected personnel covering all similar exposure groups (SEG) at the larger sites. SEGs were defined by observation based on workers who performed broadly similar work tasks and were exposed to the same materials. Contextual data also collected included working methods, exposure control measures employed, and personal protective equipment (PPE) used. Ventilation systems were assessed using a combination of smoke tests, airflow measurement and Tyndall beam illumination using a dust lamp (HSE 2015).

Air sampling methodology

Long-term inhalable dust samples were taken using Institute of Occupational Medicine (IOM) sampling heads fitted with pre-weighed quartz filters and aspirated at 2 litres/min (HSE 2014). Most air samples were taken over several hours and were considered representative of the entire shift. Task-specific sampling was carried out for activities that were identified as posing a high risk of exposure to dust or bioaerosol. These were generally cleaning and maintenance activities.

8-hour TWA results were calculated for endotoxin and inhalable dust exposures. It was not considered necessary to calculate 8-hour TWAs for fungi and bacteria because the size of the numbers involved means the interpretation of the results would not be altered by doing so and there are no health based 8-hour TWA exposure limits with which to compare the results.

Sample analysis

Inhalable dust concentrations were determined using gravimetric techniques (HSE, 2014). For endotoxin analysis the filters were then placed in pyrogen-free tubes and the collected deposits were extracted in endotoxin-free 50mM Tris buffer (Lonza). The resulting suspension was divided to provide samples for endotoxin analysis and microbial enumeration (see below). Samples for endotoxin analysis were centrifuged at 10,000 g for 10 minutes to remove particles, and dilutions of the supernatant were analysed using the Kinetic-QCL automated system, a commercial quantitative 96-well plate assay system using a temperature-controlled plate reader (Bio-Whittaker Inc., Walkersville, Maryland, USA). This system is widely accepted in the pharmaceutical industry for endotoxin-free product validation in accordance with the United States' FDA but is also widely used for assaying endotoxin in workplace samples (Reynolds et al, 2005; Liebers et al, 2007). Presence of Gram-negative bacterial endotoxin activates a proenzyme in the Limulus Amebocyte Lysate (LAL) reagent resulting in a colour (chromatic) change, and the concentration of endotoxin in the sample is calculated automatically from the rate of colour change, compared to controls of known concentrations. Results are expressed as endotoxin units (EU)/ml, which is a measure of the biologically available endotoxin in the sample. In other assay methods, endotoxin concentration may be expressed as nanogram (ng)/ml, and for cross reference 10 EU is the equivalent of 1 ng (assay manufacturers' data). Each sample was analysed with a negative and positive control. Using the known volume of air sampled the results were used to calculate the concentrations in air as endotoxin units per cubic metre (EU/m^3). For enumeration of culturable micro-organisms, a sub-sample of the extracts prepared from filters for endotoxin analysis was used for microbial analysis. A dilution series was prepared from the initial extraction suspension in ¼ strength Ringers solution and was used to inoculate agar plates. Total mesophilic fungi were isolated on Malt extract agar (Oxoid) incubated at 25°C for up to 10 days. Total thermotolerant fungi were isolated on Malt extract agar (Oxoid), incubated at 40°C for up to 10 days. Total mesophilic bacteria and bacteria capable of growth at human body temperature were isolated on Nutrient agar (Oxoid) incubated at 25°C and 37°C respectively. Following incubation, emerging colonies on agar plates were counted and, using the known volume of air sampled, numbers calculated as colony-forming units (CFU/m^3 . Predominant bacteria and fungi were isolated into pure culture and identified by gross morphology and microscopic examination.

Findings

Observational visits

Observational visits were made to seven different sites; two MBT/AD plants, two EfW plants and three WTSs. All the sites visited mainly processed unsorted domestic waste that included a high proportion of organic material, including food waste, human waste (nappies) and animal faeces. This waste would often have been in collection bins for several days prior to collection. During this time there is potential for significant growth of fungi and bacteria, and for the formation and release of endotoxin. Ambient temperatures in the UK are conducive to the growth of bacteria and fungi for much of the year. There was a risk of continuing micro-organism growth and production of endotoxin within the plants after the waste had been delivered. In most cases however, this risk is likely to be mitigated because the waste was not normally left standing in the tipping halls and bunkers for longer than a day. The waste processed by all the sites was generally not in a completely dry state. Although this can encourage microbial growth, it can also mitigate the potential for generation of high levels of airborne particulate. However, where waste is tipped and loaded into hoppers (tipping halls) and where it passes through processing plant and is agitated (trommels, shredders, conveyor drops, air separators), there will be airborne particulate generated and so will present a risk of inhalation exposure to dust and bioaerosol for workers in the vicinity.

The range of activities conducted at MBT plants was much more diverse than at the other sites visited. In broad terms, two types of MBT plants were used in the treatment of municipal waste. At some sites waste was processed in the ‘as collected’ state (ie, no drying was carried out). At the second type of MBT plant waste is shredded and then dried for a period prior to mechanical extraction of recyclables and the production of refuse-derived fuel (RDF) and solid recovered fuel (SRF). The MBT processes employed at the sites visited for this study are illustrated in the appended figures 1 to 3.

Although no observational visits were made to MRFs, it is worth noting that the feedstock for these plants is generally ‘cleaner’ than the plants handing mixed waste and, having been sorted ‘at source’, will contain less extraneous contamination, in particular organic matter. However, the material is generally drier than mixed waste and so will be more likely to release airborne particulate when handled using energetic sorting processes, many of which were similar to those described in the paragraph above. The basic MRF process is illustrated in the appended Figure 4.

Exposure monitoring results

MRFs

Exposure measurement was conducted at 8 MRFs, with a total of 124 8 hr TWA measurements being collected. The exposure data for these sites is combined and presented in tables 1-5, which give a summary of the exposures to inhalable dust, endotoxin, fungi, bacteria and *Aspergillus fumigatus* broken down by job description/location.

Table 1: Inhalable dust exposures (8-hour TWA) at MRFs

Inhalable dust	Number of samples				Mean	Median	Min	Max
	< 5 mg/m^3	5-10 mg/m^3	>10 mg/m^3	Total	mg/m^3	mg/m^3	mg/m^3	mg/m^3
All tasks	99	17	8	124	3.21	1.55	0.15	47.73
Cleaner	3			3	2.6	2.88	1.13	3.78
Forklift truck (FLT) Driver	9	3		12	2.18	1.55	0.16	5.91
Hand-Sorter	58	11	7	76	3.27	1.52	0.23	22.63
Baler	9	2		11	2.66	2.21	0.31	7.78
Supervisor	8	1	1	10	7.05	1.65	0.36	47.73
Tipping Hall Driver	9			9	0.95	0.92	0.15	2.36
Other	3			3	2.45	2.4	1.92	3.04

Note: 0 results <LOD

Table 2: Endotoxin exposures (8-hour TWA) at MRFs

Endotoxin	Number of samples				Mean	Median	Min	Max
	< 45 EU/m³	45-90 EU/m³	>90 EU/m³	Total	EU/m³	EU/m³	EU/m³	EU/m³
All tasks	65	17	42	124	116	39.1	0.31	2399
Cleaner	1		2	3	97.7	126	20	147
Forklift truck (FLT) Driver	10	1	1	12	25.1	0.46	0.34	132
Hand-Sorter	35	12	29	76	144.2	53	0.31	2399
Baler	3	3	5	11	76.0	80.0	0.33	137
Supervisor	5	1	4	10	182.4	38.5	0.39	957
Tipping Hall Driver	9			9	8.0	0.51	0.31	23
Other	2		1	3	31.4	2.0	0.32	92

Note: 20 results <LOD

Table 3 : Fungi exposure at MRFs

Fungi	Number of samples				Mean CFU/m³	Median CFU/m³	Min CFU/m³	Max CFU/m³
	< $1x10^4$ CFU/m³	$1x10^4$-$1x10^6$ CFU/m³	>$1x10^6$ CFU/m³	Total				
All tasks	22	102		124	$7.61x10^4$	$2.68x10^4$	$2.54x10^2$	$9.4x10^5$
Cleaner		3		3	$2.38x10^4$	$2.99x10^4$	$1.02x10^4$	$3.13x10^4$
Forklift truck (FLT) Driver	4	8		12	$2.05x10^4$	$1.48x10^4$	$2.35x10^3$	$8.11x10^4$
Hand-Sorter	7	69		76	$1.07x10^5$	$5.41x10^4$	$3.07x10^3$	$9.4x10^5$
Baler	2	9		11	$3.19x10^4$	$1.73x10^4$	$8.28x10^3$	$8x10^4$
Supervisor	2	8		10	$4.13x10^4$	$2.6x10^4$	$3.04x10^3$	$1.69x10^5$
Tipping Hall Driver	5	4		9	$1.72x10^4$	$4.77x10^3$	$2.54x10^2$	$1.63x10^5$
Other	2	1		3	$1.13x10^4$	$7.1x10^3$	$6.88x10^3$	$2x10^4$

Note: 0 results <LOD

Table 4 : Bacteria exposure at MRFs

Bacteria	Number of samples				Mean CFU/m³	Median CFU/m³	Min CFU/m³	Max CFU/m³
	< $1x10^4$ CFU/m³	$1x10^4$-$1x10^6$ CFU/m³	>$1x10^6$ CFU/m³	Total				
All tasks	33	91		124	$5.3x10^4$	$1.88x10^4$	$3.81x10^2$	$6.75x10^5$
Cleaner		3		3	$1.41x10^4$	$1.4x10^4$	$1.24x10^4$	$1.6x10^4$
Forklift truck (FLT) Driver	4	8		12	$3.84x10^4$	$1.64x10^4$	$1.93x10^3$	$1.73x10^5$
Hand-Sorter	15	61		76	$6.29x10^4$	$3.37x10^4$	$2.14x10^3$	$6.75x10^5$
Baler	2	9		11	$3.91x10^4$	$1.62x10^4$	$8x10^3$	$1.43x10^5$
Supervisor	3	7		10	$6.43x10^4$	$1.68x10^4$	$1.02x10^3$	$3.95x10^5$
Tipping Hall Driver	7	2		9	$2x10^4$	$5.83x10^3$	$3.81x10^2$	$9.37x10^4$
Other	2	1		3	$1.04x10^4$	$4.29x10^3$	$2.93x10^3$	$2.39x10^4$

Note: 0 results <LOD

Table 5 : Aspergillus fumigatus exposure at MRFs

Aspergillus fumigatus	Number of samples				Mean CFU/m³	Median CFU/m³	Min CFU/m³	Max CFU/m³
	< $1x10^3$ CFU/m³	$1x10^3$-$1x10^5$ CFU/m³	>$1x10^5$ CFU/m³	Total				
All tasks	94	26	4	124	$9.36x10^3$	$1.74x10^2$	$2.68x10^1$	$2.49x10^5$
Cleaner	3			3	$2.26x10^2$	$2.13x10^2$	$1.74x10^2$	$2.92x10^2$
Forklift truck (FLT) Driver	10	2		12	$1.12x10^3$	$2.72x10^2$	$3.97x10^1$	$5.8x10^3$
Hand-Sorter	54	18	4	76	$1.42x10^4$	$2.26x10^2$	$2.68x10^1$	$2.49x10^5$
Baler	10	1		11	$4.89x10^2$	$8.66x10^1$	$3.28x10^1$	$4.45x10^3$
Supervisor	7	3		10	$4.61x10^3$	$1.23x10^2$	$4.11x10^1$	$4.22x10^4$
Tipping Hall Driver	7	2		9	$2.08x10^3$	$7.29x10^1$	$3.17x10^1$	$1.62x10^4$
Other	3			3	$3.6x10^1$	$3.53x10^1$	$3.21x10^1$	$4.07x10^1$

Note: 37 results <LOD

Handling of mixed (unsorted) municipal waste.

Exposure measurement was conducted at two WTS and three MBT plants, with a total of 52 8-hour TWA measurements being collected. The exposure data for these sites is combined and presented in tables 6-10. Where possible, job descriptions that match those used for the MRF data have been applied to allow for comparison, although due to the different nature of processes being operated in these plants this has not always been possible. Note that the job category 'Hand sorter' for these data refers to workers hand sorting batteries which had been separated from the main waste stream, which is substantially different to the hand sorting which was performed at MRFs. No measurement visits were made to EfW plants since the observational visits concluded that exposure potential was low, with most waste handling operations occurring in enclosed plant.

Table 6 : Inhalable dust exposure (8-hour TWA) at mixed municipal waste plants

Inhalable dust	Number of samples				Mean mg/m3	Median mg/m3	Min mg/m3	Max mg/m3
	< 5 mg/m3	5-10 mg/m3	>10 mg/m3	Total				
All tasks	47	1	4	52	3.91	0.71	0.04	95.30
Banksman	2			2	0.28	0.28	0.04	0.52
Cleaner	6		2	8	14.80	2.30	0.60	95.30
Control Room	7			7	0.67	0.30	0.11	2.10
Crane Op	1			1	0.11	0.11	0.11	0.11
Forklift truck (FLT) Driver	5			5	1.57	0.95	0.20	4.70
Hand-Sorter	1		1	2	7.00	7.00	1.40	12.60
Maintenance	7	1	1	9	4.79	2.00	0.09	25.60
Plant Operator	6			6	1.31	1.14	0.21	2.74
Supervisor	1			1	1.89	1.89	1.89	1.89
Tipping Hall	1			1	0.87	0.87	0.87	0.87
Tipping Hall Driver	8			8	0.41	0.39	0.22	0.95
Weighbridge	2			2	0.57	0.57	0.19	0.94

Note: 3 results < LOD

Table 7. Endotoxin exposure (8-hour TWA) at mixed municipal waste plants

Endotoxin	Number of samples				Mean	Median	Min	Max
	< 45 EU/m³	45-90 EU/m³	>90 EU/m³	Total	EU/m³	EU/m³	EU/m³	EU/m³
All tasks	33	5	14	52	714	17	0.2	27400
Banksman	2			2	16	16	1	32
Cleaner	3		5	8	3890	122	12	27400
Control Room	4	2	1	7	162	40	3	960
Crane Op	1			1	0.2	0.2	0.2	0.2
FLT Driver	3		2	5	65	32	2	177
Hand-Sorter	1	1		2	57	57	33	80
Maintenance	4	1	4	9	423	67	0	2420
Plant Operator	4	1	1	6	49	0.3	0.2	210
Supervisor			1	1	202	202	202	202
Tipping Hall	1			1	6	6	6	6
Tipping Hall Driver	8			8	7	5	3	15
Weighbridge	2			2	4	4	0.3	7

Note: 9 results < LOD

Table 8. Fungi exposure at mixed municipal waste plants

Fungi	Number of samples				Mean CFU/m³	Median CFU/m³	Min CFU/m³	Max CFU/m³
	< $1x10^4$ CFU/m³	$1x10^4$-$1x10^6$ CFU/m³	>$1x10^6$ CFU/m³	Total				
All tasks	15	36	1	52	$2.67x10^5$	$4.90x10^4$	$9.91x10^0$	$8.86x10^6$
Banksman	1	1		2	$4.42x10^4$	$4.42x10^4$	$9.43x10^2$	$8.76x10^4$
Cleaner		7	1	8	$1.26x10^6$	$1.44x10^5$	$7.98x10^4$	$8.86x10^6$
Control Room	4	3		7	$2.36x10^4$	$9.09x10^3$	$6.25x10^2$	$9.09x10^4$
Crane Op	1			1	$3.39x10^3$	$3.39x10^3$	$3.39x10^3$	$3.39x10^3$
FLT Driver	1	4		5	$1.44x10^5$	$5.39x10^4$	$2.51x10^3$	$5.56x10^5$
Hand-Sorter		2		2	$1.89x10^5$	$1.89x10^5$	$1.09x10^5$	$2.68x10^5$
Maintenance	4	5		9	$1.05x10^5$	$1.55x10^4$	$9.91x10^0$	$5.21x10^5$
Plant Operator	1	5		6	$6.07x10^4$	$1.72x10^4$	$1.37x10^3$	$2.13x10^5$
Supervisor		1		1	$1.73x10^5$	$1.73x10^5$	$1.73x10^5$	$1.73x10^5$
Tipping Hall		1		1	$3.43x10^4$	$3.43x10^4$	$3.43x10^4$	$3.43x10^4$
Tipping Hall Driver	1	7		8	$1.16x10^5$	$4.63x10^4$	$5.85x10^3$	$4.17x10^5$
Weighbridge	2			2	$1.43x10^3$	$1.43x10^3$	$5.58x10^1$	$2.80x10^3$

Note: 0 results < LOD

Table 9. Bacteria exposure at mixed municipal waste plants

Bacteria	Number of samples				Mean CFU/m³	Median CFU/m³	Min CFU/m³	Max CFU/m³
	<1x10⁴ CFU/m³	1x10⁴-1x10⁶ CFU/m³	>1x10⁶ CFU/m³	Total				
All tasks	25	23	4	52	$1.84x10^6$	$1.55x10^4$	$9.91x10^0$	$4.91x10^7$
Banksman	2			2	$2.47x10^3$	$2.47x10^3$	$5.90x10^1$	$4.89x10^3$
Cleaner		7	1	8	$6.28x10^6$	$1.08x10^5$	$2.52x10^4$	$4.91x10^7$
Control Room	4	3		7	$3.05x10^4$	$9.09x10^3$	$1.57x10^3$	$9.90x10^4$
Crane Op	1			1	$1.43x10^3$	$1.43x10^3$	$1.43x10^3$	$1.43x10^3$
FLT Driver	3		2	5	$1.05x10^6$	$8.61x10^3$	$4.50x10^3$	$3.61x10^6$
Hand-Sorter		2		2	$3.82x10^4$	$3.82x10^4$	$3.12x10^4$	$4.52x10^4$
Maintenance	4	4	1	9	$4.42x10^6$	$3.34x10^4$	$9.91x10^0$	$3.94x10^7$
Plant Operator	4	2		6	$2.02x10^4$	$3.96x10^3$	$8.53x10^2$	$8.67x10^4$
Supervisor		1		1	$2.66x10^4$	$2.66x10^4$	$2.66x10^4$	$2.66x10^4$
Tipping Hall		1		1	$2.55x10^4$	$2.55x10^4$	$2.55x10^4$	$2.55x10^4$
Tipping Hall Driver	5	3		8	$1.12x10^4$	$8.13x10^3$	$1.53x10^3$	$3.55x10^4$
Weighbridge	2			2	$1.84x10^3$	$1.84x10^3$	$1.23x10^3$	$2.44x10^3$

Note: 1 result < LOD

Table 10. *Aspergillus fumigatus* exposure at mixed municipal waste plants

Aspergillus fumigatus	Number of samples				Mean CFU/m³	Median CFU/m³	Min CFU/m³	Max CFU/m³
	<1x10³ CFU/m³	1x10³-1x10⁵ CFU/m³	>1x10⁵ CFU/m³	Total				
All tasks	29	18	5	52	$1.12x10^5$	$2.53x10^2$	$2.37x10^1$	$4.82x10^6$
Banksman	1	1		2	$2.30x10^3$	$2.30x10^3$	$5.90x10^1$	$4.55x10^3$
Cleaner	3	4	1	8	$6.06x10^5$	$5.33x10^3$	$2.74x10^1$	$4.82x10^6$
Control Room	5	2		7	$4.28x10^3$	$7.81x10^1$	$2.93x10^1$	$2.67x10^4$
Crane Op	1			1	$4.78x10^1$	$4.78x10^1$	$4.78x10^1$	$4.78x10^1$
FLT Driver	3	1	1	5	$6.38x10^4$	$4.10x10^1$	$2.85x10^1$	$3.16x10^5$
Hand-Sorter			2	2	$1.16x10^5$	$1.16x10^5$	$1.11x10^5$	$1.22x10^5$
Maintenance	6	2	1	9	$3.27x10^4$	$7.43x10^2$	$2.46x10^1$	$2.89x10^5$
Plant Operator	4	2		6	$7.16x10^3$	$1.42x10^2$	$2.37x10^1$	$4.00x10^4$
Supervisor		1		1	$5.74x10^3$	$5.74x10^3$	$5.74x10^3$	$5.74x10^3$
Tipping Hall	1			1	$5.04x10^1$	$5.04x10^1$	$5.04x10^1$	$5.04x10^1$
Tipping Hall Driver	3	5		8	$4.08x10^3$	$3.12x10^3$	$2.58x10^1$	$1.39x10^4$
Weighbridge	2			2	$2.92x10^1$	$2.92x10^1$	$2.79x10^1$	$3.05x10^1$

Note: 24 results < LOD

Exposure control

Local exhaust ventilation was uncommon at MRFs, and was not present in the hand sorting areas at any of the sites visited. These are quite hostile environments for machinery in general, and LEV in particular which is likely to go some way to explaining this. In these areas, exposure control was primarily achieved through general ventilation. A variety of approaches were observed, with only a minority of sites having mechanical dilution ventilation. Most others relied on natural ventilation achieved through open doors, in combination with air movement generated by recirculating air conditioning systems.

For the MBT plants visited, most automated waste sorting equipment was fitted with LEV systems when the plants were installed. This included extraction points on machinery such as trommels, air classifiers and overband magnets. It was also applied to drop points where waste was entering a piece of machinery or dropping from one conveyor belt to another.

No LEV was used at any of the WTS or EfW sites visited.

Water-mist dust/odour suppression systems were installed at two WTS and two of the MRFs visited.

At most sites vehicles used to transfer waste around the site were fitted with filtered, air-conditioned cabs. These have the potential to provide effective exposure control for vehicle drivers, although they must be designed and used correctly in order to do so (HSE 2018).

At all sites visited, hard hats, hi-visibility clothing and safety boots were mandatory.

Respiratory protective equipment (RPE) was supplied to protect against dust and bioaerosol exposure at 6 of the 7 MRFs. Generally, this was negative pressure, filtering facepiece type equipment, and the standard varied from FFP1 to FFP3. One MRF also provided powered, positive pressure filtering hood type RPE to be used for specified plant cleaning activities. Face-fit testing of respirators had not been performed at any of the MRFs where tight-fitting facepieces were supplied. Workers using these respirators were regularly observed with incorrectly donned respirators and/or using tight-fitting face facepieces when unshaven. RPE was less common at WTS, EfW plants and MBTs, with only one MBT mandating its use in an area known to have high airborne dust and bioaerosol levels.

Discussion

MRFs

The MRFs visited during this study employed a combination of mechanical sorting techniques and manual separation to process the waste materials. Some of the larger sites carried out a significant amount of sorting using automated mechanical processes. However, like the smaller less-mechanised sites, they still relied heavily on manual sorting at various stages of the process.

For the MRFs visited, exposure to inhalable dust was below 10 mg/m^3 for the majority of the activities monitored. A small number of exposures at the more mechanised plant were above this value, this being a result of the higher energy imparted by mechanical sorting when compared to hand sorting methods.

Approximately one-third of the measured endotoxin exposures at MRFs exceeded 90 EU/m^3. Although spread across a variety of activities, the majority of the high exposures were to staff working at the more mechanised MRFs, especially those using high-energy sorting machinery, which were often poorly enclosed with no LEV applied.

Exposures to microorganisms (fungi and bacteria) were mainly at medium levels (between 10^4 and 10^6 CFU/m^3). These levels are more than 10 times higher than the upper concentrations normally found in general ambient air (10^3 CFU/m^3) (Crook and Swan, 2001). The bacteria and fungi species identified were typical of those usually found in organic dust and included *Aspergillus fumigatus*, present in 26 air samples at medium levels and a further 4 samples at levels considered to be high.

For the MRFs visited, the exposure control strategies for dust and bioaerosols relied heavily on general ventilation and the use of RPE, with only one site having applied LEV. Two sites had water mist-suppression units installed, one in the main MRF and the other in the reception areas of a civic amenity recycling site. The efficacy of these systems in reducing airborne particulate concentrations is poorly understood.

Where forced general ventilation was employed in sorting cabins its quality and design was generally not of a good standard. Systems were found where ductwork was not complete, where airflows were low and where systems were not subject to routine maintenance and testing. It appeared that the majority of the general ventilation systems present were designed to address operator comfort rather than the control of dust exposure.

RPE selection, use and management standards were deficient at most MRFs visited. In general, the need for using RPE had not been systematically assessed. RPE was usually available for use, either all the time or for specific tasks; but no selection process, face-fit testing, training or supervision of use had been implemented., although it is recognised that a workforce comprising a significant proportion of agency staff with a high turnover rate represents significant difficulties for RPE management. At all sites the RPE issued was mostly in the form of disposable ori-nasal respirators.

Cleaning activities were mandatory tasks designated as part of the job for operatives at many of the MRFs. Consequently, a period was set aside every day, usually end of shift, where workers removed spilt waste from floors and cleaned contamination from equipment around the whole plant. One site had a dedicated team of 4 cleaners that carried out two hours of cleaning per shift. Cleaning was mostly manual, including dry sweeping, use of hand shovels and moving waste by hand. Dry sweeping has the potential to resuspend settled particulate into the airborne phase, generating unacceptably high task specific exposures. A relatively short duration of cleaning in this way can add significantly to a worker's dust and bioaerosol exposure (HSE 2023).

Mixed (unsorted) municipal waste

There was a much broader range of activities carried out at the sites handling mixed (unsorted) waste than was observed at MRFs. However, in general, hand sorting was rare at these sites compared to MRFs.

In the EfW plants visited, the handling of waste and feeding of the furnace was carried out remotely and there was little routine cleaning and maintenance required in areas contaminated with untreated waste. The potential for operators at EfW plants to be exposed to dust and bioaerosol was limited during normal operation as the process was enclosed and untreated waste was mostly handled automatically, with operators stationed inside segregated control rooms. In the tipping hall, where spilt waste was occasionally pushed into the waste reception bunker using a shovel loader, the driver was inside a cab. There was potential for very short-term exposure to dust and bioaerosols for drivers of delivery vehicles who had to exit the cab during unloading and for tipping hall operators if they were required to manually clean up spilt waste. There would be a risk of exposure to untreated waste during maintenance of equipment inside the waste storage bunker (eg, crane maintenance) and of the waste feed hoppers and rams. These maintenance activities were infrequent, occurring less than six times per year. For this reason, although 2 observational visits were made to EfW plants, no measurement visits were undertaken. There was a risk of exposure to airborne particulate in downstream parts of the plant where bottom ash from the furnace and ash from flue gas treatment was handled. Although this did not pose a significant risk of exposure to bioaerosol, exposure to other hazardous materials, including toxic metals, is possible.

Bioaerosol exposures at WTS were associated with tipping waste from delivery vehicles into storage hoppers or onto the tipping room floor, transferring waste using shovel loaders, plant cleaning and maintenance operations. Exposure control at these sites relied on general ventilation, water misting systems (not always operational) and RPE. Observational visits were made to three WTS, with two of these subsequently revisited to conducted exposure measurements. The exposure measurements indicate that these controls were generally adequate. No inhalable dust exposures above 10 mg/m^3 were recorded at these sites and no fungi and bacteria results, including *Aspergillus fumigatus*, were at levels which fell into the range considered medium level exposure. Most endotoxin exposures were significantly below 90 EU/m^3, although two exposures above this level were recorded, one at 300 EU/m^3 for a maintenance operator and another at 137 EU/m^3 for a worker pressure washing in the waste compactor area.

At the MBTs visited the main areas where a risk of exposure to bioaerosol was apparent were the tipping halls, in the mechanical sorting part of the plant, hand battery sorting and activities carried out as part of the regular cleaning and maintenance programme. The mechanical sorting of waste was an energetic process and therefore likely to be a source of airborne contaminants. Compared to EfW plants and WTS there were larger numbers of people required to operate and maintain the plant who were at risk of bioaerosol exposure.

For the MBTs processing waste 'as collected' (i.e. no pre-drying) measured 8-hour TWA exposures to inhalable dust (n=32) were generally low for all the routine tasks monitored. Exceptions to this were an exposure of 12.6mg/m^3 measured for a worker hand-sorting batteries contaminated with waste and one of 11.6 mg/m^3 for a night shift cleaner. 8-hour TWA endotoxin exposures(n=32) were mostly below 90EU/m^3 with the exception of five cleaning /maintenance staff, a night shift supervisor, a worker hand-sorting batteries and an operator who covered all jobs (relief worker). None of the full shift bacteria and fungi exposures were in the high exposure category (>1x10^6 CFU/m^3). The majority (~85%) of fungi exposures were in the medium range and for bacteria half (~50%) were in the medium range. A task-specific exposure measured during blowing out an air classifier filter was in the high category (>1x10^6) for bacteria and fungi. The majority of the *Aspergillus fumigatus* exposures were in the medium range. However, for two workers hand-sorting batteries, exposures to *Aspergillus* *fumigatus* were in the high (>1x10^5 CFU/m^3) range. Cleaning and maintenance of the MBT/AD plants was carried out continuously with full-time cleaning/maintenance staff employed on both day and night shifts. Night shifts were dedicated to cleaning and maintenance while the plant was not operational. Activities carried out by cleaners and maintenance staff posed a higher risk of inhalation and dermal (eg, hands and face) exposure to dust and debris, particularly for the cleaners on the night shifts who carried out thorough cleaning of the plant throughout their entire work shift. The cleaning methods used varied between the two sites visited. At the site with the higher exposures compressed airlines and pressure washers were used to remove debris from machinery and work carried out in a way that created secondary exposure for other workers in the vicinity. At the other site the policy was to minimise the use of energetic cleaning methods. It was still the case, though, that cleaning was largely carried out by hand sweeping and shovelling debris, and endotoxin exposures above 90EU/m^3 were recorded at this site also. Vacuum cleaners were not used at either site.

For the MBT where waste was pre-dried prior to further processing, there was little risk of the operators being exposed to significant levels of untreated waste during delivery and the drying process as the handling of waste was carried out automatically and monitored remotely from the control room. For the subsequent processes, the dry state of the waste, the energetic nature of the process and the cleaning methods used led to high levels of airborne particulate. This was evident in the exposures to the cleaners and the maintenance worker who spent long periods in areas where dried waste was processed. All workers who spent time in these areas had 8-hour TWA endotoxin exposures greater than 90 EU/m^3, with an exceptionally high exposure (27400 EU/m^3) measured for a cleaning operative and a control room operator who entered the area for ~20 minutes recording an 8-hour hour TWA exposure of 960 EU/m^3. Exposures to *Aspergillus fumigatus* reflect those measured for fungi and bacteria with higher results for workers in areas where dried waste was processed. Bioaerosol exposures for staff working outside these areas were in the low to medium range.

General observations

Suitable markers for assessing exposure

Although there are differences in the regulatory approach internationally, within GB general, non-specific inhalable dust has not been assigned an occupational exposure limit. The GB Control of Substances Hazardous to Health (COSHH) regulations state that dust of any kind becomes a substance hazardous to health when present at a concentration in air equal to or greater than 10 mg/m^3 as a time-weighted average over an 8-hour period of inhalable dust. At some of the sites visited high and medium levels of bioaerosol were measured in samples that yielded inhalable dust results below 1 mg/m^3. This indicates that 10 mg/m^3 is not an appropriate level of inhalable dust exposure against which to assess respiratory risk and the adequacy of control measures for the activities studied. Results for bacteria and fungi were variable and in some cases, low to medium exposures were measured in samples that yielded high levels of endotoxin. Also, the lack of scientific evidence demonstrating the dose response of inhalation exposures to general bacteria and fungi makes health-based risk assessment challenging (Walser et al, 2015). The research carried out by DECOS has resulted in a proposed health-based limit of 90EU/m^3 8-hour TWA for endotoxin (DECOS, 2010). The exposure results from this work for endotoxin broadly matched expectations from observing working practices. Therefore, for this industry, quantifying exposure to endotoxin would be a useful part of the 'toolkit' used to assess respiratory risk and the adequacy of exposure controls. Quantifying exposure to the fungus *Aspergillus fumigatus* would also be a useful part of the 'toolkit', given that it is a recognised respiratory sensitiser and its association with degrading organic waste (Latgé and Chamilos, 2019). This is also consistent with the Environment Agency in England and Wales, who from a regulatory basis prescribe measurement of *Aspergillus fumigatus* to monitor downwind emissions from commercial composting facilities (Environment Agency, 2018).

Conclusions

The measured exposures to bioaerosols for several of the operations and activities monitored in this study would not be considered to represent a significant health risk. The exceptions to this being hand sorting of waste, high energy processing activities, especially where the material being processed was relatively dry, and certain cleaning activities especially where dry sweeping, compressed airlines or high-pressure water jetting were used. In these situations, endotoxin exposures significantly above 90 EU/m^3 (8-hour TWA) were not uncommon, with correspondingly high exposures to *Aspergillus fumigatus* in some situations. These exposures could be reduced by introducing exposure controls in accordance with the well-established hierarchy of control, specifically:

- increased sorting of waste at source to separate out food waste, a significant source of contamination in unsorted waste
- improved plant design, providing greater containment of the process
- targeted use of well-designed and suitably maintained LEV systems where practical, recognising the challenging environment that these plants represent for LEV systems
- adoption of low dust cleaning techniques using appropriately rated industrial vacuum cleaners where practical and/or low-pressure water washing.

In situations where adequate control cannot be achieved using these methods, RPE would be required to provide adequate exposure control, although given the tendency for RPE to fail for a variety of reasons, the need for an effective RPE management system should be a key consideration.

It should be borne in mind that this work was carried out in Great Britain at a time when mixed municipal waste in many areas contained a high proportion of food and other organic waste. Bioaerosol exposure profiles are likely to vary significantly in situations where different 'at-source' waste sorting arrangements are implemented by relevant local and national authorities.

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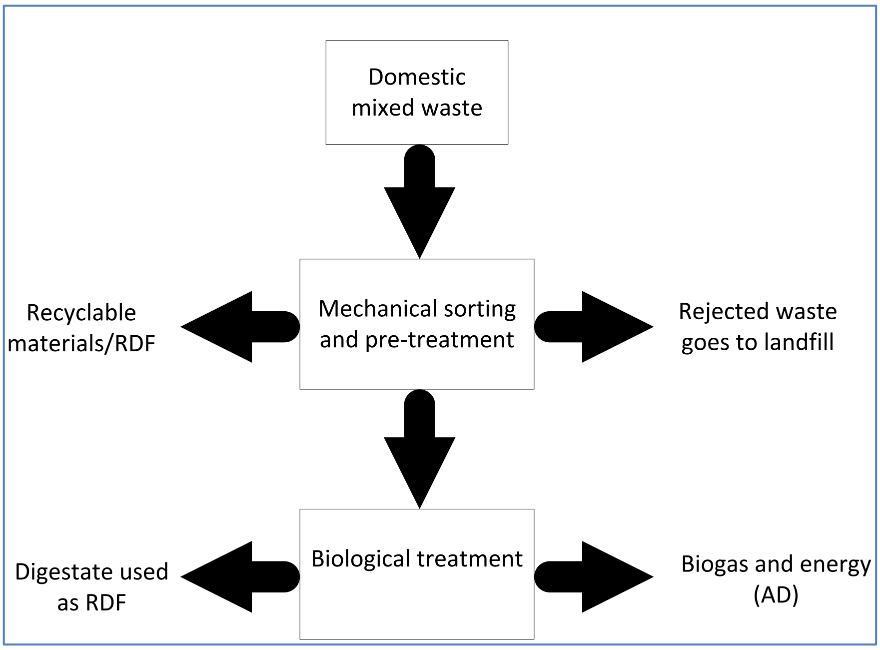
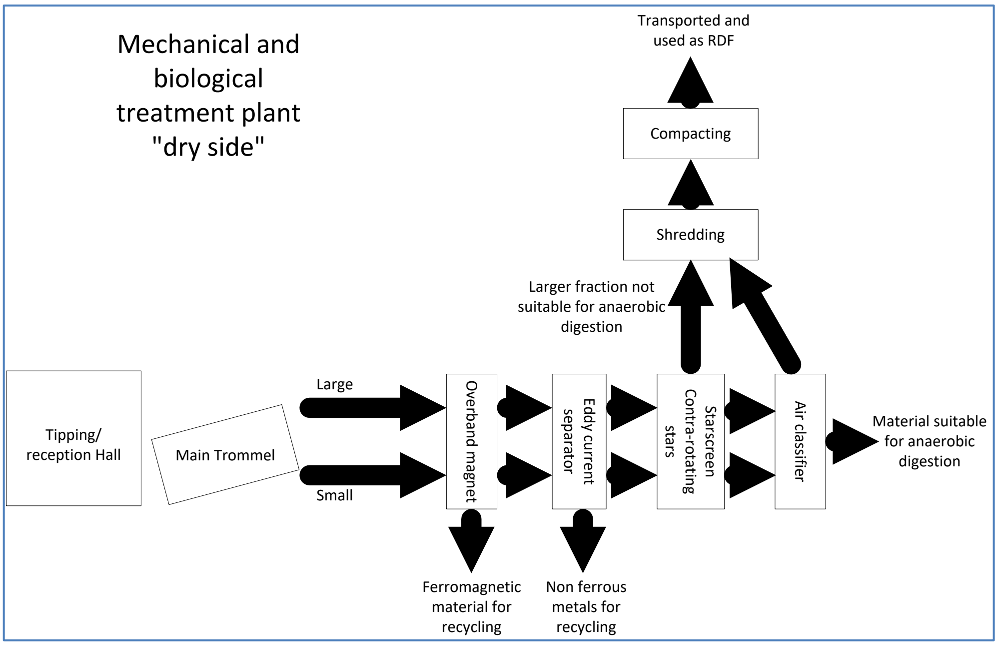
Appendix: diagrams

Figure 1. Basic process flow diagram for MBT/AD



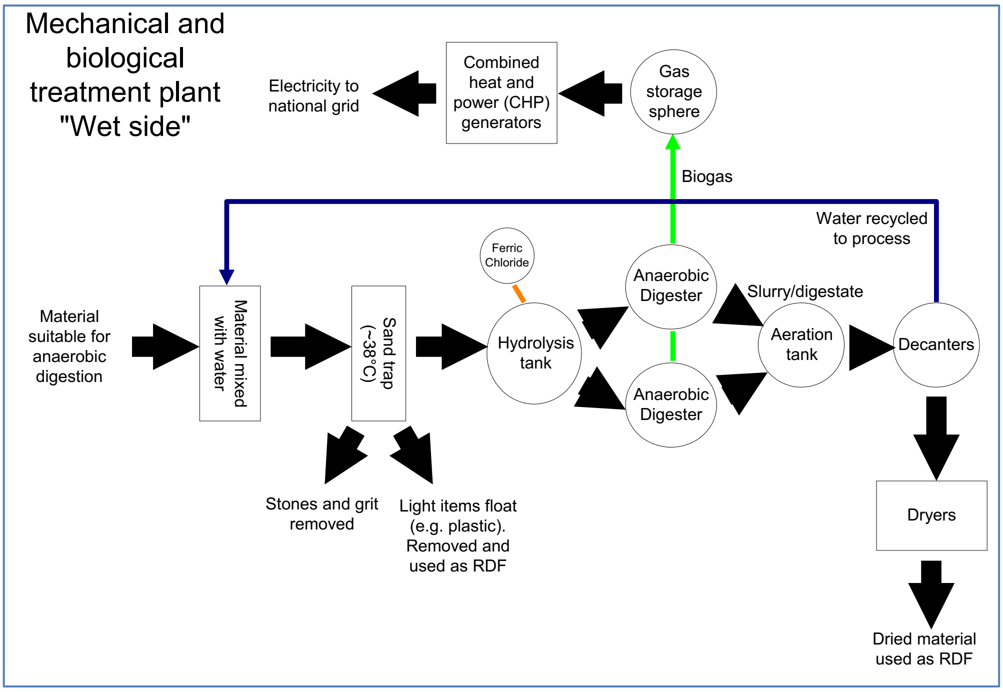
MBT = mechanical and biological treatment; RDF = refuse-derived fuel

Figure 2. MBT/AD process diagram mechanical sorting "Dry side".



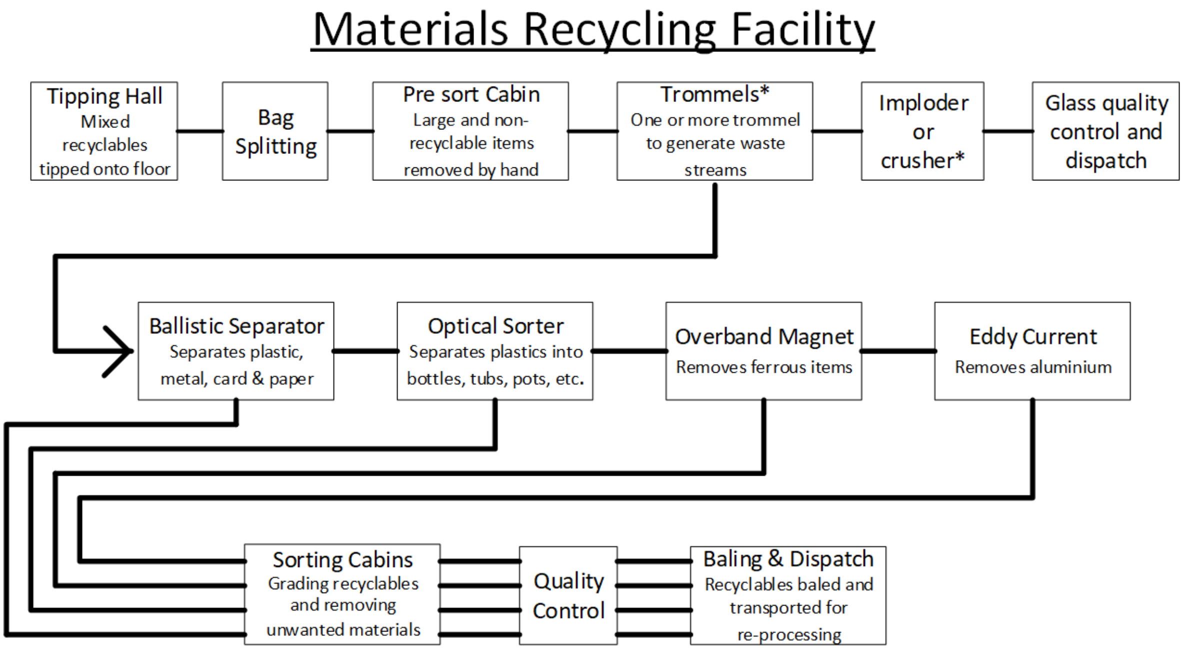
RDF = refuse-derived fuel

Figure 3. MBT/AD process diagram anaerobic digestion "Wet side".



MBT = mechanical and biological treatment; RDF = refuse-derived fuel (RDF)

Figure 4 MRF Diagram showing typical machinery.



* Trommels were not used at all sites and only the most modern plant ran a glass imploder

MRF = materials recovery facilities