Municipal Solid Waste and Health

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**List of abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABPR</td>
<td>Animal By-Products Regulations</td>
</tr>
<tr>
<td>EU</td>
<td>endotoxin units</td>
</tr>
<tr>
<td>HSE</td>
<td>Health and Safety Executive</td>
</tr>
<tr>
<td>LACMW</td>
<td>Local Authority collected municipal waste</td>
</tr>
<tr>
<td>LCD</td>
<td>liquid crystal display</td>
</tr>
<tr>
<td>MRF</td>
<td>materials recovery facility</td>
</tr>
<tr>
<td>MSW</td>
<td>Municipal solid waste</td>
</tr>
<tr>
<td>ODTSS</td>
<td>organic dust toxic syndrome</td>
</tr>
<tr>
<td>PAH</td>
<td>polycyclic aromatic hydrocarbons</td>
</tr>
<tr>
<td>PAS 100</td>
<td>publicly available specification for composted materials</td>
</tr>
<tr>
<td>PBDE</td>
<td>polybrominated diphenyl ethers</td>
</tr>
<tr>
<td>PCB</td>
<td>polychlorinated biphenyls</td>
</tr>
<tr>
<td>PVC</td>
<td>polyvinyl chloride</td>
</tr>
<tr>
<td>SES</td>
<td>socio-economic status</td>
</tr>
<tr>
<td>UOD</td>
<td>upstream-operating-downstream</td>
</tr>
<tr>
<td>VOCs</td>
<td>volatile organic compounds</td>
</tr>
<tr>
<td>WEEE</td>
<td>waste electrical and electronic equipment</td>
</tr>
</tbody>
</table>

**Photo credits**

Front cover: LornaFewtrell
1. Background

The ReVISIONS research aims to provide the knowledge and evidence base for public agencies and private companies to plan regional development together with infrastructure for transport, water, waste and energy, in a more coordinated and integrated way so as to maximise economic competitiveness, reduce impacts on the environment and resources and allow households to live more sustainably, with a socially inclusive and enhanced quality of life. The current report on waste is one of a series which examine the health impacts of selected technologies and forms part of the overall assessment.

Health issues have been associated with every step of the handling, treatment and disposal of waste (Giusti, 2009). The next section looks at waste and waste management (including household collection) in a UK context. It sets the scene for the Section 3, which details a number of the individual waste management options. Section 4 examines a number of cross-cutting issues. The report concludes with Section 5, a short discussion.

2. An introduction to waste and waste management

The mass of waste produced globally has been growing for many decades, especially in affluent countries and there is a link between gross domestic product and waste generation per person (Giusti, 2009). In the UK we produce about 430 million tonnes of waste a year, of which about 7% (29 million tonnes) is municipal solid waste (DEFRA, 2004). The UK definition of municipal solid waste (MSW) as used up to 2010/11 included the waste materials generated in the home, and by schools, shops and small businesses; provided it was collected by the local authority (or companies working for the local authority). It excluded similar waste collected from commerce and industry handled by the private sector which amounted to an additional 30 million tonnes per annum at that time. The European Commission considered this definition of MSW too restrictive in the context of the European Waste Framework Directive (2008/98/EC) and specifically the definition of MSW included in landfill directive (1999/31/EC). As a consequence, from 2011, DEFRA now reports Local Authority Collected Municipal Waste (LACMW) separately but the definition is basically the same as previously used for MSW. Commercial and Industrial waste flows continue to be separately reported as before but the commercial element will be included in the MSW data sent to Europe for statistical/compliance purposes. As this new definition has only just been introduced, all referenced research into health and MSW in the UK refers to Local Authority Collected Municipal Waste but for the purposes of this report, we use the term MSW in its old, more restrictive definition.

Municipal solid waste (now LACMW) comprises the following list of materials, in decreasing order of proportion (DEFRA, 2004):

- Recyclable paper
- Garden waste
- Other plastics
- Compostable food waste
- Unclassified fines
- Card, paper, packaging
• Non-compostable organics
• Textiles and shows
• Glass bottles/jars
• Other paper and card
• Nappies
• Steel cans
• Other metals
• Plastic bottles
• Wood
• Aluminium
• Other glass

Various EU Directives have set targets for the reduction in the amount of biodegradable waste sent to landfill and also stipulated that governments should draw up plans to:

• Prevent or reduce waste production and its harmfulness;
• Recover waste by means of recycling, re-use or reclamation;
• Use waste as a source of energy;
• Ensure that waste is recovered or disposed of without endangering human health (Matthews, 2004).

The revised Waste Framework Directive (2008/98/EC) set out five steps (the waste hierarchy) for dealing with waste as illustrated in Figure 1 (DEFRA, 2011a).

Figure 1: Waste hierarchy

These steps are outlined in more detail below (DEFRA, 2011a):

• Prevention – avoidance, reduction and re-use; using less hazardous materials. Avoidance includes buying fewer items, reducing process waste or using less material per unit in design and manufacture. Reduction covers keeping products for longer, designing them so they last longer. Re-use includes selling and buying used items, donating them for free, exchanging them etc.
• Preparing for re-use – checking, cleaning, refurbishing, repairing whole items or spare parts.
• Recycling – turning waste into a new substance or product. Includes composting if it meets quality protocols.
• Other recovery – anaerobic digestion, incineration with energy recovery, gasification and pyrolysis which produce energy (fuels, heat and power) and materials from waste. Some backfilling operations.

• Disposal – landfill and incineration without energy recovery. The revised Waste Framework Directive sets an energy efficiency threshold above which municipal waste incinerators can be classified as recovery facilities, and below which they continue to be classified as disposal facilities.

It is allowable to depart from the waste hierarchy for specific waste streams in order to deliver the best environmental outcome. Thus, for food waste, wet or dry anaerobic digestion is considered to be better than other recycling and recovery options. For garden waste, dry anaerobic digestion is preferred, while for lower grade wood, energy recovery options seem to be more suitable than recycling (DEFRA, 2011a).

The waste types, facilities and processes undertaken in the UK waste industry are shown in Table 1.

Table 1: Waste types, facilities and processes undertaken in the UK solid waste industry (HSE, 2004)

<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Civic amenity site</td>
<td>Sites to which the public delivers waste directly. The waste delivered typically includes bulky household items and recyclable objects. This waste then has to be disposed of.</td>
</tr>
<tr>
<td>Composting</td>
<td>An aerobic biological process in which organic waste is converted into stable granular materials that can be applied to soil to improve its structure and increase its nutrient content.</td>
</tr>
<tr>
<td>Commercial waste</td>
<td>Waste arising from any premises which are used wholly or mainly for trade, business, sport or entertainment (excluding municipal and industrial waste).</td>
</tr>
<tr>
<td>Industrial waste</td>
<td>Waste from any factory and from any premises occupied by an industry (excluding mines and quarries).</td>
</tr>
<tr>
<td>Kerbside collection</td>
<td>Any regular collections of recyclables from premises, including collections from commercial or industrial premises as well as from households. Excludes services delivered on demand.</td>
</tr>
<tr>
<td>Landfill sites</td>
<td>Any areas of land in which waste is deposited. Landfill sites are often located in disused mines or quarries. In areas where there are limited or no ready-made voids exist, the practice of land-raising is sometimes carried out, where waste is deposited above ground and the landscape is contoured.</td>
</tr>
<tr>
<td>Municipal waste</td>
<td>This includes household waste and any other wastes collected by a Waste Collection Authority (or its agents) such as municipal parks and gardens waste, beach cleansing waste, commercial or industrial waste and waste resulting from the clearance of fly-tipped materials.</td>
</tr>
<tr>
<td>Materials Recovery Facilities (MRF)</td>
<td>Facilities for receiving waste and sorting it into specific categories such as paper, cardboard, plastic and metal. This waste is then packaged for recycling elsewhere.</td>
</tr>
<tr>
<td>Skip hire</td>
<td>The provision of skips for hire to individuals or businesses for the purpose of collecting substantial quantities of waste which are then disposed of.</td>
</tr>
<tr>
<td>Street cleansing</td>
<td>The collection of litter from streets for disposal.</td>
</tr>
<tr>
<td>Transfer station</td>
<td>Building or area for collecting waste from a variety of sources prior to dispatch to disposal sites.</td>
</tr>
<tr>
<td>Waste-to-energy facilities</td>
<td>Power station that converts waste (which tends to be relatively combustible and of high calorific value) via incineration into power.</td>
</tr>
</tbody>
</table>
The Environment Agency is responsible for enforcing and regulating waste management facilities by means of licence and permit conditions. Transfer stations are the most common type of licensed waste site in all regions in the UK, followed by metal recycling facilities (both mixed and vehicle dismantling) and landfill sites (HSE, 2004).

2.1 Household collection

In the UK, most people’s interaction with the waste industry is sorting their waste into a variety of bins (or boxes) and having it collected, generally on an alternate weekly basis (e.g. recyclable waste one week; residual waste the next) and perhaps an occasional ‘trip to the tip’ (household or civic amenity site, where larger items can be disposed of). Where food waste is also separated, this is normally collected on a weekly basis (Photo 1). There has been some suggestion that fortnightly collections of waste may be responsible for an increase in the rat population (Daily Telegraph, 2012) but, while rats and other vermin may be on the increase, this is felt to be multifactorial and not simply related to waste collection frequencies (Letsrecycle, 2012). Before alternate waste collection was introduced a number of studies examined the possible health implications, including the possibility of increased odour and nuisance and suggested that there was no evidence that alternate week collection would impact negatively on health, although there may be increases in odour and flies (Drew et al., 2007; WRAP and CIWM, 2009).

While most source separation of household waste should not cause any health hazard to householders it has been suggested that domestic recycling of kitchen waste may pose a hazard (Blenkhorn, 2007), with some anecdotal evidence of a rise in foodborne infection associated with food waste recycling. In an informal survey of over 100 households that recycle food wastes, it was found that 61% of respondents kept kitchen waste bins within the kitchen environment (such as in a cupboard or by the door) and that only 11 households reported cleansing of food waste bins, and such cleansing was “at best irregular and probably inadequate” (Blenkhorn, 2007). Food waste bins can become heavily soiled on both internal and external surfaces, with contamination being particularly heavy on the handle and around the lid area, making it likely that hands may be contaminated when the bin is used with the potential for cross-contamination of foods for consumption. Blenkhorn suggests that suitable food bin liners should be used in order to reduce the contamination of the primary container, although many local authorities do not approve of these as they compromise the subsequent composting process. In addition to the possibility of increased foodborne infection, bioaerosols may also be an issue (see Section 3.1.2.1).

3. Waste management options

There are a number of waste management options. Traditionally landfill and incineration have been the most popular options, however (as illustrated by the waste hierarchy), there are efforts being made to move away from these methods. The main emphasis in the following section is on recycling and other recovery methods.

3.1 Recycling

There are several different types of recycling and many of these have a long history. In recent years, however, there has been a change in emphasis and recycling rates in the UK have increased. This report focuses on the potential hazards from materials...
recovery facilities, composting and the processing of waste electrical and electronic equipment.

Over 23 million tonnes of household waste was produced in England in the year to September 2010, of this 40.3% was recycled, re-used or composted (an increase from 39.7% in 2009/2010 (DEFRA, 2011b).

3.1.1 Materials recovery facilities

Materials recovery facilities (MRFs) are facilities where source segregated dry recyclable materials, such as paper, cans and plastic items, (‘clean’ MRFs) or mixed/residual waste (‘dirty’ MRFs) are sorted, both manually and mechanically (Gladding et al., 2003). A dirty MRF combines a number of screening and sorting techniques to divide the municipal waste into a recyclable materials stream and a non-recyclable residual waste stream. Advanced plants may also produce a third stream which may be biodegradable waste for anaerobic digestion or in-vessel composting or a relatively high calorific value stream for conversion to refuse-derived fuel (Last, 2012). Typically, dirty MRFs use conveyor systems, bag splitters, screens or trammels to split the waste into different size fractions. Magnets, eddy current separators, handpicking or other sorting techniques are used to divide the waste into the required streams (Last, 2012). The exact methods used vary and depend on both the type of MRF and the specific facility. Clearly, a dirty MRF will not produce recyclable materials of as high a quality as those produced from a clean facility because of the contamination with putrescible material.

Where hand-sorting is done, workers will clearly be in close contact with waste materials. Gladding (2002) outlines three main hazard types in MRFs as shown in Table 2.

<table>
<thead>
<tr>
<th>Physical</th>
<th>Chemical</th>
<th>Biological</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual handing</td>
<td>Hazardous waste residues</td>
<td>Airborne microorganisms</td>
</tr>
<tr>
<td>Ergonomics</td>
<td>Hazardous waste vapours/aerosols</td>
<td>Contaminated sharps</td>
</tr>
<tr>
<td>Accident, transport, fire</td>
<td>Heavy metals (e.g. lead, mercury)</td>
<td>Contaminated sharp edges</td>
</tr>
<tr>
<td>Noise and vibration</td>
<td>Volatile organic compounds</td>
<td>Total and respirable dust</td>
</tr>
<tr>
<td>Electromagnetic frequencies</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.1.2 Composting

The composting process can be defined as: “the controlled biological decomposition and stabilisation of organic substrates, under conditions that are predominantly aerobic and that allow the development of thermophilic temperatures as a result of biologically produced heat. It results in a final product that has been sanitised and stabilised, is high in humic substances and can be beneficially applied to land, which is typically referred to as ‘compost’ (Swan et al., 2002).

Materials suitable for composting include green waste and putrescible wastes with pre-sorting and screening to remove non-compostable material, along with other enriched organic waste streams (such as agricultural and food processing waste) – Last, 2012.

Table 3 shows the key stages of the composting process.
Table 3: Key stages of the composting process (Swan et al., 2002)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Key features</th>
<th>Stage characteristics</th>
<th>Approx. duration</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>High rate composting</td>
<td>Microorganisms consume forms of carbon they can easily break down (e.g. sugars and starches)</td>
<td>High rate of biological activity characterised by high oxygen demand and heat generation rates. Tendency for pH to initially drop below the optimum of 6-8, then rise above 8 as composting proceeds</td>
<td>4 to 40 days</td>
<td>This stage plays a key role in the thermal destruction of pathogens, weed seeds and propagules, although formation of secondary metabolites may also occur. Thermophilic actinomycetes, <em>Bacillus</em> species and <em>Thermus</em> species have been shown to dominate, while thermotolerant fungi from the genera <em>Aspergillus</em> and <em>Penicillium</em> have also been widely reported.</td>
</tr>
<tr>
<td>Stabilisation</td>
<td>Microorganisms consume forms of carbon they can break down fairly readily (e.g. cellulose)</td>
<td>Biological activity starts to decline. Oxygen demand gradually decreases. Declining heat generation. Tendency for pH to remain above 8</td>
<td>20 to 60 days</td>
<td>Variable duration depending upon test method used and intended end use</td>
</tr>
<tr>
<td>Maturation (curing)</td>
<td>Amount of available carbon is much reduced and microbial consumption slowed down. Re-colonisation by soil microbes</td>
<td>Reduced biological activity. Medium to low oxygen demand. Little heat generation: temp should be below 50 °C. Oxidation of ammonium to nitrate ions. Tendency for pH to fall towards neutral</td>
<td>Variable duration depending upon test method used and intended end use</td>
<td>Mesophilic actinomycetes and fungi begin to predominate during this stage</td>
</tr>
</tbody>
</table>

In practice there are four principal commercial approaches (windrow systems, in-vessel systems, aerated static piles and vermicomposting) that can be adopted for composting wastes on a large-scale (Swan et al., 2002); in this report two are considered.

- **Windrow system** – this is a relatively simple system where the feedstock is laid out in long piles called windrows (from the farming practice of piling hay in rows to dry out in the wind). The windrows are ‘turned’ periodically in order to blend the composting material, introduce fresh air and release trapped heat and moisture. The waste may be processed outdoors, but if kitchen wastes are included it must be conducted within a building to comply with the animal by-product regulations (HMSO, 2005). According to Smith and Pocock (2008) currently 78% of commercial composting in the UK is done in open-air turned windrow facilities.
- **In-vessel** – these contain the composting feedstock within a vessel (usually enclosed), which allows a greater degree of process and emission control. There are a variety of different in-vessel systems available. In-vessel methods are becoming increasingly popular as they can minimise odour risk.
The following Table provides a brief appraisal of the composting process technologies, i.e. windrow and in-vessel systems (Eades, pers. comm.)

Table 4: Composting process technology appraisal

| Description of process | Windrow: A composting process where biodegradable waste is processed in elongated piles. Often done outdoors, but must be conducted within a building if kitchen wastes are included. In vessel: A composting process that is contained within an enclosed vessel, so as to achieve and maintain optimal processing conditions. Benefits include  
- Volume reduction – reduces the mass of the waste  
- Nutrient recovery – produces a soil conditioner / fertiliser substitute / daily landfill cover  
- Stabilisation of wastes – reduces the biodegradability of waste by approx 50%  
- Sterilisation of waste – destroys pathogens (if ABPR compliant) |
| Output | Solids – compost or compost-like output as determined by nutrient analysis (the former can be used as a soil conditioner or fertiliser substitute, the latter as a daily landfill cover)  
Liquid – leachate is produced and this must be managed accordingly  
Gas – release of gases associated with aerobic degradation  
Energy – not usually applicable, but thermal energy can be recovered |
| Household behaviour | Not usually relevant, but due to potentially offensive odours (windrow) complaints may occur during the operation phase |
| Planning constraints | It is usually more acceptable to construct the facility in a light industrial or rural location. Location should not be within 250 m of the closest residential property |
| Technical constraints | Unless this process is used as part of a mechanical-biological treatment (MBT) or biological-mechanical treatment (BMT) the waste input must be 100% biodegradable.  
If the feedstock contains kitchen waste the process must be compliant with ABPR (2005) |

3.1.2.1 Bioaerosols

The key health concern relating to composting is the potential impacts from bioaerosols. Bioaerosols (i.e. bacteria, fungi and their metabolic products), sometimes referred to as organic dust (Sykes et al., 2011) are part of the natural environment and are ubiquitous in the ambient air (Kummer and Thiel, 2008). They result from the microbial decomposition of organic material and, as such, are prevalent, potentially at elevated levels, around waste treatment facilities as microbial decomposition occurs under intensified conditions at these sites. Composting relies on microorganisms (as indicated above: Table 3) and high concentrations of bacteria and fungi are present in composts. When composting materials are moved (e.g. during turning) the microorganisms can become aerosolised creating a bioaerosol (Swan et al., 2002).

Bioaerosols are complex mixtures and, as noted by IOM (2008), different components of the mix have variable potentials to cause illness in different individuals. The major components of bioaerosols are as follows (IOM, 2008):
**Bacteria:** These may be viable or non-viable. Actinobacteria (*Actinomycetes*) have been most commonly studied, these are Gram-positive bacteria which are important in the decomposition process and which produce external spores. Thermophilic actinomycetes are respiratory allergens. The spores are small enough to potentially penetrate deep into the lung and they are responsible for occupational allergic disease (Swan *et al.*, 2003).

**Endotoxin:** Endotoxin is found in the outer layer of the cell walls of Gram-negative bacteria and is released when the cell wall is damaged. Endotoxin is not a single uniform substance but consists of lipopolysaccharide and other compounds that occur in the bacterial cell wall. Inhalation of endotoxin can cause both acute illness (flu-like symptoms, fever, myalgia and malaise – e.g. organic dust toxic syndrome) and chronic illness, such as bronchitis, chronic obstructive pulmonary disease and decline in lung function (Swan *et al.*, 2002).

**Peptidoglycan (murein):** This is a polymer made up of sugars and amino acids that forms a homogeneous layer outside the plasma membrane of bacteria.

**Fungi and moulds:** These are important in the decomposition of organic waste. In ambient air, fungi tend to be present in the form of spores, which may be viable or non-viable. Some moulds are capable of producing secondary metabolites which are toxic – mycotoxins – which may contribute to the adverse health effects of bioaerosols.

**Beta (1→3) glucan:** This is a polyglucose compound found in the cell walls of some fungi, particularly *Aspergillus*. According to Swan *et al.* (2003) exposure has been associated with an increased prevalence of atopy, decreases in forced expiratory volume and adverse respiratory health effects. They may also enhance pre-existing inflammation.

**Volatile Organic Compounds (VOCs):** These are generated by many sources in the compost mixtures including the microorganisms (Swan *et al.*, 2002), with most emissions being in the early stages of processing. Müller *et al.* (2004a) found concentrations of single compounds belonging to alcohols, ketones, furanes, sulphur-containing compounds and terpenes ranging between $10^2$ to $10^6$ ng/m$^3$ at three different composting facilities. In dispersal studies, compost-derived VOC were measureable at distances up to 800m from the composting facilities. Terpenes (such as $\alpha$-pinene, camphene and camphor) were the dominant compounds and coincided with the typical compost odour (Müller *et al.*, 2004b).

There are a number of different ways to measure/characterise bioaerosol exposure and different methods are used in different studies, making simple comparisons difficult. There is variation in how samples are captured (e.g. filters, fluids and gels) as well as what is analysed and how it is analysed. The most commonly reported parameters are dust, viable fungi, viable bacteria and endotoxin (IOM, 2008). In order to try to preserve the viability of captured microorganisms sample times tend to be quite short, which means that to adequately characterise bioaerosol exposure a large number of samples need to be taken over an extended period (EA, 2004). Additionally, where similar microorganisms are measured in different studies the concentrations may not be comparable as the exact fraction of the bioaerosol considered may not be equivalent (IOM, 2008).
Background levels of bioaerosol are highly variable and have been found to vary by location and season. Generally, outdoor urban fungal concentrations are less than 1,000 cfu/m$^3$, although they may be considerably higher during the autumn (Swan et al., 2003). The potential variability is illustrated by measurements of Aspergillus/penicillium made in the Botanic Gardens in Birmingham, where spore counts (spores/m$^3$) varied from 439 to 21,231 and back to 472 over the course of a two day period (IOM, 2008). Typically, bacterial background levels in urban air are thought to be less than 1,000 cfu/m$^3$ (Swan et al., 2003). According to Madsen (2006) typical outdoor urban levels of endotoxin are less than 1EU/m$^3$.

Evidence suggests that waste industry workplace exposure to bioaerosols is associated with increased risks of developing upper and lower respiratory symptoms and chronic respiratory illness. There are some suggestions that exposure may also be linked with gastrointestinal illness and fatigue (IOM, 2008). Table 5 (from IOM, 2008) summarises exposure-response data for bioaerosols.

<table>
<thead>
<tr>
<th>Bioaerosol component</th>
<th>Health end point</th>
<th>Exposure-response information</th>
<th>Study population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic dust</td>
<td>Irritation of eyes and nose</td>
<td>Symptoms reported at 200μg/m$^3$</td>
<td>Waste workers</td>
</tr>
<tr>
<td></td>
<td>Chest tightness and wheeze</td>
<td>Reported at 1-2mg/m$^3$, prevalence increases with concentration</td>
<td>Various industries</td>
</tr>
<tr>
<td></td>
<td>Chronic respiratory illness</td>
<td>May arise at concentrations &gt;0.3 mg/m$^3$, but normally associated with concentrations &gt;1.2 mg/m$^3$</td>
<td>Cotton workers</td>
</tr>
<tr>
<td>Fungi</td>
<td>Respiratory symptoms, nausea, headache etc.</td>
<td>Symptoms reported at &gt;10$^4$ cfu/m$^3$ and between 10$^3$-10$^6$ spores/m$^3$</td>
<td>Waste workers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increased symptoms associated with concentrations of 2000 cfu/m$^3$ in indoor air or 1000 spores/m$^3$ in outdoor air</td>
<td>General community</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mild adverse respiratory effects may arise at concentrations &gt;350 cfu/m$^3$ in household air</td>
<td>Children</td>
</tr>
<tr>
<td>Total microbes</td>
<td>Respiratory symptoms, nausea, headache etc.</td>
<td>Symptoms reported at 10$^3$ cfu/m$^3$, very limited evidence of increase in symptom prevalence with increasing exposure</td>
<td>General community near compost operations</td>
</tr>
<tr>
<td>Endotoxin</td>
<td>Respiratory symptoms, fatigue</td>
<td>Greater prevalence of symptoms at concentrations &gt;50 EU/m$^3$, but indications of nasal irritation reported in 1 study of waste workers at 4.5 EU/m$^3$, clear evidence that risks increase with increasing exposure</td>
<td>Workers in various industries</td>
</tr>
</tbody>
</table>
Rylander (1997) has suggested a number of ‘no-effect’ levels (i.e. levels below which symptoms should be absent) for endotoxin, as shown below:

- Airway inflammation/mucosal membrane irritation: 100 EU/m$^3$
- Systemic effects: 1,000 EU/m$^3$
- Toxic pneumonitis (organic dust toxic syndrome): 2,000 EU/m$^3$

IOM (2008) noted that there is clear evidence of wide variability in individual sensitivity to bioaerosol exposure, with some people susceptible at levels (microbial counts of between $10^2 – 10^4$ cfu/m$^3$) that can be encountered in the general community in the absence of any specific point sources of bioaerosol. In addition, bioaerosol exposure, especially to endotoxin, may enhance the effect of allergens and other airborne pollutants on asthmatic people (IOM, 2008).

Bünger et al. (2007) conducted a follow-up study on respiratory disorders and lung function in composting workers and a small group of office-based controls. Changes of symptoms, respiratory disorders and lung function were determined at the start of the study and after 5 years of exposure. Limited bioaerosol monitoring was also conducted although the exposure measurements were not representative as only 6 of the 41 sites were investigated. Respirable dust did not exceed 1 mg/m$^3$. The median concentration of endotoxin was 160 EU/m$^3$ (range 80 – 340). Compost workers reported a significantly higher prevalence of mucosal membrane irritation of the eyes and upper airways than control subjects. Conjunctivitis was diagnosed significantly more often in compost workers. The forced vital capacity in non-smoking compost workers declined significantly during the observation period compared to controls. In addition a significant increase was seen in compost workers suffering from chronic bronchitis.

In terms of exposure and, hence, likelihood of health impacts, workers on the composting sites will be exposed to the greatest levels of bioaerosols. While this is true, it has been recognised that there is a possibility that people off-site could also be affected. In order to counter this the Environment Agency do not generally authorise new composting sites within 250m of homes or workplaces, unless it can be shown that bioaerosol levels can be maintained at acceptable levels. Acceptable levels have been defined as levels not exceeding:

- those before the start of the composting process or
- levels no greater than 1,000 cfu/m$^3$ total bacteria, 500 cfu/m$^3$ A. fumigatus and 300 cfu/m$^3$ Gram-negative bacteria (EA, 2010).

The figure of 250 m is based on studies which have suggested that bioaerosol concentrations tend to return to background levels within 250m of their source, although other research has demonstrated that this is not always the case (Recer et al., 2001; Fischer et al., 2008). Pankhurst et al. (2011) collected bioaerosol data over a period of two years from two commercial open-air turned windrow system composting facilities in the UK. Samples were taken both upwind and at various distances downwind of the sites and analysed for A. fumigatus, actinomycetes, Gram-negative bacteria and endotoxin levels. As with other studies, levels were found to be variable and concentrations declined rapidly from source. Compared to upwind measurements, levels were significantly higher at 180 m downwind for A. fumigatus, at 300 - 400 m for actinomycetes and Gram-negative bacteria and at 100 m for endotoxins. On occasions elevated concentrations of all the measured parameters
were found at distances further downwind. Table 6 shows the approximate geometric mean values (taken from a figure) for the peak concentrations recorded on the two sites. In each case the peak concentrations were recorded on the site (Pankhurst et al., 2011).

Table 6: Approximate geometric mean values of peak levels of bioaerosol parameters at two composting sites

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Site A</th>
<th>Site B</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>A. fumigatus</em> (cfu/m$^3$)</td>
<td>6,000</td>
<td>9,000</td>
</tr>
<tr>
<td>Actinomycetes (cfu/m$^3$)</td>
<td>55,000</td>
<td>3,200,000</td>
</tr>
<tr>
<td>Gram-negative bacteria (cfu/m$^3$)</td>
<td>1,600</td>
<td>75,500</td>
</tr>
<tr>
<td>Endotoxin (EU/m$^3$)</td>
<td>2.3</td>
<td>170</td>
</tr>
</tbody>
</table>

Despite the selection of the two similar composting sites, it can be seen from Table 6 that mean concentrations were higher at Site B by up to two orders of magnitude. It is speculated that the differences may be due to different feedstock composition, with household-derived waste (including vegetable matter) received at Site B but not at Site A. In addition, the composting process was maintained at a lower moisture level at Site B which may have facilitated bioaerosol emission.

Sykes et al. (2011) noted that currently there are no specific Workplace Exposure Limits in the UK to manage the exposure of compost workers to organic dust. Current dust exposure levels are based on the Control of Substances Hazardous to Health (COSHH) Regulations which define dust as being hazardous to health when it exceeds concentrations of 10 mg/m$^3$ for inhalable dust and 4 mg/m$^3$ for respirable dust (HSE, 2006). However, it has been speculated that these general dust levels are inadequate for managing risks from dusts containing biological material (Rylander, 1997).

In a study of four composting sites in the UK, Sykes et al. (2011) monitored employee exposure to inhalable dust, $\beta$ (1→3) glucan and endotoxin. Monitoring was undertaken at two open windrow sites, an in-vessel composting site and an enclosed bay facility. Sampling was conducted only on days when waste was being agitated in order to determine a worse case exposure. Overall, exposure to inhalable dust was low (with a geometric mean concentration of 0.99 mg/m$^3$), although 2.6% of samples exceeded 10 mg/m$^3$. Exposure to endotoxin, however, was elevated. The geometric mean value for endotoxin exposure was 35.1 EU/m$^3$, with over 25% of personal samples exceeding 200 EU/m$^3$ and 3% exceeding 2,000 EU/m$^3$ – the level at which organic dust toxic syndrome can occur. There were statistically significant differences in exposure between the sites, but given the number of different variables it was not possible to draw any conclusions about exposure from the different systems. Interestingly, and in contrast to some other studies (e.g. Wouters et al., 2006), exposure to endotoxin, dust and glucan was higher during outdoor working. Despite the relatively low dust levels, a significant correlation was found between personal dust levels and personal endotoxin concentrations, suggesting that inhalable dust may be a valuable predictor of endotoxin levels (Sykes et al., 2011).

Bioaerosols are not just a compost issue within the waste management industry, but also occur within a number of other points in the waste management chain, including during household storage of waste, collection and sorting. In one study, for example, increased concentrations of endotoxins (between 2 and 7 fold increase) was seen in
house dust where separated organic waste was stored indoors for more than a week (Wouters et al., 2000). Herr et al. (2004) conducted a small-scale study to assess health effects concerning airway, skin and general complaints in relation to storing organic waste for more than 2 days. It was found that longer indoor storage of organic waste was significantly associated with skin rash and allergy other than hayfever.

Lavoie et al. (2006), examined exposure to bioaerosols among waste collectors in Canada. They recorded exposure to aerosolised bacteria and fungi significantly above background levels in waste collectors (median bacterial exposure 50,300 cfu/m$^3$ in urban compostable waste collectors; median fungal counts 101,700 cfu/m$^3$ in rural compostable waste collectors). In order to minimise exposure and potential health impacts they recommend automation of waste and compost collection along with the use of personal protective equipment including goggles, gloves and disposable masks. Vilavert et al. (2009) measured levels of bioaerosols and VOCs at a municipal waste incinerator in Spain, and found concentrations to be low.

Bioaerosol exposure has also been observed at MRFs, with levels of bacteria and fungi up to $2.5 \times 10^5$ cfu/m$^3$ reported from a study of two UK MRFs (Gladding and Coggins, 1997). In a study of 159 workers from nine MRFs in England and Wales, handling a mixture of household and commercial waste materials (Gladding et al., 2003), individual exposure to airborne dust, endotoxin and $\beta(1\rightarrow3)$ glucan was measured. The exposure measurements were matched with self-reported symptoms from a questionnaire survey. Workers exposed to higher levels of endotoxin and $\beta(1\rightarrow3)$ glucan had an increased risk of respiratory symptoms than those with lower exposures. Stomach problems were also associated with higher $\beta(1\rightarrow3)$ glucan exposure (Gladding et al., 2003). In this study, it was also found that the longer a worker was in the MRF environment, the more likely he was to become affected by various respiratory and gastrointestinal symptoms. Symptoms related to bioaerosol exposure have also been reported in workers involved with point-of-sale glass bottle recycling in Canada (Kennedy et al., 2004). This involved either the mechanical or manual breaking of glass bottles in an indoor environment, with recorded fungal levels being associated with the breaking of visibly mouldy bottles.

3.1.2.2 Compost end use

There are potential hazards related to the end use of compost produced from waste, including the presence of pathogens and chemicals (including heavy metals) within the final material (Briancesco et al., 2008). In order to avoid potential health impacts, composts are subject to various regulations. In PAS 100 (BSI, 2011) the minimum quality in terms of a number of microbiological and chemical parameters are set down, as shown in Table 7.

Böhnel and Lube (2000), analysed samples of marketed biocompost and found that 50% of the samples contained *C. botulinum*. The significance of this, however, is unclear as the organism and its spores are widely distributed in nature and found in both cultivated and uncultivated soils. Briancesco et al. (2008) in a study of the microbiological quality of compost from Italy always found salmonella in the final compost (albeit at low levels), irrespective of the initial feedstock used.
Table 7: Minimum compost quality for general use (pathogens and chemical parameters) – BSI, 2011

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Escherichia coli</em></td>
<td>cfu/g fresh mass</td>
<td>1,000</td>
</tr>
<tr>
<td><em>Salmonella</em> spp.</td>
<td>25 g fresh mass</td>
<td>Absent</td>
</tr>
<tr>
<td>Cadmium</td>
<td>mg/kg dry matter</td>
<td>1.5</td>
</tr>
<tr>
<td>Chromium</td>
<td>mg/kg dry matter</td>
<td>100</td>
</tr>
<tr>
<td>Copper</td>
<td>mg/kg dry matter</td>
<td>200</td>
</tr>
<tr>
<td>Lead</td>
<td>mg/kg dry matter</td>
<td>200</td>
</tr>
<tr>
<td>Mercury</td>
<td>mg/kg dry matter</td>
<td>1.0</td>
</tr>
<tr>
<td>Nickel</td>
<td>mg/kg dry matter</td>
<td>50</td>
</tr>
<tr>
<td>Zinc</td>
<td>mg/kg dry matter</td>
<td>400</td>
</tr>
</tbody>
</table>

Smith (2009) notes that all types of municipal solid waste compost contain more heavy metals than the background concentrations present in soil. As there are many heavy metal containing materials in household municipal waste (including dust, batteries, plastics, paints, inks and household pesticides), composts derived from source segregated waste streams or green waste generally contain smaller concentrations of heavy metals than composts made from mechanically sorted products. As a consequence, repeated application of compost will lead to a slow accumulation of heavy metals within the soil, even where PAS100 compliant products are used, although it has been suggested that the risks to human health and the environment are minimal (Smith, 2009).

3.1.2.3 Domestic composting

This report mainly focuses on commercial waste management, but it is important to note that many homeowners with gardens traditionally compost and reuse their garden waste. Smith and Jasim (2009) conducted a three-year study in west London to examine the quantitative impact that home composting could have on the diversion of waste from landfill. In addition to quantifying the amount of waste deposited into home composting bins they also examined the quality of the final compost and investigated potential bioaerosol emissions (levels of culturable *Aspergillus* spp. measured adjacent to the composting bins during dismantling) and nuisance due to vector attraction (fruit flies). Airborne *Aspergillus* were detected during bin dismantling, but levels were low (average 79 cfu/m$^3$, max 123 cfu/m$^3$). Fruit flies were detected in some numbers, especially within the bins, but they remained within close proximity to their food source within the compost bin and numbers were low within a short distance from the bin. The authors concluded that in suburban areas, where homeowners have gardens, home composting could potentially divert 20% of the biodegradable household waste stream from the formal waste management chain.

3.1.3 Waste electrical and electronic equipment (WEEE)

WEEE (or e-waste) is one of the fastest growing waste streams, with Widmer et al. (2005) estimating that e-waste already constitutes 8% of municipal waste in the European Union. By 2015, it has been estimated that the disposal amount could be virtually double that (12 million tonnes – Goosey, 2004). The typical composition of e-waste collected in the European Union is shown in Table 8, with figures relating to the UK (domestic WEEE from 2003) shown in Table 9.
Table 8: Typical composition of WEEE collected in the European Union by WEEE category (Ongondo et al., 2011)

<table>
<thead>
<tr>
<th>No.</th>
<th>European Union WEE Category (example appliances)</th>
<th>% of WEEE collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Large household appliances (refrigerators, ovens, washing machines)</td>
<td>49.07</td>
</tr>
<tr>
<td>2</td>
<td>Small household appliances (vacuum cleaners, toasters)</td>
<td>7.01</td>
</tr>
<tr>
<td>3</td>
<td>IT and telecommunications equipment (phones, laptops)</td>
<td>16.27</td>
</tr>
<tr>
<td>4</td>
<td>Consumer equipment (DVD players, televisions)</td>
<td>21.10</td>
</tr>
<tr>
<td>5</td>
<td>Lighting equipment (lamps)</td>
<td>2.40</td>
</tr>
<tr>
<td>6</td>
<td>Electrical and electronic tools (drills, saws)</td>
<td>3.52</td>
</tr>
<tr>
<td>7</td>
<td>Toys, leisure and sports equipment (games consoles)</td>
<td>0.11</td>
</tr>
<tr>
<td>8</td>
<td>Medical devices (pulmonary ventilators, dialysis)</td>
<td>0.12</td>
</tr>
<tr>
<td>9</td>
<td>Monitoring and control instruments (smoke detector, thermostats)</td>
<td>0.21</td>
</tr>
<tr>
<td>10</td>
<td>Automatic dispensers (drink, money dispensers)</td>
<td>0.18</td>
</tr>
</tbody>
</table>

The WEEE Directive (Directive 2002/96/EC) requires manufacturers and importers within the European Union to take back their electrical and electronic products from consumers and ensure that they are disposed of appropriately (Widmer et al., 2005). The Directive aims to prevent the generation of WEEE and also aims to promote reuse and recycling in order to reduce the disposal of waste (Ongondo et al., 2011). As part of the Directive each European Union member state is required to separately collect household WEEE.

Table 9: Domestic WEEE generated in the UK in 2003 (Ongondo et al., 2011)

<table>
<thead>
<tr>
<th>Category</th>
<th>Discarded '000 tonnes</th>
<th>%</th>
<th>Units discarded (millions)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large household appliances</td>
<td>644</td>
<td>69</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>Small household appliances</td>
<td>80</td>
<td>8</td>
<td>30</td>
<td>31</td>
</tr>
<tr>
<td>IT/telecoms equipment</td>
<td>68</td>
<td>7</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td>Consumer equipment</td>
<td>120</td>
<td>13</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Lighting equipment</td>
<td>2</td>
<td>&lt;1</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Electrical and electronic tools</td>
<td>23</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Toys, leisure and sports equipment</td>
<td>2</td>
<td>&lt;1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Monitoring and control instruments</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Total</td>
<td>940</td>
<td>100</td>
<td>93</td>
<td>1000</td>
</tr>
</tbody>
</table>

A number of hazards have been associated with e-waste recycling, these include the presence of heavy metals (including mercury, cadmium and lead) and exposure to flame retardants (Tsydenova and Bengtsson, 2011). There are some common components/ parts of e-waste that contain much of the hazardous substances, these are outlined in Table 10.

Table 10: Overview of the hazardous components and substances commonly found in WEEE (Tsydenova and Bengtsson, 2011)

<table>
<thead>
<tr>
<th>Components</th>
<th>Found in</th>
<th>Substance of concern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode ray tubes</td>
<td>Old TV sets, computer monitors, oscilloscopes</td>
<td>Lead, barium, cadmium</td>
</tr>
<tr>
<td>Printed circuit boards</td>
<td>Ubiquitous, from beepers to personal computers</td>
<td>Lead, antimony, cadmium, beryllium, mercury, brominated flame retardants</td>
</tr>
<tr>
<td>Batteries</td>
<td>Portable devices</td>
<td>Cadmium, lead, mercury</td>
</tr>
<tr>
<td>Gas discharge lamps</td>
<td>Backlights of liquid crystal displays (LCD)</td>
<td>Mercury</td>
</tr>
<tr>
<td>Plastics</td>
<td>Wire insulation, plastic housing, circuit boards</td>
<td>Polyvinyl chloride (PVC), brominated flame retardants</td>
</tr>
</tbody>
</table>
Brominated flame retardants such as polybrominated diphenyl ethers (PBDEs) are synthetic additives mainly used in electrical and electronic appliances and in construction materials (Morf et al., 2005). In a study in the USA, PBDE exposure was found to be between 6 times and 33 times higher in electronic recycling workers than in the general US population (Schecter et al., 2009). In Finland, a study using personal air samplers from four recycling sites found that PBDEs were the most abundant flame retardants identified (Rosenberg et al., 2011). Improvements in site ventilation and ventilation maintenance, however, were generally found to be effective in reducing exposure. The authors speculate that exposure to flame retardants may be a health hazard and suggest that exposures should be minimised by using adequate control measures and maintaining good occupational hygiene practice (Rosenberg et al., 2011).

In a review of the chemical hazards associated with the treatment of WEEE, Tsydenova and Bengtsson (2011) note that “there is a paucity of workplace monitoring data and virtually no studies on the effects of occupational exposure to e-waste-associated chemicals and, perhaps therefore, its hazards appear to have been overlooked so far.”

3.2 Other recovery

3.2.1 Anaerobic digestion

Anaerobic digestion is a waste management process for organic waste materials which involves the decomposition of solid waste in an oxygen-free atmosphere. The outputs include biogas (comprising mainly methane and carbon dioxide) which, in the UK, is generally burned for electricity generation, and a digested waste material that can be composted and spread onto land (DEFRA, 2004). Anaerobic digestion can be divided into four steps (DEFRA, 2005) as shown below:

- Hydrolysis – complex organic compounds converted into soluble sugars, fats and amino acids;
- Acidogenesis – Products from hydrolysis converted into organic acid, alcohols, carbon dioxide, hydrogen and ammonia;
- Acetogenesis – Products from acidogenesis converted into acetic acid, carbon dioxide and hydrogen;
- Methanogenesis – Products from above converted into methane and carbon dioxide.

According to Moller et al. (2009) anaerobic digestion plants have several different designs and no single type dominates. The facility can be characterised according to the following options:

- Dry/wet digestion (‘dry’ – less than 75% moisture content; wet - more than 90%);
- Thermophilic/mesophilic digestion (mesophilic – approximately 35 °C; thermophilic – 53-55 °C);
- One-stage/two-stage digestion;
- One-phase/two-phase digestion.

Irrespective of the specific technology type, the operation of the facility includes the following main stages:
The mesophilic and thermophilic processes have both advantages and disadvantages (DEFRA, 2005). The mesophilic anaerobic digestion is more robust than the thermophilic process, but has a lower gas production rate, requiring the use of larger digestion tanks. The thermophilic process has higher gas production and a faster throughput, but needs effective control (e.g. of heat inputs). Both require a separate sanitisation stage to ensure that the products meet appropriate regulations (DEFRA, 2005).

Biogas grid injection occurs in a number of European countries (including France, Germany, Sweden, Switzerland, Austria and The Netherlands) providing that the biogas meets local specifications (biogas should contain 95-98% methane and be free of water, ammonia, hydrogen sulphide and carbon dioxide). Biogas composition varies depending upon how it is produced (landfill, anaerobic digestion) and the raw materials although, as noted above, the major components are methane and carbon dioxide, with other constituents typically being hydrogen sulphide, oxygen and nitrogen, thus raw biogas requires processing before grid injection. Naja et al. (2011) looked at the potential health hazards of using biogas (produced from either landfill sites or from anaerobic digestion) for cooking, and concluded that the injection of processed biogas into the distribution network did not present any additional chemical or microbiological risk to consumers when compared to using natural gas.

### 3.2.2 Energy from waste

Energy from waste (EfW) covers a range of complementary processes which recover additional value from waste. EfW generally refers to some sort of combustion/heating under controlled conditions with the production of electricity and/or heat. The principal aim is to “get the most energy out of waste, not to get the most waste into energy recovery” (DEFRA, 2011).

The DEFRA report on the application of the waste hierarchy (DEFRA, 2011) outlines three common routes for producing energy from residual waste, namely:

- **Processing the residual waste using intermediate technologies (such as mechanical and biological treatment or autoclave) to produce solid recovered or refuse-derived fuel. The refuse-derived fuel can be used in industrial combined heat and power production, cement kilns, purpose built waste combustion plants and co-firing with other fuels.**

- **Direct combustion (incineration with energy recovery). This is, generally, the most common method for recovery the energy stored in waste (Papageorgiou et al., 2009). Energy recovery may be electricity only, heat only or combined heat and power - with combined heat and power providing higher overall conversion efficiencies (Astrup et al., 2009b).**

- **Gasification or pyrolysis. Gasification is the heating of organic materials (including mixed waste or biomass) at temperatures greater than 700 °C with a reduced amount of oxygen and/or steam. Pyrolysis is also a high temperature**
decomposition process, but is conducted in the absence of oxygen. Both of these processes produce a solid residue and a synthetic gas.

These are summarised in the flowchart below (Figure 2).

![Flowchart](image)

**Figure 2: Energy from waste options (DEFRA, 2011)**

### 3.3 Disposal

#### 3.3.1 Landfill and incineration

“Landfill is a specially engineered area of land where waste is deposited. Once an individual section of landfill is full, it is sealed with a permanent cap. The biodegradable part of the waste then decomposes and reduces in volume. Much of the non-biodegradable content of MSW is stable and is not released from the landfill at discernible rates. The gas produced by decomposition of MSW is increasingly used to generate electricity. Landfill will probably always be needed for the final disposal of unusable residues.” DEFRA, 2004.

In 1999, the European Landfill Directive was adopted and this introduced three classes of landfill, namely:

- landfills for inert waste only;
- landfills for non-hazardous waste;
- landfills for hazardous waste.

As a result of this legislation there are now strict restrictions on the type of waste that can be accepted and co-disposal of different waste (which used to be common) is no longer allowed. In addition, some materials are banned from landfill including all liquid wastes, corrosive, explosive or flammable waste, hospital and clinical infectious waste, and tyres (whether whole or shredded) – HPA, 2011.

Incineration involves the burning of waste to reduce the volume of solids (typically up to 70%) and the generation of heat and/or electricity. The incinerator ash (bottom ash) can be re-used or sent to landfill site. Flue gases from the incineration process are
cleaned, removing hydrochloric acid, sulphur dioxide, nitrogen oxides, persistent organic pollutants and heavy metals before the emission of the flue gas to the atmosphere (Astrup et al., 2009b). The residue from air pollution control systems is a fine ash, typically about 4% of the weight of the waste processed. This is a hazardous material and normally needs to be disposed of at a landfill licensed to accept this kind of waste (DEFRA, 2004).

### 3.3.2 Health impacts

The health impacts of landfills and incinerators have been extensively studied and reviewed and are largely beyond the scope of this report. Many of the studies are based on facilities that predate current legislation (which has acted to tighten pollution controls) or, in the case of some landfills, were illegal dumps. Most reviews of health-related studies generally conclude that modern well-managed landfills and waste incinerators pose little risk to public health (e.g. Nap 2000, Farmer and Hjerpe 2001, Davoli et al., 2010; HPA 2011). The following section briefly outlines a number of more recent studies, looking at landfill first.

#### 3.3.2.1 Landfill

It is thought that landfills may account for between 10 and 25% of all odour complaints to local authorities in the UK (DEFRA, 2004). Potential sources of odour at landfills include leachate, landfill gas and smells from newly deposited waste. According to the Health Protection Agency (HPA, 2011) landfill odours have been detected over 1 km away from sites. Strong smells and odours considered to be unpleasant can cause affected individuals to feel unwell, often with non-specific symptoms, including nausea, drowsiness, fatigue and respiratory problems (Steinheider, 1999). Individual responses to odours are highly variable.

Davoli et al. (2010), for example, took a pollutant concentration approach to examining the health risk from a landfill site in Italy. The risk assessment was based on measured emissions and maximum chronic population exposure. The results indicate that both cancer and non-cancer effects are largely below values accepted by organizations such as the World Health Organization and the US Environmental Protection Agency.

Forastiere et al. (2011) conducted a health impact assessment of landfilling and incineration (see below) in Italy, Slovakia and England. The study population was based on residents living within 2 km of a landfill. Excess risk estimates were taken from epidemiological studies, following a literature review and basing the estimates on those studies considered to be the most reliable. For landfill sites in England (based on a study population of 1,425,000) it was estimated that there would be an additional 2.7 congenital malformations a year and an additional 58 cases of low birth weight a year.

#### 3.3.2.2 Incineration

Roberts and Chen (2006) assessed the health risk from a proposed medium-sized waste incinerator. The exposed population were residents living within 5.5 km of the proposed site (25,398 people). Data on emissions and predicted maximum ground level concentrations were obtained and estimated pollution rates were based on the limits set by the European Waste Incineration Directive. Compounds of potential concern included dioxins, furans, polyaromatic hydrocarbons and heavy metals.
Effects resulting from SO\textsubscript{2} and fine particulate emissions estimated for the proposed incinerator were also assessed. It was calculated that over a 25 year period (the operating period of the incinerator) stack emissions would result in an additional 0.018 cancers, 0.46 deaths brought forward due to sulphur dioxide and 0.02 deaths due to fine particulates in the exposed population. The estimated overall risk of dying due to the emissions in any one year was 1 in 4 million.

As outlined above, for landfill, Forastiere et al. (2011) conducted a health impact assessment of landfilling and incineration in Italy, Slovakia and England. The study population was based on residents living within 3 km of an incinerator. Air pollution dispersion monitoring was used to estimate levels of particulate matter (PM\textsubscript{10}) and nitrogen dioxide, while excess risk estimates were taken from epidemiological studies. In England it was estimated that 1,125 additional cancers would be attributable to incinerators during 2001 to 2050, with the vast majority of them (1,005) being due to exposure before 2001. Based on the exposed population (1,203,208), this is equivalent to less than 1 additional cancer per thousand population over a 50 year period. The group also calculated years of life lost attributable to air pollution (PM\textsubscript{10} and NO\textsubscript{2}) from incinerators up to the year 2050; this was estimated to be 4,165 – equivalent to 1.26 days per person. The authors characterised the health impacts of landfilling and incineration as “moderate when compared to other sources of environmental pollution, e.g. traffic or industrial emissions, that have an impact on public health”.

4. Cross-cutting

A number of cross-cutting themes are explored in the following sections. These relate to occupational injuries within the waste management industry, greenhouse gas emissions, exportation of waste and issues of inequality that arise from the distribution of waste management facilities.

4.1 Occupational injuries

The waste management industry has a fairly poor health and safety record, both in the UK and globally (HSE, 2004; Olorunnishola et al., 2010; Engkvist et al., 2011). According to the Health and Safety Executive (HSE), the UK waste industry typically reports around 4,100 to 4,300 accidents per year (HSE, 2004). The overall accident rate for the waste industry in 2001/2 in the UK was estimated to be around 2,500 per 100,000 workers, which is over four times the national average for work-related accidents (559/100,000 workers). The fatal injury accident rate (for the same period) was estimated to be 10/100,000 workers in the waste industry, compared to a national rate of 0.9/100,000). According to the HSE report (HSE, 2004):

- Accidents mainly occur during refuse collection, with significant numbers also occurring during loading/unloading and on-site transfer activities.
- Over 3-day injury accidents account for approximately 85% of all accidents, and handling and sprain injuries sustained from handling refuse during the collection process account for the largest proportion of the over 3-day accidents.
- Being struck by refuse collection vehicles, being struck by falling objects, trips and low falls are particularly significant when considering accidents that result in fatal or major injuries.
• Considering all injury severities, handling/sprain injuries are the most significant, with heavy objects being the most frequently involved in handling injuries, followed by sharp objects and awkward loads.

Table 11 shows the accident rate within the UK waste industry in comparison with other industries. It can be seen from this Table, that the overall accident rate in the waste industry is over twice that seen in the construction industry.

Table 11: Accident rates in UK industry 2001/02 (HSE, 2004)

<table>
<thead>
<tr>
<th>Industry</th>
<th>Fatalities</th>
<th>Major</th>
<th>Over 3-day</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>9.2</td>
<td>239</td>
<td>622</td>
<td>813</td>
</tr>
<tr>
<td>Construction</td>
<td>4.2</td>
<td>333</td>
<td>759</td>
<td>1107</td>
</tr>
<tr>
<td>Extractive/Utility</td>
<td>7.6</td>
<td>251</td>
<td>1239</td>
<td>1418</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>1.2</td>
<td>187</td>
<td>936</td>
<td>1058</td>
</tr>
<tr>
<td>Services</td>
<td>0.3</td>
<td>79</td>
<td>404</td>
<td>454</td>
</tr>
<tr>
<td>Waste</td>
<td>10.2</td>
<td>328</td>
<td>1909</td>
<td>2459</td>
</tr>
</tbody>
</table>

Engkvist (2010) examined work-related injuries at a number of recycling centres in Sweden (similar to UK civic amenity sites). A total of 122 employees completed a questionnaire and 32 of these employees also agreed to a face-to-face interview. Engkvist noted that there was a high frequency of injuries. Over a 12 month period 60% of employees reported lower back musculoskeletal symptoms. Nearly two-thirds of employees reported minor accidents (such as cuts or injuries due to crushing) during a 12 month period. The most common accidents reported were due to heavy lifting, slips and trips and splinters in the eye while handling waste. Over-exertion accidents were reported during the manual handling of large household items such as televisions, furniture, washing machines etc. The task assessed by the employees as having the highest risk of resulting in an injury was picking out wrongly sorted waste.

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While the majority of incidents relate to people employed within the waste industry, accidents do also, occasionally, involve members of the public. In 2009, for example, a man was crushed to death in a bin truck after he climbed into an commercial wheelie bin in Brighton and fell asleep (BBC News, 2009). As a result of this death it has been recommended that large commercial bins are locked and located away from public areas (Gibbs, 2010).

4.2 Greenhouse gas emissions

The waste sector (including wastewater) is a significant contributor to greenhouse gas emissions accountable, according to Lou and Nair (2009), for about 5% of the global greenhouse budget. Emissions include carbon dioxide, methane, nitrous oxide and fluorine gases (Bogner et al., 2008). In the UK, according to DEFRA (2004) management of MSW accounts for 3.6 million tonnes of carbon dioxide a year (2.4% of the national total) and 0.7 million tonnes of methane a year (27% of the national total).

Landfills are responsible for much of the estimated greenhouse gas emissions, as a result of both the amount of waste currently sent to landfill and the relatively high level of emissions. The landfilling of a tonne of MSW has, for example, been calculated as being equivalent to approximately 4.8 tonnes of carbon dioxide, as
opposed to 0.8 tonnes of carbon dioxide resulting from incineration of a tonne of waste; a difference in potency of a factor of six (Eduljee, 1995).

There are a number of different accounting/reporting mechanisms used to estimate greenhouse gas emissions from waste management, however, these vary substantially with respect to the inclusion of indirect emissions, inclusion of upstream processes and downstream savings which, clearly, leads to different results according to which mechanism is employed. The disparity between different systems led Gentil and colleagues (2009) to suggest the ‘upstream-operating-downstream (UOD) framework to provide a transparent reporting structure. Staff from the Technical University of Denmark have written a series of papers using the UOD framework looking at greenhouse gas emissions, and the resulting global warming factors, from a range of recycling processes and other waste management options (Astrup et al., 2009a and b; Boldrin et al., 2009; Damgaard et al., 2009; Larsen et al., 2009; Manfredi et al., 2009; Merrild et al., 2009; Moller et al., 2009). It should be noted that most methods used to account for greenhouse gas emissions (including the UOD framework) assume that biogenic (as opposed to fossil fuel derived) carbon has a global warming potential of 0 – i.e. biogenic carbon is considered to be ‘neutral’ (Astrup et al., 2009b).

Figure 3 shows the conceptual overview of anaerobic digestion in relation to greenhouse gas accounting (Moller et al., 2009).

![Figure 3: Conceptual view of anaerobic digestion in relation to greenhouse gas accounting](Moller et al., 2009)

Squares represent processes, ovals represent material flows and octagons represent substituted processes and avoided emissions

Conducting the greenhouse gas analysis on a generic anaerobic digestion facility with either biogas utilisation at the facility or the upgrading of the gas for vehicle fuel resulted in a global warming factor ranging from -375 (i.e. a saving) to 111 (a load) kg CO₂ equivalent per tonne of wet waste (Moller et al., 2009). The large variation was due to a number of factors, including the energy substitution by biogas, nitrous oxide emission from the digestate in soil, fugitive emissions of methane and so on. Conducting the analysis on a specific type of anaerobic digestion facility (rather than a generic one) suggested savings of between -95 and -4 kg CO₂ equivalent per tonne of wet waste.
The greenhouse gas analysis of incineration was found to be largely dependent on the amount of fossil carbon (e.g. plastic) within the waste and the energy conversion efficiencies achieved (Astrup et al., 2009b).

For most of the recycling options examined, accounting for the downstream use of the recycled material (especially where the recycled product can be substituted for virgin material) demonstrates large potential savings in greenhouse gas emissions although, as might be expected, the results are dependent upon the technologies utilised and the system boundary choices. For plastics recycling the analysis showed that substitution of virgin plastic is the preferred option. Where this is not viable the plastic should be used for energy utilisation as, in greenhouse gas terms, substitution of other materials (such as wood) with plastic waste was not effective (Astrup et al., 2009a). For metals recycling it was shown that, because of the high energy savings and as a result of the range of avoided impact, metals recovery will always be beneficial over primary production (Damgaard et al., 2009). Two different options for the reuse of glass were investigated (reuse of whole bottles and remelting of cullet added to glass production), both of these downstream options were found to lead to greenhouse gas savings and to vastly outweigh the impact of upstream and operating impacts (Larsen et al., 2009). Grant Thornton (2006) reported similar savings for remelting glass, but found less benefit when it was used as shotblast, aggregate or filtration media. With paper recycling large savings in greenhouse gas emissions are possible, but the data for both reprocessing of paper waste and also data for virgin paper production are highly variable (Merrild et al., 2009).

4.3 Exporting waste

Although there are controls on exporting waste and local users are now often the main source of electronic waste in a lot of developing countries (e.g. a number of African countries – Lubik, 2012) illegal imports of old computers, TVs and so on from Europe, Asia and North America still reach developing countries. It has been estimated that at least 250,000 tonnes of e-waste enters five African countries (Benin, Cote d’Ivoire, Ghana, Liberia and Nigeria) each year, much of it from Europe (UNEP, 2011).

Waste recycling in developing countries is often done in poor conditions leading to a number of potential health issues in both workers and those living around the sites, where there can be environmental exposure to lead, cadmium, chromium, PBDEs, PCBs (polychlorinated biphenyls) and PAHs (polycyclic aromatic hydrocarbons). High levels of these chemicals have been found in pregnant women and young children living in close vicinity to informal and primitive waste recycling sites, leading to concerns about developmental neurotoxicity, although human studies of adverse effects are scarce (Chen et al., 2011).

4.4 Inequalities

Inequalities in health, due to different socio-economic status (SES) need to be accounted for when considering health impacts potentially resulting from exposure to waste management options, as SES is a powerful determinant of health and as such socio-economic factors have a strong potential to act as confounders. Within this section, health per se is not the issue, the question is whether the distribution of waste management sites is equitable or not. According to Martuzzi et al (2010) “available data provide consistent indications that waste facilities are often disproportionately
more located in areas with more deprived residents, or from ethnical minorities. This applies to waste incinerators, landfills, hazardous waste sites, legal or illegal.”

In the UK, a number of studies have looked at the association between social characteristics and residence in the vicinity of waste sites and found that solid waste and other polluting facilities were far more likely to be located in more deprived areas (FoE 1999, 2004; Walker et al., 2003), while a study of incinerators and landfill sites found a direct relationship between social class and residence near waste facilities in the UK and Italy (Forastiere et al., 2011). The proximity of waste sites to residents of lower social classes, however, is not a universal truth. In Wales, for example, an inverse relationship between social class and a landfill site was found, where more affluent people were found to be living closer to the site (Fielder et al., 2000).

5. Discussion

Each year in the UK we produce about 29 million tonnes of MSW (DEFRA, 2004), which needs to be collected and dealt with safely. Until recently, landfill was the disposal method of choice. Recent legislation and the increasing need not to waste resources is changing this picture and there is now a far greater emphasis on recycling and other recovery methods rather than simply disposal. Although other methods are increasing in prominence there is always likely to be a need for some disposal to landfill (for example of incinerator or energy from waste fly ash).

The main health impact from recycling seems to be respiratory problems in workers exposed to bioaerosols. Bioaerosol levels from different processes are difficult to compare as there is no standard way to measure exposure and it is likely that concentrations are highly variable. Where measurements have been taken levels they are often low, but periodically high concentrations are recorded (e.g. Sykes et al., 2011) which may give rise to health problems. In a five year study comparing compost workers with office-based controls (Bünger et al., 2007), compost workers reported significantly more eye irritation, upper airway irritation and poorer lung function tests. It may be possible to address some of these issues through adequate ventilation and also the use of additional personal protective equipment for workers.

There is also some suggestion that bioaerosols may also be an issue where organic waste is kept in the home (typically the kitchen) for periods greater than two days. This is an area that would benefit from more research to enable appropriate advice to be given to home owners.

The increase in recycling of waste has raised issues about increased transportation and its attendant risks (such as transport-related accidents and greenhouse gas emissions. However, it has recently been shown that the recycling of paper and card is much more beneficial to the environment than allowing to degrade within a landfill site, even when the recovered paper and card is transported to China to be recycled (WRAP, 2008).

There is a need to ensure that materials that are recycled are not used inappropriately, Weidenhamer and Clement (2007a), for example, report on inexpensive jewellery, imported into the USA from China. Given the low cost of the items, they speculated that scrap materials may have been used and analysed 39 pieces of the jewellery, which had previously been shown to have a high lead content. The lead (90%+) and
antimony (3%) content of the jewellery was suggestive that battery lead had been used. In a separate study the make up of the jewellery items suggested that solder-based source material had been used (Weidenhamer and Clement, 2007b). The authors suggest that the recycling of lead batteries and e-waste in China needs to be investigated.

Both landfill sites and incinerators are unpopular with the public due to perceptions relating to negative health impacts. A lot of studies have been conducted to examine potential health effects from these waste management options on nearby residents. Many of these studies have been conducted on old sites, that would not meet current regulations and few have produced unequivocal results. As noted by Saffron et al. (2003), it is one thing to show that hazardous materials (e.g. bioaerosols or chemicals) leave the waste facility, it is quite another to show that local people are exposed to these and that as a result they suffer from health impacts. The majority of non-occupational epidemiological studies that have been conducted rely on the worst type of exposure evidence (i.e. residence within a defined area). Other studies, for example the one conducted by Roberts and Chen (2006), use concentrations of specific emissions based on the regulations (e.g. upper limits of the European Waste Incineration Directive) to demonstrate that a well run site will not cause health problems. This however, raises the question of whether any continuous monitoring is conducted on incinerator emissions, to ensure that emissions remain within the prescribed levels at all times (including both start-up and shut-down). As noted by Giusti (2009): “Despite important technological advancements, improved legislation and regulatory systems in the field of waste management, and more sophisticated health surveillance, the public acceptance of the location of new waste disposal and treatment facilities is still very low due to concern about adverse effects on the environment and human health.”

The majority of clearly demonstrable health impacts in the waste management injuries occur in the workforce, and the industry has a fairly poor health and safety record. Many of the health impacts, especially the fatal ones, involve being struck by vehicles, typically during the refuse collection process.

6. References


Weidenhamer JD, Clement ML (2007a) Evidence of recycling of lead battery waste into highly leaded jewellery. *Chemosphere* 69, 1670-1672.
Weidenhamer JD, Clement ML (2007b) Lead contaminated electronic waste is a possible source material for lead-contaminated jewellery. *Chemosphere* 69, 1111-1115.
WRAP (2008) CO₂ impacts of transporting the UK’s recovered paper and plastic bottles to China. WRAP.