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Bioaerosol Releases from Composting Facilities

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PhD

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ABSTRACT

The use of composting is expected to increase dramatically due to its economic and environmental benefits. For public health protection, regulators and licensing authorities are requesting risk assessments to be conducted prior to the development and operation of composting. Significant amounts of microrganisms can be aerosolised and transported by winds to points of exposure. However, the source term factors that influence their release and their dispersal are not fully understood.

In this thesis a method to measure viable bioaerosols emission rates from static compost pile surfaces and during the agitation of compost was developed. The factors that influence the emission of bioaerosols from compost piles of different ages and during different agitation activities were evaluated. A wind tunnel analysis was successfully used to measure the surface flux bioaerosols emission rate. Newly estimated emission rates from various source terms were then modelled to produce source depletion curves.

The surface emission flux of a static pile was estimated to be 10^2 to 10^4cfu/m^2/s for both *A. fumigatus* and actinomycetes. The turning of compost releases the highest bioaerosols concentration range from 10^4 to 10^8cfu/s compared with the shredding and screening. The turning of an early stage compost windrow emitted the highest amount of bioaerosols. This study introduces a new method for quantifying bioaerosols dispersal, thus improving the risk assessments required for environmental permitting.

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ABBREVATIONS AND NOTATION

A	*Aspergillus*
ABPA	Animal by-product order
Af	*Aspergillus fumigatus*
ac	Actinomycetes
BS	British standard
CO_2	Carbon dioxide
COSHH	Control of substances hazardous to health
cfu	Coliform forming unit
cfu/g-wet	Coliform forming units per gram wet sample
cfu/m^3	Coliform forming units per cubic metre
cfu/m^2/s	Coliform forming units per square metre per second
DEFRA	Department for environment, food and rural affairs
EM	Electron microscope
g/cm^3	Gram per cubic centimetre
IOM	Institute of occupational medicine
l/m	Litre per metre
MCE	Mixed cellulose ester
μm	Micrometre
μg/kg	Microgram per kilogram
mg/kg	Milligram per kilogram
m^3/h	Cubic metres per hour
MSW	Municipal solid waste
ng/m^3	Nano gram per metre cubic
pbb	Parts per billion

$SBER_1$	Surface bioaerosols emission rate measured using the wind tunnel
$SBER_2$	Surface bioaerosols emission rate corresponding to ground level wind velocity
tCO_2e	Tonne of carbon dioxide equivalent
tpa	Tonnes per year
TSE	Transmissible spongiform encephalopathy
USEPA	United States Environment Protection Agency
v/v	By volume
w/w	By weight

CHAPTER 1 INTRODUCTION

Composting is the decomposition of organic biodegradable material by an aerobic process into a safe, nuisance-free, humus-like material (Gilbert *et al.*, 2002). It has become one of the most important waste technologies and has developed from a traditional peasant's practice to an environmentally friendly waste process for major cities. Composting has evolved during the twentieth century from an art to a science (Epstein, 1997). It has advantages over landfill in reducing the amount of greenhouse gases and has a capacity to convert waste into useable materials. Many studies have been conducted into various aspects of composting to ensure the process and products are safe to the public and workers, to improve the process effectiveness and to expand product use.

The development and operation of composting facilities is controlled by regulations and best practice guidance to ensure the products meet the required standards without posing a threat to environmental and public health. One of the principal current concerns from composting operation is the release of bioaerosols. Bioaerosols emitted from composting activities include microorganisms and particulate organic matter that are known to have an impact on public health. Measures are needed to ensure that composting operations adhere to the appropriate regulations.

1.1 The legislative context

The establishment and operation of composting facilities is controlled by interrelated legislation, regulation and licensing requirements to ensure the environment and public health are protected (Gilbert *et al.*, 2001). These have been introduced by the European Union and by National and Local Governments. The main regulations are briefly described below:

a) The European Union's composting related legislations include:
   - the Directive on the Landfill of Waste (EC/31/99), which aims to harmonise the operation of landfill sites across Europe (EU Council, 1999);
   - the Framework Directive on Waste 75/442/EEC, as amended by 91/156/EEC, which sets the principle of the waste management hierarchy and establishment of "polluter pays" principle and the responsibilities Competent Authorities in Member Country (EU Council, 1991);
   - the Packaging Waste Directive (94/62/EC), which aims to prevent packaging waste and to increase the re-use, recovery and recycling of such waste (EU Council,, 1991);
   - the Sewage Sludge Directive (89/278/EEC), which aims to protect the environment and in particular the soil (EU Council, 1986); and
   - the European Community working document on "Biological Treatment of Biowaste" (European Commissioner, 2001)

b) In the United Kingdom, there are a number of regulations either in the form of Statute or supporting regulations that cover the development of composting facilities and the handling, treatment and disposal of waste. Some of the regulations are:

- the Town and Country Planning Act 1990 (as amended by the Planning and Compensation Act 1991), which sets out the legislative framework from the preparation of the structure and plans and the administration of development control (UK Act, 1990);
- the Control of Pollution (Amendment) Act 1989 (UK Act, 1989) and the Controlled Waste (Registration of Carriers and Seizure of Vehicle) Regulation 1991 (as amended) (UK Act, 1991), which sets out the registration of carriers;
- the Environmental Protection Act 1990(UK EP Act, 1990), which is a broad-ranging Act that covers pollution control, waste management licensing and statutory nuisances;
- the Controlled Waste Regulations 1992 (as amended), which defines controlled waste(UK EP, 1992);
- the Waste Management Licensing Regulation 1994 (as amended) which states the waste management licensing condition (UK Waste Regulation, 1994);
- the Statutory Nuisance (Appeals) Regulation 1995 which sets out the appeals procedure for persons appealing against a nuisance abatement notice (UK Nuisance Regulation, 1995);
- the Environment Act 1995, which introduces the requirement for a National Strategy, establishes the Environment Agency and sets out the principle of Best

Practical Environmental Option for each waste stream (UK Environment Act, 1995).

- the Finance Act 1996 and Landfill Tax Regulations 1996, which introduces the landfill tax and its operation (UK Finance Act, 1996);
- the Producer Responsibility Obligation (Packaging Waste) Regulation 1997 (as amended), which implements the recovery and recycling targets (UK Regulation, 2003); and
- Animal By-Product Order 1999, which controls the disposal of animal by-products (UK Oder, 1999).

In addition to the above, the British Standards Institution's publicly Available Specification for Composted Materials (WRAP, 2005) has recommended that composting be based on a risk assessment and suggests the use of a HACCP methodology (Hazard Analysis and Critical Control Point) (Composting Association, 2002) in their operation. The standard and HACCP are focused on product quality and safety, although they also cover other contributing elements such as management, planning and monitoring (WRAP, 2002).

The destruction of pathogenic bacteria is crucial in composting. To ensure the compost is clean from pathogenic microorganisms, the Animal By-Product Order (ABPA) 1999 was introduced (UK Order, 1999). The regulation has a range of operational options depending on the composting materials and systems. Some of the options provided, for

example in a windrow composting, the maximum particle size of the composting materials have to be 40 mm and the minimum temperature is 60^0C for at least 8 days.

In general, the regulations above could contribute to the expansion of composting use and provide safe regulation and control. The development of composting facilities requires planning permission to ensure their location is appropriate and compatible with the vicinity. Subsequently, the facilities have to be licensed or registered before being allowed to operate under the Waste Management Licensing Regulations 1994.

1.2 The role of composting in waste management

The use of composting for the treatment of biodegradable waste is expected to increase because of its economic and environmental benefit (Strategy Unit, 2002). Proportionate regulation will encourage the development of composting facilities. Composting is envisaged not only as a treatment for green waste, but also for other types of biodegradable waste such as kitchen waste, where additional controls are required.

a) Regulatory drivers

The European Communities Landfill Directive (1999/31/EC) limits the amount of biodegradable waste landfilled and is stimulating the demand for alternative waste disposal systems that divert waste from landfill (EU Council, 1999). Stringent targets on member countries are expected, in part, by the rapid expansion of composting as a waste

treatment technology (DEFRA, 2000a). By 2010, each member country is obliged to limit their amount of biodegradable municipal waste disposed in landfill to 75% of the amount disposed of in 1995. The limit is further decreased to 50% and 35% by 2013 and 2020, respectively.

It is estimated that the final target of biodegradable waste that needs to be composted or treated in the UK by year 2020 will be *ca.* 5 million tons per annum (Mtpa) (Evans *et al.*, 2002). In line with this, the UK government has set a target to increase recycling and composting of household waste to at least 25% by 2005; 30% by 2010 and 33% by 2015. These policies and local authorities target will clearly encourage the development and expansion of composting facilities in the future.

A study by Slater *et al.* (1999) on the state of composting in UK, stated that there were 197 composting sites through out the UK, run by 90 operators and processing *ca.* 833 044 tonnes of biodegradable waste annually. The major waste stream composted was green waste. It contributed *ca.* 90% w/w of all composted municipal waste. The study suggested that by 2010, more composting facilities would be needed because, by that time the estimated amount of biodegradable wastes would be between 12.4 -15.5 Mtpa (DEFRA, 2003). This estimate does not consider agriculture wastes, domestic sewage sludge or commercial biodegradable wastes.

b) **Environment benefits**

Another factor promoting the increased use of composting is its environmental benefit. Composting reduces biodegradable waste volume to about 38% - 55% v/v (Mbuligwe *et al.*, 2002). Municipal solid wastes constitute >60 % w/w of biodegradable organic materials (Harrison *et al.*, 2000).

The decomposition of biodegradable waste results in the production of greenhouse gases such as methane. Landfills, which also involve biological decomposition, emit about 25% of the total amount of methane gas generated in the United Kingdom (DEFRA, 2000a). The greenhouse gases are known to contribute to climate change (Ayalon *et al.*, 2000). A study using life cycle analysis (LCA) in Cameroon suggested that composting has the ability to completely eliminate the green house gases generated by landfill, that is about 1.77 tonne of carbon dioxide equivalent (tCO_2e) per tonne of household waste (Ngnikam *et al.*, 2001). The study showed that composting produces lesser greenhouse gases than uncontrolled landfill.

c) **Economic drivers**

Compost, the end product of the process, with appropriate quality and characteristics can be used for various purposes. For many years, compost has been used as a fertilizer and soil conditioner. Research has shown that compost can provide nutrients to plants, improve the soil structure and facilitate the re-vegetation of disturbed or eroded soils

(USEPA, 1998). Polprasert (1989) described the characteristics of compost that enhance soil fertility. Compost has the ability to modify a soil pH and increase its water retention capacity. Compost contains high concentrations of organic nitrogen, which slowly mineralise to become an inorganic ammonium or a nitrate for plants to grow. The slow release of nutrients provides a supply of nutrient to the plant for a longer period of time.

Research conducted by Serhat *et al.*,(2003) shows that hazelnut waste, after being ground and composted for four months, could improve hydraulic conductivity, total porosity and macro- and micro- pore percentages of the clay loam and sandy loam soil. Use of compost for soil improvement has other benefits. Compost may inoculate soil with nitrifying bacteria and activate indigenous mircoorganisms (Kawalchuk *et al.*, 1999). Research on use of compost has been extended to the remediation of contaminated soils, for storm-water management, to control odours, degrading volatile organic compounds (VOCs), implementing reforestation, remediating wetlands and erosion control (USEPA, 1997). Ertunc *et al.* (2002), for example, reported that simazine (herbicide) was biotransformed to a stable and safe metabolite when treated in compost.

These advantages of composting contribute to its important role in waste management. Applied wisely, composting supports and increases the material recycling rate and strengthens the environment conservation. It is expected that composting will continue to play an important role in the future. This said, more research into process improvement, beneficial use and health and environment control needs to be conducted.

1.3 The composting process

Composting involves the biological decomposition of organic matter under controlled, aerobic conditions into a humus-like, stable product (Epstein, 1997). The process is managed to achieve the favourable conditions required for micro-organisms to proliferate, accelerate the biodegradable process, reduce the emission of unwanted gases (Ngnikam *et al.*, 2001) (Hellmann *et al.*, 1997) and, at the same, time destroy pathogenic bacteria (Beffa *et al.*, 1996; Vinneras *et al.*, 2003; Hassen *et al.*, 2001). Sometimes, process control is dictated by the quality of the intended product (Zurbrug *et al.*, 2002; Hogg *et al.*, 2002), such as soil improvement, to disinfect pathogenically infected organic waste and to bioremediate contaminated soil (Laine *et al.*, 1996).

The input and products of the composting process are illustrated in Figure 1.1. The composting rate is dependent on the type of organic matter used as substrate. Simple organic matter such as sugar and carbohydrates decompose more rapidly compared with leaves and woodchips which are more complex lignocellulosic materials of low biodegradability. Composting, an aerobic process, is controlled by several key parameters and factors which are discussed in the following section.

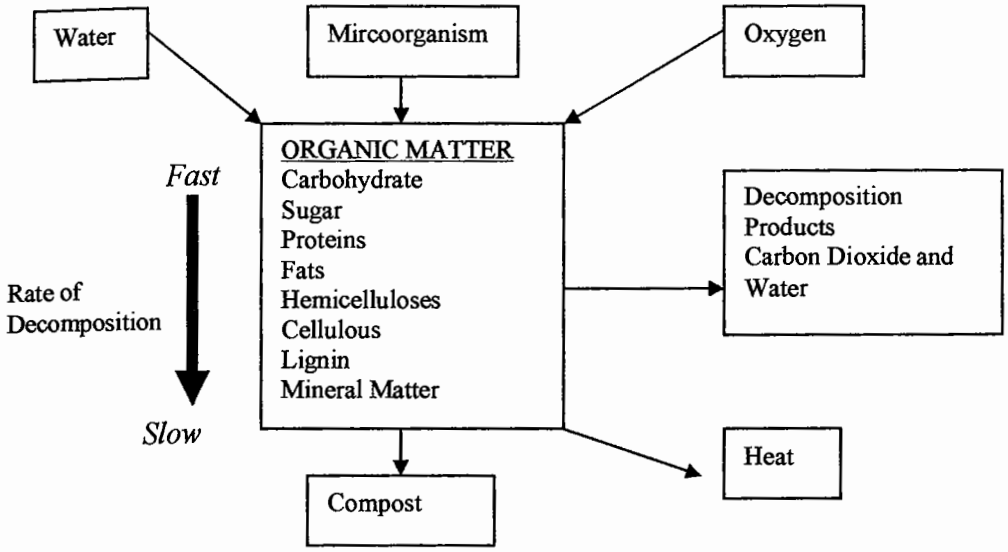


Figure 1.1: Composting process (Epstein, 1997)

1.3.1 Key parameters

The composting process is successful when a stable product is produced, pathogenic microorganisms killed, the waste volume reduced significantly and the process performed in an aerobic environment. There are several key parameters that dictate the completion of the composting process.

a) Carbon to nitrogen ratio

Micro-organisms need carbon for energy and nitrogen for growth. The ideal carbon to nitrogen ratio is approximately 30:1 w/w, although this ratio may need to be adjusted based on the bioavailability of carbon and nitrogen (Titko *et al.*, 1996). Green leaves have higher nitrogen content than brown or dried leaves (Richard and Trautmann, 2002).

Excess nitrogen results in formation of ammonia gas or other mobile nitrogen compounds which could cause odours and other environmental problem.

b) Moisture content

Moisture is essential for micro-organisms to survive and remain active. A high percentage of moisture content reduces the supply of oxygen and results in the domination of anaerobic processes (Richard *et al.*, 2002). Epstein (1997) suggests an optimum moisture content of *ca.* 60% with free air space of *ca.* 35%. The water content also could determine the structure and texture of compost and subsequently the shape of windrow.

c) Oxygen

The most common microorganisms in the biodegradation of waste are bacteria and fungi. During degradation, oxygen is consumed and CO_2 and water released. When oxygen is lacking, the anaerobic conditions prevail. The anaerobic process produces odorous gases such as ammonia and hydrogen sulfide (Fukumoto *et al.* 2003). It is therefore important to ensure that aerobic processes are maintained through the composting period. The aerobic degradation process is shown in the *Equation 1.1* below (Wiley and Pierce, 1955; Epstein 1997). Organic matter present in waste and oxygen from air are consumed by microorganisms to produce a stabilized organic matter, known as compost, water and carbon dioxide.

$$C_pH_qO_rN_s \cdot aH_2O + bO_2 = C_tH_uO_vN_w \cdot cH_2O + dH_2O + eH_2O + CO_2$$

organic matter	oxygen demand	compost	water evaporation	water and carbon products

Equation 1.1

In some facilities, composting material is mixed with other materials to improve the structure and ventilation of the windrow (Haug *et al*, 1980). High water content reduces the amount of oxygen transferred into the composting mass, unless high levels of agitation are used to continuously expose new substrate surfaces for oxygen supply.

Three approaches are frequently used to balance ventilation supply and moisture content:

1) recycling of compost and blending with dewatered cake before composting (which is mostly used in sludge only composting);

2) addition of organic amendments to the sludge;

3) addition of bulking agents such as wood chip and the un-composted bulking agent which are then screened out from the composted product.

d) Temperature

Temperature is one of the most important process factors in composting because it determines the species mix of microorganisms in the compost system. Heat is generated from microbial and biochemical activity and the temperature will increase and vary depending on the amount of compost material, mass transfer into gases and water evaporation (Weppen 2001; Quazi *et al.*, 2000). Temperature increases the reaction rate.

Several temperature ranges are common in compost systems; psychrophilic for 10°C to 30°C, mesophilic for 20°C to 50°C and thermophilic for 45°C to 75°C. Most of the time, composting is either mesophilic or thermophilic, because of the heat generated from biotransformation, which is exothermic (Mohaibes and Tanski, 2004; Burton, 1992).

Beffa *et al.* (1996) identified the numbers of spore-forming and non-forming thermophilic bacteria at the beginning and cooling phases of the open-air

Table 1.1: The amount of bacteria growth in composting process at difference stage

Times (days)	Temperature of compost sample (^{0}C)	N. of bacteria/g (dry wt) of compost	
		Oval spore-formers	Non spore-formers
0(starting material)	25-40	10^6-10^7	10^2-10^4
4	60-65	10^9-10^{10}	10^4-10^6
6	65-71	10^8-10^9	10^6-10^7
10	67-78	10^8-10^9	10^8-10^9
115	20-35	10^7-10^8	10^3-10^4

windrow composting system as shown in Table 1.1 above. The oval-spores forming bacteria or bacilli enrich in the temperature range between 50^{0}C to 65^{0}C, while non-spore forming bacteria are dominant and active at temperatures above 70^{0}C. The study demonstrated that functional bacterial diversity during the thermogenic phase appears to make it possible to compost at high temperatures (65^{0}C to 75^{0}C) for a longer period of time for better destruction of human pathogens and allergenic moulds, as well as phytopathogens and seeds.

All the key parameters discussed will change throughout the process and have to be balanced accordingly to ensure the desired condition is achieved.

e) pH

There are certain types of micro-organisms that are dependent on pH for growth (Epstein *et al.*, 1997). The bacteria that require pH of 5 or less for maximal growth, called "acidophiles" and the bacteria which grow best between pH 7 to 12 are termed as "alkalophiles. Bacteria that prefer to grow at pH near 7 are known as "neutrophiles". Epstein (1997) also suggested that the range of pH that produces high temperatures for longest period of time is from pH 6.5 to 9.6. Smars *et al.*, (2002) has suggested that actively preventing the temperature from rising until pH reaches a certain value could reduce the degradation time. This is further evidence that pH is one of the controlling factors in the composting process.

f) Substances of low biodegradability

Wood chips are one of the low biodegradability substances because of the presence of lignin that forms in the cell structure. Much research has been conducted to characterise these problems and a number of solutions suggested. One of them is by culturing specific bacteria to accelerate the degradability (Volchatav *et al.*, 2002). Frequent turning of the compost stimulates xylan (a constituent of hemicelluloses) degradation by redistributing the substrates, the free enzymes and the microorganism (Lyon *et al.*, 2000). Another

study by Han *et al.* (2002) using rumen microorganisms, taken from the stomach of a cow resulted in an efficiency increase compared with that achieved by employing mesophilic acidogens. The widespread use of plastic has contributed to significant difficulties in operation of composting facilities and has reduced the number of composting facilities in Japan (Ohtaki *et al.*, 2000). It also reported that Japan has no more than 30 composting plants and the impurities such as plastic in compost are frequently not acceptable and result in unmarketable compost.

The successful completion of composting is dependent on the growth of microorganisms. Therefore, an environment conducive to microorganisms' growth and proliferation is important. This can be achieved by introducing an engineering and technological approach in which key process parameters are continually balanced and maintained throughout.

1.3.2 Microorganisms in composting

Bacteria and fungi are the principal microorganisms in the composting system. Bacteria have a high surface area to volume ratio because of their small size. They are efficient at transferring oxygen and nutrients to produce a stable compost, water and carbon products. Bacteria dominate comprising about 80% to 90% of the microorganisms in compost. Most of the bacteria are not infectious but there is always a possibility of pathogenic bacteria being present in the receiving waste (Ryckeboer *et al.*, 2003).

Fungi are multicellular microorganisms larger than typical bacteria. They are eukaryotic organisms that have a nucleus and other well-developed intracellular compartments. Many form long tubular, filamentous structures called hyphae. Fungi can tolerate lower moisture and require lower nitrogen levels than bacteria.

In the early stage of composting, mesophilic organisms actively breakdown organic material and their number can proliferate to 10^6 and 10^8 colony forming units per gram (cfu/g) of wet substrate for bacteria and fungi, respectively. This is followed by an increase in thermophilic microflora up to about 10^9 cfu/g-wet. Temperature rises to 70^0C and then temperature sensitive organisms start to be destroyed. At this stage, chemical oxidation is at its peak. The reduction of nutrients and bacteria death from these high temperatures slows down the chemical oxidation and eventually reduces the temperature. It causes the re-proliferation of mesophilic organisms that compete for the remaining organic material and utilise cellulose and lignin in the waste (Agamuthu, 2001).

Temperature dictates the number and type of organisms that grow in the composting process as shown in Table 1.1. Many studies have been conducted to explore and understand this relationship. Lyon *et al.* (2000) described the temperature interval as a function of bacteria growth during composting;

- 70^0C to 78^0C for Thermus strain, (Beffa *et al.* 1996);
- 62^0C to 69^0C for thermophilic bacillus strains and highly thermophilic actinomycetes, (Beffa *et al,* 1996);

- 53^0C to 61^0C for less thermophilic actinomycetes and fungi; and
- below 53^0C for moderate thermophilic, thermotolerant and mesophilic microorganisms.

Beffa *et al.* (1996) identified the numbers of spore-forming and nonspore-forming thermophilic bacteria at the beginning and cooling phases of the open-air windrow composting system. The oval spore-forming bacteria, or bacilli, are enriched in the temperature range between 50 to 65 ^{0}C, while non spore-forming bacteria are dominant at temperatures above 70 ^{0}C. The study illustrated that a different temperature will stimulate a different microorganism community.

1.3.3 Destruction of pathogenic bacteria

High temperatures and enough heat for certain duration are crucial for the human pathogenic bacteria destruction (Elorrieta *et al.* 2003). This process is called auto-sterilization. Elorrieta *et al.* (2003) reported that phytopathogenic bacteria are destroyed when the temperature is >50^0C for a period >15 hours. This finding is in line with research conducted by Koivula *et al.* (2000) on separated kitchen waste in Finland where windrow temperatures reached 85°C and the compost produced is hygienic. The concentration of pathogenic microbes detected in this study was <100 cfu/g, far less than the 5000 cfu/g, level set by the Ministry of Environment in Finland (Koivula *et al.*, 2000).

Hassen *et al.* (2001) conducted research to quantify the amount of pathogenic bacteria destroyed during the composting of municipal solid waste (MSW) and reported a reduction of *Escherichia coli* and faecal *Streptococci* from $2x10^7$ to $3x10^3$ cell/g and $2x10^3$ to $1x10^7$ cell/g waste dry weights, respectively. Yeast and filamentous fungi decreased from 4.5×10^6 to 2.6×10^3 cell/g waste dry weight and mesophilic bacteria reduced from 5.8×10^9 to 1.8×10^3cell/g waste dry weights. The heat generated from the composting process was shown able to inactivate faecal pathogens by a safety margin of 37 to 700 000 x, as long as sufficient insulation was provided and high temperature consistent throughout the organic matter (Vinneras *et al.*, 2003).

In brief, temperatures between 50^0C-65^0C are recommended to destroy pathogenic bacteria, while allowing useful microorganism growth (Beffa *et al.*, 1996; Elorrieta *et al.*, 2003).

1.4 Composting facilities

A composting facility provides a favourable environment for the composting process to take place. It has technology to handle compost materials and manage their physical characteristics (Zach *et al.*, 2000; Richard, 2000). The processes and equipment present at composting facilities are dependent upon the type of material to be composted. Solid wastes consist of a vast variety of substances possessing a range of physical, chemical and biological properties. Some of the properties need specific handling and treatment. Ideally, consistent and non-contaminated wastes are sent to be treated in a composting

facility. In most composting facilities, the separation and identification of waste is conducted at a reception facility before being placed into the system. Pre-screening is sometimes conducted to remove contaminants.

The main composting technologies (Haug, 1980) are:

- the aerated static pile or bed: once constructed, the piles remain in place until the decomposition is completed and the process control is by blowing air through pipes located at the bottom of compost. Piles are typically covered with a layer of wood chips or mature compost.

- the agitated windrow: the compost is periodically turned by a mechanical turner or front loader which serves several functions: increasing the porosity of the pile, redistributing material and breaking-up the clumps to improve product consistency.

-In-vessel types: these are typically vertical composting reactors or horizontal bed reactors (McLanaghan, 2002). In-vessel treatment is good for temperature control and is therefore often used for animal-by-products to ensure pathogen kill throughout.

1.5 Windrow composting

This thesis focuses on issues related to windrow composting. Mixed wastes or substrates are placed in rows. Height, width and shape of the windrows will vary depending on the nature of the feed material and the type of equipment used for turning. However for stability, most windrows are trapezoidal in shape with a flat top. This practice has been

used for many years. Due to technology and knowledge advancement, many features and mechanised equipment are deployed to increase process efficiency and compost quality. Nowadays, most composting facilities are provided with a waste separation facility to ensure compost quality and to extract recyclable material. In some facilities, the composting material is added with other material to improve the structure and ventilation of the windrow (Haug *et al.*, 1980). The United Kingdom Composting Association has introduced a manual for the operation of large-scale composting facilities and the communication of information to composting operators (Gilbert *et al.*, 2001)

In recent times, most windrow composting utilizes mechanical equipment to handle and manage the material. In practice, composting involves several activities from the receiving point to the end point at which the matured compost is stored, packed or transported to other places. The most common processes practiced in windrow composting are shredding, turning, screening, loading and unloading.

Windrow composting operational capacities vary from a few hundred tonnes per year (tpa) to a few thousands tpa. The equipment provided in the facility may also be different depending on the operation capacity. Some facilities hire the equipment they require, such as shredders, windrow turners, screens and front-end loaders.

a) **Shredding**

Particle size reduction is one of the first steps of the composting process in most of the facilities (Goldstein *et al.*, 2005). The material size is reduced to 25 mm-75 mm to increase the surface area of contact with micro-organisms and to obtain the average particle size of the end product. Chippers, grinders, and shredders are examples of equipment mostly used for this purpose. Chippers cut wood into pieces of various sizes using a set of knives mounted on a rotating disk or plate. A grinder repeatedly pounds the wood into smaller pieces through a combination of tensile, shear and compressive forces. Shredders tear particles apart by using compression forces. This machine uses rotating shafts, attached with a set of cutting disks or knives. Many shredders use a pair of counter-rotating shafts that draw the material down, forcing the pieces out between the two shafts.

b) Turning/aeration

Oxygen is needed for the aerobic decomposition of organic matter. Depletion of oxygen can be due to the high water content and lack of air spaces for ventilation. For windrow composting, turning during the compost cycle is crucial. It is performed by agitation of the pile to move the outer material into the centre part of the pile and to loosen the pile for better air exchange (Richards, 2000). The turning is widely performed by specialised equipment; turners, or front-loaders. Both type of equipment disturb and break the windrow pile in some manner during the compost cycle (Haug, 1980). Turners are

dedicated to this role and available at different turning capacities that range from 2 m x 1 m to 8 m x 3 m in wide by height (Rynk, 2003). A front-end loader is effectively used to move, agitate, and aerate the material, although it will take longer time than a turner. It comes in difference bucket sizes from 0.3 m^3 to 5 m^3 (Fabian, 1993)

c) Screening

Screening is usually conducted at the end of the composting process once the compost is already matured. Post-screening sizes the matured compost for market purposes. However, prescreening of newly arrived waste is also conducted to remove contaminants and undesirable substrate (admixture). There are two types of screens used in composting, trommel screens and vibratory deck screens. A trommel is commonly used for post-screening. The screen size is about 9 mm to 20 mm opening. The compost for screening should be friable, blendable, flowable and not wet with the preferable moisture is < 50% w/w. The throughput is about 25 to 45 m^3/h (Goldstein, 2005)

d) Loading, un-loading and vehicular activity within the facility

Loading and unloading of material are common in a windrow composting facility. They involve the scooping, shovelling and agitation of materials, and also movement of vehicles such as trucks, bulldozers and front-end loaders. The arriving green waste is unloaded at the receiving end and placed into a shredder or grinder by a loader.

e) Summary

The construction of composting facilities requires proper planning, a full understanding of the processes and characteristics of the waste received, and of the compost market. A composting facility, like other waste management facilities, is not always welcomed by neighbouring communities (Holden, 2001). Therefore special consideration and a complete study of environmental impacts are needed for location selection (Zurbrugg *et al.*, 2002; Abou *et al.* 2002). To ensure the facility is not a health threat, it has to be governed and regulated by policies, regulations and guidelines (Hogg *et al.*, 2002, Gillett *et al.*, 2000). Improper operation of a composting facility results in an odour problem (Fukumoto *et al.*, 2003), low quality compost, and raises various environmental issues. Under modern regulation regimes, risk assessment and management are used as proactive measures to address environmental issues associated with composting facilities and direct the responsible operation of facilities.

1.6 Hazards associated with composting facilities

Epstein (1996) presents a rudimentary analysis of possible hazards and risks associated with handling various types of feedstock for composting (Table 1.2). The analysis suggested that the processes involved such as agitation, screening and handling of waste could pose a hazard to the workers. Bioaerosol particles and pathogens are two of the most serious threats to the occupational health of workers and the public health of the nearby population. He suggested that high levels of pathogens in biosolids resulted from

Table 1.2 Rudimentary risk analysis (Epstein, 1996)

Feedstock	Hazard				
	Pathogens	**Bioaerosols**	**Toxic organics**	**Heavy metals**	**Dust**
Biosolids	High	High	Low	Very Low	Medium
Municipal solid waste	High	High	Low to Medium	Very Low	Medium to High
Yard trimmings	Medium	High	Low	Very low	Medium to high
Food waste	Low	High	Very low	Very low	Low to medium
Animal waste	Medium to High	High	Very Low	Very Low	Low to Medium
Predominant exposure routes	Oral	Respiratory	Dermal, respiratory	Oral	Respiratory

faecal matter in wastewater. Municipal solid wastes contain pathogens from faecal matter in discarded diapers and domestic animal faeces.

The sources of hazard from composting activities can transfer to the receptor through a variety of pathways. Epstein (1996) suggested that different hazards transferred to the receptor by different pathways: pathogens through the oral route, bioaerosols and dust through the respiratory route, toxic organics through dermal and respiratory routes and heavy metals through the oral route.

Deportase *et al.* (1995) illustrated how receptors can be exposed to the hazards as shown in Figure 1.2. They suggested that workers are the most vulnerable to the exposure of hazards posed.

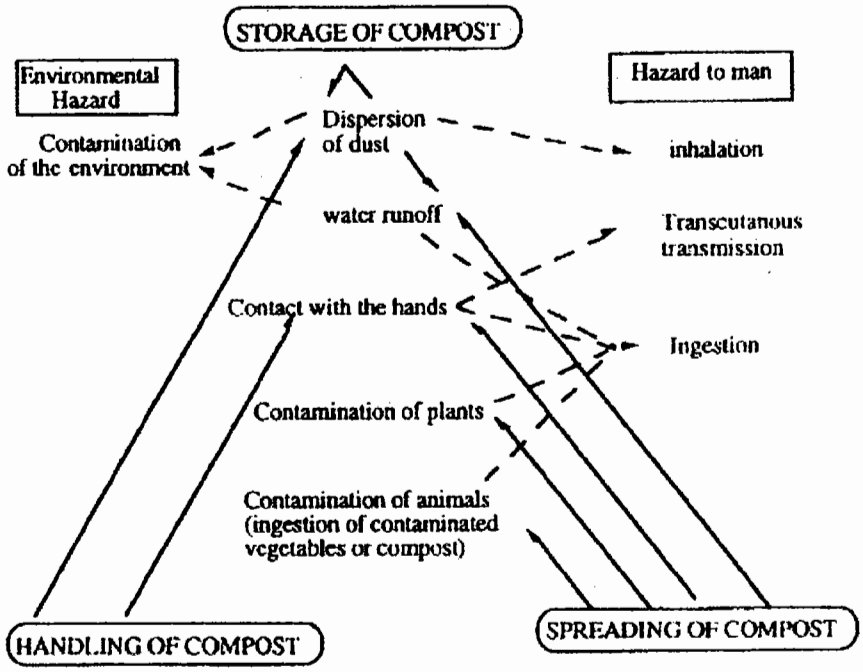


Figure 1.2: Route of Exposure (Deportase *et al.*, 1995)

The important sources of hazard identified from earlier research can be summarised as follows:

a) **Particulate matter**

One of the pertinent hazards highlighted from several studies is particulate matter, which constitutes microorganism and dust (Wheeler *et al.*, 2001; Deportase *et al.*, 1995). The concentration of bioaerosols and dust in air close to operational areas is usually higher than background air. Bioaerosol and dust generated during composting can be inhaled by workers and poses a health hazard. In addition, the pathogenic micro-organisms and toxic substances may penetrate through wounded skin which could impact on worker health.

Bad and inadequate protection of stored compost could pose a threat to the environment. Pollutants may leach, when there is rain, through run-off or percolation into the soil. Wind can carry and disperse the dust and bioaerosols.

b) Heavy metals and toxic organic substances

The characteristics of the receiving waste are important for operating the composting facility. It will determine the type of equipment and process required and subsequently the type and quality of end-product produced (Plahl *et al.*, 2002). Agricultural wastes are relatively easy to compost compared to co-mingled household waste. Hazardous chemicals contained in household waste such as dry cell and car batteries, paint, plastic, electrical components and glassware can contaminate compost. These chemicals may pose a threat to the environment and public health (Deportase *et al.*, 1995). Various studies have shown that some of the chemicals leach out of the compost applied to the soil and these could potentially pollute ground and surface waters (Arno *et al.*, 2002). Most of the persistent organic pollutants such as phthalic acid esters (plasticizer compounds in plastic product Bauer *et al.*, 1997) and polychlorinated biphenyls and inorganic metals such as cadmium and zinc cannot be degraded. Their concentration will increase due to a reduction of mass. Some of the chemicals may be assimilated by plants and enter into the food chains and subsequently be ingested by animals or humans.

Metals and inorganic substances that come together with wastes are non-biodegradable and their concentration will be increased due to reduction of weight and volume. Based

on studies by Deportase *et al.* (1995), Canet *et al.* (2000) and Wheeler *et al.* (2001) the levels of selective chemicals in compost is tabulated (Table 1.3). The table shows that major metal constituents of the compost are iron, magnesium, copper, manganese lead and zinc. Using the standard set by Spain and France (Brinton, 2001) for metal constituents in compost as the criteria (Table 1.3), most levels shown in the Table 1.4 are within the standard limit. The standards of metal constituent in compost for UK was recently promulgated (WRAP, 2005).

Clopyralid is one of the organic residues of herbicide reagents commonly found in compost (Bezdivic *et al.*, 2001). It is poisonous to certain types of plants such as potatoes and tomatoes. A study by Rynk (2002) on clopyralid in Oregon USA showed that 30% of samples taken from composting facilities in the month of June contained clopyralid at concentrations ranging from 7.6 to 38 μg/kg (pbb). For samples taken in the month of October, almost all were found to contain clopyralid and with concentrations in the range 6.3 to 94 ppb. The greater prevalence of clopyralid in October is due to the garden trimming season during the summer. The study also showed that the level detected can affect the growth of certain plants. It is important to monitor the quality of waste received for composting, and to ensure the clopyralid contaminated waste is separated from others.

Table 1.3: Selected heavy metal residue and chemical limits for France and Spain (Brinton, 2001)

Selected heavy metals residue	Heavy metals limits in compost (mg/kg dry weight) for selected European Countries		
	France	Spain	British (WRAP,2005)
Cadmium	3	8	1.5
Lead	150	800	200
Copper	150	--	200
Mercury	3	8	1.0
Zinc	500	--	400
Chromium	150	--	100

Table 1.4: Range of concentration of residue and chemical parameters in compost (mg/kg dry weight)

Parameter	Range of Concentration of Residue and Chemical Parameters in Compost (mg/kg dry weight)		
	Deportase. *et al.* (1995) (Review from other studies in France)	Wheeler *et al.* (2001) - Thorpe compost analysis (U.K)	Canet *et al.* (2002) (Spain)- selected parameters
Organic Matter			24.4 - 71
Total Nitrogen (%)			0.6 - 2.3
Organic N (%)			0.6 - 2.3
C/N ratio			9.0 - 36.5
Mg	1400 - 33700		0.5 - 3.1
Cadmium	0.3 - 11.8	0.8 - 2.0	0.4 - 6.2
Chromium	8.4 - 403	19.0 - 23.0	16.0 - 944
Cu	0.1 - 1143	52.0 - 69.0	100.0 - 1790
Mercury	0.9 - 23.3	< 2.0	< 0.2 - 14.7
Nickel	0.8 - 1220	0.0 - 20.0	10.0 - 415
Iron	2200 - 8000		5000 -25000
Mn	125 - 1206		85 - 743
Pb	10.6 - 1312	140.0 - 190.0	110 - 771
Zn	75 - 2427	250.0 - 290.0	340 - 2100
Mo	0.1 - 7.8		
Na	1200 - 10000		
Se	0.1 - 8.8	< 10.0	
Ti	900		
V	0.4 - 37.4		
As	7.0 - 9.0	3.0 - 7.0	
B	27.0 - 81.0	24.0 - 28.0	

c) Pathogenic bacteria

Pathogenic organisms such as the exotic pig virus, *E. coli* 0157, campylobacter, salmonellas, Newcastle disease and parasites may exist in organic waste, and be transferred to breeder animals if the composting process is not appropriately operated, and inferior quality compost produced (Gale, 2002). Exposure to an elevated temperature for a sufficient period of time is required to ensure the pathogenic micro organisms are killed during the composting process. Temperature control is crucial in composting to kill pathogenic bacteria and is needed for catalysing the good bacteria to grow.

1.7 Composting qualitative risk assessment

Environmental risk assessment is a way to demonstrate and inform on public health and environmental protection of new composting facility developments to the public. It is to ensure the proposed composting facilities are safe to the population and environment. As a result of public health concerns and the need for operators to demonstrate the safe and responsible operation of their facilities, environmental regulators have been requesting regulatory risk assessments prior to licensing composting plants (Pollard *et al.*, 2005; Wheeler *et al.*, 2001; Gillett, 2000).

Municipal waste consists of various types of waste materials. It can easily be contaminated with hazardous and toxic materials (Hartlieb *et al.*, 2003). Composting provides a soil conditioner or nutrient source and is used as a means of waste

management for large volumes of sludge and manure. Although the product is intended to be clean, odour-free and fit for garden amendment, the process may be messy, odorous and attract many complaints, even though people recognize it as a "green" alternative to landfills and incinerators (Gilbert, 2002).

An illustrative, generic risk assessment is provided in Table 1.5, based on the DEFRA guidelines for risk assessment (DEFRA, 2000b). A risk screening of generic windrow composting was conducted and the reports and findings of other work used as inputs in the analysis. The screening result is presented in Table 1.5. In brief, pathogenic bacteria and toxic chemicals possibly present in the waste materials pose a high risk to workers and population. Agitations, vehicular movements and improper waste separation are some of the process activities that could contribute to these risks.

1.8 Bioaerosols

Bioaerosols are defined as a collection of aerosolised biological particles (Pillai and Ricke, 2002; Hryhorczuk *et al.*, 2001; Cox and Wathes, 1995,). Although there is no evidence of association between exposure to composting bioaerosols and ill health effects, some constituents that form bioaerosols are known to have health effects on humans. The Health & Safety Executive have stated that there is a potential ill-health effect due to exposure to compost bioaerosols by workers and neighbouring residents (HSE, 2003). Currently precautionary measures are taken under which, where

Table 1.5 Environmental Risk Assessments of Source Pathway Receptor

Source	Secondary Source	Hazard	Pathway	Transport /Medium	Receptor	Probability of Exposure*	Severity **	Risk ***	References#
Recieving Waste/Materials Debris and waste from garden or nurseries which used herbicide that contain clopyralid or picloram as the ingredient and also manure from animals feed grass or straw treated with one of the chemical. Chemical hazardous material ; batteries, paint waste etc	Improper segregation of contaminated waste and pre- screening	Clopyralid and picloram: phytotoxicity and abnormal growth to plants VOC, PCB, Lead and Others Heavy Metal, Zn, Cd, As: Deterioration of surface water quality Health threat; above safe level intake.	Presence in compost (end product) due to the slow breaking down of both chemical. Presence in compost (end product), can not be degraded by bacteria and will increase in concentration resulted from volume reduction	Contaminated compost applied to the farm as soil conditioner or fertilizer Surface run off from farm Surface run-off from stock-pile Ingestion of soil/compost by children Inhale by Farmer, Facility Worker Entering into the food chain through assimilation by plants	Including legumes (peas, beams, lupine), tomatoes ect. No direct impact to human health Source of Drinking Water/ Human Human/Animals Human/Animal Human/Animal	H H L L M	mo mo mi mi mi	High High Low Low Low	Plahl *et al.* (2002 Rynk (2003) Krogmann *et al.* (2000) Carnet *et al.* (2002) Deportes *et al.* (1995) Carnet *et al.* (2000)
Receiving Waste/Material Contaminated with Pathogenic Bacteria;	Cross contamination and improper process control (mixed with newly incoming waste, short circuiting in the process) , re-growth of bacteria in compost	(BSE, FMD, Scrapie and E.Coli O157) Health threat, disease	Survive in compost that later is utilized for soil improvement in farm or garden.	Direct contact to animal and human from the contaminated grass of grazing farm and unwashed crops, respectively. Entering the food chain (New Castle Disease) Farmer and family, sheep, goats etc.	Human/Animal	M	s	High	Gale, 2002
Debagging and sorting the Waste, Screening and Sorting		Bioaerosol; Dust, Airborne Bacteria and Fungi, Viable Thermophilic Fungi, *Aspergillus Fumigates*, Respirable Gram Negative Bacteria, Endotoxcin	Become airborne during the process	Inhaled (direct)	Worker	H	mo	High	Werf *et al.* (1996)
				Blown by the wind; inhaled by human, precipitate on surface of materials that have a contact with human.	Human (Inhale) digest)	L	mo	Medium	

				Precipitate on surface of materials that have a contact with human.	Human, animal (digest, grazing)	L	mi	Low	
Turning, Pile up the waste	Agitation and movement of the waste material of composting subtract releasing and exposing gases and bioaerosol	VOC (Toxic gas)	Release to ambient	Inhale	Worker Resident	M L	n n	Low	Ayalon *et al.* (2000)
		Methane (Flammable)	Release to ambient	Ignition could cause fire with the present of chipping wood and lignin material	Property, Human	H	mo	Low	
		Gases; Odour, Nuisance	Release to ambient		Humans	H	n	Medium	Ayalon *et al.* (2000)
		Bioaerosol; Dust, Airborne Bacteria and Fungi, Viable Thermophilic Fungi, *Aspergillus Fumigatus*, Respirable Gram Negative Bacteria, Endotoxcin Dust, Fibres and particulates; acute effects,	Become airborne during the process	Inhaled (directly)	Worker, visitor	H	mo	High	Wheeler *et al.* (2001) Swan *et al.* (2003) Millner *et al.* (1980)
				Blown by the wind; inhaled by human, precipitate on surface of material that have a contact with human	Human (Inhale, ingestion); Human (skin contact); Properties (residential)	M L	mo mo	Medium Mediun	Millner *et al.* (1994)
		Blocking of Sunlight	Airborne	deposition on leaves and plants	Sensitive plant species	L	n	Low	
		Spread of Moulds and Fungi	Air borne	Deposition	Agricultural land	L	n	Low	
	Leachate flowing out from the heap and drainage	Contamination by Microorganism, Heavy metals	Leachate mixed with surface runoff	Mix with Surface run-off	Source of surface Drinking; Water/Eventually Human Deterioration of ground water, aquifer quality.	M L	mi	Low	Krogmann *et al.* (2000) Sobsey, 1978 Wheeler *et al.* (2001)

*** Qualitative Probability of Exposure**

Qualitative Value		Description
High	H	Direct exposure likely with no/few barriers between hazard source and receptor
Medium	M	Feasible exposure possible-barriers to exposure less controllable
Low	L	Several barriers exist between hazards source and receptors, to mitigate against exposure
Negligible	N	Effective, multiple barriers in place to mitigate against exposure

*****Risk**

	Increasing Acceptability	Consequences			
		Severe	Moderate	Mild	Negligible
Probability	High	High	High	Medium/low	Near Zero
	Medium	High	Medium	Low	Near Zero
	Low	High/Medium	Medium/low	Low	Near Zero
	Negligible	High/Medium/Low	Medium/Low	Low	Near Zero

**** Qualitative Magnitude of Consequences**

Qualitative Value		Description
Negligible	n	No evidence of adverse health effects and or physiological and pathological effects following exposure to chemical. Sub-lethal effects in individuals that do not cause a change in population structure or size
Mild	mi	Health effect not apparent though chemical experts reversible physiological and/or pathological changes (e.g. biochemical, haematological changes or enzyme induction but no other apparent effect) occurring at the population level. Effect on ecosystems that are not regarded as being of high value for what so ever reason
Moderate	mo	There is sufficient evidence that exposure to chemical may result in health effects that are not severe in nature and are reversible one exposure ceases (e.g. irritant)
Severe	s	Sufficient evidence that short and long term exposure may result in serious damage to health; death, clear functional disturbance or morphological changes, which are toxicological significant, latency of effect and reversibility during and following exposure should be considered, global extinction (depending on species) and widespread effects on the functioning of communities and ecosystems impact on functioning of global system

These works are relevance to the parameters mentioned.

communities are < 250 m from composting facility quantitative risk assessments are required.

A recent study on somatic systems in the vicinity of composting plants by Herr *et al.* (2002) showed that higher rates of complaints were received from people living nearer to the facility and these rates were higher than the national average. The bioaerosols emitted from composting facilities are mainly fugitive releases that disperse when agitated or blown by the wind. The source term contains several types of thermophilic actinomycetes, fungi and organic dust. *Aspergillus fumigatus (A. fumigatus)* is a ubiquitous fungus associated with decaying matter. It is very small and can be inhaled and poses a threat to human health (Kramer *et al.*, 1989).

Bacterial endotoxin originates from the cell wall of gram-negative bacteria. Since bacteria are usually attached to organic dusts, the presence of organic dust could indirectly indicate the possibility of endotoxin present. Considerable research has shown that the level of bioaerosol in ambient air closer to the composting plant is higher than background levels. Recer *et al.* (2001) for example, reported that mean bioaerosol levels at the composting facility could exceed the background means by 20-fold and that downwind locations received higher amounts of bioaerosol compared with other areas. Their research also suggested that the bioaerosol level varies depending on season, with a low result recorded during winter. However, this study did not relate their sampling to the type of composted materials and activities carried out. Also not considered was the composting method and topographic features. A study by Wheeler *et al.*, (2001) showed

that green waste composting facilities could generate airborne bacteria exceeding 10^6cfu/m^3. The emission of bioaerosol particles and other particulate matter is mainly caused mainly by the agitation, turning, down and up loading of waste and compost.

1.8.1 Bioaerosol constituents

Bioaerosol particles are airborne organisms or biological agents that include bacteria, fungi, actinomycetes, arthopods, protozoa as well as microbial products such as endotoxins, microbial enzymes, β-1, 3-glucans and mycotoxins (Millner *et al.*, 1994). A study by Werf *et al.* (1996) on the Sarnia Composting facility shows that significant concentrations of dust, airborne bacteria and fungi (total fungi), *A. fumigatus*, gram-negative bacteria and endotoxin can be detected. The most important bioaerosol constituent and their health significance are briefly discussed below.

a) *A. fumigatus*

A. fumigatus is a member of the genus *Aspergillus*. It belongs to the plant kingdom and is a heat tolerant microorganism which can survive at high temperatures. *A. fumigatus* is strongly associated with composting facilities (Millner *et al.*, 1994). Its optimal temperature growth is 37 ^{0}C (Swan *et al.*, 2003). *A. fumigatus* is a pathogenic fungus that, with prolonged exposure, causes aspergillosis, an acute and chronic inflammatory, granulamatous infection of the respiratory tract. Studies have shown that *A. fumigatus* grows on numerous materials such as wood, green leaves, grass, paper, fabric, leather,

rubber and plastics, aviation fuel and biosolids. Fungal spores vary in size, but most are in the range of 2-50 μm (Cox *et al.*, 1995). Wheeler *et al.* (2001) reported that *A. fumigatus* represents 60% of the total fungi detected in composting bioaerosols with a further 20% being *Penicillium*.

b) Endotoxin

Endotoxin is a micromolecule that forms an integral part of the cell wall of gram-negative bacteria. Endotoxins are released into the environment during cell growth and after the cell dies. It is toxic to humans and animals and always attached to organic dust. Inhaled endotoxin increases the activity of macrophages, which leads to a series of inflammatory conditions. It is found in the organic dust resulting from the processing of cotton, poultry facilities, MSW, biosolids, hemp, hay, grain, biosolids drying and other vegetable dusts. The permissible level of two agricultural industries is as follow (Epstein, 1997): cotton mills: 1.0-10 ng/m^3 and animal feed: 0.2-470 ng/m^3.

c) Bacteria

Bacteria can be divided into gram-negative bacteria and gram-positive bacteria. The gram-negative bacteria do not retain the crystal violet stain in the presence of alcohol or acetone. They include the important genera: *Acetobacter, Agrobacterium, Alcaligenes, Bordetella, Brucella, Campylobacter, Caulobacter, Enterobacter, Erwinia, Escherichia, Helicobacterium, Legionella, Nesseria, Nitrobact, Pasteurelia, Pseudomonas, Rhizobium,*

Rickettsia, Salmonella, Shigella, Thiobacilus, Veiellonealla, Vibrio, Xanthomonas and *Yersinia*. The gram-positive bacteria retain the crystal violet stain in the presence of alcohol or acetone. They include the important genera: *Actinomyces, Bacillus, Bifidobacterium, Cellulomonas, Clostridium, Corynebacteriumk, Micrococcus, Mycobacterium, Nocardia, Staphylococcus, Streptococcus* and *Streptomyces*. Some of the Gram-positive bacteria notably those of the genera *Corynebacterium, Mycobacterium* and *Nocardia* retain dyes even in the presence of acid. These are known as acid-fast bacteria. Gram-negative bacteria are important because of their ability to release endotoxin. Epstien (1997) suggests the permissible level of gram-negative bacteria is 1000 cfu/m^3.

c) Actinomycetes

Actinomycetes are a form of fungus-like, gram-positive bacteria. They form long, thread-like branched filaments that look like "grey spider webs" stretching through compost and give a soil smell. Actinomycetes are quantitatively and qualitatively important in the rhizosphere where they influence plant growth and protect plants roots against invasion of root pathogenic fungi (Crawford *et al.*, 1993). Composting is a principal source of actinomycetes (Lacey, 1997.). Therefore, isolation of actinomycetes for quantitative measurement is crucial in any bioaerosol study. Different species of actinomycetes predominate during each phase of the composting process (the mesophillic, thermophillic, and maturation phases) but are most easily seen during the early stages of the composting process, in the outer 10 to 15 centimetres of the pile. Actinomycetes spores are smaller than fungi and average about 1 μm in diameter (Madelin *et al.*, 1995).

Actinomycetes are the primary decomposers of plant materials like bark, newspaper and woody stems. They are especially effective at attacking tough, raw plant tissues (cellulose, chitin, and lignin) and grow on less nutrient media. Actinomycetes are known to cause "mushroom farmer's lung disease" (Flannigan *et al.*, 1991). An exposure to the sudden increase of actinomycetes level could cause sensitisation.

Like endotoxin, there are other aerosol agents that are released from parts of fungi and bacteria. Mycotoxin, one of them, produced by fungi, can be carcinogenic, neutrotoxic and teratogenic, and a common route of exposure is ingestion. The other important similar constituent is *β-(1→3)-glucans* (Douwes *et al.*, 2003) *etc.*

1.8.2 Bioaerosol properties

Cox (1995) describes bioaerosols as having similar physical properties to aerosol particulate particles, except they are different in term of biological action such as viability, infectivity, allergenicity, toxicity, pharmacological, or other biological properties. They have an aerodynamic diameter range from 0.5 μm to 100 μm (Dowd and Maier, 2000) and are subject to the same physical laws as aerosol particles. Bioaerosols composition, size and concentration vary with the source, dispersal mechanisms and environmental conditions prevailing at the particular site (Pillai, 2002). The properties reported by Cox (1995) are summarized as follow:

a) **Physical**

Brownian motion has a significantly effect on particles having a diameter less than 1μm. Brownian motion increases with temperature and decreases with particle diameter size. For particles that have a diameter more than 1 μm, gravitational settling is more significant. The gravitational settling is considered to have no effect at particle size less than 0.5μm. Most bioaerosol particles have a density in the range of 0.9 to 1.3 g/cm^3 with the average of 1.1 g/cm^3 used for computational purposes. Gravitational settlement causes the bioaerosol concentration to decrease with time and this loss is referred to as "physical losses" or "physical decay". There are many others factor that influence the "physical decay" such as temperature, shape of particles, humidity *etc* (Cox, 1995).

With sufficient wind velocity, bioaerosol could be airborne and transported. There are several factors that influence the resuspension such as bioaerosol shape and size, wind velocity, ambient concentration, the effect of mechanical disturbance including vehicular etc. Bioaerosols also tend to clump to each other (Wheeler *et al.*, 2001). This occurrence will increase its size and the settling rate. The understanding of bioaerosols physical decay is very limited and more studies are needed.

b) Biological

The ability of bioaerosols to cause disease depends on their viability, the extent of exposure and the susceptibility of the receptor host. For many microbes, the airborne

environment is unreceptive. This is due to desiccation, exposure to radiation, oxygen and pollutants (Cox, 1995). The desiccation depends on the relative humidity, most microbes will be dehydrated in low relative humidity conditions. Oxygen toxicity kills vegetative bacteria especially when the relative humidity is below 70%. Some pollutants, such as ozone, are toxic to microbes. Radiation also plays a role in deactivating bioaerosols and the effect is more significance at low humidity (Pillai and Ricke, 2002; Cox, 1995; Dowd and Maier, 2000).

1.8.3 Bioaerosols in composting

Dee *et al.*, (2001) reported that each gram of compost contains 10^9 cells of fungi and bacteria. The rate of bioaerosol emitted is different from one research study to another in terms of level (Swan *et al*, 2002). It is greatly dependent upon the scale and type of operation. However a few general observations can be suggested as follows:

a) the emission rate of bioaerosols is higher during receiving waste, shredding, screening, debagging and tipping;
b) the emission rate is higher when turning compost; and
c) the emission rate is higher when the compost is dry, friable and not frequently turned.

Werf (1996) suggested that of the huge amount of aerobic bacteria and fungi in the initial feedstock, thermophilic fungi is highest during the active composting phase; the gram-

negative bacteria are highest in incoming feedstock followed by when the windrow is active (active composting phase). His research shows that the highest endotoxins are found in bulk feedstock and active windrow samples and endotoxins decrease as the process progresses from de-bagging to production of finished product. Most of the study carried out is on viable microorganisms. This is due to the availability of sampling techniques. Non-viable organisms such as bacteria still pose a health threat to humans. Bacteria may die due to the high temperature of composting. Millner (1995) suggested that additional studies on other types of compost facilities are needed to determine the effectiveness of the following operational methods which should lead to reduced bioaerosol emissions:

1) use of added moisture in the composting materials and/or area water spraying to control all particulate emissions from the operation;

2) mechanical agitation (handling) of materials with a high potential for creating bioaerosols should be minimized consistent with the need to maintain other controls;

3) agitation of compost materials should be timed to coincide with the stage of the material when (i) the potential for release of bioaerosol is minimal; (ii) the potential for off-site dispersal is minimal; and/or (iii) the receptor populations are least; and

4) temperature and moisture conditions of bulking agents should be managed to minimize the formation of bioaerosols.

Not withstanding the prior art on the released bioaerosols, there is no research to date that estimates the emission rate of bioaerosol from composting activities. Most researchers

Table1.6: The concentration of bioaerosol agents; on site analysis

Research	Parameter	Concentration detected/ generated (cfu/m^3)	Location	Activity
Wheeler *et al* 2001	Airborne bacteria	10^6	Three composting sites in the UK	Handling green waste in open
	Gram-negative bacteria, fungi, actinomycetes (respectively)	10^5		
	Air borne bacteria	10^6		Mixed waste
	Gram-negative	9×10^3		
	Total fungal	$<9 \times 10^5$		
	Aspergillus	5×10^5		
	Penicillium	2×10^5		
Sanchez *et al.*, 2003	*Aspergillus*	10^5	Site I, UK	Biowaste, sewage sludge; static pile and forced aeration
	Mesophilic bacteria	10^5	Site III, UK	Biowaste, green waste, forced aeration

measure the concentrations of bioaerosols in the air at considerable distances downwind of the source as shown in Table 1.6.

1.8.5 Health effects

The first comprehensive literature study to discuss the issues of bioaerosols associated with the operation of biosolids or solid waste composting to the health and welfare of the general public was conducted in 1994 (Millner *et al.*, 1994). The study included a workshop attended by groups of engineers and scientists from the composting industry. The study first recognised that a potential hazard, bioaerosols, generated from a composting facility is a major concern in decision making for the planning and

installation of a new facility. Several conclusions were made. The general population is not at risk from the composting bioaerosols. The concern, however, is on immunocompromised individuals.

A study by Otto *et al.*, (1995) suggested that, on the basis of current availability of the data, exposure to fungi at several activities of the composting processes may range between 10^5-10^7 cfu/m^3 and for airborne gram-negative bacteria can >10^4 cfu/m^3. High exposures were suggested for thermophilic actinomycetes that can reach 10^8 cfu/m^3. The study highlighted the fact that the levels measured for all three indicators were high enough to pose a health threat, under prolonged exposure conditions, to the workers from various respiratory diseases such as pulmonary problems, ODTS (organic dust toxic syndrome)-like symptom and allergies (Heldal *et al.*,2004, Dutkiewicz J, 1997)

Bioaerosols are generally less than 10 μm in size and are not filtered out by the hairs and specialised cells that line the nose. They can penetrate deep into the lungs, causing both respiratory and gastro-intestinal symptoms (Sigsgaard *et al.*, 1994; Thorn *et al.*, 1998; Ivens *et al.*, 1999; Douwes *et al.*, 2003) and, where prolonged exposure occurs, can result in possible allergic lung diseases such as Farmers Lung Disease and Mushroom Workers Lung Disease (Flannigan *et al.*, 1991; Qian *et al.*, 1995; Davies, 1968). Although the link between bioaerosols and these symptoms and diseases has been shown, clear dose-response relationships have yet to be defined (Douwes *et al.*, 2003). Kramer *et al.*, (1989) suggested that *A. fumigatus* spores release from a green waste composting site led to the development of allergic bronchiopulmonary aspergillosis (ABPA) in a patient living less

than 250 feet from the facility. In addition, a study by Vogeser *et al.* (1997) has reported that, there is an association between *A. fumigatus* and invasive aspergillosis cases.

1.8.6 Dispersal of bioaerosols

The concentration of bioaerosols encountered by exposed individuals reduced at distance from the composting facility (Sanchez-Mondero *et al.*, 2003). Most studies suggest that the level will reduce to background level when the distance reaches 100-500 m. Bioaerosol particles are typically small, between 0.5 and 100 μm in aerodynamic diameter. They can be carried away by winds and have a small settling velocity. The dispersal of bioaerosol to the surrounding areas is dependent upon various factors such as emission rate, prevailing atmospheric conditions (wind speed and direction, solar incidence, temperature gradients and relative humidity) and local topography. The modelling of bioaerosols was carried out by Wheeler *et al.* (2001), using United States Environment Protection Agency air dispersion model "SCREEN3". The bioaerosol particles tended to aggregate with each other resulting in too large a particle to behave like a gas. It is suggested that the concentration declines with distance at a greater rate than a Gaussian dispersal model would normally predict (Wheeler *et al.* 2001).

Borodulin *et al.*, (2005) simplified the bioaerosols dispersal behaviour into two type of characteristic: total protein that is known to be following the laws of continual statistics, and culturable microorganisms which obeys the laws of discrete statistics. The dispersal of bioaerosol is subject to physical and meteorological characteristics and operational

characteristics (Millner, 1995). Meteorological characteristics at a site, in conjunction with topography, may affect the exposure of workers and nearby public to bioaerosol emissions from compost facilities. Wind conditions and the height of the location or point of release of the facility can be used to maximize diffusion and distribute the aerosols over a large area. If the design goal is to keep the mass of airborne material close to the facility, then composting operations should be shielded from winds and preferably emit aerosols only at low heights. Diffusion models may be used to estimate the impact of facility emissions on sensitive receptors. Limited data are available to quantitatively evaluate the effectiveness of various operational characteristics on bioaerosol emissions.

1.9 Air dispersion models

Various models have been developed to describe dispersion of atmospheric particles from sources which could be used for bioaerosols. Gaussian plume models predict concentrations of particles in a downwind plume and are probably the most commonly used dispersion models. The SCREEN3 model (USEPA, 1995a) developed by United States Environmental Protection Agency was used by Wheeler *et al.*, (2001) in their study. Dannerberg *et al.* (1997) used the German TA Luft model to predict bioaerosols dispersal from a biofilter and trommel screen. They assume that turbulence causes airborne particles to randomly disperse, so that an aerosol plume shows increasing scatter around its origin with increasing distance from the source, characterized by a Gaussian distribution.

Variations of these models specify dispersion parameters as functions of downwind distance and atmospheric stability. Such models are relatively easy to manipulate mathematically, but one disadvantage lies in the assumption of a continuous source and uniform wind speed. During experimental releases of recombinant bioaerosol, the time span of interest may be very short (*e.g.*, minutes), and a high level of precision in estimating movement of airborne particles is required. Since, the particle source is small and discontinuous in time, minor variations in wind speed and direction over short time periods can significantly affect predicted dispersal patterns. The CALPUFF (USEPA, 1995b) diffusion model calculates the position of a particle cloud at successive time steps and offers an improvement over simple Gaussian plume models, but its main disadvantage lies in the increasing computational difficulty as the time step length is decreased or wind vectors change. Also, it is not flexible enough to easily adapt to different plot sizes, particle size distributions, evaporation (which effectively alters aerosol droplet size), and deposition of aerosol particles. Thus, the above models are not suitable for small-scale field releases of microbes. Random walk models are more suitable: they follow a discrete number of particles released from a source, producing a representative picture of the entire plume in space and time. Time is treated as a discrete variable. In pollen study, the Lagrange approach was used to develop the pollen dispersal model (Richter *et al.*, 2002) and also used by Searcy *et al.* (1998) for modelling of volcanic ashes. Oetti *et al.* (2003) has used Markov Chain Monte Carlo modelling for the dispersion modelling of air pollution caused by road traffic.

As discussed above, there are several air dispersal modelling methods available that could be considered to estimate bioaerosol dispersal. Currently absent is a method to gather the required information to be used as input for the simulation. For example, a surface flux emission rate (cfu/m^2/s) for area mode source emission and flow rate (cfu/s) for volume and point mode source.

1.10 Summary

Composting use is expected to increase. To ensure the facility does not pose an environmental and health threat, a risk assessment approach is needed. Bioaerosols are one of the highest risks and of public concern. They can be emitted and travel considerable distances. Their dispersal is not fully understood. To date, no study has been conducted on bioaerosols source term releases which could be used in air dispersal modelling. With this data, the quantitative analysis of risk assessment could be dramatically improved. This thesis sets out to understand and characterise the bioaerosols source term released from composting facilities to facilitate the analysis of regulatory risk.

CHAPTER 2 STUDY RATIONALE AND OBJECTIVE

2.1 Statement of problem

The use of composting for the treatment of biodegradable waste is expected to increase as a result of the economic and environmental benefits of compost, coupled with recent legislative demands and regulatory requirements. To ensure the protection of public health, regulators and licensing authorities are requesting risk assessments to be conducted prior to development and operation of composting facilities. Microorganisms proliferate in enormous amounts during composting and significant amounts can be aerosolised and transported by wind to points of public exposure. Bioaerosols are known to have a variety of effects on human health. Numerous studies have shown that significant amounts of *A. fumigatus*, actinomycetes, and other allergy-related fungi are isolated from the ambient air of composting sites and their vicinity. However, the source term factors that influence their release dispersal and transportation are not fully understood. The understanding of these source term factors is important for estimating bioaerosol dispersal with confidence and for the improvement of composting bioaerosol risk assessments. Smoother regulatory approvals will help the compost sector expand.

2.2 Statement of hypothesis and research objectives

It is hypothesised that improved understanding of the bioaerosol source term at compost facilities will result in improved bioaerosol estimates of exposure point concentration. To test this, the following research objectives were established:

1. To develop a method to measure the viable bioaerosol emission rates from static surfaces and during agitation.

2. To determine the factors which influence the emission of bioaerosol from compost piles of different ages and different agitation activities.

3. To perform dispersion modelling using newly estimated emission rates from various source terms, and compare the estimated results with data from the published literature with particular with reference to source depletion with distance.

2.3 Experimental approach

Two types of bioaerosols were studied, to represent each fungi and bacteria. Both species are commonly associated with composting and have health significance. Only viable bioaerosols were analysed. The sampling method had to be one that could be used in a high bioaerosols concentration environment and easily repeated. Both bioaerosol species had to be isolated from the same sample and the appropriate dilution performed if required.

Three sampling exercises were completed. The first, for a pilot analysis to become familiar with the required sampling technique and to set the sampling criteria such as sampling flow rate, sampling period, sampling location, bioaerosol isolation and enumeration. The second, for the development of a method to study source term bioaerosol release. Two release terms were studied: the surface emission flux from a static pile and the dynamic release during agitation. The third, for measurement of source term emission rates under various process conditions to include type of activity,

the age of compost and equipment used. For each exercise, the sampling of ambient air was taken upwind, inside the facility and downwind. The surface emission flux was measured using a portable wind tunnel and the emission rate during agitation was estimated by extrapolation of SCREEN3 air quality impact modelling. The concentration of *A. fumigatus* and actinomycetes in compost was also analysed.

2.4 Structure of thesis

For ease, this thesis is presented in chronological order. Chapter 1 provides an introduction to the composting process. Chapter 2 sets out the hypothesis and research objectives. Chapter 3 describes the materials and methods adopted for the three sampling exercises. The results are reported in Chapter 4. Chapter 5 discusses the result by reference to other studies. Chapter 6 presents the overall contribution, summary findings, and proposed future work.

CHAPTER 3 MATERIALS AND METHODS

To achieve the objectives set in Chapter 2, an appropriate sampling regime had to be planned and implemented. To the author's knowledge, this is the first bioaerosol source term evaluation to be conducted at the authentic point of release. Several new approaches and modifications of others' work were required. The sampling and experimental regime is discussed in several sections; sampling site, sampling methodology, isolation and enumeration of bioaerosols, flux emission of static compost piles, measuring emission rates during agitation activities, analytical quality control, statistical analysis, bioaerosols dispersal and source depletion.

3.1 Sampling site

Three sampling exercises were conducted at 3 green waste composting facilities which adopted windrow composting as their operational approach. The first site was at Marsh Farm Pitsea, where pilot sampling was conducted to familiarise the author with the sampling requirements and determine basic criteria for sampling, sample handling and bioaerosol analysis. The second site was at Shanks Calvert Composting in which the bioaerosols source term methodology was developed. It was then followed by the third site, Carmarthen Composting, where the source term emission rate under the range of condition and activities was measured. Covered composting area and the stopping of Calvert's composting operation were the reasons for the changing of site to Carmarthen. Samplings can be conducted without interruption from the weather.

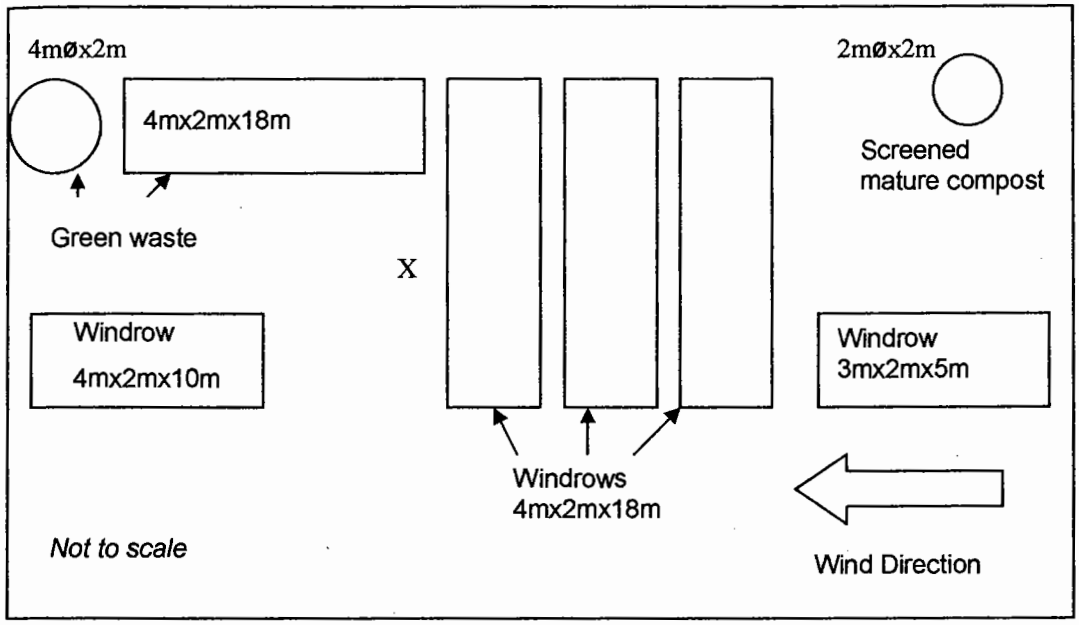
a) Marsh Farm, Pitsea, Essex

Marsh farm is a family operated composting facility, handling about 800 m^3 wastes per annum. The screening and shredding of green waste is conducted by a contractor 3-5 times a year. The purpose of the sampling at this site was to help develop and refine an analytical method for sampling and enumerating bioaerosols at high concentrations. A schematic diagram of the site is shown in Figure 3.1 and sampling was conducted on 14 Oct 2003. Two specific objectives were set for the study:

i) to determine the range of bioaerosol concentrations at a composting facility and set criteria for sampling; and

ii) to select the appropriate media and incubation temperatures for the isolation of bioaerosols.

The pilot analysis was conducted to improve the bioaerosols sampling technique and to determine the appropriate sampling location, sampling period and to select a suitable type of filter and culture media. Two types of filters were used in this sampling; 1 μm (pore size) fibreglass (SKC) and 0.8 μm MCE (mixed cellulous ester). At the same time, the effect of autoclave on sampling apparatus; pumping tube, sampler head, filter holder and cartridge was studied. The pump was set to run at 2 l/min and 2.2 l/min as suggested by the sampler supplier and the pumping period was ca.30 minutes. Sampling was conducted upwind, on-site and downwind included during short turning by a tractor (1m^3 bucket).



X; *sampling point*

Figure 3.1: Layout of Pitsea Marsh Farm Composting.

b) Shanks Calvert Composting, Buckingham

Shanks Calvert Composting, Buckingham is located about 30 km from Cranfield University and close to Calvert Landfill site. Sampling was conducted from 26 October 2003 to 25 May 2004. The facility handles green waste at ca. 2000 m^3 per annum. Most of the compost was used to cover the landfill. The windrows are properly laid in a trapezoidal shape with the dimensions of 3 m x 2 m x 20 m width, height and length respectively. The facility is equipped with a shredder capable of processing about 200 m^3/h green waste and a screen process composts at 50 m^3/h. The schematic diagram of the site is shown in Figure 3.2.

The method development for the sampling of bioaerosols source term emission was

performed at this site. Therefore specific objectives were set;

a) to develop a method to estimate the emission rate during surface flux and dynamic release;

b) to estimate a static pile emission flux rate and bioaerosol active dispersal emission rate during agitation; and

c) to apply the measured data in order to construct a bioaerosol source depletion curve.

Several samples under different conditions were conducted including inside the facility, with and without activity turning, upwind, downwind, wind tunnel sampling and during shredding, turning and screening.

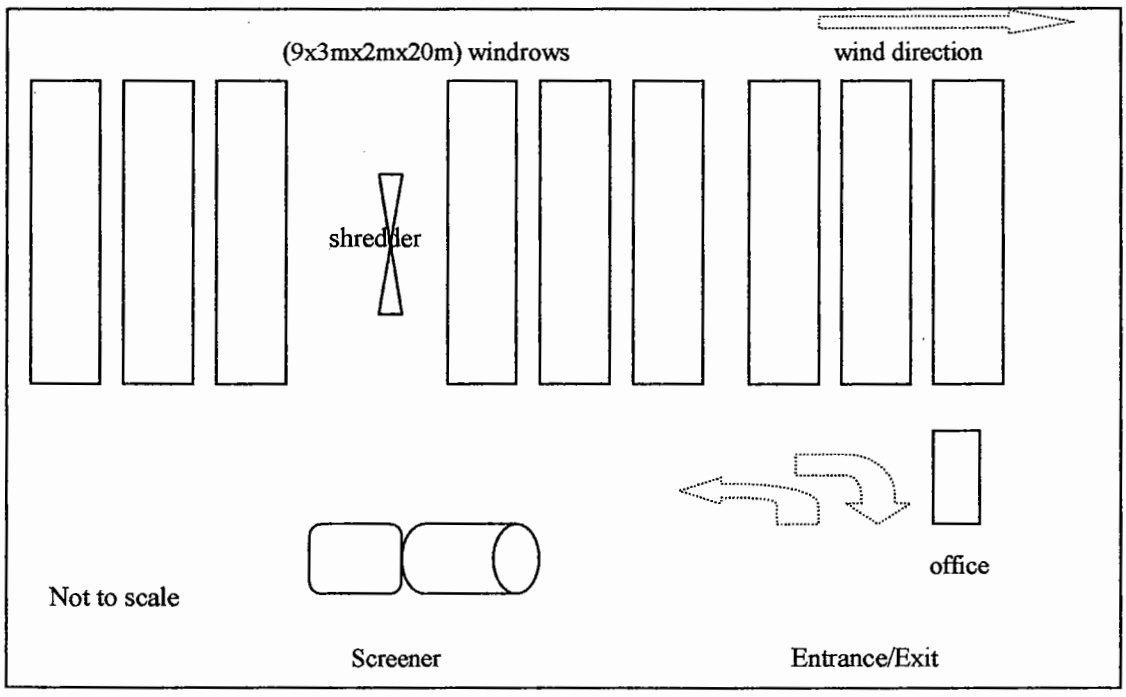


Figure 3.2 Layout of the Shanks Calvert Composting Facility

c) Carmarthen Composting, Wales

Carmarthen composting is a research composting facility managed by Cardiff University handling *ca.*1000 m^3 per annum of green waste. It has 1500 m^2 of covered building as a shelter for the shredded green waste which is piled in rows for composting. It is equipped with a shredder (*ca.* 200 m^3/h), windrow turner, screen and two tractors (1 m^3 bucket). Sampling was conducted from 13 January to 10 March 2005 with the following specific objectives:

a) to characterise the bioaerosol source term in consideration of compost pile age and dispersal during turning, screening and shredding;
b) to estimate the static pile emission flux and bioaerosol active dispersal emission rate during agitation.

The surface flux of bioaerosols from a static pile aged 1, 2, 4, 6, 8, 12 and 16 weeks and the emission rate of dynamic releases during turning, shredding and screening was measured. For turning, measurement was conducted at weeks 1, 4, 8 and 12 of composting. The composting lay-out is shown in Figure 3.3

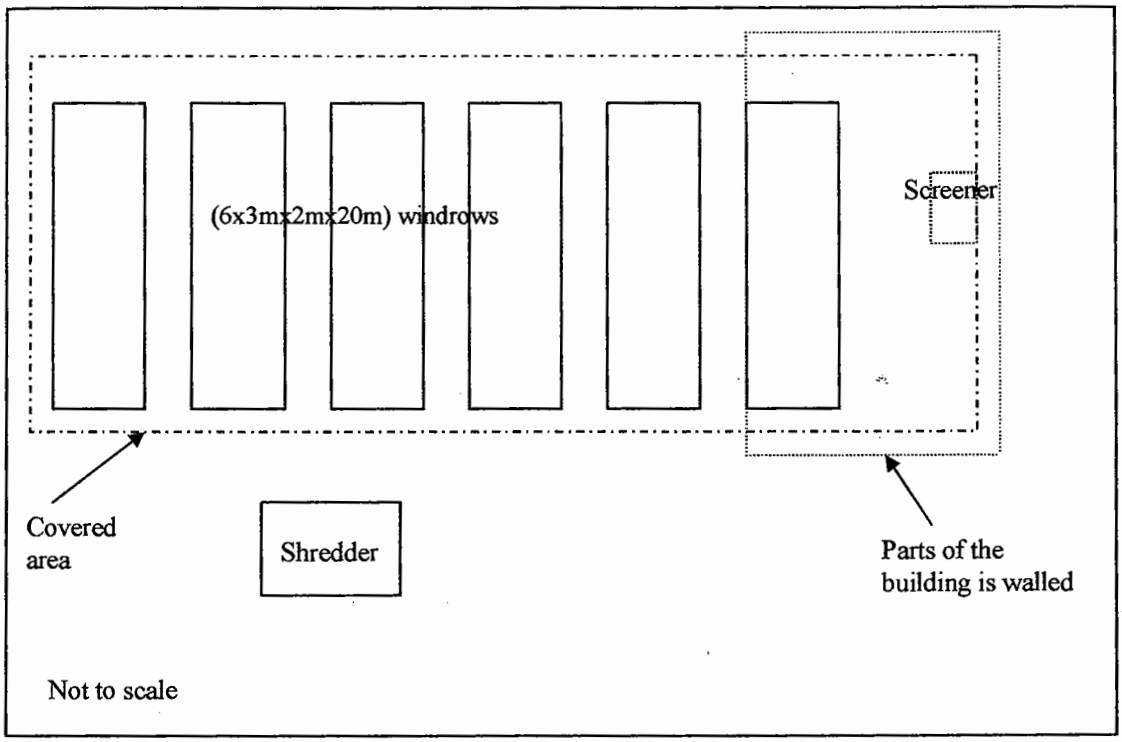


Figure 3.3: Layout of Carmarthen Composting

3.2 Sampling location

The background information on the facilities was gathered together with their schematic diagrams and the type of equipment used.

a) Upwind

The sampler was located at 1.8 m height above ground and at distance more than 15 m up wind of the composting facility boundary. The wind direction was found using a Kestrel 3000 anemometer (Meteorologica Ltd., Lancashire) or by visual inspection of air blowing dust.

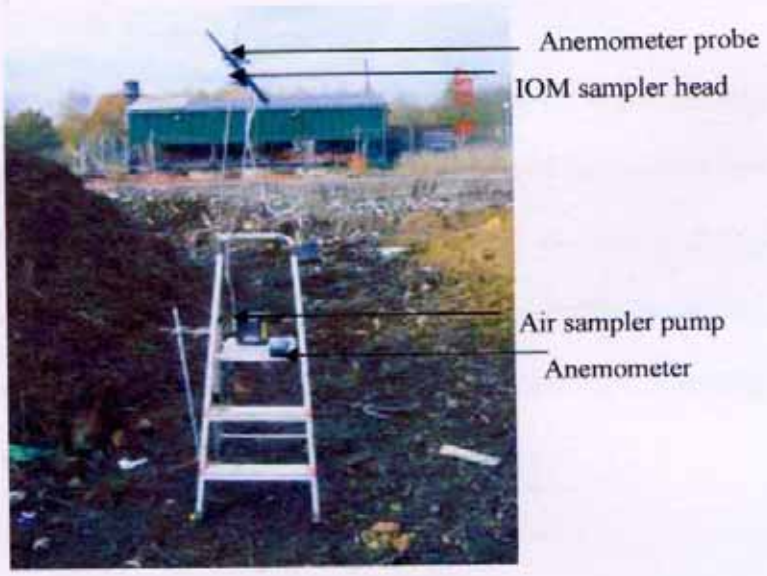


Figure 3.4: Ambient air sampling at Calvert Composting.

b) Downwind

The sampler was located more than 15 m from the composting facility in a downwind direction. Several samples were also taken at 100 or 200 m downwind.

c) Inside facility

Sampling was conducted to measure the concentration of bioaerosols inside the composting facility. The samples were taken at 1.8 m above ground inside the facility either during periods of activity or not.

d) Agitation emission rate sampling

The sampler was located at between 5 m -10 m, from where compost agitation was performed. The location has to be appropriate to avoid any disruption of the activity and the safety of the sampler. Agitation involves activities such as vehicle movement. Rapid operation of machinery can cause objects to become airborne such as wood chip during shredding, turning and material loading/unloading. The sample apparatus was located at 1.8 m above ground and downwind of the activity.

e) Wind tunnel analysis for surface flux emission

At each facility a portable wind tunnel was located on top of the selected compost pile. Since wind tunnel analysis requires an electrical power supply, only the point where the power supply cable could physically reach was selected. Compost piles at different stages of ageing were selected in order to study the effect of compost age on bioaerosol emission. This was undertaken only at the final site, Carmarthen Composting. The bioaerosol samples were located at the top and bottom of the wind tunnel's mixing chamber (explained further in section 3.10).

f) Air close to the compost pile

Sampling was also conducted at about 0.3 m above the compost pile surface to measure the concentration of bioaerosols in the air close to the compost pile. These were

conducted at the compost surface where emission flux analysis was conducted. This was conducted to compare the data with the concentration measured in the wind tunnel.

3.3 Local weather parameters

The wind velocity, relative humidity and temperature were measured inside and outside the composting facility, using the following equipment:

a) Wind velocity and temperature

The Testo 425 (Testo Ltd., Hemisphere UK) is a thermal anemometer that measures the wind velocity in a range from 0 m/s to 20 m/s (accuracy is ± 0.05 m/s or 5% of the reading) and the temperature range of 0 to 70°C (accuracy ± 0.5 ^{0}C). It uses a heated wire sensor to measure wind velocity and temperature. It has a telescopic probe that can be lengthened to a maximum length of 675 mm. The Testo 425 was used to measure the mean wind velocity and temperature during sampling.

The Kestrel 3000 (Meteorologica Ltd., Lancashire) is a pocket size anemometer with built in temperature and humidity sensor. It is of a rotating vane type which could be used to determine the wind direction. It measures a velocity range of 0.3 m/s to 40 m/s (accuracy of ± 0.1 m/s) and a temperature range of -29^{0}C to 70^{0}C (accuracy of ± 1^{0}C). Relative humidity is measured within the range of 5% to 95%. The Kestrel 3000 was used to measure the relative humidity and determine the wind direction.

b) Moisture content

Moisture content of the compost is one of the key parameters critical to good composting. Conventionally moisture content is rapidly estimated using the touch or "squeeze test" (Gilbert *et al.*, 2001). For more accurate and quantitative measurement, a gravimetric procedure was used. The compost was weighed to determine the initial weight of compost material and moisture, the wet weight. The compost was then dried in the oven at 103-105°C until a consistent dry weight was attained. The moisture content was calculated by dividing the amount of water by the wet weight of compost and it is also known as the wet basis moisture content.

c) Microorganism count in compost

The dry weight was used to calculate the *A. fumigatus* and actinomycetes count of a soil compost. About 50g of compost was taken from the surface of compost pile for moisture content analysis and microorganism count. From that one gram of compost was used for microorganism count analysis. The sample was placed into a 30 ml vial containing 10 ml of Tween-80 solution. The vial was shaken several times before the supernatant was inoculated on a Petri dish. The total count of bioaerosols was divided by the dry weight, calculated using the moisture content ratio.

3.4 Bioaerosols sampling

Sampling of bioaerosols is complex and requires a delicate approach. This is because bioaerosols constitute hundreds of species and biological agents with wide varieties of size and shape (Dowd *et al.*, 2000; Buttner *et al.*, 1993, Bradley, 1957). Therefore, each sampling technique could only serve for certain purposes and circumstances (Griffiths *et al.*, 1999). This fact hampers the comparison between studies.

There are two ways to quantify bioaerosol that is, culture-based methods and non-culture methods (Douwes *et al*, 2003, Eduard *et al.*, 1998, Lacey *et al.*, 1976). Sampling bioaerosols using culture-based methods involve impacting a high flow sample either directly onto the culture medium (Sanchez-Mondero *et al.*, 2003; Crook, 1995) into a liquid impinger (collected in liquid collection fluid) or filtering through a micro-pore filter with a slow/medium flow rate (Nielsen *et al.*, 1997). A non-culture analysis is obtained by a direct count of the microorganism cells under the microscope.

a) Culture

Bacteria and fungi colonies are grown on culture media at a defined temperature over a 3-7 day period. The growths are counted manually. The disadvantage of the culture-based method is that the dead micro-organisms, cell debris, and microbial components are not detected. This method is proven to be of limited use for quantitative exposure assessment. Direct impaction onto agar medium can result in reading that are "too numerous to count"

especially when sampling from a high bioaerosol concentration environment. In this thesis we refer to the following methods.

i) Fluid impinger, (AGI-30 or BioSampler)

AGI 30 and BioSampler are fluid impinger bioaerosol samplers. Air is transported with a flow rate of 12.5 l/min through a liquid, in which the micro-organisms are trapped and suspended. Sampling is typically conducted for 1 or 8 hours.

ii) Direct impactor to culture media (six-stage Andersen (AMS), Bio-stage)

This method has the advantage of collection directly onto culture media for incubation and analysis with no further dilution or plating (Composting Association, 1998). The sampling pump is run at *ca.* 28.3 l/min and the sampling period varies depending on bioaerosols concentration. This method is used mainly for viable bioaerosols. The major disadvantage is the rapid and frequently observed overloading of the plates that may occur in environments with high viable bioaerosol levels. The minimum and maximum concentration that can be measured are 18 cfu/m^3 and 10^4 cfu/m^3, respectively (Stetzenbach *et al.*, 2004). This limitation is due to the fact that agar will dry and harden if exposed too long to the flowing air (>5 minutes) resulting in particle bounce (Stewart *et. al.*, 1995). High concentrations however cause multiple cells to be inoculated at the same location on the agar surface.

iii) Collection by filter

This method involves the collection of airborne micro-organisms onto filter media using a medium flow pump followed by elution and plating (Herr *et al,* 2003; Wheeler *et al.,* 2001; Palmgren *et al.*, 1989). The flow rate is typically 2 l/min and filter media used are MCE, nuclepore or polycarbonate. Samples are diluted and cultured to measure the viable bioaerosols. The major disadvantages with the membrane filter method are the loss of viability and poor recovery of the organisms from the filters (Nielsen *et al.*, 1997). The loss of viability is due to the breaking of the cell wall caused by impaction onto a filter media with loss of moisture. Sampling at the site by this method is easier than a fluid all glass impinger method and more samples can be taken due to it simplicity.

b) Non-culture (direct count)

Non-culture analysis is based on air filtration and liquid impinge methods. Microorganisms are filtered onto a black filter medium and stained with a fluorochrome e.g. acridine orange, and counted with an epifluorescence microscope, electron microscopy or scanning electron microscope (Nielsen *et al.*, 1997). This method measures the non-viable micro-organisms. A personal air filter sampling can be used for this purpose.

3.5 Filter sampling

This thesis reports data conducted using a personal air filter sampler. This method was chosen due to its sampling simplicity at site, therefore repeat sampling can be performed. Dilution could be conducted for samples containing high amounts of bioaerosols. The trial analysis conducted at Pitsea Composting adopted two types of sampling filter, i.e. 1μm (pore size) glass fibre and 0.8 μm MCE (mixed cellulous ester, SKC) fitted into 25 mm SKC dust sampling IOM (Institute of Occupational Medicine) heads. Both filters did not show any damage caused by sterilization and the pump ran well. However, the glass fibre filter disintegrated during suspension of the bioaerosol captured. The fragments of the disintegrated filter blocked the titration tip during inoculation causing substantial methodological complication. Therefore the MCE filter was selected for future bioaerosols sampling. Filter cassettes, filters and IOM sampler heads were autoclaved before taking to site. The autoclaved apparatus was wrapped in aluminium foil to distinguish it from the un-sterilised and used one. The pump flow rate adopted during sampling was 2 ±0.2 l/min, as suggested by the equipment manual (SKC Ltd) and the sampling time 30 min, which can be reduced to 10 minutes if the bioaerosol concentration is high. The sampling time was changed depending on expected bioaerosol; a longer sampling period was needed when the expected bioaerosol concentration was low for example sampling of background air. The sampler head was located within 0.5 to 2 m of where the static compost and within 5 m to 10 m where the waste or compost was agitated or mechanically processed. This range was chosen to assure personal safety and

Personal air sampler pump

IOM sampling head

Figure 3.5: Personal air sampler pump and 25 mm IOM sampling head (SKC Ltd.)

to allow the activity to be conducted without interference. For this experiment a medium flow, personal aerosol filter sampler (SKC Universal dust and vapour sampling pump) was used (Figure 3.5). Three pumps were used in the sampling; one SKC Aircheck sampler (224-PCXR8) and two numbers of Air Sampling Deluxe (224-PCTX8).

The IOM sampler head was connected to the pump by a 10 mm internal diameter tygon tube. Two air samples were collected simultaneously using two samplers. One pump was used as a standby for a replacement if any of the pumps malfunctioned. All the pumps were calibrated before use. The calibration is explained in Section 3.12.

The filters used were 0.8 μm pore size mixed cellulose ester filters (MCE), 1 μm pore size fibres glass filter and 0.8 μm pore size polycarbonate filters. The change of filter types were needed because of some difficulty faced during sampling from certain type of filters. The sampling time was between 10 and 45 minutes depending on the sampling types.

3.6 Parameters

The common species or parameters measured in composting bioaerosols study are total mesophilic bacteria, total fungi, mesophilic and thermophilic actinomycetes and *A. fumigatus* in sampled air (Swan *et al.*, 2003; Sanchez-Mondero *et al.*, 2003; Swan *et al.*, 2002; Recer *et al.*, 2001; Nielsen *et al.*, 1997). These micro-organisms are known to pose significant health effect to humans with prolonged exposure and proliferate in very large amounts during composting.

However in this study, the viable actinomycetes and *A. fumigatus* were measured to represent the bioaerosols concentration in the studied air samples. Both species are widely used in composting studies therefore comparison with other research works can be made.

a) Actinomycetes

Actinomycetes are frequently evaluated in composting bioaerosol studies because they are abundant in the environment and produce spores that could be easily aerosolised. The actinomycetes population is dominated by Thermomonospora species, which has a white aerial mycelium and is a slow growing species. Actinomycetes spores, mostly white, are easily detached and may become airborne when disturbed (Cowan, 1974). Actinomycetes colonies can be recognized by a white powdery colour on a medium plate after 7 -10 days incubation. Generally the actinomycetes are divided into mesophilic and thermophilic which have temperature ranges of 20 – 50 ^{0}C and 45 – 75 ^{0}C, respectively. Actinomycetes prefer to grow in a low nutrient media. In this work, the type of media and the incubation temperature was determined after the pilot sampling. The mesophilic actinomycetes were used in the analysis with an incubation temperature of c.a. 44 ^{0}C, and were identified by the appearance of a white powdery colour on the culture media.

b) *A. fumigatus*

A. fumigatus is ubiquitous in the environment. It is known as a secondary pathogenic

fungus that, with prolonged exposure causes aspergillosis. It can survive high temperatures but prefers to grow at 37^0C as discussed in Chapter 1. *A. fumigatus* is identified by a dark greenish colour on the surface media plate and white at the bottom. It is distinct from *Penicillium* where the bottom is brownish. The incubation temperature and period are 37^0C and 3 days respectively.

3.7 Isolation

Micro-organisms were quantified using the CAMNEA-method (Collection of airborne micro-organisms on Nuclepore filters, Estimation and Analysis) (Palmgren *et al.*, 1986). Immediately after sampling, the sampled filters were placed inside a 30ml vial containing 10ml 0.05%v/v Tween-80 mixed with 0.1%w/w NaCl to prevent cell osmosis. The samples were placed in the cold box filled with ice packs at a temperature of $< 4^0$C. On return to the laboratory, bioaerosols were re-suspended by separating the filter from the IOM heads and manually shaking them together in the vial for about 1 minute. Based on a preliminary test a longer time of shaking did not give different result in the analysis. The solution was then diluted in a common logarithm order and inoculated within 48 hours on nutrient plates. All equipment was sterilised before use.

3.8 Enumeration

Bioaerosols enumeration involved three main activities, discussed as follow;

a) Media and incubation

Aspergillus fumigatus and actinomycetes were enumerated by visual inspection. Media preparation, inoculation, dilution and sterilisation were performed in accordance with BS 5763: Part 0. At the outset of work, several trials were conducted to determine appropriate media for actinomycetes. Two media were used and developed simultaneously:

(i) half strength nutrient agar (Oxoid); and

(ii) compost agar (a supernatant of 10%w/w of loam-based compost John Innes No. 1 compost in agar).

After preparation, both media were autoclaved (105°C, 15 minutes), left to cool to below 47°C and then treated with 1%v/v antifungal cycloheximide, dissolved in less than 2 ml of ethanol. The loam-based compost John Innes No.1 was used throughout the analysis to ensure consistency in nutrient content. The compost was mixed with deionised water at 10% w/w ratio. The solution was centrifuged at 5000 rpm for 5 minutes. The supernatant was then filtered.

For *A. fumigatus*, malt extract agar (Merck) was mixed with 0.01%w/w of antibacterial chloramphenicol (Sigma). Nutrient agar plates and soil compost agar plates were incubated at 44°C. Malt extract agar plates were incubated at 37°C.

successive dilutions, and where at least one contains a minimum of 15 colonies;

V is the volume of inoculums applied to each dish, in millilitres;

n_1 the number of dishes retained at the first dilution;

$n2$ is the number of dishes retained at the second dilution;

d is the dilution factor corresponding to the first dilution retained [$d = 1$ when the undiluted liquid product (test sample) is used].

If there were no plates that have the colonies more than 15, the estimated value of bioaerosols in solution *(N)* is calculated using the following equation;

$$N = \frac{\sum C}{V \times n \times d} \qquad \textit{Equation 3.2}$$

Where,

$\sum C$ is the sum of colonies counted on the two dishes

V is the volume of the inoculums applied to each dish, in millilitres;

n is the number of dishes retained (in this case, $n = 2$);

d is the dilution factor corresponding to the dilution retained.

The calculated concentration of the solution (10 ml liquid in 30 ml vial) was then used to determine the concentration of bioaerosols in sampled air in cfu/m^3 by the following equation;

$$B_{con} = \frac{N}{F_s \times t} \qquad \textit{Equation 3.3}$$

b) Plates preparation

Agar culture media were poured into petri dishes to 2 mm thickness. Typically, this required 12 ml for each 90mm diameter dish. The agar was allowed to cool and solidify by placing the petri dishes on a cool, horizontal surface. The agar plates can also be dried in a laminar-flow safety cabinet for 30 min with half-open lids or overnight with the lids in place.

c) Colony count

Colonies growing on both media were enumerated visually after 3 days for *A. fumigatus* and 7 days for actinomycetes. In the case of actinomycetes, if the growth was not fully detected at this stage (7^{th} day), the plate/s needed to be re-incubated and the enumeration completed on the following days until clear growth could be recognized.

The concentration of bioaerosols in the sampling solution (N) was calculated using the following equation (British Standards Institution, 1996) if any of the plate has colonies more than 15 and less than 300;

$$N = \frac{\sum C}{V \times [n_1 + (0.1 \times n_2)] \times d} \qquad \textit{Equation 3.1}$$

where

$\sum C$ is the sum of the colonies counted on all the dishes retained from two

Where

B_{con} is the sampled air bioaerosols concentration in cfu/m^3

N is total number of bioaerosols in solution

F_s is the air pumping or sampling flow rate

t is the sampling period.

All the results were rounded to two significance figures to avoid spurious precision.

3.9 Confidence limit interval

A confidence limit interval is used to estimate the validity of the results and to avoid too precise an interpretation of the analysis. It characterizes the statistical distribution of the microorganisms. The 95% confidence interval of micro-organisms dispersed in a solution was calculated using guidelines provided in the BS 5763 standard (British Standards Institution, 1996)

$$\delta = \left[\frac{\sum C}{B} + \frac{1.92}{B} \pm \frac{1.96\sqrt{\sum C}}{B} \right] \frac{1}{d} \qquad \textit{Equation 3.4}$$

when

$$B = (n_1 + 0.1 n_2) \qquad \textit{Equation 3.5}$$

and

δ = the confidence interval;

$\sum C$ = the sum of colonies counted on all the dishes retained;

n_1 = the number of dishes retained at the first dilution;

n_2 = the number of dishes retained at the second dilution;

d = the dilution factor corresponding to the first dilution retained

For estimated count, the concentration was estimated by *Equation 3.3,* the confidence interval limit was estimated using Table A1 and A2 of Annex A of BS 5763-0:1996 shown in Appendix 1

3.10 Emission flux from a compost pile

A number of studies have been conducted to measure the bioaerosols concentration both inside and outside composting facilities. However, to the author's knowledge, no study has been carried out to estimate the bioaerosol emission flux and to understand the factors that influence their dispersal at source. This research was targeted to determine the bioaerosol emission flux of static pile as one of the studied source terms and the research rationale are shown in Figure 3.6. A wind tunnel was erected for this purpose. The wind tunnel adopted the same principles and approaches used in measuring the emission flux of suspended particles and gases from an open area.

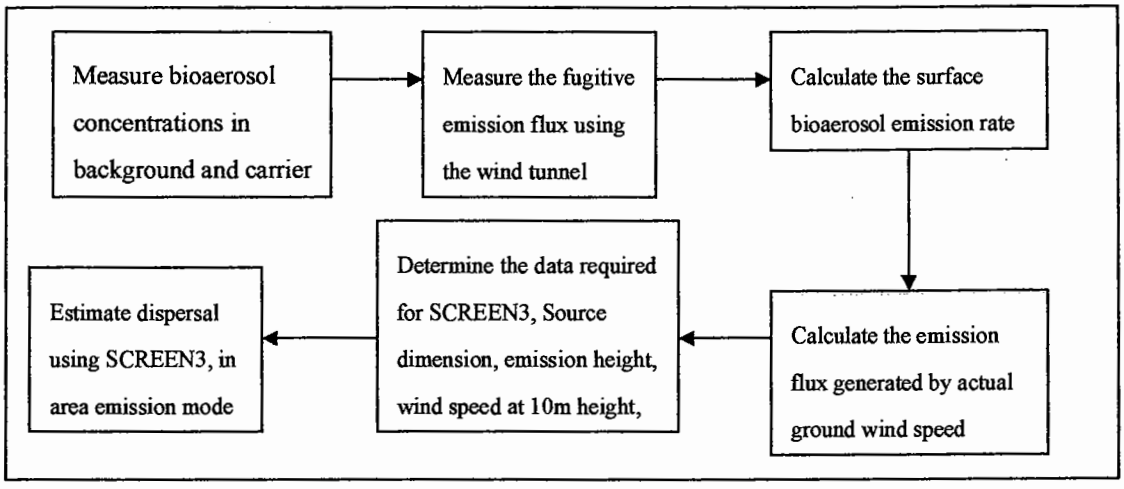


Figure 3.6: Rationale and steps in measuring the emission flux and dispersal of Bioaerosols.

The portable wind tunnel has been widely used in waste water treatments for measuring odour. It has been used since 1970s with improvements made to systems such as the aerodynamic performance and characterisation of the relationship between the evaporation rate and air velocity. It has the capability to collect repeatable and reproducible samples from surfaces. The gases and particulates emitted from the surface area are sampled into the horizontal air stream at a known velocity across the surface. The system comprises several parts: extension inlet duct, connection duct, expansion section, main section, contraction suction and mixing chamber.

Previously, the portable wind tunnel (Figure 3.7) had been used for research on the modelling of odours in sewage works (Gostelow, 2002). In this research, the portable wind tunnel was located on top of compost windrows to allow measurement of the bioaerosol emission flux under static conditions (Figure 3.8). The fugitive dust emitted from the surface area was sampled within the horizontal air stream of the wind tunnel.

The air was filtered by activated carbon before being blown into the inlet duct of a wind tunnel using a fan with the velocities range from 3 m/s to 8 m/s (Figure 3.9). The wind velocities were different from one sampling to another were because of the wind was supplied by a constant speed rotating fan, therefore the wind speeds in the supplying hose were varied depending on the sampling location such as the elevations and distances to the supplying fan. The air is controlled through flat vanes in the expansion section and enters the main section via a perforated baffle. The air entering the main section forms a consistent parallel flow over a solid surface under the wind tunnel. The particle matter and bioaerosols are aerosolized when the wind 'erodes' the compost surface. A convective mass transfer takes place above the emitting surface and bioaerosols are then mixed into the bulk of the carrier air and vented from the hood. Samples were taken from the outlet of mixing chamber and the air flow velocity was measured by Testo 425 anemometer.

The base of the wind tunnel was embedded *ca.* 25 mm inside the surface of the pile to ensure no loss of air volume around the sides. Samples were taken from the hood outlet and the airflow velocity measured using a hot wire anemometer (Kestrel 3000). Three compost pile locations were selected on the basis of access and suitability (the availability of power supply and of a flat surface). Ambient (*i.e.* on-site background) air bioaerosol concentrations were measured at 1.8m height close to the compost windrow, downwind of the pile.

The bioaerosols sampler heads were located at the top and bottom of the mixing chamber,

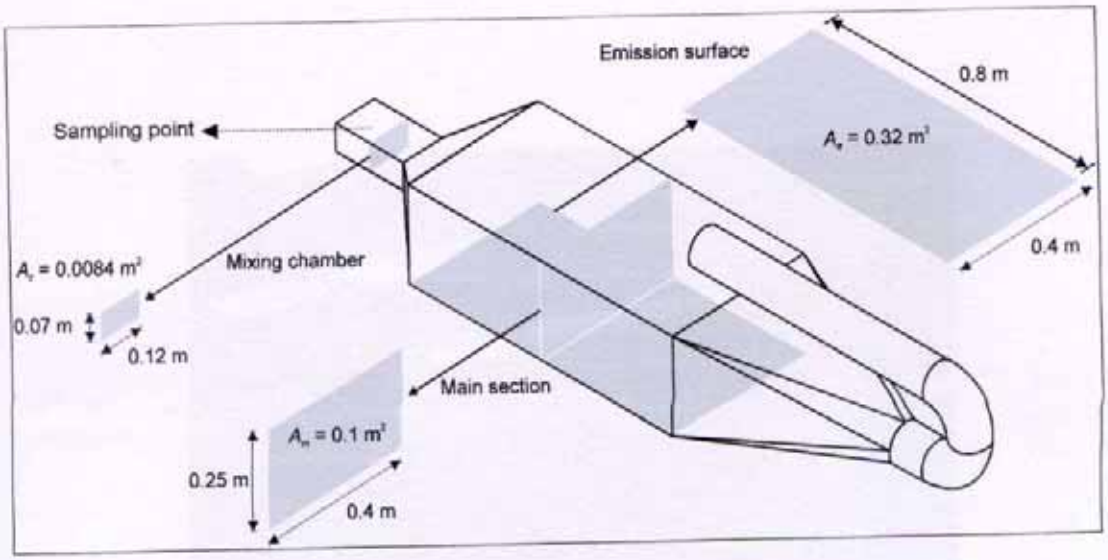


Figure 3.7: Schematic of wind tunnel and dimensions

which was located at the outlet end of the wind tunnel. The bioaerosols concentration of the incoming air, which was filtered by activated carbon, was measured before the start of the sampling.

The net bioaerosols concentration in the wind tunnel was estimated by subtracting the inlet bioaerosols concentration from the measured data at the outlet of wind tunnel. The air velocity inside the wind tunnel is calculated from:

$V_1 = V_2 x A_2 / A_1$ *Equation 3.6*

where:

V_1 and A_1 = air velocity (m/s) and area (m^2) of the main section of wind tunnel; and

V_2 and A_2 = air velocity (m/s) and area (m^2) of the mixing chamber, where sampling is carried out.

Figure 3.8: Portable wind tunnel located on top of compost pile at Carmarthen Composting.

Figure 3.9: Air fan and activated carbon filter.

The surface bioaerosols emission rate (SBER) is the quantity of bioaerosols emitted per unit time from a unit surface. The equation is adapted from the one that was used to determine the specific odour emission rate (Jiang *et al.* 2001) from surfaces and, for this initial assessment, an assumption was made that bioaerosols exhibit gaseous-like properties:

$$SBER = \frac{Q \times BC}{A} \qquad \textit{Equation 3.7}$$

where:

SBER= specific bioaerosol emission rate (cfu/m^2/s);

Q = flow rate through the wind tunnel (m^3/s);

BC = bioaerosol concentration in air (cfu/m^3); and

A= area covered by the wind tunnel (m^2)

Bioaerosol concentrations measured in the mixing chamber were taken as an average of those measured at the top and the bottom of the mixing chamber. The specific bioaerosol emission rate corresponding to actual ground level wind speeds, as opposed to those in the chamber, is then estimated using (Jiang *et al.* 2001):

$$SBER_2 = SBER_1 \times \left(\frac{V_2}{V_1}\right)^{0.5} \qquad \textit{Equation 3.8}$$

where:

$SBER_1$ = surface bioaerosols emission rate measured using the wind tunnel (cfu/m^2/s);

$SBER_2$ = surface bioaerosols emission rate corresponding to ground level wind velocity (cfu/m^2/s);

V_1 = air velocity inside wind tunnel for sample collection; and

V_2 = actual ground level wind velocity (m/s)

3.11 Emission rates during agitation

In order to determine the bioaerosol emission rate during agitation, the approach described by Dowd *et al.* (2000) was adopted, whereby field analysis data is used to estimate the flux rate using an airborne transport model. In this research, SCREEN3 air dispersal model (USEPA, 1995a) was used because of its simplicity and widespread adoption for the screening of industrial pollution. Furthermore, SCREEN3 includes a feature to analyse fugitive dispersal, making it particularly applicable for bioaerosol studies (Section 3.7.1)

The estimation of the bioaerosol emission flux from static compost piles is written up in the previous section and published as Taha *et al.* (2005). The estimation of bioaerosol emission rate during compost and waste agitation was calculated by performing a back-extrapolation using SCREEN3. Various candidate emission rates were tested as inputs to SCREEN3 together with the measured mean temperature (^{0}K), wind speed (m/s) and height of sampling (1.8 m).

Air dispersion models are capable of modelling sources as three possible types, namely point, volume or area. Initially, two source types were deployed in the trial, namely a point and volume source type. The volume source type was chosen instead of the area source, because the agitation involved not only the surface but also down to the base of the compost pile, which could be observed as a mass of dust emitted in either a block or column form.

The size of the dust cloud created by agitation was observed and the dimensions estimated. The 'internal stack' (an artificial representation of the release) diameter for the point source was assumed to be 3 m and the dimensions for the volume source were 3 m x 3 m x 3 m. Due to the fact that the material was disturbed from the base of the compost pile, the release height used was set to 0 m (Dowd *et al.*, 2000).

Figure 3.10: Shredder for shredding the green waste into small pieces.

Selected emission rates were plotted against bioaerosol concentrations at a dispersal distance of 10m, to generate modelled concentrations that could be used as a comparison with the work of other researchers. These comparisons revealed that a higher emission rate was required by a volume source compared to a point source, for an identical concentration measured at 10 m from the pile. A point source type was therefore suggested as a more appropriate type of source for this study, and was in line with the method adopted by Dowd *et al.* (2000). The graph of an array of emission rate verses modelled concentration at 10 m downwind was plotted. The emission rate was matched iteratively to the corresponding bioaerosol concentration of air sampled at 10m distance downwind and used as an input to SCREEN3. Several simplifying assumptions were made in performing the modelling:

- the particles displayed a Gaussian distribution in both lateral (crosswind) and vertical direction;
- the source was continuous;
- the wind velocity and direction were constant over the modelled time and distance;
- the modelled surface was relatively flat;
- the gravitational settling of particles was negligible;
- the particle and wind velocity were essentially the same; and
- microbial inactivation was not considered.

The results must be viewed in the light of these simplifications and methodological constraints.

3.12 Analytical quality control

Quality control was conducted not only to ensure the quality of results but also the safety of the sampler and those involved. Several measures were taken to maximise reproducibility.

a) Calibration of sampling pump

The pump flow was calibrated every day before the start of sampling. The calibration was performed by a rotameter (variable area flowmeter). The set up is similar to the sampling set up but the IOM sampler fitted head with filter paper located on top of the Rotameter. The sampler head was pressed tight to the mouth of the rotameter to ensure no air could leak through. When the pump was running, the float inside the rotameter graduated glass tube was inspected. The top of the float indicated the flow of air through the IOM filter head. The required flow rate was checked by adjusting the pump.

b) Blank sample

A blank sample is an essential requirement for quality control to monitor the possibility of background contamination during sampling and analysis. The blank filter cartridge was placed into the sample head and connected to the pump, and then performed the same procedure to sample the ambient air but without the pump running. The filter

sample was analysed according to the steps discussed above.

c) Media preparation and inoculation in an air flow chamber

Media, sample and inoculation were conducted in a safety cabinet or air flow chamber to avoid possible cross-contamination from the environment and of the test portion. In practise it is advisable to begin the activity by analysing a sample known to contain very few organisms followed by one known to be more contaminated. The safety cabinet was cleaned with 70% ethanol before and after use. All equipment used in the analysis has to be sterilised and the samples were handled in such a manner as to avoid any and all risk of contamination. All plates, plastic bags, vial *etc.* were properly and clearly marked.

d) General safety

At the composting site, the health and safety requirement of the facility management were followed including wearing a safety helmet, reflective safety jack and safety boots. The COSHH (Control of substances hazardous to health) assessments were prepared accordingly.

3.13 Statistical Analysis

A basic statistical analysis was conducted to determine the statistical relationship between measured and calculated data and group of data. Most of the measurements of the same conditions were conducted twice and an average was used in calculation or estimation of

other parameters. A mean, maximum and minimum value was used to describe the data and in some cases when the data were widely varied a median value was used. A variance and standard deviation were used to measure the variability. The statistical tool used for this purpose was by STATISTICA 7 (StatSoft Ltd.).

3.14 Bioaerosols dispersal

The newly estimated data was used in SCREEN3 (USEPA, 1995a) air dispersal modelling to construct a source depletion curve for the estimation of bioaerosols dispersal with distance away from the point of release.

3.14.1 SCREEN3

SCREEN3 (USEPA, 1995a) is a tool to calculate screening level impact estimates for stationary sources. It is a simple, single source model but can be aggregated to conservatively estimate the dispersal of multiple sources. It calculates a short-term 1-hour average concentration of pollutant from ground level up to the top of the building. It calculates the maximum concentration at any number of user-specified distances in flat or elevated simple terrain as far as 100 km from the source. SCREEN3 incorporates a full range of meteorological conditions, all stability classes and wind speeds, and presents the maximum impacts (Turner, 1994).

SCREEN3 has a capability to estimate the maximum level of concentration using an

automated distance array option. The usual receptor height is set to 0 m (ground level), however if there is concern about exposure above ground level such as at the balcony of a high building, flagpole receptors can be considered. It also incorporates the effect of building downwash and simple elevated terrain. Single area and simple volume sources can be modelled with SCREEN3 using the numerical integration approach. The SCREEN3 estimates need to be converted for comparison with longer concentration values such as 8-hour and 24-hour. The overall impact should consider all possible sources such as background monitored levels, other sources and historic data, where these are available.

3.14.2 Source depletion curve.

Source depletion curves were constructed using SCREEN3 air modelling as explained above. Bioaerosols concentrations downwind of the facility were estimated using SCREEN3 in its area source term mode for the static pile emission flux and the point source term for dynamic release. The power-law equation (Turner, 1994) was used to determine the velocity at 10m height to select the Pasquill stability categories and inputs to SCREEN3.

Power-law: $u_z = u_a(z/z_a)^p$ *Equation 3.9*

Where u_z= wind velocity (m/s) at a vertical height z above ground;

u_a= wind velocity (m/s) at the anemometer height;

z = vertical height above ground (1.8m);

z_a = anemometer height above ground (10m); and

p = exponent dependent on stability; 0.07 (unit less) for unstable.

3.15 Summary

Chapter 3 has summarised the rationale, sampling sites and methodological innovations used in this study. The research described includes a novel application of compost agar for improved enumeration, the portable wind tunnel for authentic source term analysis from static piles and a rudimentary modelling approach for the generation of source depletion curves.

CHAPTER 4 RESULTS

The study results are presented in the following sections, and sub-sections by reference to sampling sites. The sections describe the bioaerosols analysis and enumeration, ambient bioaerosols concentration, bioaerosols concentration in compost, specific bioaerosols emission rate of static compost pile and dynamic release of bioaerosols. Detailed results are presented in Appendixes II and III for analysis at Calvert Composting and Carmarthen Composting, respectively.

4.1 Bioaerosols analysis and enumeration

4.1.1 *A. fumigatus*

From the trial analysis conducted at two different temperature, 37^0C and 25^0C, the *A. fumigatus* was easily identifiable and enumerated at the incubation temperate of 37^0C. *A. fumigatus* was identified by the blackish green and light brown colour of colonies viewed from the bottom of the plates. Figure 4.1 shows *A. fumigatus* growth on media plates at different dilutions. The figure illustrates *A. fumigatus* colonies were clearly identified and counted. Enumeration was performed on plates of 10^0 and 10^{-1} serial dilution and the single colony growth on one of the 10^{-2} dilution plates was discounted because it was not statistically valid.

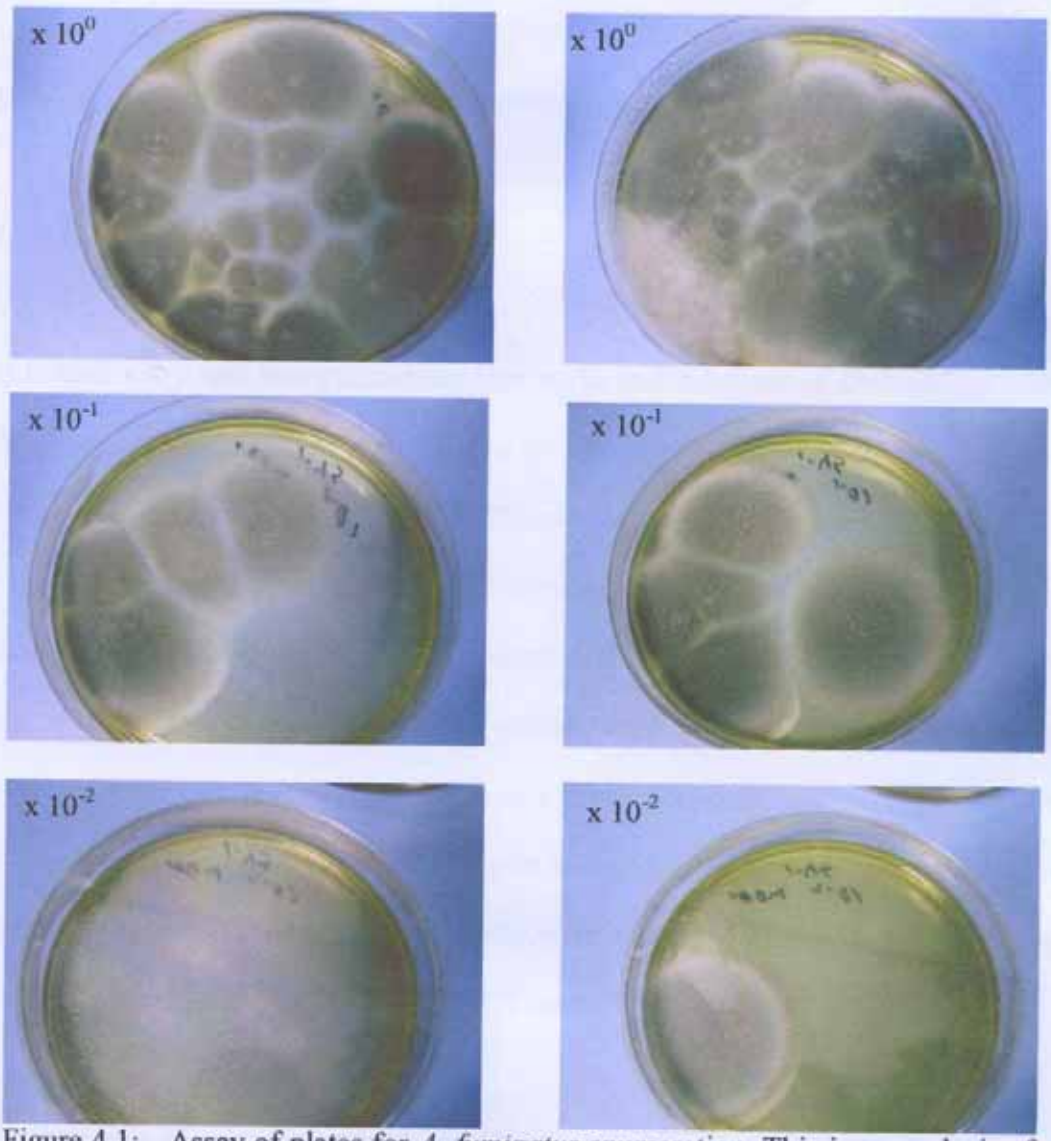


Figure 4.1: Assay of plates for *A. fumigatus* enumeration. This is an analysis of bioaerosols sampled during shredding. At the top are duplicate plates of 10^{0} dilution followed by the plates of 10^{-1} and 10^{-2} dilution, respectively.

The plates incubated at 25^{0}C showed substantive growth of other species which hampered *A. fumigatus* identification and enumeration.

4.1.2 Actinomycetes

Plates loaded with a half strength nutrient agar media and incubated at 25^{0}C and 37^{0}C did not show positive actinomycetes growth. The growth of actinomycetes is coincident with other types of bacteria and was extremely difficult to elucidate and count. Similar results were produced for the plates incubated at a temperature of 44 ^{0}C. Figure 4.2 shows the results of actinomycetes growth on half strength nutrient agar at 44^{0}C. The plates were covered with several types of bacteria that entirely mask the plate surface. The masked plates were rejected. Only the plates that show a consistent count between the two plates of the same dilution and that are proportionate to the dilution factors were accepted in this analysis. Therefore, other types of media were tested; tap water and soil compost supernatant at incubation temperatures of 44 ^{0}C and 55 ^{0}C.

The positive results were only shown on plates using soil compost agar at incubation temperatures of 44^{0}C (Figure 4.3). Other specimens either showed no growth or have eubacterial and fungal overgrowth that swamped the media surface (Figure 4.2). The growth of both microorganisms, eubacterial and fungal, retards the slowly growing

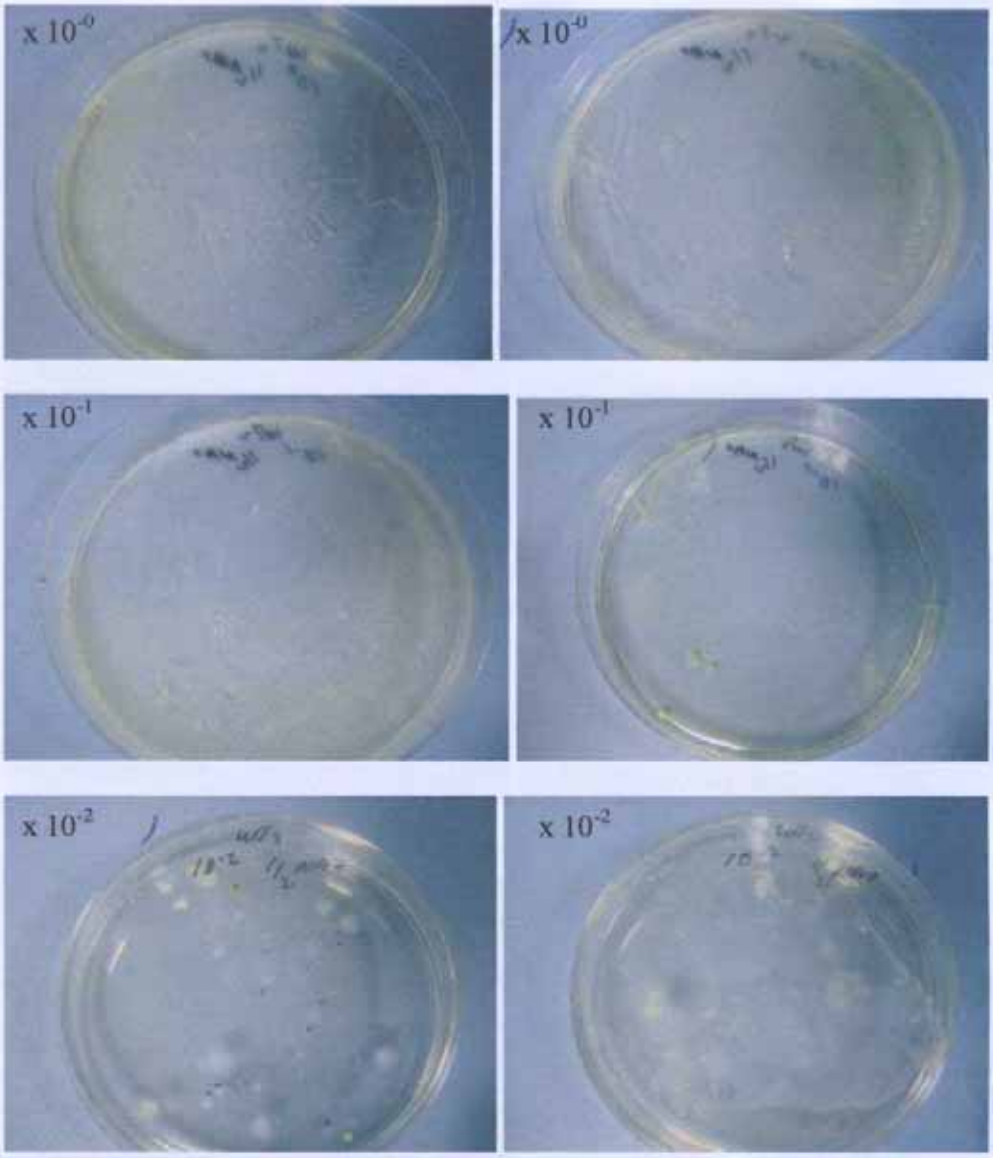


Figure 4.2: Plates of half strength nutrient agar for actinomycetes, enumerated from samples collected during windrow turning. The duplicate plates at the top are 10^0 dilution followed by the duplicate plates of 10^{-1} and 10^{-2}. The growth of other bacteria obscures actinomycetes growth as shown in plates 10^0 and 10^{-1}. Actinomycetes growth could only be seen on 10^{-2} plates mixed with the growth of other bacteria.

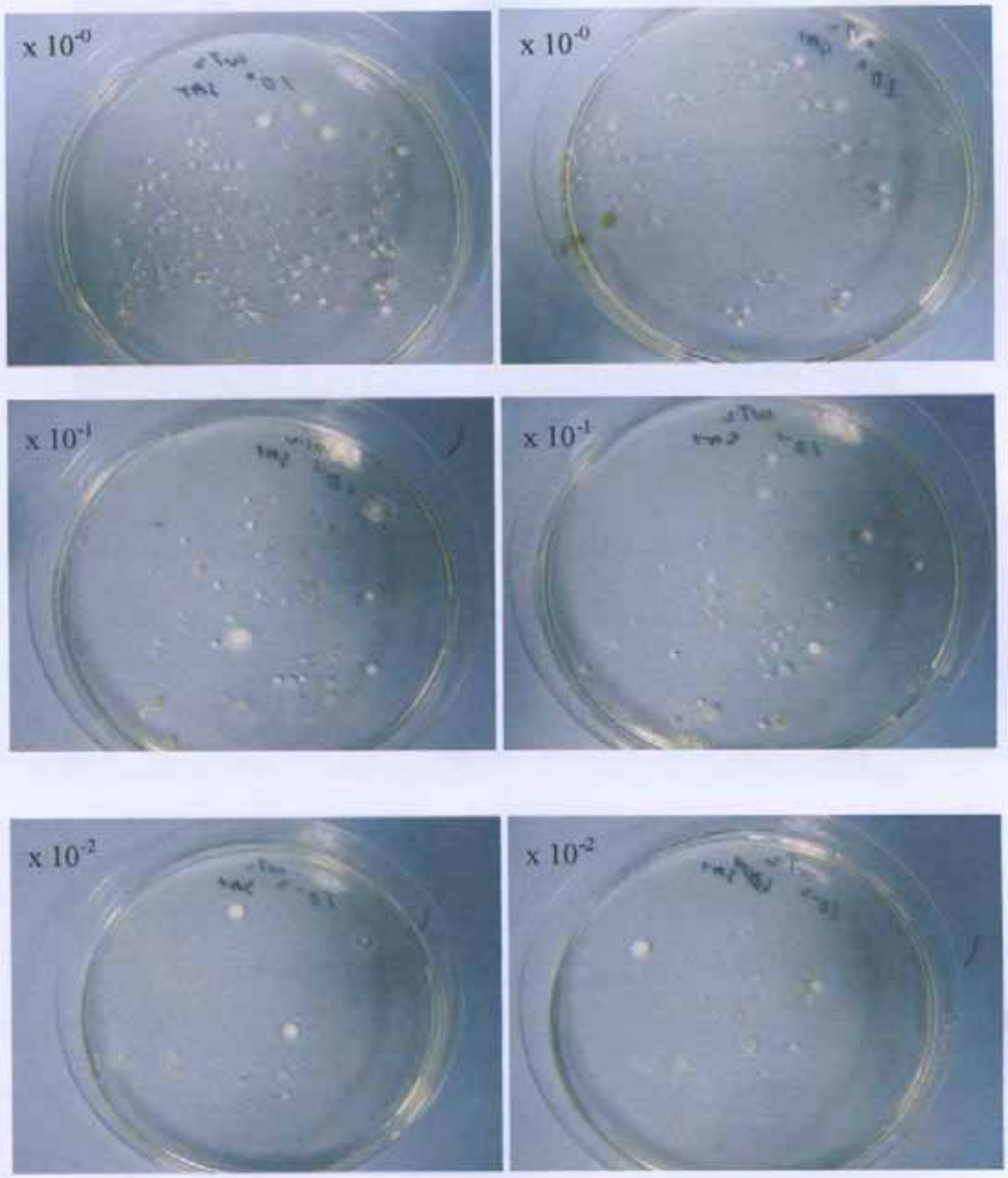


Figure 4.3: The example of assay of compost media plates for actinomycetes enumeration. This is an analysis of bioaerosol during turning by windrow turner. At the top are plates of 10^0 dilution followed by the plates of 10^{-1} and 10^{-2} dilution. The actinomycetes is easily identified and counted on plates 10^{-1} and 10^{-2}

Figure 4.4: Close up of actinomycetes growth on compost soil agar (25 x magnifications).

actinomycetes (Crawford *et al.*, 1993). In this research, more than 7 days were needed for actinomycetes to grow and sporulate. The actinomycetes grown on soil compost agar were easily identified by the white powdery colour of their spores and spider web-like formation appearing on the colonies (Figure 4.4). The analysis showed that the number of colonies was consistent between dilution factors and in proportion to the serial dilution factors, improving the confidence interval limit. The plates which were placed in the 55^0C incubator became too dry even though the plates were loosely wrapped in a plastic envelope.

Only the plates that had colonies less than 300 and more than 15 were used for enumeration using *Equation 3.1*. However in some cases, especially when the bioaerosol concentration was low, there were no plates that contained more than 15 colonies. For these situations, *Equation 3.2* was used.

There were 105 samples analysed from three sampling sites where estimated count was used on about 50% of them. This was because there were no assay plates having more than 15 colonies. Most of the samples were in an environment that had a concentration lower than 10^4cfu/m^3. Therefore, this analysis is more appropriate for the sample having bioaerosols concentration more than 10^3 cfu/m^3. In a lower bioaerosols concentration area, a longer sampling period is required or an increase in the inoculation volume of sample solution. In brief, the innovative adoption of soil compost agar dramatically improved the enumeration of actinomycetes.

4.2 Ambient bioaerosols concentrations

4.2.1 Pitsea Composting

This being the pilot analysis, a number of methodology challenges was encountered during analysis, such as those relating to the types of media and incubation temperature (as discussed in the previous section). No reading was recorded for ambient air within the composting boundary. Bioaerosols were not detected upwind or downwind of the site. The initial inference was that the concentration was simply too low to be detected by this method. The turning was conducted, approximately 10 m from the sampling point, for *ca.* 5 minutes when the sample was taken. The initial data is presented in Figure 4.5. These initial results confirmed that the bioaerosols concentration in the air increased when the agitation of the compost pile is performed, a known result. The primary purpose of the analysis from Pitsea was to allow practical refinement of the sampling and

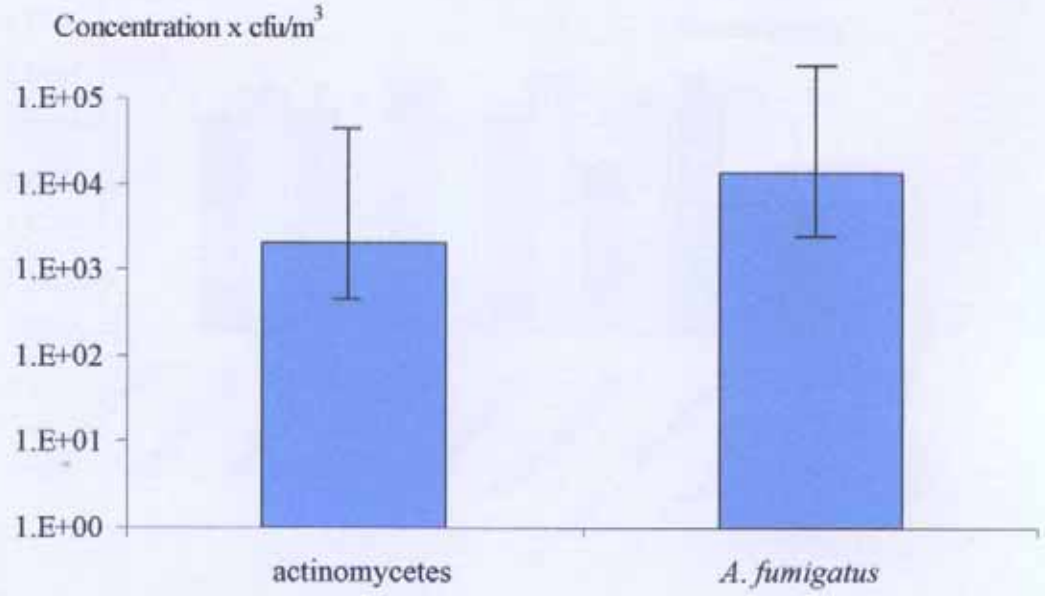


Figure 4.5: Concentration of actinomycetes and *A. fumigatus* in ambient air at Pitsea Composting during short turning. The error bars in the graph indicate the confident limit interval (Section 3.9) of the analysis.

enumeration methodologies.

4.2.2 Calvert Composting

A number of ambient air sampling exercises were conducted at Calvert composting site. Most of the ambient air sampling was conducted before source term samplings were conducted to understand the general background levels. The background sampling was conducted upwind, inside and downwind of the facility. The upwind and downwind samples were located at 50 m and 15m from the edge of the facility respectively.

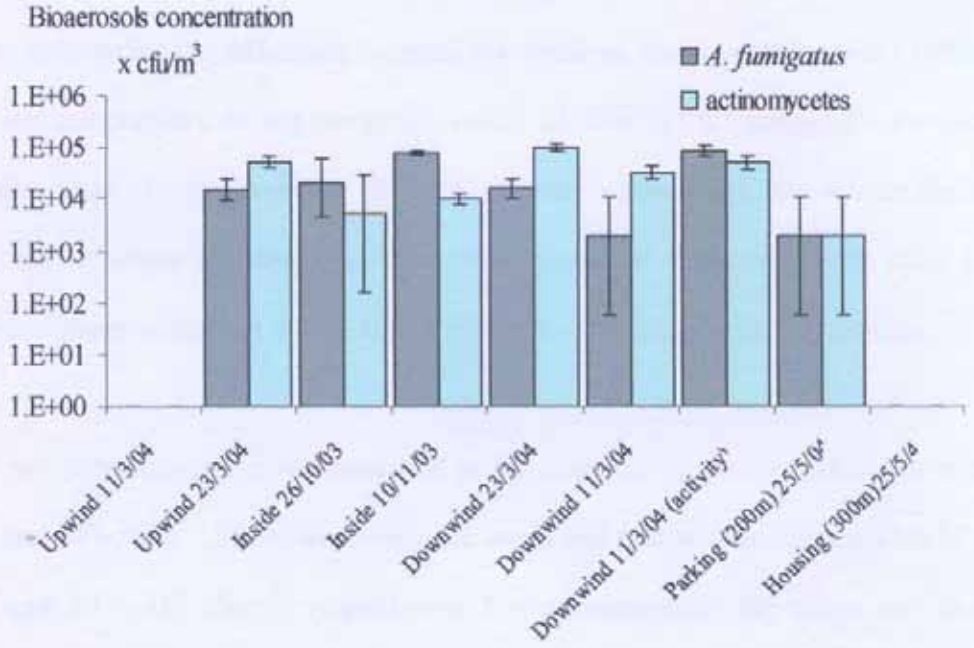


Figure 4.6: Ambient concentration with of actinomycetes and *A. fumigatus* in ambient air at Calvert Composting. The samplings were conducted inside and outside the facility. Mean wind velocity and temperature; 26/10/03;1.5 m/s and 10^0C: 10/11/03; 1.0 m/s and 12^0C: 11/03/04; 0.4 m/s and 6^0C: 23/03/04; 0.2 m/s and 17^0C, respectively.

Sampling was also conducted at a parking area and adjacent to nearby housing 200 m and 300 m from the site, respectively. Most of the sampling was conducted during agitation except for the downwind sample-11/3/04 (activity) where loading and unloading were performed. Results are shown in Figure 4.6.

Two samplings were conducted to measure the upwind bioaerosol concentration. Both times, the wind was blowing from a nearby landfill which was located at about 500 m from the facility. No bioaerosols were detected on the 11/03/04 sampling but a significant result was recorded on a sample taken on 23/3/04. The *A. fumigatus* and actinomycetes

level detected were 16 000 cfu/m^3 and 53 000 cfu/m^3 respectively. No specific reason was found to account for the difference between the readings. However there was a difference in ambient temperature during sampling; where 23/3/04 (17^0C) sampling's temperature was higher than 11/3/04 sampling (6^0C). There was a possibility that a high biological activity during warm conditions released more gases and transported with them higher amounts of bioaerosols than during cold conditions. This is speculative, however.

The bioaerosols concentrations measured at the composting facility were between 10^3 cfu/m^3 and 10^5 cfu/m^3. For *A. fumigatus*, the mean and standard deviations were 50 x 10^3 cfu/m^3 and 39 x 10^3 cfu/m^3, respectively. For actinomycetes the mean and standard deviations were 8 x 10^3 cfu/m^3 and 3 x 10^3 cfu/m^3, respectively. These bioaerosols were contributed by an incoming wind and a fugitive emission generated by the compost pile. From observation, a fugitive emission might also be found in the water vapour emitted from the compost piles. Within the facility, the data shows *A. fumigatus* concentration was higher than actinomycetes, although lower in incoming air.

The bioaerosols concentration at 20 m downwind of the composting site was similar to that measured inside, became lower at 200 m downwind and was not detected at ca. 300 m. The downwind concentration was higher when there was activity performed on the site.

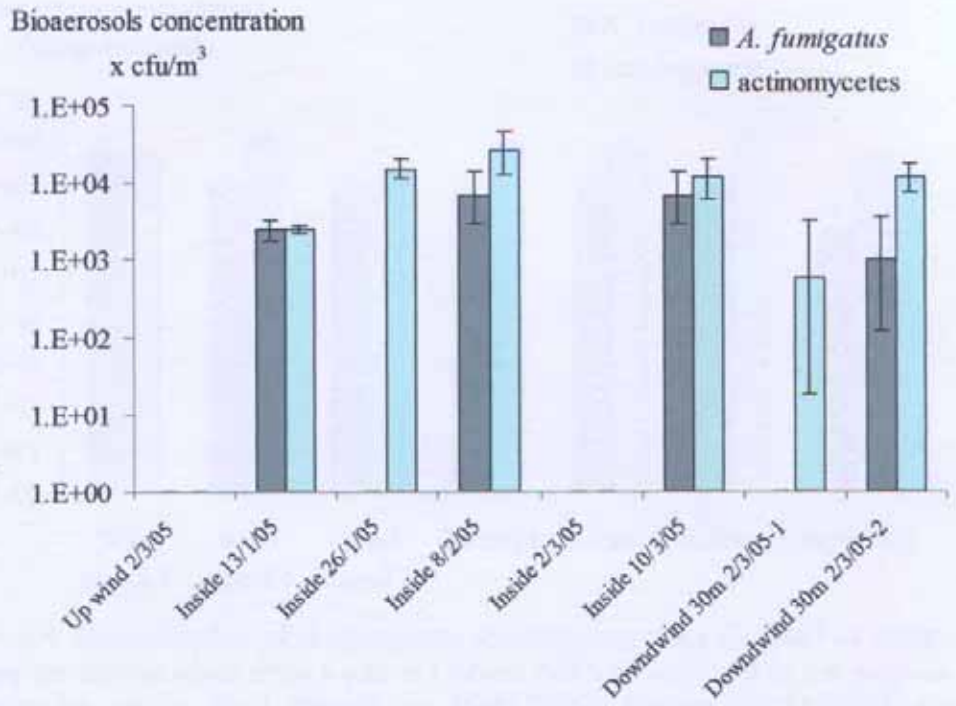


Figure 4.7: Background concentration of bioaerosols taken for different dates at Carmarthen. The samplings were conducted at inside and outside covered area as explained in Section 3.1c.

4.2.3 Carmarthen Composting facility

Similarly with the concentration detected at Calvert, at Carmarthen the ambient inside concentration of *A. fumigatus* was between < 10^3 cfu/m^3 to10^4 cfu/m^3 (Figure 4.7). No colonies were detected in the upwind sample. However a significant bioaerosols concentration was recorded from downwind sampling outside the facility, suggesting a bioaerosols contribution downwind of the facility.

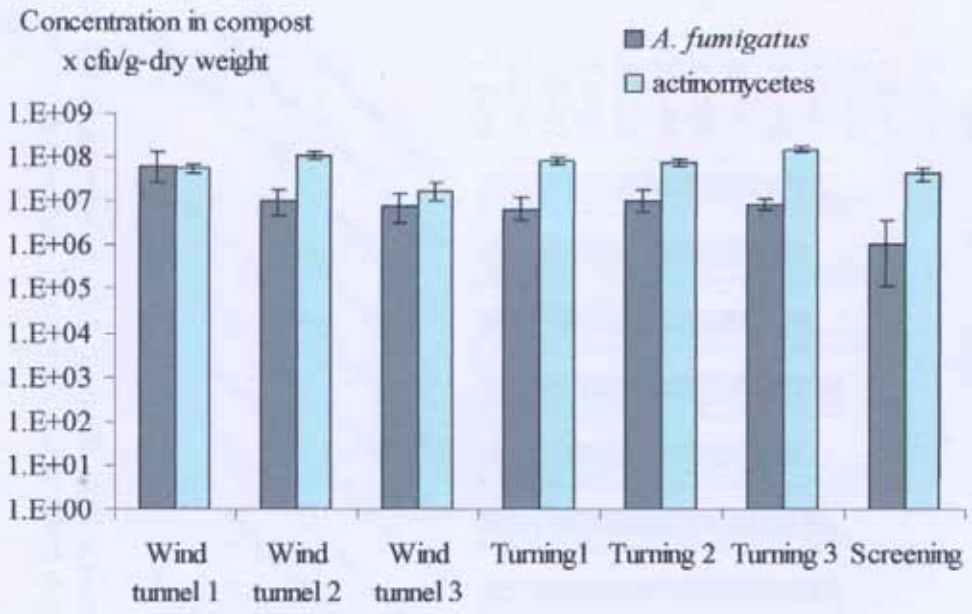


Figure 4.8: Concentration of *A. fumigatus* and actinomycetes detected in a gram of compost sample taken from a pile at Calvert that was involved in the analysis. The samples taken; wind tunnels on 10/11/2003; turning on 11/03/04 and screening on 23/03/04.

4.3 *A. fumigatus* and actinomycetes concentration in compost sample

Since bioaerosols emitted are coming from compost, it is essential to determine the concentration of bioaerosols in compost itself. For Calvert Composting, the amount of *A. fumigatus* and actinomycetes in compost involved in various activities are presented in Figure 4.8. The mean and standard deviation of *A. fumigatus* recorded was 22 x 10^6 cfu/g-dry and 28 x 10^6 cfu/g-dry, respectively. Correspondingly, for actinomycetes the values were 82 x 10^6cfu/g-dry and 49 x 10^6 cfu/g-dry.

The *A. fumigatus* and actinomycetes concentrations of compost at Carmarthen are presented in Figure 4.9 and have similar magnitude to those found at Calvert

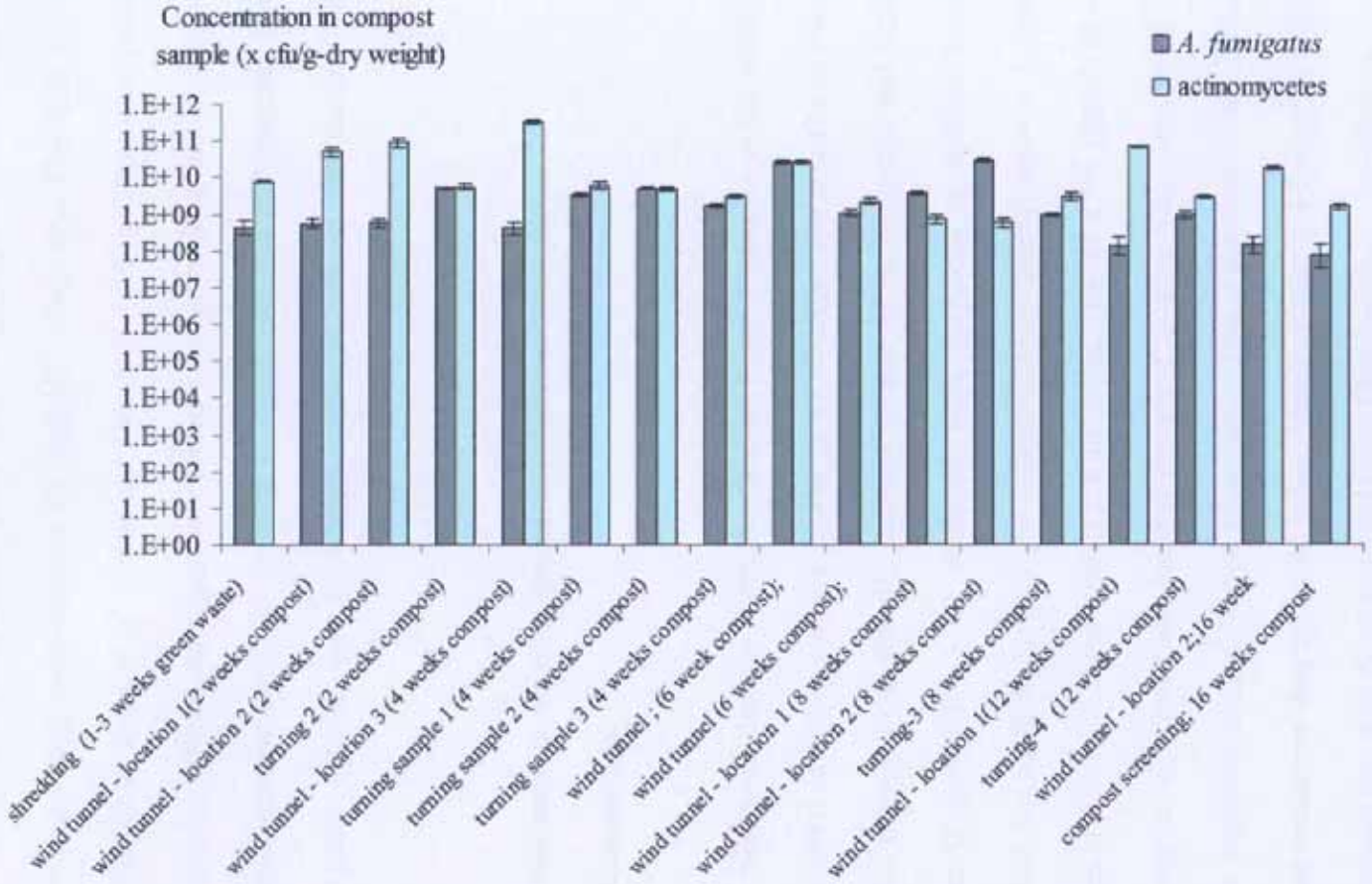


Figure 4.9: Concentration of *A. fumigatus* and actinomycetes detected in a gram of compost sample that was involved in the analysis. The samples were taken during analysis conducted for the surface flux and agitation emission.

Composting. In general from both sites, the *A. fumigatus* and actinomycetes concentrations in compost were between 10^7 and 10^{11} cfu/g- dry. This is in agreement with data presented by Beffa *et al.* (1996) and Dee *et al.* (2001). There were significant numbers of samples where actinomycetes recorded a higher reading than *A. fumigatus* at the end stage of composting. Slow growing actinomycetes that only became dominant when the organic nutrient was diminished could be one of the reasons for that observation.

4.4 Specific bioearosols emission rates from static compost piles :

Calvert Composting

Net fugitive bioaerosol data for windrow samples 1 and 3 samples in the wind tunnel outlet from Calvert sampling are of a similar order of magnitude to ambient bioaerosol concentrations, though lower than the ambient sample for *A. fumigatus* and higher for actinomycetes (Figure 4.10). We observed, large variations in ambient bioaerosol monitoring data. For example, on previous occasions at this facility, ambient *A. fumigatus* concentrations of 120 x 10^3 cfu/m^3 and 21.5 x 10^3 cfu/m^3 (c.f. 77 x 10^3 cfu/m^3) have been measured using an identical filter sampler technique (Figure 4.6). Also noted in this research is an important methodological observation. This is the observation (Wheeler *et al.*, 2001) that bioaerosol data collected using Anderson samplers frequently reports an order of magnitude less than those collected using filter samplers. Irrespective, it is clear from our study that there are contributions to the site bioaerosol load beyond fugitive emissions from static windrows, as one would expect. The bioaerosols transported by

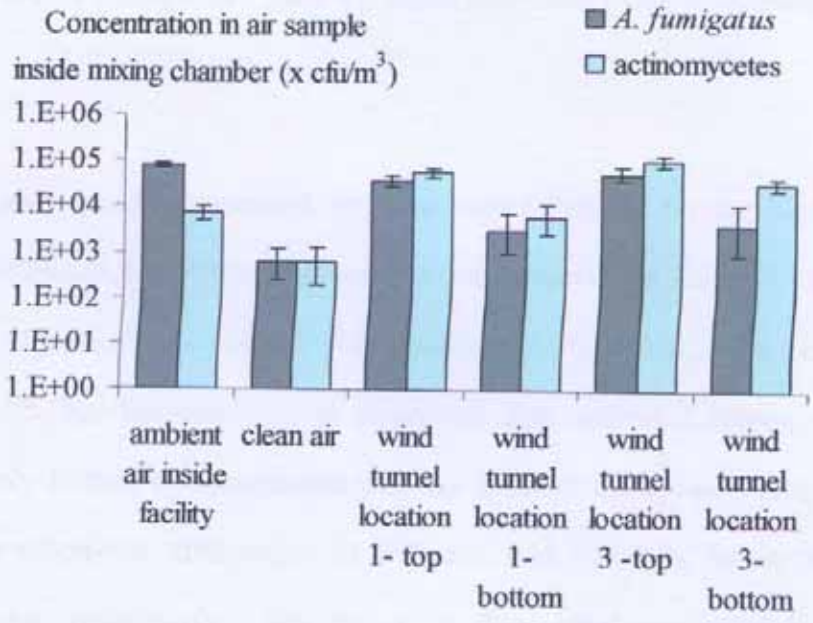


Figure 4.10 Bioaerosols concentration measured in air samples collected at the top and bottom of portable wind tunnel during static surface flux analysis at Calvert. The detail result is presented in Appendix II. The pumps were malfunctioning at location 2 analysis.

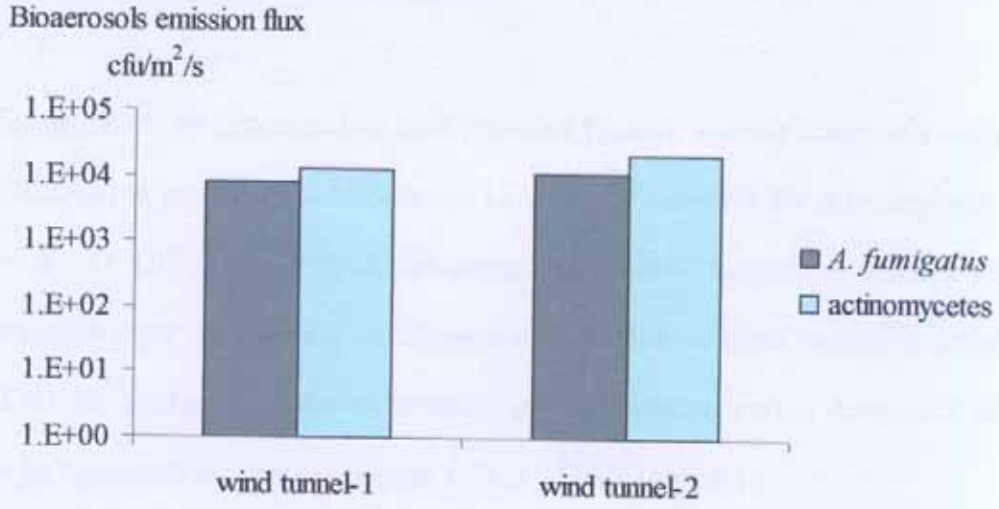


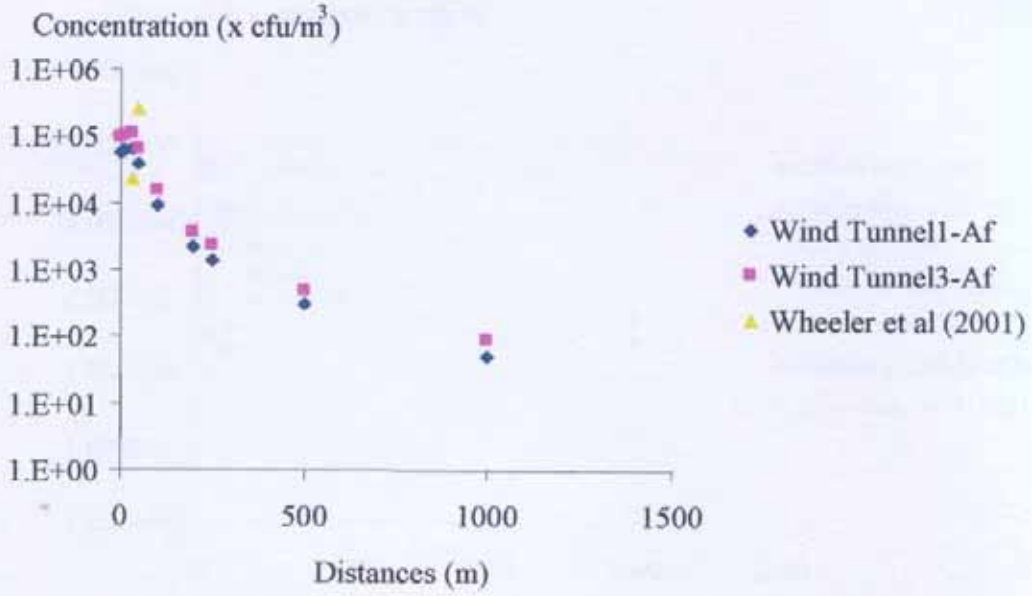
Figure 4.11: Surface emission flux of composting site estimated from the measurement conducted by portable wind tunnel analysis at Calvert. The values are estimated using actual wind speed, temperature and weather condition on the day of sampling.

incoming air, for example as Figure 4.6, could contribute to the bioaerosol amounts at the facility.

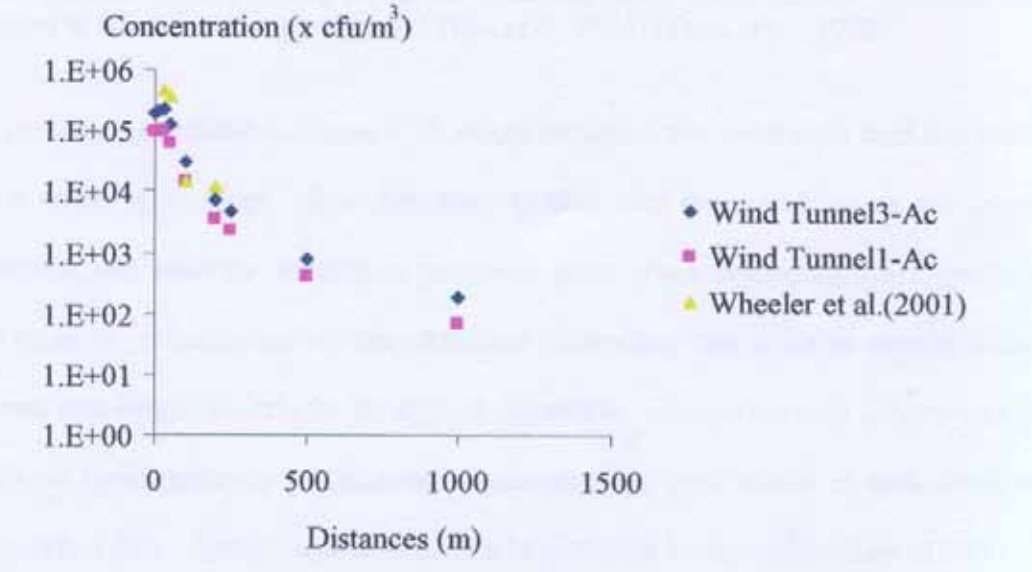
The estimated specific bioaerosol emission rates ($SBER_2s$) for the fugitive release of actinomycetes and *A. fumigatus* in this study are presented in Figure 4.11 and the detail derivation is presented in Table II.V (Appendix II). The $SBER_2s$ were estimated using *Equation 3.8*. For the wind tunnel bioaerosol data, activated carbon influent air is demonstrably filtered by comparison with the ambient background sample, these data suggesting adsorption efficiencies of 99%w/w and 92%w/w for *A. fumigatus* and actinomycetes, respectively. For the outlet data, good agreement is demonstrated between locations 1 and 2 (Figure 4.11) (with location 2 providing a greater flux for both determinants) suggesting less variability for consecutive wind tunnel experiments on material from a common source.

Transformation of the concentration data provided fugitive specific bioaerosol emission rates ($SBER_2s$) at ground level of between 13 - 22 $x10^3$ $cfu/m^2/s$ for actinomycetes and between 8 - 11 $x10^3$ $cfu/m^2/s$ for *A. fumigatus*. These rates are used as the area source term emission input data for the air dispersion modelling of these emissions using the SCREEN3 air dispersion model to generate source depletion curves downwind of the facility for comparative purposes (Figure 4.12, 4.13 and Table 4.1).

The modelled *A. fumigatus* source depletion curves for these data using the area source term emission rates generated in wind tunnel experiments are shown in Figure 4.12 and Figure 4.13 alongside literature data acquired by environmental sampling at distance



(a)



(b)

Figure 4.12: Source depletion curve of *A. fumigatus* (a) and actinomycetes (b) estimated by SCREEN3 and wind tunnel analysis data at Calvert . The curves illustrate the bioaerosol dispersal. Wheeler *et al.* (2001) indicates the range of bioaerosol concentration inside the composting facility.

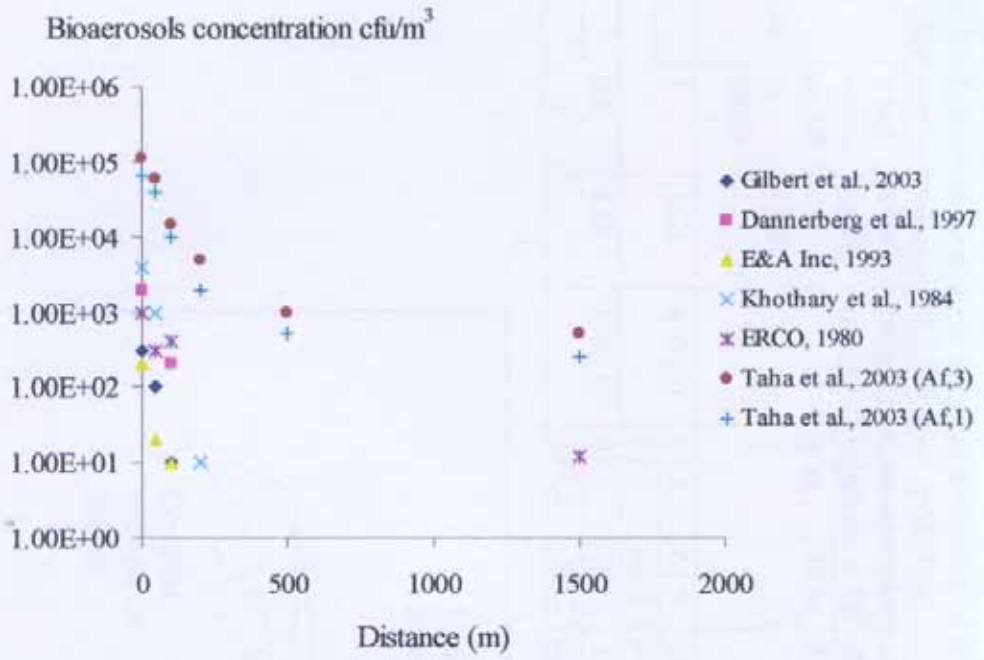


Figure 4.13: Source depletion curves (cfu/m^3) for *A. fumigatus* from selected monitoring studies (Millner *et al.*, 1994) alongside modelled data using fugitive emission rates generated in wind tunnel experiments. (Taha *et al*, 2004) (Taha *et al.*, 2005)

from composting facilities. Figure 4.13 mixes modelled and monitored data and studies from a range of facilities. It is important to note that these studies are not directly comparable and used for illustrative purposes alone. Two observations are worthy of merit however, notwithstanding the additional difficulties and artificial nature of using Gaussian distribution models for bioaerosol dispersion. Comparing with other works one notices the rapid depletion of bioaerosol concentrations from source in both monitored and modelled data. Further, source depletion to proposed background values of 1000

Table 4.1: Estimated bioaerosols dispersal downwind of facility using SCREEN3.
This table was derived using SCREEN3 air modelling.

wind tunnel and bioaerosols	**wind speed at 1.8 m (m/s)**	**wind speed at 10m**	**Pasquill stability**	**Concentrations estimated by SCREEN3 at various distances (m) from compost windrow x 10^3 cfu/m^3 (1 hour average)**								
				1 m	**10 m**	**30 m**	**50 m**	**100m**	**200 m**	**250 m**	**500 m**	**1000 m**
1 (Af)	1	1.33	A-B (1)	57.8	61.3	66.3	39.5	9.3	2.2	1.4	0.3	0.05
1 (Ac)				91.3	96.7	104.7	62.3	14.8	3.7	2.2	0.5	0.07
3 (Af)	0.8	1.06	A-B (1)	97.1	102.9	111.3	66.2	15.5	3.7	2.4	0.5	0.09
3 (Ac)				189.8	201.2	217.5	129.5	30.4	7.3	4.6	0.8	0.18

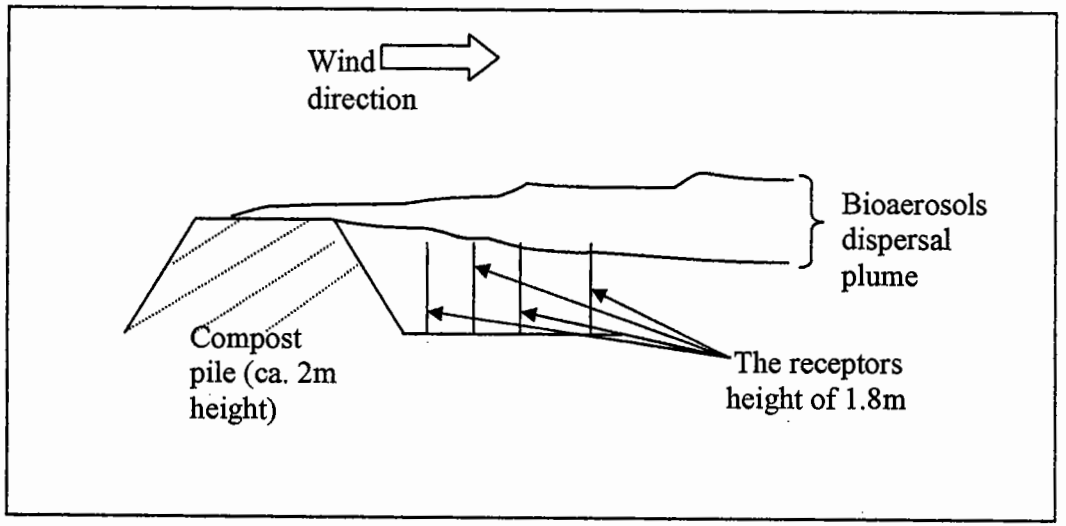


Figure 4.14: Illustration of bioaerosol dispersal from static compost pile.

cfu/m^3 typically occurs, for these studies between 250-500 m from source in the wind tunnel data and typically within 250 m for the monitoring studies. We propose that the data generated by our study are generally consistent with literature data. For example, for *A fumigatus* and mesophilic actinomycetes, Sanchez-Mondero and Stentiford (2003) have recently reported that at up to 40 m from composting sites, the concentrations of these bioaerosols are between $3.8x10^3$ and $98x10^3$ cfu/m^3 and between 23 $x10^3$ and 110 $x10^3$ cfu/m^3, respectively.

Table 4.1 shows the concentration at 1.8m receptor level was increased at the distance close, ca. 30m, to the point of release. This is due to the receptor point location which is lower than the release point (2m). Therefore the receptor point is not inside the bioaerosol dispersal plume or column at distances less than 30m because of the smaller bioaerosol plume diameter. The plume diameter becomes bigger with the distance. Once the receptor point is inside the plume, the high concentration will be recorded as illustrated in Figure 4.14.

4.5 Surface flux release study: Carmarthen Composting

Similar studies were conducted at Carmarthen Composting but in addition composts of different ages were studied. The analysis was conducted using portable wind tunnel analysis as described in Chapter 3. Sampling was conducted on 2, 4, 6, 8, 12 and 16 week old composts. Several samples showed a negative result due to the malfunction of the pump especially at the early stage of the sampling (Figure 4.15). The pump

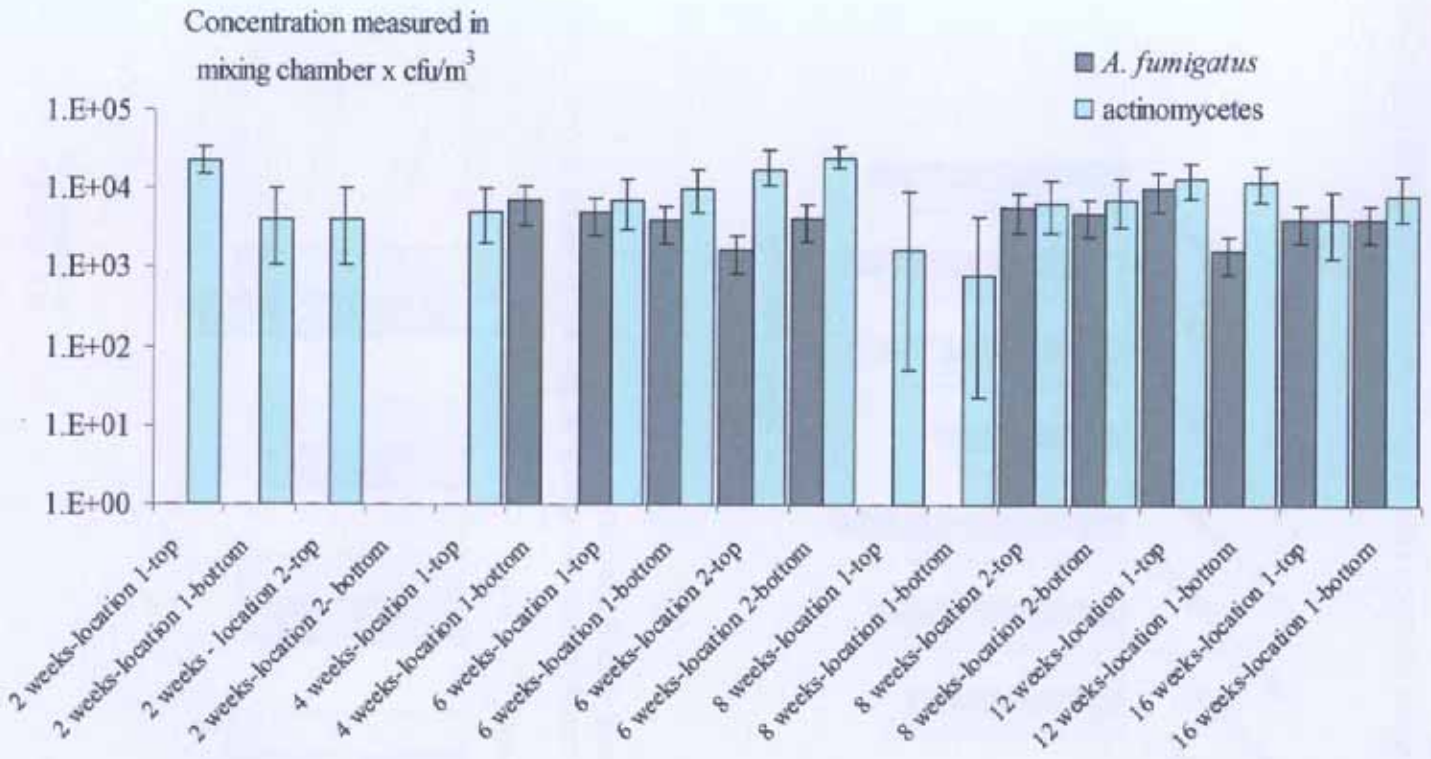


Figure 4.15: The bioaerosols concentration measured in the mixing chamber of the portable wind tunnel during surface flux analysis at Carmarthen for a different composting age.

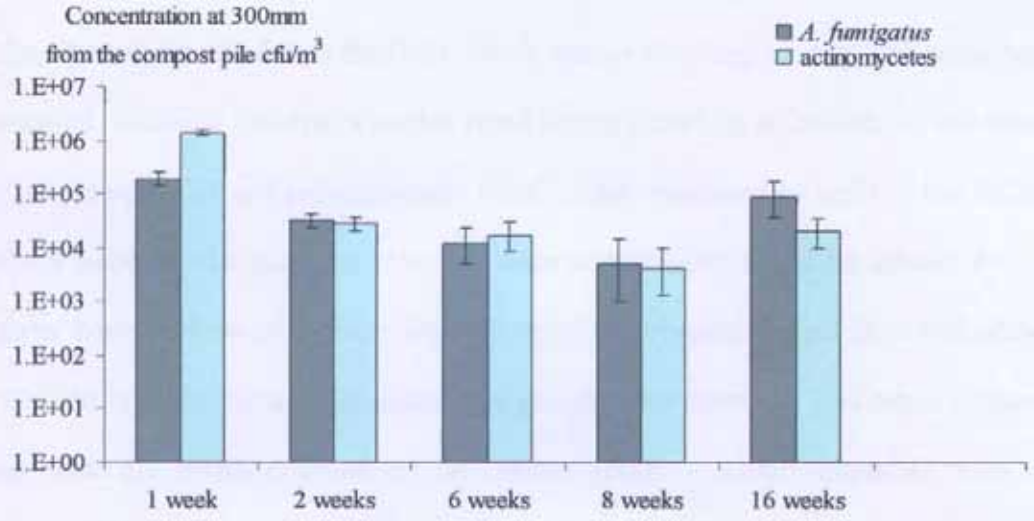


Figure 4.16: Bioaerosols concentration measured in the air at about 300mm from a surface of different composting ages at Carmarthen.

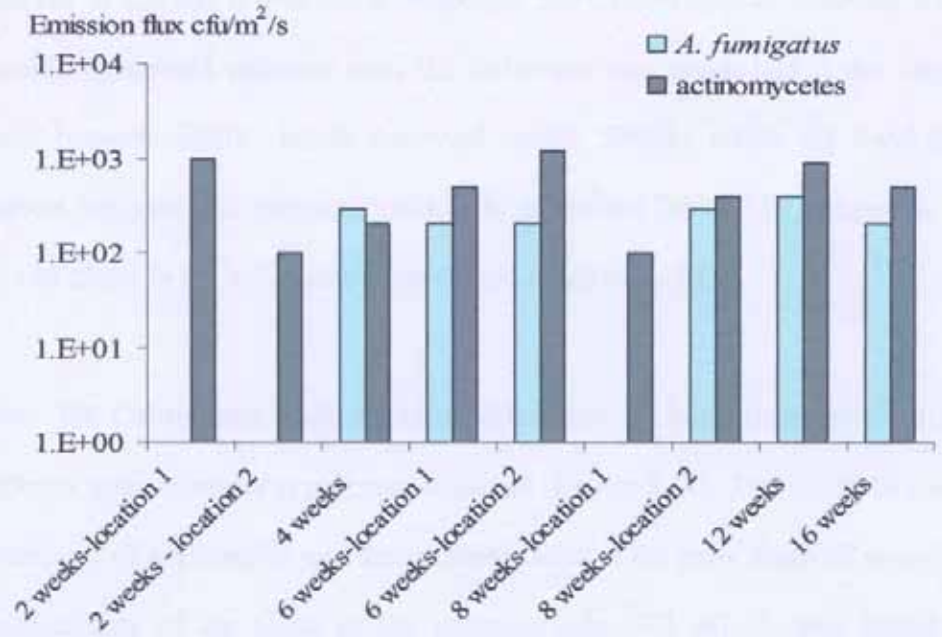


Figure 4.17: Bioaerosols surface emission flux of the compost pile estimated from wind tunnel analyses at Carmarthen.

malfunction was caused mainly by a wet filter absorbing water vapour directly from the pile. The vapour cloud wets the filter, which causes the pump to stop. The pump has to be restarted. A similar problem was also faced during sampling at Calvert. At this later stage of sampling a 0.8 μm polycarbonate (SKC) filter was used to replace the MCE filter which resolved the problem. The non-detectable results could be caused by > 1000 cfu/m^3 concentration in the samples. The $SBRE_2$s estimated ranged from 100 cfu/m^2/s to 1200 cfu/m^2/s for the samples where bioaerosols were detected. This range is lower by a log than the $SBRE_2$s measured at Calvert (8000 - 22000 cfu/m^2/s). One of the contributing factors to this finding, inferred from both sites analysis, is the difference in ambient wind velocity. At Carmarthen the measured wind velocity average was 0.3m/s whereas at Calvert it was 1m/s. Although the Calvert results recorded a much higher specific bioaerosol emission rate, the difference was much less if the comparison was made between $SBER_1$ inside the wind tunnel. $SBER_1$ inside the wind tunnel in the Calvert analysis was between 1100-4000 cfu/m^2/s (Table II.IV, Appendix II) and 100 to1100 cfu/m^2/s at Carmarthen (Table III.IV, Appendix III).

From the Carmarthen data, no clear difference of bioaerosol emission between the different ages of compost pile was observed (Figure 4.17). This could be caused by non-sensitivity of the sampler and the problem faced at the early stage of sampling. Ambient measurement of air close to the compost pile (0.3 m) showed higher bioaerosols concentrations at the early stage of composting, steadily reducing by weeks (Figure 4.16) of curing. However, the concentration was suddenly increased when the compost age was 16 weeks. These appear anomalous. These observations indicated the presence of

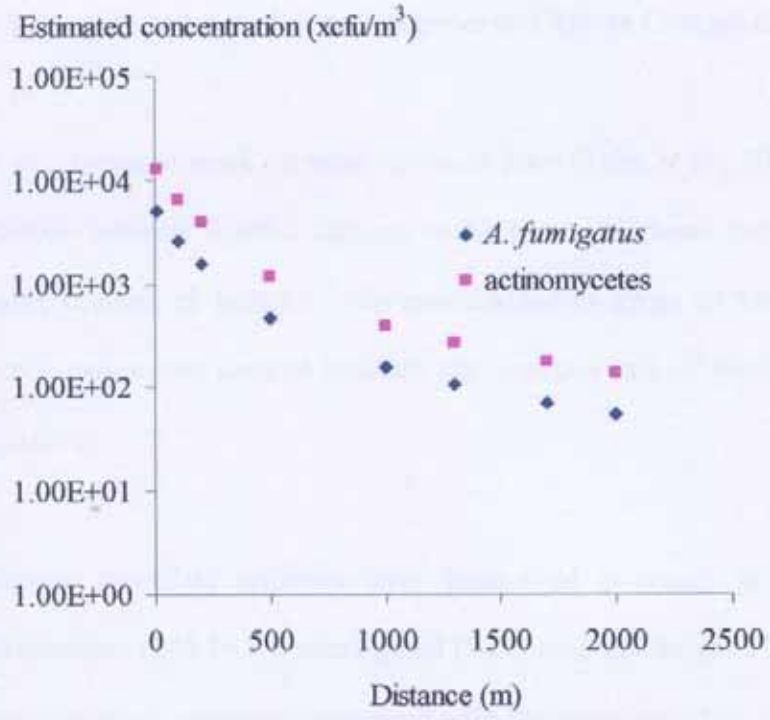


Figure 4.18: Source depletion curve of static surface emission flux derived from Carmarthen Composting wind tunnel analyses.

significant amounts of bioaerosol in air close to the compost piles during the static condition.

The source depletion curve graph generated from this analysis (Figure 4.18) showed similar results to analysis conducted at Calvert although readings were lower. Bioaerosol concentrations reduced to background (10^3cfu/m^3) at a distance of less than 250 m. In actual bioaerosol dispersal, the concentration of viable bioaerosols values are expected to be lower due to the reported clumping tendency of bioaerosols (physical decay) and deactivation (biological decay) caused by sunlight and heat.

4.6 Dynamic release of agitation process: Calvert Composting

In our previous work on static compost piles (Taha *et al.*, 2004), we have been able to directly measure fugitive releases at the point of release using a portable wind tunnel. Here, because of agitation, we have needed to adopt an alternative approach. Back-extrapolation was used to estimate the emission rate of bioaerosols during turning and agitation.

Various candidate emission rates were used as inputs to SCREEN3 together with temperature (284.16 K), wind speed (0.06 m/s) and height of sampling (1.8 m) and the concentrations generated compared with our measured data. Initially, two source types were deployed in the trial, namely a point and volume type. The 'internal stack' diameter for a point source was assumed as 3 m and the releasing height 0 m, as employed by Dowd *et al.*, (2000); whereas a dimension for the volume (box) source was estimated to be 3m x 3m x 3m. The height is considered as 0 m because the agitation of the compost pile was performed close to the pile base. Emission rate was plotted against bioaerosol concentration at a 10 m distance (Figure 4.20). Point source emission term was also used by Dowd *et al.* (2000). After comparisons were made, a point source was suggested as a more appropriate type of source for this study, due to the very high emission rate required by a volume compared to a point source to generate measured concentrations measured at 10 m from the pile.

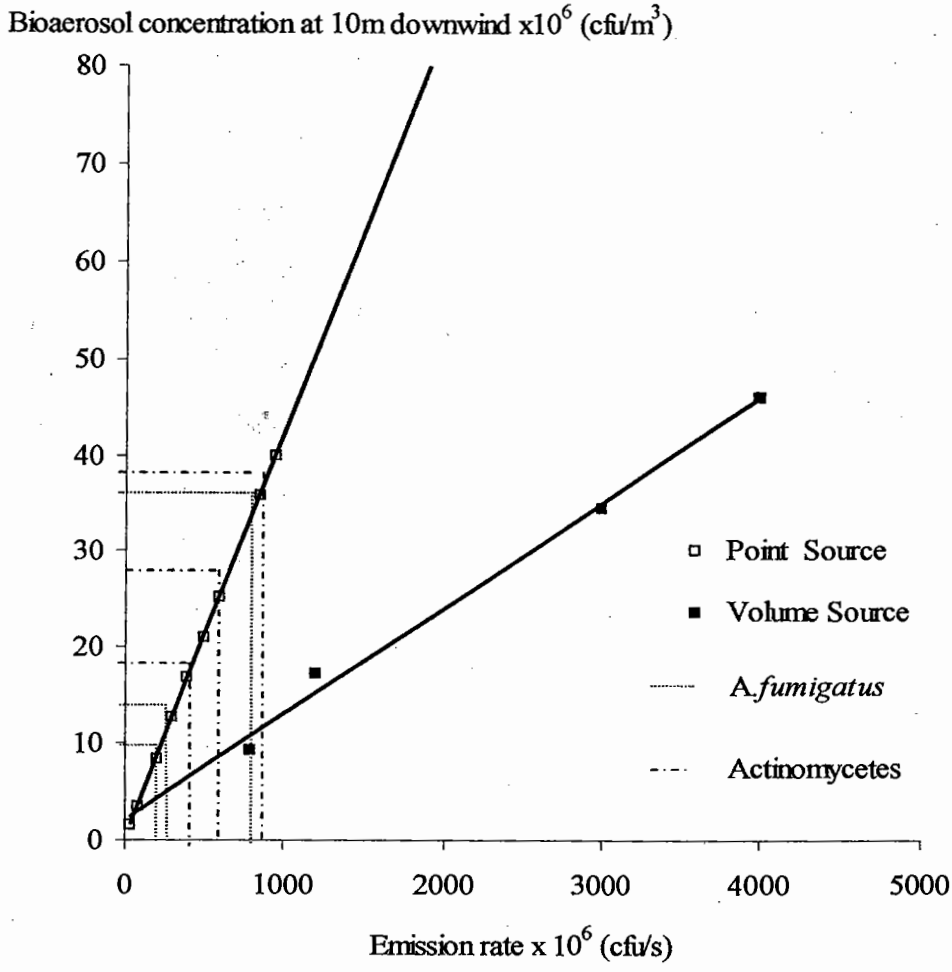


Figure 4.19: Emission rates are estimated by a back-extrapolation of the SCREEN3 point source term model, matching the measured concentration at 10m with correlating emission rates. Developed from data measured at Calvert Composting (Appendix II: Table II:V)

Figure 4.19 was used to back extrapolate the emission rate at source and used as an input in SCREEN3 for dispersion modelling. Several assumptions are implicit to this screening approach and the results must be considered carefully. It is assumed that the bioaerosol particles display Gaussian distribution in both lateral (crosswind) and vertical directions, that they are a continuous source, that wind velocity and direction are constant over the

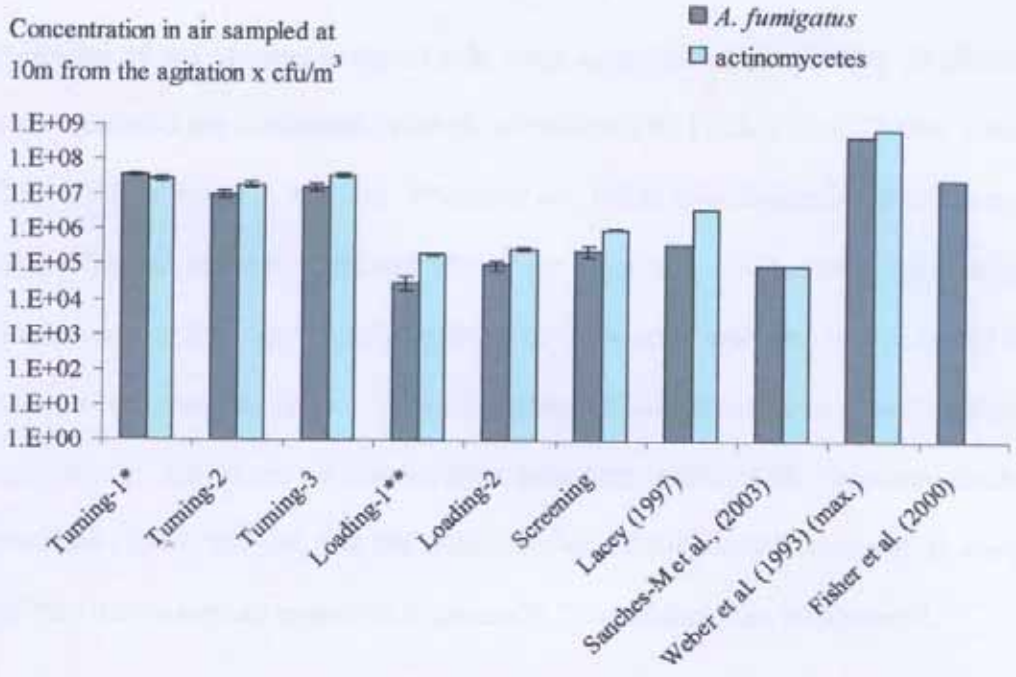


Figure 4.20: Bioaerosols concentration measured in air sampled close to the agitation activity at Calvert Composting and concentration reported by other earlier workers. Number 1, 2 and 3 represent the activity turning conducted consecutively within 45 minutes. The detail reading is in Table II.V
* samples were taken on 11/03/04 between 14.30 to 15.15;wind speed: maximum 3.92 m/s, mean=0.06m/s;temperature= 11°C sampling time= 15±1 minutes
**samples were taken on 23/03/04 between10.00-15.30; wind speed: maximum1.59 m/s, mean=0.08-0.54m/s during the whole period of sampling; temperature=16.3-19.3°C sampling time= 12 and 7 min (loading of mature screened compost onto the truck.

modelled time and distance, the modelled surface is relatively flat, the gravitational settling of particles is negligible, the particle and wind velocity are essentially the same and microbial inactivation is not considered. The practical effect of these assumptions at this screening level of assessment is to generate worst-case estimates of modelled bioaerosol depletion with distance. Measured bioaerosols concentrations are presented in Figure 4.20. The concentrations of *A. fumigatus* and thermophilic actinomycetes at 10 m

downwind of the agitated compost pile were in the range of 10^4 and 10^7cfu/m^3. The levels measured are comparable with those recorded by Fischer *et al.* (2000), which were 32 x 10^6cfu/m^3 for *A. fumigatus*. Weber *et al.* (1993) also reported a similar range of 1-500 x10^6cfu/m^3 and 0.6 – 800 x10^6cfu/m^3 for fungi and total bacteria, respectively. By comparison, our data are higher than those of some other workers. It is proposed that this is due to two principal factors: (i) the sampling of authentic source term data directly on compost pile; and ii) use of passive filter sampling in this work. Sanchez-Mondero and Stentiford (2003) suggest that the concentration of bioaerosols released at composting facilities during normal operation is generally 2-log higher than background.

Lacey (1997), during the dismantling of compost piles, recorded 4x10^6 cfu/m^3 and 4x10^5 cfu/m^3 for actinomycetes and fungi respectively, both sampled 10m downwind. Bioaerosol concentrations measured 10 m adjacent to active processing operations are 3-log higher than for passive release, confirming that mitigation should focus on minimising releases during compost turning. In this study *A. fumigatus* concentrations vary by 1-log between the three agitation activities and 3-log within turning and other activities. These variations are typical, the difference due to issues such as sampling technique (Eduard and Heederik,1998; Wheeler *et al.*, 2001), wind conditions, properties of the compost windrows (such as pile age and moisture content), and between-turn variations in the method used during agitation (Sanchez-Mondero and Stentiford, 2003). The estimation of emission rates and fluxes are critical to perform meaningful risk assessments at compost facilities as they dramatically affect the modelled downwind

concentrations estimated using air dispersion techniques. Back-extrapolation in this study resulted in *A. fumigatus* and actinomycetes emission rates of $10^4 - 10^9$ cfu/s (Figure 4.21).

By way of an order of magnitude comparison, the predicted release rate of *Salmonella* during the application of biosolids to land was measured as from 2-5 $x10^6$ cfu/s (Dowd *et al.*, 2000). These workers used a modified Pasquill equation in their dispersal modelling which incorporates a microbial inactivation factor. Inactivation is dependent partially on wind speed and travelling distance. Since our analysis is based on a bioaerosol

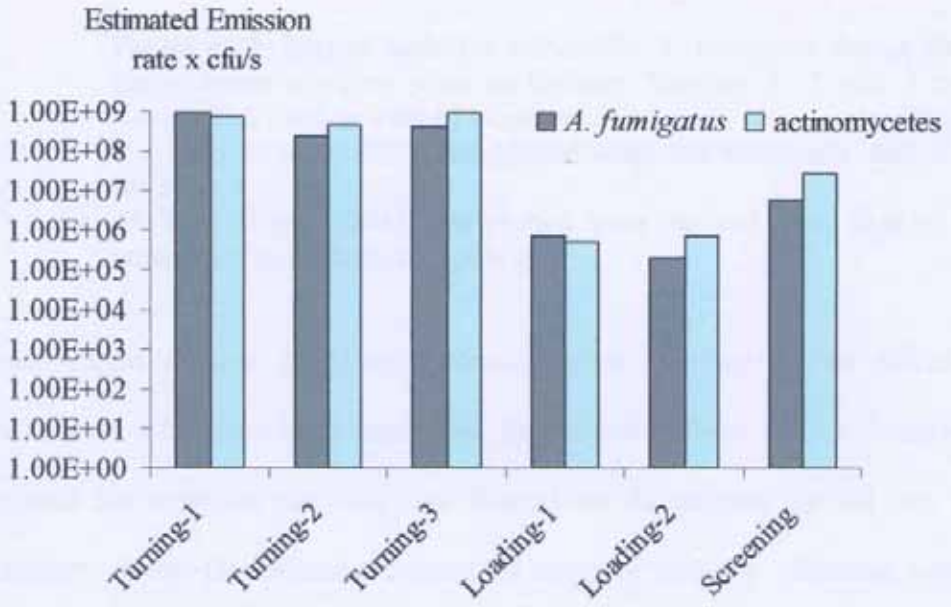


Figure 4.21: Estimated Bioaerosols emission rate from agitation activities (Table II.VI, appendix II). The values were derived by back-extrapolation using SCREEN3

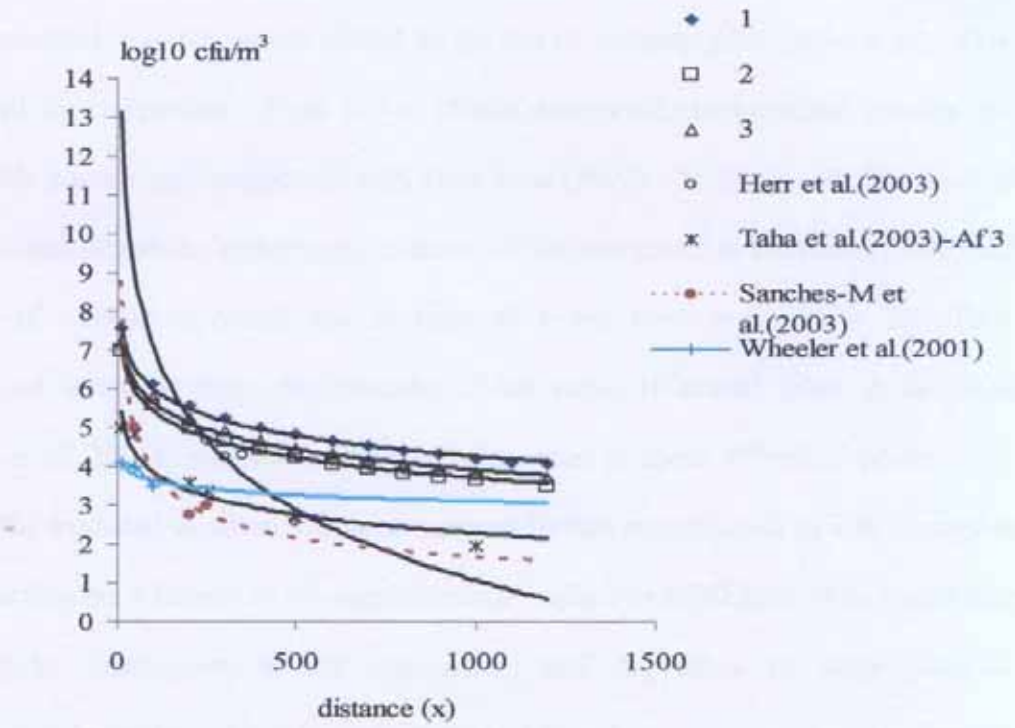


Figure 4.22: Source depletion curves for A. *fumigatus* during the turning of green waste compost piles at Calvert. Number 1, 2 and 3 represent the consecutive turning with 45 minutes.

* Herr *et al.* (2003) data plotted were the maximum data measured for moulds.

** Taha *et al.* (2004) data plotted were derived from fugitive bioaerosols emission flux of static compost pile.

concentration at 10m travelling distance, which is close to the source, microbial inactivation is assumed to be negligible. In addition to these factors, Swan *et al.* (2002) suggests the emission rate will also depend on the process carried out, the type of machinery used, the moisture content of compost and the microbial content of the material processed. Using the estimated emission rates in Figure 4.21, source depletion curves were derived for *A. fumigatus* (Figure 4.22).

The data reported by Herr *et al.* (2003) and the modelled data using fugitive emission fluxes generated in wind tunnels placed on the top of compost piles (Taha *et al.*, 2004) are plotted for comparison. From 200 to 1500m downwind, the modelled data are of a comparable pattern and magnitude with Herr *et al.*(2003). However, all three sets of modelled data deplete to background at about 1000m compared to Herr *et al.*(2003) and Taha *et al.* (2004) in which the background levels were achieved at 200-500m. Background levels of fungi are typically of the order 10^3cfu/m^3 (Herr *et al.* 2003; Wheeler *et al.* 2001c) and whereas for actinomycetes is about 10^2cfu/m^3 (Recer *et al.* 2001). The extended depletion distances warrant further investigation as it is reasonable to assume they are a feature of the simplifications implicit to SCREEN3. The model does not consider inactivation or the aggregation and deposition of large particles. Microorganisms are known to clump together and form large aggregates and are rapidly deposited on the ground. The viability of microorganism is dependent on various environmental factors such as air temperature, wind speed, humidity and exposure to the sunlight.

This research does show, however that the methodology can be used to estimate concentrations of bioaerosols in air close to composting facilities and at various distances downwind. The same approach can be deployed for other types of agitation, such as screening, shredding, loading-unloading and vehicle movements. Together with an emission rate analysis, the source of bioaerosols at composting facilities can be estimated and subsequently used to assess potential downwind exposures.

4.7 Dynamic Release: Carmarthen Composting

The dynamic release of bioaerosols was analysed by estimating the bioaerosol emission rate during different activities, and here, of different compost ages. The activities studied were shredding, turning and screening of the compost, similar to the sampling conducted in Calvert. However at this site, the windrow turner emission rate was also estimated. The concentrations of bioaerosol measured at *ca.*5-10m from agitation activities are shown in Figure 4.23. It is important to note that turning activity either by front-end loader or windrow turner is a moving activity in which compost is actively transferred in piles. The turning by front end loader is performed by scooping the compost pile and moving it to the adjacent row.

From the measurement data as shown in Figure 4.23, the emission rate was then estimated using SCREEN3 air modelling. The estimated emission rate is shown in Figure 4.24. Turning at this site recorded emission rates between 10^4 to 10^7 cfu/s where the maximum reading is lower than that estimated at Calvert by 2-log. The difference may be contributed by the methods of turning conducted in which Carmarthen was using a $1m^3$ front-end loader compared to a $3m^3$ front-end loader at Calvert or to relative moisture contents. The results show no significant emission rate difference between different ages of compost pile. However there is significant difference between activities, where turning by a front-end loader emitted the most bioaerosols, followed turning by a windrow turner, screening and shredding. Turning early stage compost released higher levels of bioaerosols compared with turning later stage compost. During the first weeks the

bioaerosols release rate during turning was between 10^4 and 10^7cfu/s compare with 10^4 to 10^6cfu/s for the turning of compost aged from 4 weeks to 16 weeks. A higher bioaerosols concentration in compost at the first 4 weeks of composting (Figure 4.9) may contribute to this observation.

Similarly, the source depletion curves were constructed based on agitation activity conducted at the site (Figure 4.25). Bioaerosols were estimated to reduce to background level at a distance of less than 1000m. However the estimated depletion distance is expected to be higher than that in practice because the modelling does not consider the clumping and inactivation effects. The comparison between modeled and measured data at 30m from the source (Figure 4.7) shows the difference to be about x2 for actinomycetes and x50 for *A. fumigatus*. However this observation was only based on one of the two samplings conducted in which the other one recorded a much lower reading.

4.8 Source depletion curves estimated from composting operations of varying tonnage.

An important process variable is the size (capacity) of the compost facility under study. Larger facilities offer larger source terms. The estimated emission rate from different sources can be used to make a prediction of bioaerosols dispersal from facilities of different size. The bioaerosols dispersal from fugitive release of a static compost pile was

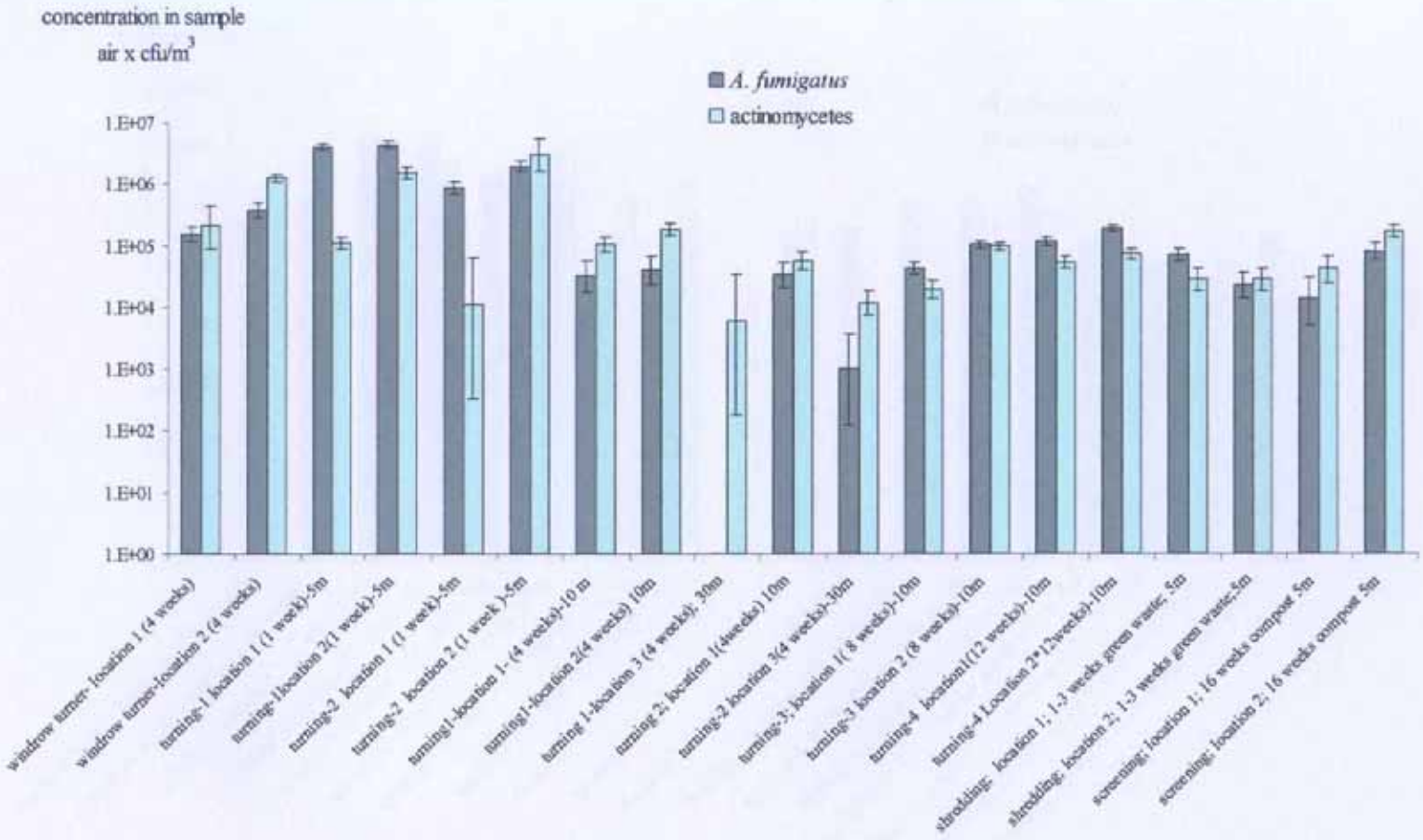


Figure 4.23: Bioaerosols concentration at 5m, 10m and 30m measured while agitation activities were taking place at Carmarthen

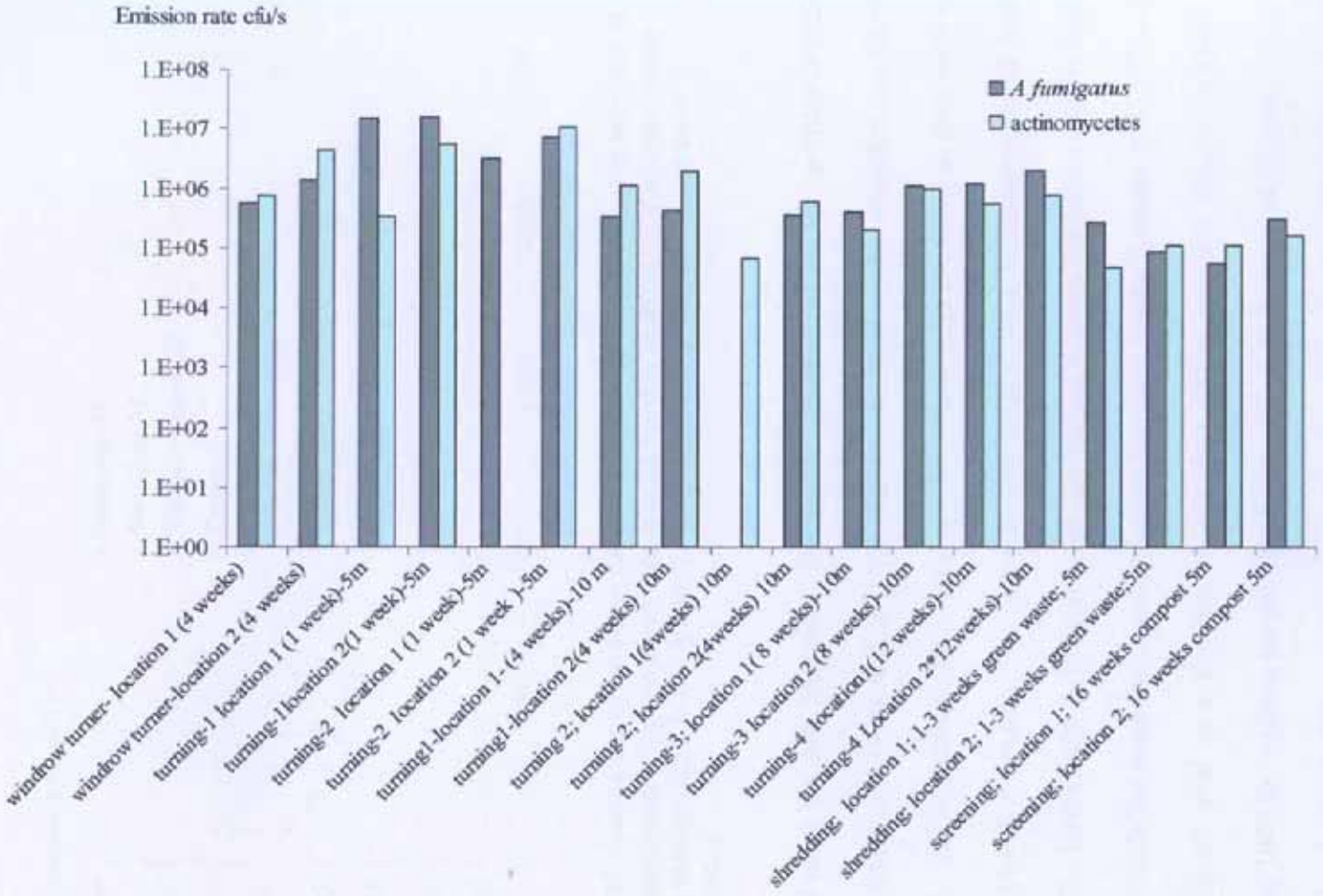


Figure 4.24: Bioaerosols emission rate of agitation activities estimated for Camarthen .

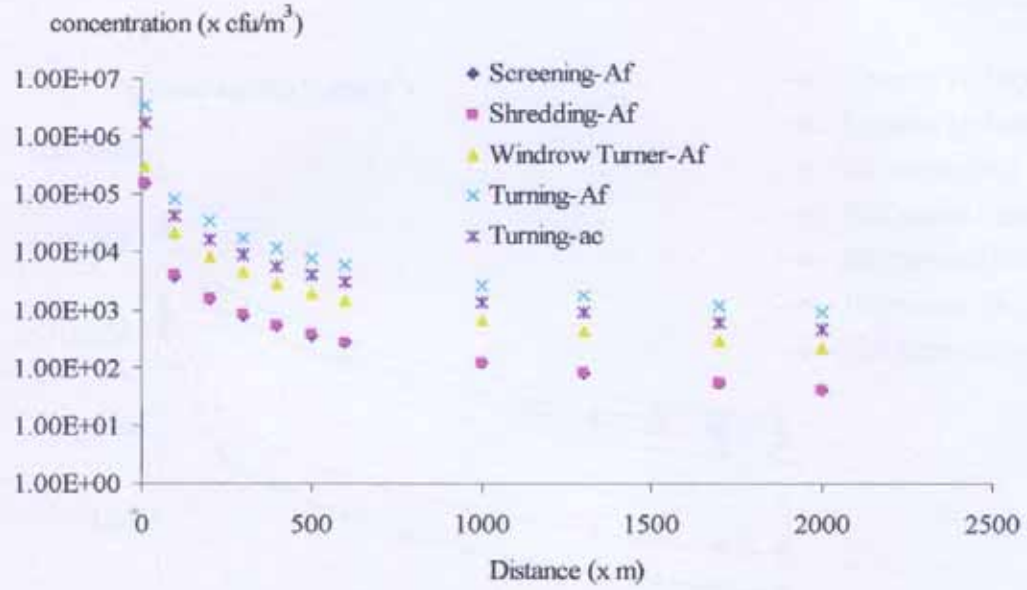


Figure 4.25: Source depletion curve bioaerosols emitted during agitation activities at Carmarthen Composting. Average data is used for this analysis. The actinomycetes release is also included in the graph (turning-ac). Af is *A. fumigatus* and ac is actinomycetes.

simulated using the data generated. The source depletion curves for facilities of different size are shown in Figure 4.26 and the dimensions used in the modelled are shown in Table 4.2. The receptor height used was 1.8m. Areas were modelled as plan view of the compost (width x length). The compost pile heights were considered as the point of release. The bioaerosols emitted from all operational tonnage capacities were reduced by distance. Modelled bioaerosols emitted from the three lowest tonnage piles had reduced to background level at a distance of less than 250 m whereas the two highest only reduced at 1000 m. Release height also has an effect on bioaerosol dispersal. Since the receptor level used in this analysis was 1.8m, the release height of 2m was estimated to cause more bioaerosols concentration at the receptor than 3m height

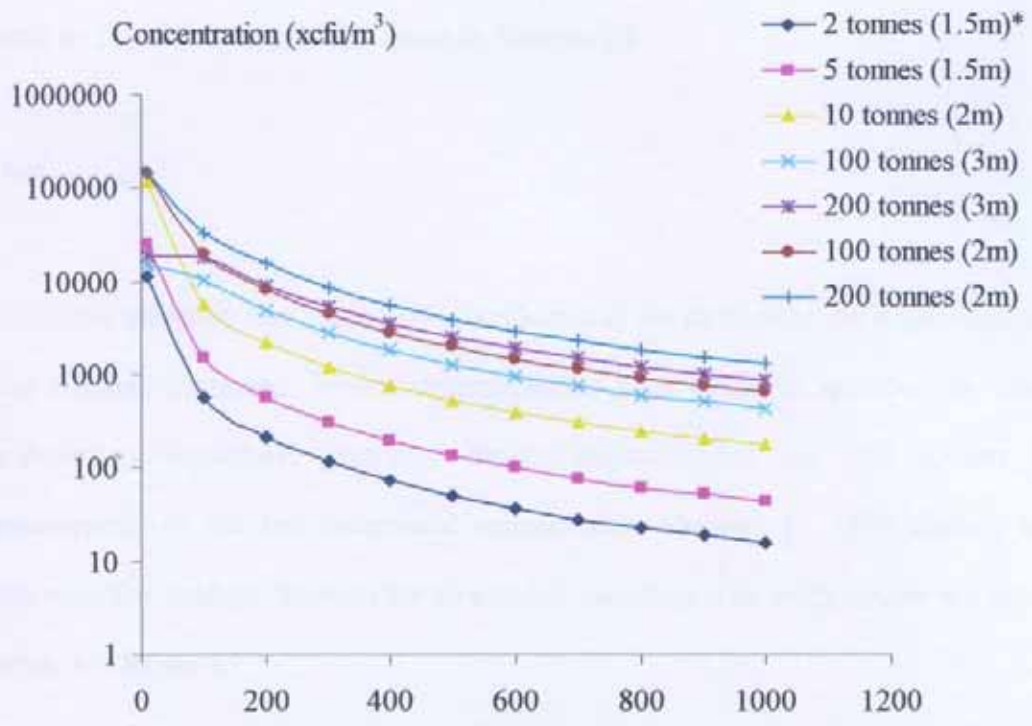


Figure 4.26: Bioaerosols dispersal from different tonnage operation capacity. Calvert weather conditions were used in this analysis.
* (2m) denote the compost height, point of release used in the simulation.

Table 4.2: Parameters and dimensions used in modelling of source depletion curve of Figure 4.26.

Operation Tonnage (ton)	Volume (m^3)	Wide (m)	Height (m)	Length (m)
2	5	1.5	1.5	2
5	12.5	2	1.5	4
10	25	2	1.5	4
100	250	5	3	16
200	500	5	3	16 x2
100	500	5	2	24
200	500	5	2	24x2

The compost density = 0.4 tonne/m^3

even with the same operation tonnage. The graphs that have the compost pile height of 3m show an increase of bioaerosol concentrations at distance close to the dispersal. This is due to a similar reason to that given in Section 4.4.

4.9 **Summary**

Bioaerosol sampling was successfully conducted at the three sites and bioaerosols source term releases estimated. Several improvements were made to increase the sampling methodology capability. However further improvements are still needed for a measurement of the low bioaerosol concentration samples (< 1000 cfu/m^3) and to determine the strategic location for downwind sampling. The study results are discussed further in Chapter 5.

CHAPTER 5 DISCUSSION

The availability and quality of the bioaerosol source term data is essential for quality risk assessments (Pollard *et al.*, 2005). Source term data is frequently unavailable or limited, in part because of the practical difficulties of microbiological analyses and cost constraints. This research (Taha *et al.*, 2004; 2005) focused on improving the quality of regulatory risk assessments for composting facilities by providing authentic source term data at the point of release, as compared to 50, 100 or 200 m downwind, where further data uncertainties abound because of transport phenomena. This is critical because bioaerosols deplete rapidly with distance from their source and measurements at distance (say >50 m and beyond) are far more difficult to authenticate as being from a specific operation or sub-process as opposed to other, non-compost sources.

In practice, most waste management operations generate episodic or periodic releases, as opposed to continuous release, due to factors such as their operational cycles (composting), the fluctuations in diurnal temperature that alter the characteristics of emissions (*e.g.* odour profiles), or the fluctuations in atmospheric pressure that dictate the initial releases of pollutants (*e.g.* landfill gas). Furthermore, with the integration of multiple waste processing technologies on single sites, there are often a number of sources contributing to a facility's 'source term'. This research has sought to understand the key contributing sources of bioaerosol releases at green waste composting facilities and, using rudimentary air dispersion analysis, characterise the depletion curves (log concentration with distance downwind) under static and active conditions in order to inform regulatory risk assessments. These data are of value to

regulatory agencies guiding operators on the requirements of regulatory risk assessment, to operators themselves and to their professional advisors, as well as the public living in the vicinity of such facilities. The work presented in this thesis is already seeing application within Environment Agency internal guidance for regulatory staff on the review of risk assessment submitted in support of environmental permitting.

In this work, an improved means of enumerating bioaerosols has been developed. This study has also successfully introduced a novel sampling method to measure the source term bioaerosol emission of green waste composting. The method is compatible with a high concentration bioaerosols environment. Two modes of source term were measured: static and dynamic. These parameters were then used to estimate the source depletion and its dispersal.

5.1 Analytical method development

As mentioned earlier in this thesis and stated by several researches (Swan *et al.*, 2003; Wheeler *et al.* 2001), measurement of composting bioaerosols in air is a complex task. This is due the fact that composting bioaerosols constitute a wide variety of microorganisms and particulate fragments. Most bioaerosol constituents are present in normal air, therefore it is extremely difficult to determine the source unambiguously. This research has successfully characterised the source term release for compost bioaerosols in order to further understand their dispersal. Since it is impossible to quantify all constituents of bioaerosols, the dominant microorganisms were chosen to represent the viable bioaerosols present in sampled air. *A. fumigatus*, which

represents more than 60% of fungi in composting bioaerosol (Wheeler *et al.*, 2001), and actinomycetes, the dominant bacteria in compost (Lacey, 1997), were chosen to represent the concentration of bioaerosols at source.

These methodological improvements represent a valuable step forward for improved bioaerosol enumeration. This finding is more significant for actinomycetes in which the use of compost agar produces an improved method for its isolation. The results presented here concur with those of Crawford *et al.*, (1993) who stated that actinomycetes prefer to grow in low organic nutrient media. The compost media discourages the eubacterial and fungal growth that otherwise mask the assay plates. Actinomycetes were successfully grown under these conditions and sporulated. The masking of the plate surface by eubacterial microorganisms retards the slow growing actinomycetes. The overcrowded and large size (>2mm) of bacteria growth could also reduce the efficiency of enumeration (Chang *et al.*, 1994). With the methodological improvement introduced here, this effect was minimized by serial dilution and the low organic nutrient provided by the compost agar. To our knowledge compost agar has not previously been used for the enumeration of bioaerosol actinomycetes, although it has been used, amongst other media, for isolating actinomycetes in rhizosphere studies (Crawford *et. al.*, 1993).

Use of the medium flow personal air filter for monitoring and quantifying the concentration of bioaerosols at source was successful. This conclusion is based on the numbers of samples that were successfully analyzed, despite some initial problems faced at the beginning of the sampling. One of the main problems was the intermittent flow of the sampling pump. This was caused by the damp vapor from the

compost pile. This problem was successfully solved by changing the filter to a 0.40 μm polycarbonate filter (SKC). However the use of filter sampling was less effective at low bioaerosol concentrations. Results showed that the range of confidence limit was extreme at bioaerosol concentrations < 1000 cfu/m3. Two improvements are suggested:

a) to improve microorganism viability, it is proposed to used a better solution for storing and re-suspension such as using peptone as one of the solution substances;

b) to improve confidence limits at low release sites, it is suggested to lengthen the sampling period to increase the number of microorganism collected, so that greater a confidence limit could be achieved; and

c) to increase the volume of sample to be inoculated from 100 μl to 200 μl.

5.2 Estimating release and flux

The bioaerosol sampling and analysis conducted in this study focused on determining source term bioaerosol emission and flux. Two approaches were selected to achieve that objective; static and dynamic bioaerosol release. The static release is represented by a specific bioaerosol emission rate ($SBER_2$), measured on top of the static compost pile. The dynamic release was estimated by extrapolation of concentration close to the source using a SCREEN3 air dispersal modelling approach.

5.2.1 Background concentration of bioaerosols

Background concentrations are difficult to predict on account of the many ambient sources of bioaerosols and aforementioned difficulties of sampling analysis. Wheeler *et al.* (2001) has suggested that the best available estimates for threshold limit values (a 'natural' background) for gram-negative bacteria, total bacteria and fungi in air are 300, 1 000 and 1 000 cfu/m^3 respectively though the scientific consensus is limited. Clearly, these are at or near the practical limit of detection.

Some bioaerosol risk assessments have used low (5 000 cfu/m^3), medium (10 000 cfu/m^3) and high (30 000 cfu/m^3) estimates of bioaerosol concentrations at proposed or existing facilities to represent source data for onward dispersion modelling. In this context, the ambient air concentrations of *A. fumigatus* (77 000 cfu/m^3) and actinomycetes (10 300 cfu/m^3) measured at Calvert Composting are high (Figure 4.6). This high value included contributions to the static release from incoming air. One feature of this research is that, on account of the direct source term measurements and improved capture and enumerations, the concentrations reported are often larger than those presented in the prior literature. This is attributed to the sampling technique.

5.2.2: Surface flux of static release

Research has shown that bioaerosols were released at rates in the range 10^3-10^4 cfu/m^2/s during static condition (Figure 4.11 and Figure 4.17). Bioaerosols release,

like fugitive dust emission, is dependent upon particle size, surface loading, surface conditions, wind speeds, atmospheric and surface moisture and the presence of dust suspending activities. Watson *et al.* (2000) suggest that wind speeds of more than 0.19 m/s have the capacity to elevate loose dust particles and transport them long distances. A wind tunnel analysis conducted, at a wind velocity (inside the tunnel) of 0.2 m/s, has shown that a significant amount of bioaerosol will be aerosolised and transported.

The analysis on air within 0.3m of the compost pile, conducted at Carmarthen, showed that the bioaerosols concentrations were between 10^3 and 10^4 cfu/m^3 (Figure 4.16) and were reduced with pile age. However this observation was not clearly shown by the surface flux analysis (Figure 4.17).

The dispersal of bioaerosols is subject to physical, meteorological and operational considerations. Meteorological characteristics at a site, in conjunction with topography, affect bioaerosol exposures of workers and the nearby public. Wind conditions and the height of the location or point of release of the facility determine the diffusion and distribution of bioaerosols over a spatial area and so where the intent is to maintain the mass of airborne material close to the facility, then composting facilities should be shielded from wind and preferably emit aerosols at low heights, or at elevations below surrounding sensitive areas. Diffusion models can be used to estimate the impact of composting emissions on sensitive receptors, but at present, only limited data are available to quantitatively evaluate the effectiveness of process operational characteristics on the bioaerosol emission flux (Taha *et al.* 2005). This research provides improved source term data for these exposure estimates.

There are several important sources of analytical and methodological uncertainty in quantifying these agents and wind tunnel experiments may add an additional source of model artefact to the analysis. Nevertheless, these initial data allow quantification of fugitive bioaerosols release at source above static compost windrows and an estimation of source depletion with distance for comparison with other literature studies. These data must be interpreted in the context of their acquisition. Calvert data were acquired during normal operations in which waste unloading, shredding, windrow piling and turning were concurrent. We were unable to interrupt normal operations during the sampling period to specifically disaggregate ambient contributions from windrows from associated activities at the site.

5.2.3 Dynamic release

During conventional compost processing, agitation activities, such as screening, shredding and the turning of waste and compost, result in episodic bioaerosol releases to air (Millner *et al.*, 1980). The agitation of green compost windrows may result in airborne fungi and bacteria levels averaging 10^4 - 10^7 cfu/m^3 (Lacey, 1997; Wheeler *et al.*, 2001; Recer *et al.*, 2001). In contrast, static compost windrows typically emit bioaerosols at concentrations of 10^3 cfu/m^3 for actinomycetes and *A. fumigatus* (Taha *et al.*, 2005).

Bioaerosol emission rate and dispersal is influenced by a number of factors, including (Swan *et al.*, 2002) (i) the materials being composted; (ii) the on-site processes involved; (iii) the associated vehicle movements; (iv) the process equipment used; (v)

individual bioaerosol properties; and (vi) the geographical, topographical and meteorological conditions on- and off-site.

In previous studies (Taha *et al.*, 2005), and in order to determine the most appropriate mode of dispersal during agitation, this research has treated bioaerosols as a fugitive, continuous large point source for which both area and volume type release modes have been considered. Both sets of assumptions are acknowledged to be gross simplifications of the reported behaviour of bioaerosols, characterised by total protein and culturable microorganisms (Borodulin *et al.*, 2005). This research did not encapsulate the characteristic aggregation (so-called 'clumping') behaviour of bioaerosols emitted at composting facilities or account for microbial inactivation within the air column following release. Bioaerosols settle by a gravitational force and the settlement rate is dependent on its size; for example to settle 0.01 m of micro organism associated with mouldy hay takes about 10s for large fungal spore, 34s for small fungal spore such as *A fumigatus*, 48s for bacterial cells and 91s for actinomycetes (Crook, 1995).

This study has reported net *A. fumigatus* concentrations in air (passive) sourced directly from static compost windrows of 19 and 28 $x10^3$ cfu/m^3 and modelled concentrations 10m from compost windrows of 61 and 102 $x10^3$ cfu/m^3 (Taha *et al.*, 2005) and this was further discussed in section 5.2.5. The increase of bioaerosols levels immediately downwind of an actively agitated compost pile is reported elsewhere and known to dissipate to background levels about 15 minutes after the agitation ceases (Millner *et al.*, 1980). Kothary *et al.* (1984) reported a concentration range for *A. fumigatus* of 2 - 4 $x10^3$ cfu/m^3 close to the compost pile, with

concentrations declining to less than 50 cfu/m^3 at a distance of 250 m from the site. Similarly, Danneberg *et al.* (1997) reported concentration of 2 x10^3 cfu/m^3 for *A. fumigatus* near the source.

In general, however, the recorded concentrations in this research are within the broad range reported by Wheeler *et al.* (2001), which cites that during shredding, turning and screening, fungi and bacterial counts are typically in the range of 10^3 – 10^7 cfu/m^3. Sanchez-Monedero and Stentiford (2003) suggest that the concentration of bioaerosols released at composting facilities during normal operations are generally 10^2 higher than background levels.

One complication is that many studies only report figures for fungi and total bacteria, which makes direct comparisons difficult. For example, Weber *et al.* (1993) reported a range of 1 - 500 x 10^6cfu/m^3 and 0.6 – 800 x 10^6cfu/m^3 for fungi and total bacteria, respectively. Herr *et al.* (2003) reported concentrations of total moulds of 1.3 x 10^5 cfu/m^3 at 200 m downwind of a composting site. Clearly, as illustrated by this research, the distance should always be taken into account when analysing results from different studies. The discrepancies highlight the need for guidance on bioaerosol sampling and monitoring. This said, a 3-log difference between passive and active bioaerosol concentrations measured at source is an important finding for regulators and risk analysts.

5.3 Source depletion curves

Source depletion curves of surface static release and dynamic release of agitation activities were developed based on the estimated emission generated from sampling and air dispersal modelling (Figures 4.12, 4.13 and 4.18). These represent modelled curves based on emission flux from an authentic site. The interest in this work is in the extent of depletion with distance by reference to the current regulatory 'trigger' distance of 250 m, used as a distance below which regulatory risk assessments are being required in England and Wales. Based on the measured data the source depletion curves for the static windrows of varying geometries were drawn (Figure 4.22). The higher tonnage compost piles produce higher emissions that take longer to reduce to background concentrations when modelled using SCREEN3. The initial bioaerosol concentrations that approach 10^5cfu/m^3 (Figure 4.22) warrant discussion. For static samples, these are a combined feature of the direct sampling method employed and the initial rise in modelled concentrations noted above. These concentrations are generally in excess of those measured close to the source by others and arguably represent a 'first flush', though this has not been substantiated in this study. For the active sampling initial results (Figures 4. 16 and 4.17), use of personal aerosol filter samplers is known to provide bioaerosol estimates up to 10x those sampled using Anderson samplers (Wheeler *et al.*, 2001; Taha *et al.*, 2005). Stetzenbach *et al.* (2004) for example suggest this is because high impact samplers reduce the viability of bioaerosols captured directly onto agar gel. In this study, we have sampled much closer to agitation activities (*ca.* 10 m distance from agitation operations) than in studies previously reported (typically 50- 250 m), in an attempt to gather authentic source term data for subsequent risk assessment.

For the turning operations in Figure 4.20, modelling was extended to 2000 m from the source term and undertaken in triplicate (Figure 4.25). Depletion to background concentrations of 10^3cfu/m^3 (Wheeler *et al.*, 2001) of the bioaerosols released during turning occurs rapidly with distance from this facility (*ca.* 100 m). Here, the data appear to corroborate the use of a generalised 'trigger' distance of 250 m as a conservative limit, below which, quantitative bioaerosol risk estimates are required for compost facilities in close proximity to housing (Environment Agency, 2001). For the site in this study and the data presented here, *A. fumigatus* concentrations released during turning operations appear to have depleted significantly by this distance to background concentrations.

All tonnages represented in Figure 4.22 reduce steadily with distance from the source. By 250 m downwind, the three lowest tonnage piles have reduced to background concentrations (10^3 cfu/m^3). The highest tonnage pile does not reach this level within the 1000 m distance modelled; hence there are implications here for very large scale facilities where 'trigger' distances might be revised. However this single study at Calvert is insufficient evidence alone for this and at authentic sites, rather than modelled ones, it will be important to consider the combined releases from multiple compost piles rather than those from a single surface. Nevertheless, these results show the importance of considering the amount of compost processed and the pile height when requiring and undertaking a risk assessment.

Another aspect that needs to be understood is that the SCREEN3 model is estimating the bioaerosol dispersal plume in which the plume size is represented by "z" and "y"

in the SCREEN3 output. Its size is much dependent on height of release and weather conditions (Turner, 1994). Therefore the concentration estimated is the concentration within the plume. It is difficult to accurately locate the bioaerosol sampler within the plume for off-site measurement.

5.4 Pilot study in Carmarthen

Similar analyses were conducted at Carmarthen Composting as a pilot to study the source emission term of a composting facility. The source terms were studied using the approach developed at Calvert. Bioaerosol releases were estimated and source depletion curves developed as shown in Figures 4.13 and 4.17. This information could be used in risk assessment of a composting facility within 250 m. The surface emission flux could be used for estimation of continuous release and dynamic release of agitation processes for episodic release. Aggregation of these source terms together with other sources (background) could be used to estimate the change of bioaerosol concentration downwind.

Analysis showed that turning using a 1 m^3 front-end loader is the main generator of bioaerosols compared with other sources. It generated an average of $4x10^6$cfu/s over a period of 30-60 min. A source depletion curve developed for these activities shows that the bioaerosols level does not reduce to background level at 250 m distance. As discussed earlier, the modeled data is conservative in which the clumping and viability aspect of bioaerosols is not considered (Figures 4.13 and 4.17). The closer relationship between measured and modeled data of actinomycetes may be accounted for by their small size compared to *A. fumigatus*. This study also shows that the use of

a windrow turner could reduce the emission rate and its dispersal capacity by four times that of turning by a front-end loader. Other activities were shown not to cause a significant rise of bioaerosol concentration at 250 m downwind.

5.5 Contribution to knowledge

This research has contributed to several aspects of bioaerosol generation parameters and their dispersal at distance less than 250 m from composting facilities. The determined parameters can be used to estimate bioaerosol concentrations off-site.

5.5.1 Source term characterisation

Two source terms of bioaerosols were characterised; static surface emission and dynamic release. Both source terms could be quantified for used in air dispersal modelling. The static surface emission was identified by a wind tunnel analysis and the dynamic release by measuring the bioaerosols strength close to source. Bioaerosols properties and the air modelling principles have to be taken into account when interpreting model data. The concentration of bioaerosols in the close proximity to composting could be estimated for a risk assessment analysis. Identifying the main bioaerosol contributors and their release patterns could facilitate the mitigation measures.

5.5.2 Methodological improvements

Use of low organic nutrient compost extract agar improved the isolation and enumeration of actinomycetes. It could prevent over size and masking of bacteria growth that could reduce the accuracy of enumeration. Compost is easily available which means that the cost of analysis will be reduced, therefore facilitating the analysis of more samples.

5.5.3 Sampling improvement

Personal air sampling loaded with a 0.80 μm polycarbonate filter was successfully used for measuring the bioaerosols in a high concentration environment. The sample could be diluted for better enumeration and repeat sampling could be conducted. The polycarbonate filter does is not damaged during autoclaving and is suitable for use in analysis of damp vapour samples.

5.5.4 Source depletion curve

The source depletion curve generated by SCREEN3 could be used for regulatory risk assessment. It could be a starting point or as a reference for quantifying the bioaerosol dispersal. From that, other information or factors could be deployed for improvement of the depletion curve. For example, the settlement by size, inactivity by heat, reduced humidity and light. The significant difference of off-site measured data reported by numerous of researcher is a clear indication of the measurement difficulty.

5.6 Limitations of the study

Notwithstanding the contributions summarised above, this research has indicated several limitations to bioaerosol analysis. The sampling process required is lengthy and needs to be caréfully performed to ensure no contamination. A lot of handling and transferring of samples is involved and an autoclaved filter cartridge had to be placed into the IOM sampler head and be removed once the sampling was completed, followed by preparation of sample dilution and re-suspension of bioaerosols in the dilution solution. Caution has to be taken not to touch the equipment and only use sterilised utensils.

In a low bioaerosols environment, the filter sampler is not effective unless a longer period of sampling is conducted. This will limit the number of samples taken at a site. Furthermore, longer sampling periods could harm the microorganisms by drying. All-glass impingers are more suitable for low bioaerosols concentrations and as liquid is used, longer sampling periods are possible.

Since the analysis has to be conducted within 24 hours, long distances between the analytical laboratory and sampling site could cause a problem. Some samples that could not be analysed within that period must be stored below 4^0C.

The wind tunnel received the wind from a fixed speed rotating fan, therefore the wind speed could not be varied for experimental purposes. The long hose had to be properly arranged to ensure enough wind could be blown into the tunnel. The wind

velocity had to be closely monitored to ensure continuous wind flow and at the same the system needed to be checked for leaks.

SCREEN3 is a conservative air dispersal modelling and more accurate estimation was not within the scope of this study. The deployment of more sophisticated air dispersal modelling that could address some of bioaerosols properties, such as non-gaseous behaviour, clumping and inactivation which could improve the estimation.

This analysis was conducted on viable bioaerosols and they are only a part of a wider bioaerosols constituent. Therefore the results presented in this study are only for *A. fumigatus* and actinomycetes not other parameters as explained in Chapter 1.

CHAPTER 6 CONCLUSION

6.1 Research conclusion

The study conducted has achieved the objectives set to improve the understanding and methods of characterising bioaerosol releases from composting facilities. It will facilitate the risk assessment analysis of composting facilities, especially the need to quantify the bioaerosols concentration within 250 m of the composting facility. Several conclusions were arrived at based on the results and experience of the study.

The role of composting in waste management will continue to rise in line with environmental and regulatory requirements toward creating an environmentally sustainable society and surroundings. The siting of composting facilities requires a regulatory risk assessment analysis to ensure the development and operation of composting do not pose harm to the population and environment. For the completion of risk assessment, an effective method for identification and quantification of hazard are crucial.

Composting provides an environment conducive for *A. fumigatus* and actinomycetes, both known to be health concerned microorganisms, to proliferate in huge amounts. In an appropriate condition *A. fumigatus* and actinomycetes could be aerosolised and transported by the wind as bioaerosols. *A. fumigatus* and actinomycetes are known to be associated with several health concerns.

An IOM air sampler loaded with a 0.8μm polycarbonate filter is compatible with the measurement of bioaerosols in high concentration areas such as for source term emission study. The sample could be diluted to the appropriate dilution for a statistically better enumeration. Actinomycetes could be grown on soil compost agar media for enumeration. The low organic nutrient of soil compost evades the plate masking, size overgrowth and the growth of other microorganism.

Bioaerosols are released by a static surface emission flux and dynamic emission during agitation. The static surface emission flux can be quantified using wind tunnel analysis whereas dynamic emission is quantified by extrapolation of SCREEN3 air modelling and close-proximity measured concentration respectively.

Static surface bioaerosols emission fluxes measured from the analysis ranged from 10^2 to10^4 cfu/m^2/s for A. *fumigatus* and similarly for actinomycetes. The wide range in emission flux release could be caused by several factors such as wind velocity and the rate of steam cloud and gases release. However, further study is needed to verify these and determine other factors.

The estimated dynamic release from turning ranged from 10^4 to 10^8cfu/s whereas other activities (shredding, loading and screening) ranged from 10^4 to 10^6cfu/s. However, the methods of turning emitted different emission rates, where the bigger capacity front-end loader produced the highest.

The source depletion curve developed shows that, although high concentrations of bioaerosol were emitted at source, the concentration is rapidly reduced with distance. This is in line with other work and the sampling conducted.

The SCREEN3 analysis using the measured data could be used to estimate the bioaerosol dispersal. However one has to be cautious in interpreting this data because of the fact that bioaerosol properties are more complex than gases or particulate matter. Quantifying the rate of bioaerosols deposition and inactivation and introducing that to the modelling could improve the bioaerosols dispersal estimation.

The method developed could be used to quantify the bioaerosols dispersal for improved risk assessments analysis within 250 m of a composting facility required by the regulatory authority. Better estimation and measurement of bioaerosols concentration within this area could be used in dose-response study of health risk.

6.2 Future work

Considerable future work is suggested to improve the method and explore other aspects of composting bioaerosols.

a) To determine and quantify the rate of composting bioaerosols deposited while transported in the air. This could be done by a settling plate technique and a better method for measuring the ambient bioaerosols in the composting

vicinity. The ambient air could be measured by all-glass impingers with a longer period of time; 1 hour and 8 hours. The rate of bioaerosols deposited during dispersion is crucial for improved air modelling.

b) To determine, by this method, the dispersal of other bioaerosol constituents such as endotoxin, mycotoxin etc. Some of these agents may pose health concerns and having a gaseous property, they could be transported further.

c) To study the correlation between composting particulate dispersal and bioaerosols. This correlation could be used for rapid bioaerosols estimation.

d) To use the developed methodology in the risk assessment of a composting facility.

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APPENDIX 1 CONFIDENCE INTERVAL LIMITS FOR ESTIMATED COUNT

Table A.1- Counting from one Petri dish

Number of microorganisms[a]	Confidence limit at 95 % level		Percent error for the limit [b]	
	Lower	Upper	Lower	Upper
1	<1	6	-97	+457
2	<1	7	-88	+261
3	<1	9	-79	+192
4	1	10	-73	+156
5	2	12	-68	+133
6	2	13	-63	+118
7	3	14	-60	+106
8	3	16	-57	+97
9	4	17	-54	+90
10	5	18	-52	+84
11	6	20	-50	+79
12	6	21	-48	+75
13	7	22	-47	+71
14	8	24	-45	+68
15	8	25	-44	+65

[a] Equal to the number of colonies.
[b] Compared to the microorganism count (1st column).

Table A.2- Counting from two Petri dishes

Number of colonies	Number of Microorganisms	Confidence limit at 95% level		Percent of error for the	
		Lower	Upper	Lower	Upper
1	1	<1	3	-97	+457
2	1	<1	4	-88	+261
3	2	<1	4	-79	+192
4	2	1	5	-73	+156
5	2	1	6	-68	+133
6	3	1	6	-63	+118
7	4	2	7	-60	+106
8	4	2	8	-57	+97
9	4	2	9	-54	+90
10	5	2	9	-52	+84
11	6	2	10	-50	+79
12	6	2	10	-48	+75
13	6	2	11	-47	+71
14	7	4	12	-45	+68
15	8	4	12	-44	+65
16	8	5	13	-43	+62
17	8	5	14	-42	+60
18	9	5	14	-41	+58
19	10	6	15	-40	+56
20	10	6	15	-39	+54
21	10	6	16	-38	+53
22	11	7	17	-37	+51
23	12	7	17	-36	+50
24	12	8	18	-36	+49
25	12	8	18	-35	+48
26	13	8	19	-35	+47
27	14	9	20	-34	+46
28	14	9	20	-34	+45
29	14	9	21	-33	+44
30	15	10	21	-32	+43

APPENDIX II DATA OF BIOAEROSOL ANALYSIS- CALVERT

Table II.I: Bioaerosols concentration in ambient air at various locations

sampling location	*A. fumigatus* x 10^3 cfu/m^3	confidence limit x % max.	confidence limit x % min.	actinomycetes x 10^3 cfu/m^3	confidence limit x % max.	confidence limit x % min.
Upwind 11/3/04	<1	NA	NA	<1	NA	NA
Upwind 23/3/04	16	56	-41	53	26	-21
.Inside 26/10/03	22	192	-79	5	457	-97
Inside 10/11/03	77	9	-8	10	27	-21
Downwind 23/3/04	17	54	-39	100	18	16
Downwind 11/3/04	2	457	-97	33	34	-25
Downwind 11/3/04 (activity)	85	25	-20	52	33	-25
Parking (200m) 25/5/04	2	457	-97	2	457	-97
Housing (300m)25/5/4	0	0	0	0	0	0

Mean wind velocity and temperature; 26/10/03;1.5 m/s and 10^0C: 10/11/03; 1.0 m/s and 12^0C: 11/03/04; 0.4 m/s and 6^0C: 23/03/04; 0.2 m/s and 17^0C, respectively. NA (not vailable)

Table II.II: Bioaerosols Concentration in Compost Soil

compost sample	moisture content	*A. fumigatus* x 10^6 cfu/g-dry weight	confidence limit x % max.	confidence limit x % min.	actinomycetes x 10^6 cfu/g-dry weight	confidence limit x% max.	confidence limit x% min.
Wind tunnel 1	55	80	106	-60	100	27	-21
Wind tunnel 2	50	10	84	-52	76	19	-16
Wind tunnel 3	52	40	97	-57	160	58	-41
Turning1	56	8	93	-45	70	21	-17
Turning 2	49	100	77	-42	120	24	-19
Turning 3	48	8	34	-25	17	16	-14
Screening	47	2	261	-88	36	35	-26

Table II.III: The summary of bioaerosol concentration measured from various air samples of wind tunnel analysis at Calvert composting facility.

	***A fumigatus* concentration in sample**			**actinomycetes concentration in sample**		
	x 10^3 cfu/m^3	**confidence limit**		**x 10^3 cfu/ m^3**	**confidence limit**	
Sampling Date: 11/10/2004		**max. x%**	**min. x%**		**max. x%**	**min. x%**
blank (fit into sampling head without running the pump)	<1	NA	NA	<1	NA	NA
incoming air; air filtered by carbon as carrier in wind tunnel; air velocity at host out let is 8m/s	1	97	-57	1	90	-54
ambient, background (inside facility); 1m from compost pile-down wind, 1.8m above ground; ambient air velocity 1 m/s; temperature 17 ^{0}C	77	9	-8	10	27	-21
wind tunnel - location 1, located at the top of outlet mixing chamber; ; air velocity 2.0 m/s	35	31	-24	56	25	-20
wind tunnel - location 1 ; located at the bottom of outlet mixing chamber; air velocity 2.0 m/s	3	133	-68	6	97	-57
wind tunnel - location 2 ; located at the top of outlet mixing chamber; air velocity 1.9 m/s*	PM	NA	NA	PM	NA	NA
wind tunnel - location 2 ; located at the bottom of outlet mixing chamber; air velocity 1.9 m/s*	PM	NA	NA	PM	NA	NA
wind tunnel - location 3 ; located at the top of outlet mixing chamber; air velocity 1.9 m/s	54	39	-28	100	29	-22
wind tunnel – location 3 ; located at the bottom of outlet mixing chamber; air velocity 1.9 m/s	4	192	-79	32	33	-25

* not able to determine the pump running time because the pump malfunction (PM); filter was tainted with soil. NA(not available)

Table II.IV: Measured bioaerosol data and estimated specific bioaerosol emission flux rate for fugitive release

sample and location	**mean wind speed x m/s**	**mean air velocity (m/s) mixing chamber**	**air velocity inside wind tunnel (m/s)**	**net bioaerosol in carrier air x10^3 cfu/m^3**		**$SBER_1$ x10^3 cfu/m^2/s**		**$SBER_2$ x10^3 cfu/m^2/s**	
				Af	**Ac**	***Af***	**Ac**	***Af***	**Ac**
ambient, background; 1m from compost pile-down wind, 1.8m above ground	1			77	10	NR-	NR	NR	
incoming air; air filtered by carbon as carrier in wind tunnel	*ca.* 3			1	1	-			
wind tunnel - location 1; located at the top and bottom of outlet mixing chamber	1	2.0	0.2	19	30	4	6	8	13
wind tunnel - location 3; located at the top and bottom of outlet mixing chamber	0.8	1.8	0.2	29	56	5	11	11	22

*wind tunnel 2 data invalidated due to pump malfunction; 2 *Af, Aspergillus fumigatus*; Ac, actinomycetes)

$SBER_1$; specific bioaerosols emission rate generated inside the wind tunnel.

$SBER_2$; specific bioaerosols emission rate generated under

Table II.V. Bioaerosols concentrations 10m downwind of green waste compost piles during 3 successive turning events, 15 minutes apart.

sample	***A. fumigatus***			**actinomycetes**		
	x10^3 cfu/m^3	**confidence interval %**		**x10^3 cfu/m^3**	**confidence interval %**	
		max (+)	**min (-)**		**max (+)**	**min (-)**
Turning-1*	37 000	13	12	28 000	15	13
Turning-2	9 800	27	21	19 000	19	16
Turning-3	16 000	22	18	36 000	15	13
Loading-1**	30	57	36	200	19	16
Loading-2	100	40	28	300	22	18
Screening	250	51	33	1 100	22	18
Upwind	10	55	35	20	26	21
Downwind	20	47	32	100	18	16

* samples were taken on 11/03/04 between 14.30 to 15.15
wind speed: maximum 3.92 m/s, mean=0.06m/s.
temperature= 11°C
sampling time= 15±1 minutes

**samples were taken on 23/03/04 between10.00-15.30
wind speed: maximum1.59 m/s, mean=0.08-0.54m/s during the whole period of sampling
temperature=16.3-19.3°C
sampling time= 12 and 7 min (loading of mature screened compost onto the truck)

Table II.VI: Estimated emission rate

Sample	*A. Fumigatus*		Actinomycetes	
	Concentration at 10m from source (x10^{6}cfu/m^3)	Estimated emission rate at source (x10^{6}cfu/s)	Concentration at 10m from source (x10^6/cfu/m^3)	Estimated emission rate at source (x10^{6}cfu/s)
Turning-1	36.8	890	28.2	700
Turning-2	9.8	240	18.9	480
Turning-3	15.9	395	36.0	860
Loading-1	0.03	0.7	0.02	0.5
Loading-2	0.01	0.2	0.03	0.7
Screening	0.25	5.9	1.1	26.1

wind tunnel and bioaerosols	wind speed at 1.8 m (m/s)	wind speed at 10m	Pasquill stability	Concentrations estimated by SCREEN3 at various distances (m) from compost windrow x 10^3 cfu/m^3 (1 hour average)								
				1 m	10 m	30 m	50 m	100m	200 m	250 m	500 m	1000 m
1 (Af)	1	1.33	A-B (1)	57.8	61.3	66.3	39.5	9.3	2.2	1.4	0.3	0.05
1 (Ac)				91.3	96.7	104.7	62.3	14.8	3.7	2.2	0.5	0.07
3 (Af)	0.8	1.06	A-B (1)	97.1	102.9	111.3	66.2	15.5	3.7	2.4	0.5	0.09
3 (Ac)				189.8	201.2	217.5	129.5	30.4	7.3	4.6	0.8	0.18

Table II.VII: Estimated bioaerosol dispersal downwind of facility using SCREEN3. This table was derived using SCREEN3 air modelling and the sample of it running programme is shown in Appendix IV.

Table II.VIII: Sample of modelling output by SCREEN3 analysis for area mode fugitive emission.

```
****** SCREEN3 MODEL ******
**** VERSION DATED 96043 ****

ENTER TITLE FOR THIS RUN (UP TO 79 CHARACTERS):
Bioaerosol Dispersal Estimated From Wind Tunnel Analysis: Culvert

ENTER SOURCE TYPE: P   FOR POINT
                   F   FOR FLARE
                   A   FOR AREA
                   V   FOR VOLUME
  ALSO ENTER ANY OF THE FOLLOWING OPTIONS ON THE SAME LINE:

    N   - TO USE THE NON-REGULATORY BUT CONSERVATIVE BRODE 2
          MIXING HEIGHT OPTION,
    nn.n - TO USE AN ANEMOMETER HEIGHT OTHER THAN THE REGULATORY
          (DEFAULT) 10 METER HEIGHT.
    SS  - TO USE A NON-REGULATORY CAVITY CALCULATION ALTERNATIVE
  Example - PN 7.0 SS (entry for a point source)

  ENTER SOURCE TYPE AND ANY OF THE ABOVE OPTIONS:
a
ENTER EMISSION RATE (G/(S-M**2)):
8300
ENTER SOURCE RELEASE HEIGHT (M):
2
ENTER LENGTH OF LARGER SIDE FOR AREA (M):
80
ENTER LENGTH OF SMALLER SIDE FOR AREA (M):
20
ENTER RECEPTOR HEIGHT ABOVE GROUND (FOR FLAGPOLE RECEPTOR) (M):
1.8
ENTER URBAN/RURAL OPTION (U=URBAN, R=RURAL):
r
SEARCH THROUGH RANGE OF DIRECTIONS TO FIND THE MAXIMUM?
ENTER Y OR N:
y
ENTER CHOICE OF METEOROLOGY;
1 - FULL METEOROLOGY (ALL STABILITIES & WIND SPEEDS)
2 - INPUT SINGLE STABILITY CLASS
3 - INPUT SINGLE STABILITY CLASS AND WIND SPEED
3
ENTER STABILITY CLASS, 1(=A) TO 6(=F):
1
ENTER ANEMOMETER HEIGHT WIND SPEED (M/S):
1.33
USE AUTOMATED DISTANCE ARRAY? ENTER Y OR N:
y
ENTER MIN AND MAX DISTANCES TO USE (M):
10
1000

*********************************
*** SCREEN AUTOMATED DISTANCES ***
*********************************

*** TERRAIN HEIGHT OF    0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES
***
```

```
 DIST    CONC          U10M  USTK  MIX HT  PLUME  MAX DIR
  (M)  (UG/M**3)  STAB (M/S) (M/S)   (M)  HT (M)  (DEG)
------- ---------- ---- ----- ----- ------ ------ -------
   10.  .6132E+11   1    1.3   1.3  425.6   2.00     0.
  100.  .9271E+10   1    1.3   1.3  425.6   2.00     0.
  200.  .2230E+10   1    1.3   1.3  425.6   2.00     0.
  300.  .9432E+09   1    1.3   1.3  425.6   2.00     0.
  400.  .4829E+09   1    1.3   1.3  425.6   2.00     0.
  500.  .2689E+09   1    1.3   1.3  425.6   2.00     0.
  600.  .1564E+09   1    1.3   1.3  425.6   2.00     0.
  700.  .9832E+08   1    1.3   1.3  425.6   2.00     0.
  800.  .6721E+08   1    1.3   1.3  425.6   2.00     0.
  900.  .5201E+08   1    1.3   1.3  425.6   2.00     0.
 1000.  .4513E+08   1    1.3   1.3  425.6   2.00     0.
ITERATING TO FIND MAXIMUM CONCENTRATION . . .

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND    10. M:
   41.  .6817E+11   1    1.3   1.3  425.6   2.00     0.

USE DISCRETE DISTANCES?  ENTER Y OR N:
y
TO CEASE, ENTER A DISTANCE OF ZERO (0).

**********************************
*** SCREEN DISCRETE DISTANCES ***
**********************************

*** TERRAIN HEIGHT OF    0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES
***

 DIST    CONC          U10M  USTK  MIX HT  PLUME  MAX DIR
  (M)  (UG/M**3)  STAB (M/S) (M/S)   (M)  HT (M)  (DEG)
------- ---------- ---- ----- ----- ------ ------ -------
ENTER DISTANCE (M) (0 TO EXIT):
30
   30.  .6632E+11   1    1.3   1.3  425.6   2.00     0.
ENTER DISTANCE (M) (0 TO EXIT):
50
   50.  .3948E+11   1    1.3   1.3  425.6   2.00     0.
```

Table II.IX: Example of modelling output by SCREEN3 analysis for point source dynamic fugitive emission.

```
*** SCREEN3 MODEL ******
**** VERSION DATED 96043 ****

ENTER TITLE FOR THIS RUN (UP TO 79 CHARACTERS):
Analysis for Agitation Activities.

ENTER SOURCE TYPE: P    FOR POINT
                   F    FOR FLARE
                   A    FOR AREA
                   V    FOR VOLUME
  ALSO ENTER ANY OF THE FOLLOWING OPTIONS ON THE SAME LINE:

    N    - TO USE THE NON-REGULATORY BUT CONSERVATIVE BRODE 2
           MIXING HEIGHT OPTION,
    nn.n - TO USE AN ANEMOMETER HEIGHT OTHER THAN THE REGULATORY
           (DEFAULT) 10 METER HEIGHT.
    SS   - TO USE A NON-REGULATORY CAVITY CALCULATION ALTERNATIVE
  Example - PN 7.0 SS (entry for a point source)

  ENTER SOURCE TYPE AND ANY OF THE ABOVE OPTIONS:
p
ENTER EMISSION RATE (G/S):
180
ENTER STACK HEIGHT (M):
3
ENTER STACK INSIDE DIAMETER (M):
3
ENTER STACK GAS EXIT VELOCITY OR FLOW RATE:
OPTION 1 : EXIT VELOCITY (M/S):
 DEFAULT - ENTER NUMBER ONLY
OPTION 2 : VOLUME FLOW RATE (M**3/S):
        EXAMPLE "VM=20.00"
OPTION 3 : VOLUME FLOW RATE (ACFM):
        EXAMPLE "VF=1000.00"
0.2
ENTER STACK GAS EXIT TEMPERATURE (K):
283
ENTER AMBIENT AIR TEMPERATURE (USE 293 FOR DEFAULT) (K):
283
ENTER RECEPTOR HEIGHT ABOVE GROUND (FOR FLAGPOLE RECEPTOR) (M):
1.8
ENTER URBAN/RURAL OPTION (U=URBAN, R=RURAL):
r
CONSIDER BUILDING DOWNWASH IN CALCS?  ENTER Y OR N:
n
USE COMPLEX TERRAIN SCREEN FOR TERRAIN ABOVE STACK HEIGHT?
ENTER Y OR N:
n
USE SIMPLE TERRAIN SCREEN WITH TERRAIN ABOVE STACK BASE?
ENTER Y OR N:
n
ENTER CHOICE OF METEOROLOGY;
1 - FULL METEOROLOGY (ALL STABILITIES & WIND SPEEDS)
2 - INPUT SINGLE STABILITY CLASS
3 - INPUT SINGLE STABILITY CLASS AND WIND SPEED
1
USE AUTOMATED DISTANCE ARRAY? ENTER Y OR N:
```

```
y
ENTER MIN AND MAX DISTANCES TO USE (M):
10
2000

**********************************
*** SCREEN AUTOMATED DISTANCES ***
**********************************

*** TERRAIN HEIGHT OF   0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES
***

 DIST    CONC          U10M  USTK  MIX HT  PLUME  SIGMA  SIGMA
  (M)  (UG/M**3)  STAB (M/S) (M/S)   (M)  HT (M)  Y (M)  Z (M) DWASH
------- --------- ---- ----- ----- ------ ------ ------ ------ -----
   10.  .1537E+09   6   1.0   1.0 10000.0   1.80    .49    .38   NO
  100.  .3868E+07   6   1.0   1.0 10000.0   1.80   4.10   2.38   NO
  200.  .1509E+07   6   1.0   1.0 10000.0   1.80   7.75   4.13   NO
  300.  .8192E+06   6   1.0   1.0 10000.0   1.80  11.24   5.65   NO
  400.  .5199E+06   6   1.0   1.0 10000.0   1.80  14.65   7.07   NO
  500.  .3624E+06   6   1.0   1.0 10000.0   1.80  17.97   8.41   NO
  600.  .2688E+06   6   1.0   1.0 10000.0   1.80  21.24   9.70   NO
  700.  .2084E+06   6   1.0   1.0 10000.0   1.80  24.46  10.94   NO
  800.  .1691E+06   6   1.0   1.0 10000.0   1.80  27.64  11.99   NO
  900.  .1406E+06   6   1.0   1.0 10000.0   1.80  30.78  12.99   NO
 1000.  .1191E+06   6   1.0   1.0 10000.0   1.80  33.89  13.96   NO
 1100.  .1030E+06   6   1.0   1.0 10000.0   1.80  36.97  14.83   NO
 1200.  .9020E+05   6   1.0   1.0 10000.0   1.80  40.02  15.67   NO
 1300.  .7982E+05   6   1.0   1.0 10000.0   1.80  43.05  16.48   NO
 1400.  .7128E+05   6   1.0   1.0 10000.0   1.80  46.05  17.27   NO
 1500.  .6414E+05   6   1.0   1.0 10000.0   1.80  49.03  18.04   NO
 1600.  .5812E+05   6   1.0   1.0 10000.0   1.80  52.00  18.79   NO
 1700.  .5297E+05   6   1.0   1.0 10000.0   1.80  54.94  19.52   NO
 1800.  .4853E+05   6   1.0   1.0 10000.0   1.80  57.87  20.24   NO
 1900.  .4468E+05   6   1.0   1.0 10000.0   1.80  60.78  20.94   NO
 2000.  .4131E+05   6   1.0   1.0 10000.0   1.80  63.68  21.63   NO
ITERATING TO FIND MAXIMUM CONCENTRATION . . .

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND   10. M:
   10.  .1537E+09   6   1.0   1.0 10000.0   1.80    .49    .38   NO

USE DISCRETE DISTANCES?  ENTER Y OR N:
```

APPENDIX 111 : BIOAEROSOLS ANALYSIS: CARMARTHEN

Table III.I Background bioaerosols measured at Carmarthen Composting.

	A. *fumigatus*	Conf. Limit (x %)		actinomycetes	Conf. Limit (x %)	
		max	min		max	min
Upwind- Mar 2	ND	NA	NA	ND	NA	NA
Inside-Jan13	2400	34	-25	2500	11	-10
Inside-Jan26	ND	NA	NA	15000	36	-26
Inside-Feb8	7000	97	-57	26000	79	-50
Inside-Mar10	7000	97	-57	12000	79	-50
Downwind 30m-2 Mar	ND	NA	NA	ND	NA	NA
Downwind 30m –Mar 2 (turning-1)	ND	NA	NA	6000	NA	NA
Downwind 30m –Mar 2 (turning-1)	1000	261	-88	12000	50	-36

*ND= not detected

NA= not available

Inside facility: A. *fumigatus*; maximum=7000 cfu/m^3, minimum=0 cfu/m^3, mean= 4100 cfu/m^3 and standard deviation= 3500 cfu/m^3. Actinomycetes ; maximum= 26000 cfu/m^3, minimum= 0 cfu/m^3, mean= 9100 cfu/$m^3$and standard deviation= 8900 cfu/m^3

Table III.II Bioaerosols concentration in compost soil sample

Compost sample	MC*	A. *fumigatus* (x cfu/g -dry) $x10^6$	Confidence limit (x %)		actinomycetes (x cfu/g-dry) $x10^6$	Confidence limit (x %)	
			max.	min.		max	min.
shredding; 1-3 weeks green waste (10/3/05)	70	440	54	39	7700	9	8
wind tunnel - location 1;2 week compost;(13/1/05	64	560	34	25	49000	38	27
wind tunnel - location 2 ;2 week compost (13/1)	72	570	39	28	88000	30	23
turning 2; 2 weeks compost (13/1)	64	5000	10	9	5300	19	16
wind tunnel - location 3 ;4 week compost (13/1)	74	410	53	38	320000	16	13
turning1; 4 weeks compost (26/1)	44	3400	10	9	5700	26	21
turning1; 4 weeks compost (26/1)	54	4900	9	8	4500	10	9
turning1; 4 weeks compost (26/1)	51	1700	15	13	3100	11	10
wind tunnel ; 6 week compost (8/2)	69	26000	16	14	26000	16	14
wind tunnel ; 6 week compost (8/2)	67	1100	24	19	2200	17	14
wind tunnel ; location 1 ;8 week compost (8/2)	71	3900	13	12	730	33	25
wind tunnel - location 2 ;8 week compost (8/2/)	66	29000	14	12	580	34	25
turning-3; 8 weeks compost; (2/3)	66	930	13	11	2900	25	20
wind tunnel - location 1;12 week compost (10/3)	52	140	71	47	69000	8	7
turning-4 12 weeks compost (10/3)	66	920	27	21	2900	14	12
wind tunnel - location 2;16 week (10/3)	40	150	58	41	18000	13	12
compost screening; 16 weeks compost (10/3)	48	77	97	57	1600	15	13

* MC= moisture content

A. *fumigatus*; maximum=$260x10^8$ x cfu/g-dry , minimum = $4 x10^8$ x cfu/g-dry mean = 44 x 10^8 x cfu/g-dry, standard deviation= 77 x 10^8 x cfu/g-dry.

Actinomycetes; maximum=$3200x10^8$ x cfu/g-dry, minimum = $6 x10^8$ x cfu/g-dry, mean = $400x 10^8$ x cfu/g-dry, standard deviation= 800 x 10^8 x cfu/g-dry.

Table III.III: Bioaerosols concentration in mixing chamber of wind tunnel measured in the surface flux sampling.

Sampling Date:13/01/2005	A. *fumigatus* (Af) concentration in sample			Actinomycetes (Ac) concentration in sample		
	x cfu/m^3	confidence limit		x cfu/m^3	confidence limit	
		max. (%)	min. (%)		max. (%)	min. (%)
blank (fit into sampling head without running the pump)	<1	NA	NA	<1	NA	NA
incoming air; air filtered by carbon as carrier in wind tunnel; air velocity at host out let is 8m/s	<1	NA	NA	<1	NA	NA
ambient, background (inside facility); 1.8m above ground; ambient air velocity 0.3m/s; temperature 9.5^{0}C	2500	192	-79	2500	192	-79
air sample 300mm from compost pile ;	32 000	33	-25	28 000	36	-26
wind tunnel - location 1(2 week compost); located at the top of outlet mixing chamber; ; air velocity 2.4 m/s	<1	NA	NA!	23 000	46	-34
wind tunnel - location 1(2 week compost); located at the bottom of outlet mixing chamber; air velocity 2.4 m/s	<1	NA	NA	4 000	156	-73
wind tunnel - location 2 (2 week compost); located at the top of outlet mixing chamber; air velocity 2.1 m/s	<1	NA	NA	3000	156	-73
wind tunnel - location 2 (2 week compost); located at the bottom of outlet mixing chamber; air velocity 2.1 m/s	<1	NA	NA	<1	NA	NA
wind tunnel - location 3 (4 week compost); located at the top of outlet mixing chamber ; air velocity 2.6 m/s	<1	NA	NA	5000	106	-60
wind tunnel - location 3 (4 week compost); located at the bottom of outlet mixing chamber; air velocity 2.6 m/s	7500	177	-49	<1	NA	NA!
sampling date 8/2/05						
blank (fitted into sampling head without running the pump)	<1	NA	NA	<1	NA	NA!
incoming air; air filtered by carbon as carrier in wind tunnel; air velocity at host out let is 8m/s	<1	NA	NA	<1	NA!	NA
ambient, background (inside facility); 1m from compost pile-down wind, 1.8m above ground; ambient wind velocity 0.2m/s; temperature 40C	1700	261	-88	26000	39	-28
wind tunnel - location 1(6 week compost); located at the top of outlet mixing chamber; ; air velocity 2.3 m/s	5000	192	-79	7000	97	-57
wind tunnel - location 1(6 week compost); located at the bottom of outlet mixing chamber; ; air velocity	4100	133	-68	10000	75	-48

2.3 m/s						
wind tunnel - location 2(6 week compost); located at the top of outlet mixing chamber; ; air velocity 1.8 m/s	1700	457	-97	18000	79	-36
wind tunnel - location 2(6 week compost); located at the bottom of outlet mixing chamber; ; air velocity 1.8 m/s	4200	133	-68	26000	39	-28
wind tunnel - location 1 (8 week compost); located at the top of outlet mixing chamber; ; air velocity 2.1 m/s	0	NA	NA	1700	457	-97
wind tunnel - location 1 (8 week compost); located at the bottom of outlet mixing chamber; ; air velocity 2.1 m/s	0	NA	NA	800	457	-97
wind tunnel - location 2 (8 week compost); located at the top of outlet mixing chamber; ; air velocity 1.8 m/s	5900	106	-60	6700	97	-57
wind tunnel - location 2 (8 week compost); located at the bottom of outlet mixing chamber; ; air velocity 1.8 m/s	5000	118	-63	7500	90	-54
air at 300 mm off compost at location 2 ; 6 weeks compost	12000	97	-57	17000	79	-50
air at 300 mm off compost at location 3; 8 weeks compost	5000	192	-79	4200	133	-68
sampling date 10/3/05						
blank (fitted into the sampling head as the pump is off)	<1	NA	NA!	0	NA!	NA
ambient, background (inside facility); 1.8m above ground; ambient wind velocity 0.2m/s; temperature 100C	6700	97	-57	12500	65	-44
incoming air; air filtered by carbon as carrier in wind tunnel; air velocity at host out let is 7m/s	800	457	-97	<1	NA	NA
wind tunnel - location 1;12 week compost; located at the top of outlet mixing chamber; ; air velocity 1.9 m/s	11000	68	-45	14000	60	-42
wind tunnel - location 1;12 week compost; located at the bottom of outlet mixing chamber; ; air velocity 1.9 m/s	1700	261	-88	12500	65	-44
wind tunnel - location 2;16 week compost; located at the top of outlet mixing chamber; ; air velocity 2.6 m/	4200	133	-68	4200	133	-68
wind tunnel - location 2;16 week compost; located at the bottom of outlet mixing chamber; air velocity 2.6 m/	4200	133	-68	8300	84	-52
compost air about 300mm from compost pile surface- 16 weeks	87000	29	-23	20000	73	-41

Table III.IV: Summary of Surface Flux Bioaerosol Emission Rate Calculation

sample and location	mean wind speed (m/s) (at 1.8 m)	mean air velocity (m/s) mixing chamber	air velocity inside wind tunnel (m/s)	bioaerosol concentration * in air samples ($x10^3$ cfu/m^3)		net bioaerosol in carrier air ($x10^3$ cfu/m^3)		$SBER_1$ ($x10^3$ cfu/m^2/s)		$SBER_2$ ($x10^3$ cfu/m^2/s)	
				Af	Ac	Af	Ac	Af	Ac	Af	Ac
sampling date: 13/1/2005											
ambient, background (inside facility); 1m from compost pile-down wind, 1.8m above ground;	0.3	NR	NR	3.2	2.5	NR	NR	NR	NR	NR	NR
incoming air; air filtered by carbon as carrier in wind tunnel; air velocity at host out let is 8m/s	NR	NR	NR	0	0	NR	NR	NR	NR	NR	NR
wind tunnel - location 1(2 week compost);	0.3	2.4	0.2	0	13.4	0	13.4	0	0.8	0	1.0
wind tunnel - location 2 (2 week compost);	0.3	2.1	0.2	0	1.7	0	1.7	0	0.1	0	0.1
wind tunnel - location 3 (4 week compost);	0.3	2.6	0.2	3.8	2.7	3.8	2.7	0.3	0.2	0.3	0.2
sampling date:8/2/2005											
ambient, background (inside facility); 1m from compost pile-down wind,	0.2	NR	NR	1.7	25.8	NR	NR	NR	NR	NR	NR

incoming air; air filtered by carbon as carrier in wind tunnel; air velocity at host out let is 8m/s	NR	NR	NR	0	0	NR	NR	NR	NR	NR	NR
wind tunnel - location 1(6 week compost);	0.2	2.3	0.2	3.3	8.5	3.3	8.5	0.2	0.5	0.2	0.5
wind tunnel - location 2(6 week compost);	0.2	1.8	0.2	3.2	22.8	3.2	22.8	0.2	1.1	0.2	1.2
wind tunnel - location 3 (8 week compost);	0.2	2.1	0.2	0	1.3	0	1.3	0	0.1	0	0.1
wind tunnel - location 4 (8 week compost);	0.2	1.8	0.2	5.4	7.5	5.4	7.5	0.3	0.4	0.3	0.4
sampling date 10/3/2005											
ambient, background (inside facility);	0.2	NR	NR	7.7	12.7	NR	NR	NR	NR	NR	NR
incoming air; air filtered by carbon as carrier in wind tunnel; air velocity at host out let is 7m/s	NR	NR	NR	0.8	0	NR	NR	NR	NR	NR	NR
wind tunnel - location 1;12 week compost;	0.2	1.9	0.2	8.0	15.5	7.2	15.5	0.4	0.8	0.4	0.9
wind tunnel - location 1;16 week compost;	0.2	2.6	0.2	4.2	7.0	3.3	7.0	0.2	0.5	0.2	0.5

- The average of a top and bottom sampling point in the mixing chamber as shown in the Table III.III
- NR= not relevant
- Mean $SBER_2$: A. *fumigatus* = 200 cfu/m^2/s, actinomycetes= 500 cfu/m^2/s and
- standard deviation : A. *fumigatus* = 150 , actinomycetes = 400

Table III.V Bioaerosol concentration measured at 5, 10 or 30 metres from the agitation activity to determine the dynamic emission release.

Sampling date 26/1/05	Af concentration in air sample			Ac concentration in air sample		
	x 10^3 cfu/m^3	confidence interval limit (%)		x 10^3 cfu/m^3	confidence interval limit (%)	
		max	min.		max	min.
blank (fit into sampling head without running the pump)	<1	NA	NA	<1	NA	NA
ambient, background (inside facility); 1m from compost pile-down wind, 1.8m above ground; ambient wind velocity 0.14 m/s; temperature 1.8^{0}C	<1	NA	NA	15	62	-43
windrow turner- sample location 1 (4 weeks compost)	150	31	-23	219	106	-60
windrow turner- sample location 2 (4 weeks compost)	371	32	-24	1242	16	-14
turning-1 sample location A (1 week compost)	4167	13	-11	108	26	-21
turning-1 sample location B(1 week compost)	4442	14	-12	1488	26	-20
turning-2 sample location A(1 week compost)	857	24	-19	11	457	-97
turning-2 sample location B(1 week compost)	1909	24	-19	3000	77	-48
air at 300mm off pile surface (1-2 week compost)	195	34	-25	1495	11	-10
Sampling 2/3/2005 :						
blank (fitted into the sampling head with the pump off)	<1	NA	NA	0	NA	NA
ambient, background (outside facility); 20m from compost pile up wind, 1.8m above ground ; wind velocity 0.1m/s; temperature 5^{0}C	<1	NA	NA	0	NA	NA

turning1; 4 weeks compost ; sample location A 10 meter at outlet space	32	71	-47	104	33	-25
turning1; 4 weeks compost; sample location B 10 meter at outlet space	40	62	-43	177	25	-20
turning 1;4 weeks location C; 30m Outside building	<1	NA	NA	6	457	-97
turning 2; 4 weeks compost; location A ;10 meter at outlet direction;	34	56	-40	56	39	-28
turning-2; 4 weeks compost; location C; at 30 meter outside building	1	261	-88	12	50	-36
turning-3; 8 weeks compost; location A ;10 meter at outlet space	42	25	-20	19	39	-28
turning-3; 8 weeks compost; location B; 10 meter at outlet space	102	15	-13	96	15	-13
turning-4 12 weeks compost ; location A ;10 meter at outlet space	115	17	-14	52	25	-20
turning-4 12 weeks compost; location B; 10 meter at outlet space	189	13	-11	73	21	-17
Sampling: 10/3/2005						
blank (fitted into the sampling head as the pump is off)	<1	NA	NA!	0	NA	NA
ambient, background (inside facility); 1m from compost pile-down wind, 1.8m above ground; ambient wind velocity 0.2m/s; temperature 10^0C	7	97	-57	12	65	-44
shredding; location 1; 1-3 weeks green waste;	70	28	-22	28	47	-35
shredding; location 2; 1-3 weeks green waste;	23	56	-40	28	50	-36
screening; location 1; 16 weeks compost	14	118	-63	42	60	-42
screening; location 2; 16 weeks compost	80	39	-28	168	25	-20

Table III.VI Estimated emission rate of agitation activities.

Activity	A. *fumigatus*		Actinomycetes	
	bioaerosol concentration (x 10^3 cfu/m^3)*	Estimated emission rate (x 10^3 cfu/s)	bioaerosol concentration (x 10^3 cfu/m^3)*	Estimated emission rate (x 10^3 cfu/s)
windrow turner- sample location 1 (4 weeks compost) at 5 m from the source	150	550	220	750
windrow turner- sample location 2 (4 weeks compost) at 5 m from the source	370	1360	1200	4500
turning-1 sample location A (1-2 week compost at 5 m from the source	4200	15000	110	330
turning-1 sample location B(1-2 week compost) at 5 m from the source	4400	16000	1500	5400
turning-2 sample location A(1-2 week compost) at 5 m from the source	857	3200	<1	-
turning-2 sample location B(1-2 week compost) at 5 m from the source	1900	7100	3000	11000
turning1; 4 weeks compost ;	32	340	100	1100
turning1; 4 weeks compost;	40	420	180	1900
turning 1;4 weeks location C;	<1	-	6	65
turning 2; 4 location A ;10 meter at outlet direction; weeks compost;	33	360	56	600
turning-3; 8 weeks compost; location A ;10 meter at outlet space	42	400	19	200
turning-3; 8 weeks compost; location B; 10 meter at outlet space	102	1100	96	1000
turning-4 12 weeks compost ; location A ;10 meter at outlet space	120	1200	53	560
turning-4 12 weeks	190	2000	73	770

compost; location B; 10 meter at outlet space				
shredding; location 1; 1-3 weeks green waste;	70	270	12	48
shredding; location 2; 1-3 weeks green waste;	23	87	29	110
screening; location 1; 16 weeks compost	14	55	29	110
screening; location 2; 16 weeks compost	80	300	42	160

* shows negative reading when the concentration is deducted with the background reading.

** the net concentration (minus background reading) is used for emission rate estimation.

APPENDIX IV PUBLICATIONS AND PROCEEDINGS

Published papers

Taha M.P.M, S.J.T. Pollard, U. Sarkar, P. Longhurst (2005), Estimating fugitive bioaerosol releases from static compost windrows: Feasibility of a portable wind tunnel approach, *Waste Management*, 25, 445–450

Taha M.P.M, G.H. Drew, P.J. Longhurst, R. Smith and S.J.T Pollard (2005) Bioaerosol releases from compost facilities: evaluating passive and active source terms at a green waste facility for improved risk assessments, *Atmospheric Environment*, Received 29 June 2005; revised 24 October 2005; accepted 1 November 2005. Available online 19 December 2005.

Taha M.P.M, A. Tamer, D. Aldred, G.H. Drew, P.J. Longhurst and S.J.T Pollard (2006) Improved enumeration of actinomycetes burden in bioaerosols from compost facilities using a low-nutrient, soil compost agar, *Atmos. Environ. submitted 14th February, 2006* (short communication)

Conference proceedings

Taha M.P.M, S.J.T Pollard, U.Sarkar and P.Longhurst (2004).The influence of process variable on bioaerosol emission flux and exposure-estimating fugitive bioaerosol release from static compost windrows, *Proc. Biodegradable and Residual Waste Management*, Harrogate, UK, 18-19 February, ISBN 0-9544708-1-8, pp. 268-275

Taha, M.P.M., Pollard, S.J.T. and Longhurst, P.J. (2004) Source term monitoring and depletion for bioaerosols at green waste composting sites – improving regulatory risk assessments, presented at Tackling Waste 2004, 20-21st July 2004, University of Nottingham

Taha M.P.M, S.J.T Pollard (2004), Emission and Dispersal of Bioaerosols during Agitation of Green Waste Compost Piles, *Proc. Integrated Waste Management and Pollution Control: Policy Practise, Research and Solutions*, Stratford-upon-Avon, UK, 28-30, pp. 735-743

Taha M.P.M. (2004) Characterising the bioaerosols source term at windrow composting sites for improved environmental risk assessment, Water Science Show-case for Doctoral Research, Cranfield University.

Taha M.P.M. S.J.T Pollard, P.J., Longhurst (2005).Characterising the Bioaerosol Source at Windrow Composting Sites for Improved Environmental Risk Assessment, In Proc. The 3rd Annual MRG Conference, 14 June 2005, Manchester.

Pollard S.J.T, N. Sweet, A. Owers, P. Longhurst, S. Tyrrel and M.P.M. Taha, A Risk Management Framework for Composting Facilities, In Proc. 8th European Biosolids Conference, Wakefield, 2003

Longhurst P. M.P.M. Taha, S.J.T. Pollard, Source term monitoring and depletion for bioaerosols at green waste composting sites- improving regulatory risk assessments, Fugitive Health Perspective ands Fugitive Emissions, AQM Resource Centre and South West NSCA 7th Annual Conference 2005, 27th January 2005.