UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE & MATHEMATICS

School of Civil Engineering and the Environment

Physical Chemical Processes and Environmental Impacts Associated with Home Composting

by

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Thesis for the degree of Doctor of Philosophy

July 2008

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING, SCIENCE & MATHEMATICS
SCHOOL OF CIVIL ENGINEERING AND THE ENVIRONMENT

Doctor of Philosophy

PHYSICAL CHEMICAL PROCESSES AND ENVIRONMENTAL IMPACTS ASSOCIATED WITH HOME COMPOSTING

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This thesis reports on experimental and modelling work carried out in order to make quantitative estimates on the environmental impacts of home composting. The focus of the work was climate relevant gaseous emissions, and developing and utilising a methodology for quantifying them. Experiments using 220L open bottomed home compost bins, alongside purpose built 200L composting reactors with airflow control were performed. A variety of composting conditions were tested, using different compositions of garden and kitchen wastes. The experiments were monitored for headspace gas composition, including CO_2, O_2, NH_3, N_2O, CH_4 and volatile organic compounds, as well as temperature, humidity, moisture and solids losses and pH.

From the CO_2 emission rates calculated from the reactor experiments, theoretical analysis and modelling and airflow pathway tests on home compost bins, it was concluded that molecular diffusion, rather than bulk convective flow, is the dominant gas transfer mechanism from home compost bins. There were no detected emissions of N_2O but emissions of NH_3 up to 16 g/T feed. Only a few cases of CH_4 emission were detected, typically in the first 2-3 days following a feed addition, with the highest single concentration measured at 86 ppm within the headspace.

The total anthropogenic greenhouse gas emissions from home composting were estimated as between 3 and 12 Kg CO_2E/T_w with almost 90% coming from the lifecycle of the compost bin. This compares with between 20 and 56 Kg CO_2E/T_w from centralised facilities, at least more than double that for home composting. Total anthropogenic CO_2-equivalent emissions from home composting in the UK in 2008 were estimated to be in the region of 7 thousand tonnes CO_2E.

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DECLARATION OF AUTHORSHIP

I, Stephen Peter McKinley, declare that the thesis entitled:

Physical Chemical Processes and Environmental Impacts Associated with Home Composting

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
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McKinley, S., Williams, I., Banks, C. J. and Heaven, S. (2006). A Study of the Environmental Impacts of Home Composting. Waste 2006, Stratford-Upon-Avon.

McKinley, S. Williams, I. (2007) Assessing the Environmental Impacts of Home Composting. Sardinia 2007, Eleventh International Waste Management and Landfill Symposium Proceedings

Signed: ………………………………………………………………………..

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Definitions and abbreviations

BMW	Biodegradable Municipal Waste
CIPFA	Chartered Institute of Public Finance and Accountancy
DEFRA	Department for Environment Food and Rural Affairs
EA	Environment Agency
EPSRC	Engineering and Physical Sciences Research Council
FAS	Free Air Space
GWP	Global Warming Potential
H.C.	Home Compost(ing)
IPCC	Intergovernmental Panel on Climate Change
Kg/hh/yr	Kilograms per household per year
LPM	Litres per minute
MGW	Municipal Garden Waste
MSW	Municipal Solid Waste
SUE	Sustainable Urban Environment
VFA	Volatile Fatty Acids
VOC	Volatile organic compounds
WRAP	Waste and Resources Action Programme

1. Introduction

Waste disposal in the UK is a major contributor to the release of the greenhouse gases; carbon dioxide and methane, as well as other environmentally harmful emissions. About 3% of UK greenhouse gas emissions come from methane released in landfills due to the presence of biodegradable municipal waste (BMW). The EC Landfill Directive (CEC 1999) has established mandatory targets for the phased reduction of biodegradable municipal waste (BMW) going to landfill:

By **2010** to **75%** of that produced in 1995
By **2013** to **50%** of that produced in 1995
By **2020** to **35%** of that produced in 1995

The waste hierarchy provides the order of preference for the treatment of waste, giving not only environmental benefits but also financial savings from using fewer natural resources and reducing the costs of waste treatment and disposal. England has made significant progress towards these targets, since the waste strategy in 2000 (DEFRA 2007). Recycling and composting of waste has nearly quadrupled since 1996-97, achieving 27% in 2005-06. Less waste is being landfilled, with a 9% fall between 2000-01 and 2004-05. Waste growth is also being reduced with municipal waste growing much less quickly than the economy at 0.5% per year. This progress has been driven by significant changes in policy. The landfill tax escalator and the introduction of the Landfill Allowance Trading Scheme (LATS) has created sharp incentives to divert waste from landfill. Additional funding for local authorities, including through the private finance initiative, has led to a major increase in kerbside recycling facilities and new waste treatment facilities (DEFRA 2007). In the waste hierarchy, the composting of waste is the 3rd highest option, following prevention and re-use (DEFRA 2007). Thus composting and home composting have a central role in the Government’s strategy for delivering the target reduction in household waste disposal to landfill. Home composting provides a low cost option for Local Authorities with no collection or treatment costs and has been the target of a multi-million pound recycling campaign launched by the Waste Resources Action Programme (WRAP). Historically diversion of biodegradable waste via home composting has not counted towards Local Authority recycling targets due to the difficulties in measuring it, but this situation is likely to change within the next few years (Eunomia Research and Consulting 2002; The Composting Association 2004).

For these reasons, 73% of Local Authorities were involved in the distribution of compost bins in 2004 and it is becoming an increasingly significant waste disposal route for biodegradable household waste in the UK, with approximately 15% of households participating in some form in 2004 (DEFRA 2005). Typical household diversion rates of between 100-400 kg/household/yr have been reported (Punshi 2000; Mansell et al. 2001; Smith et al. 2001; Bexley Coucil et al. 2004), which equates to between 0.15-0.65 million tonnes of waste composted at home per year in the UK. As participation rates in home composting grow, so too does the need for a better understanding of the emissions from home composting and the composition and quality of the compost produced. Ideally, composting is the aerobic microbial degradation of organic substrates to produce carbon dioxide, water, heat and a final product that is stable and can be safely and beneficially applied to land (Haug 1993). Outputs from an individual process depend on the specific microbial activity taking place, which is linked to the type and quantity of feedstock, management regime, temperature fluctuations, oxygen availability and pH levels of the compost in ways not currently understood in detail (Beck-Friis et al. 2001). Depending on these parameters, composting can also lead to emissions of gases such as CH_4, N_2O, NH_3 and volatile organic compounds (VOCs) (Hellman et al. 1997). Although the emissions of these gases per bin may be quite low, when considered collectively, they may make a substantial contribution to total CO_2 emissions, and hence to global warming.

This project was part of the SUE waste consortium programme funded by the EPSRC. Specifically it comes under the heading of Project 3: Appropriate scales and technologies for bioprocessing of organic urban wastes. Its role was to answer an identified gap in the literature regarding the environmental impact of home composting and how it compares with large scale centralised composting. The primary outcomes from the project were to:

- Identify and compare the available techniques for measurement and analysis of the emissions from home composting in order to find the most accurate and reliable methodology.

- Assess the potential for environmentally harmful emissions from home composting.

- Add to the body of knowledge within composting science regarding the relationship between key factors, including temperature, CO_2 emission, pH, moisture content and feed properties.

- Compare the environmental impacts of unmonitored and possibly poorly managed home composting with well monitored and controlled centralised composting and its associated transport and processing emissions, in order to recommend which disposal route local authorities should emphasize.

2. Literature review

2.1. The composting process

Composting is an aerobic process where organic material is transformed through decomposition into a soil-like material called compost. It is a process that occurs naturally in the environment but as a controlled process, composting can be an invaluable waste management tool, causing a volume and weight reduction in the raw materials and producing a potentially valuable end product. The product is rendered more stable and made suitable for application to gardens and productive land as a soil improver. When carried out under ideal conditions the only outputs to the atmosphere from composting are carbon dioxide and water. When the same plant matter is disposed of through landfill however, its degradation is far from ideal, with significant potential for harm to the environment, as the main source of methane emissions and a contributor to leachate (Richard et al. 1990; Beck-Friis et al. 2001; Ward et al. 2005).

The overall material balance for composting can be seen in Figure 1; in basic equation form this approximates to:

$$C_qH_qO_rN_s \cdot aH_2O + bO_2 \rightarrow C_tH_uO_vN_w \cdot dH_2O + dH_2O + eH_2O + CO_2$$

Organic matter + oxygen → compost + water + carbon dioxide

Equation 1

The transformations that take place occur through a range of processes initially involving bacteria, fungi, moulds, protozoa, actinomycetes, and other saprophytic organisms feeding upon decaying organic matter, while in the later stages of decomposition, macroscopic organisms such as mites, millipedes, centipedes, beetles and earthworms further break down and enrich the composting materials (see Figure 2). The composting process is difficult to analyse or model in detail as many of the parameters involved are interrelated so cannot be considered in isolation. The microbial reactions involved in biodegradation are exothermic and produce moisture. The reactions themselves, however, are affected by both the temperature and the moisture content of the compost. The temperature, moisture content and degree of contamination (by non-organic materials, heavy metals and chemicals) affect the growth rates and hence concentrations of micro-organisms in the composting material, which again affects the rate of degradation (Haug 1980; Fletcher et al. 2000; Trautmann et al. 2002). In the following sections, the key parameters involved in the composting process have been considered individually.

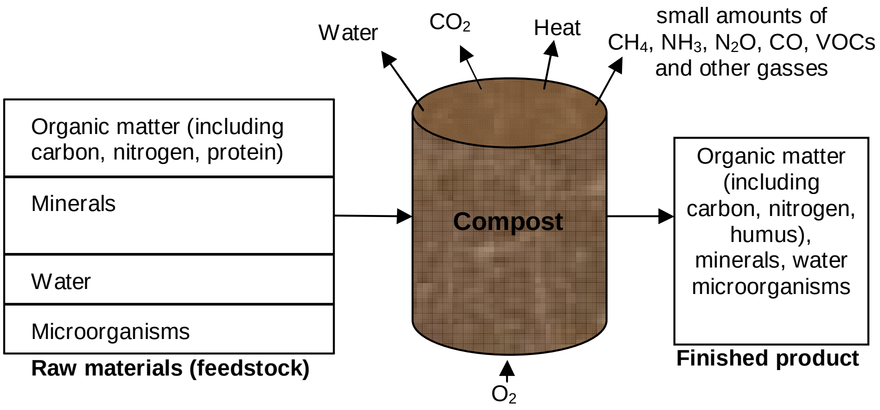

Figure 1: Inputs and outputs of the composting process

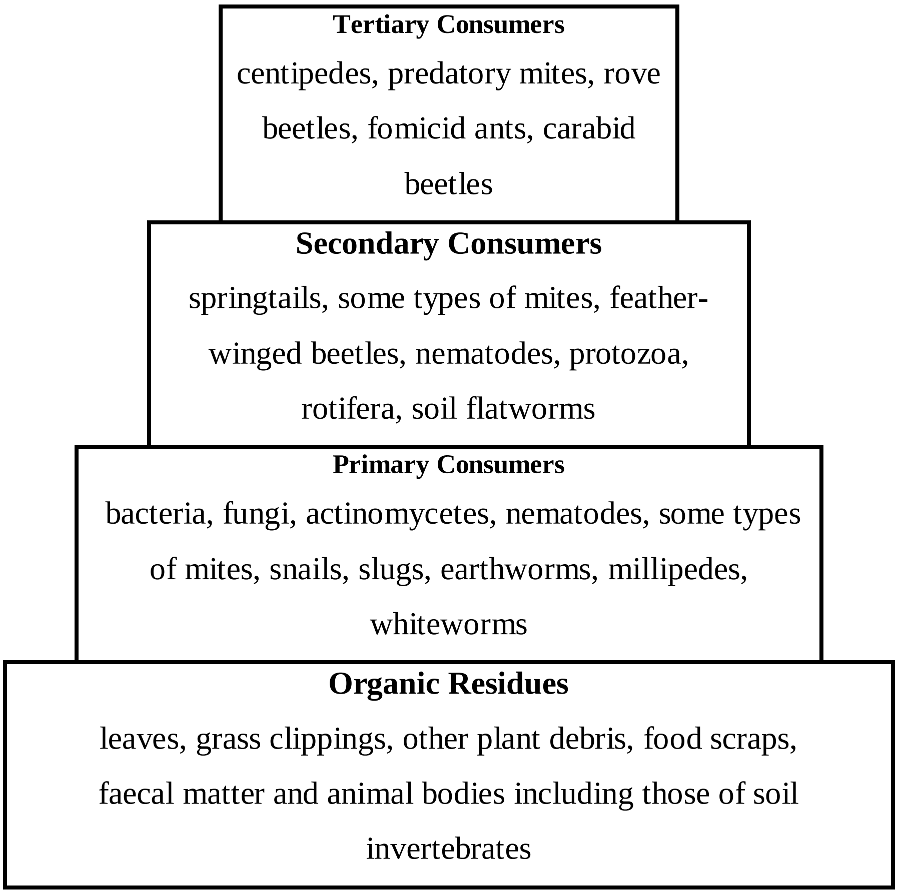

Figure 2: Food web at work within a compost pile (Trautmann et al. 2002)

The decomposition of organic materials, which essentially makes up composting are mainly carried out by microscopic organisms. The state and properties of any composting system, therefore is heavily dependent on the numbers, species and environmental influences on the microscopic life present. Microbiological populations involved are numerous, often reaching concentrations of 10^9 to 10^{10} per gram of compost. Populations include mesophilic and thermophilic bacteria, fungi and actinomycetes. Temperature is the single most important factor in microbial succession, 0 lists species of bacteria and fungi isolated at different temperatures and stages of composting.

Under optimal conditions, a composting process passes through four stages in terms of microbial succession and associated physical and chemical properties (Burman 1961; Porteous 1977; Skitt 1979; Trautmann et al. 2002) (see Figure 3):

Mesophilic: Initially the compost is at ambient temperature and is usually slightly acidic. Mesophilic microorganisms perform the initial decomposition where soluble, readily degradable compounds are rapidly broken down. The heat they produce causes the compost temperature to rise rapidly. Simple organic acids are among the products of this stage, causing the pH to drop

Thermophilic: Above about 40°C, the mesophilic microorganisms become less competitive and are replaced by thermophilic microorganisms. Decomposition occurs most rapidly in this high temperature phase (40-70°C), which lasts from a few days to several months. The high temperatures of this stage destroy many thermo-sensitive human and plant pathogens. Above about 65°C however, most species of microorganisms are killed, which limits the rate of decomposition.

Cooling: During the thermophilic phase, microorganisms feed on high energy compounds such as proteins, fats and complex carbohydrates. Once these are exhausted, the temperature begins to decrease and mesophilic organisms dominate again.

Maturation: This phase takes far longer than the others, usually requiring several months. It takes place at ambient temperature with mesophilic organisms predominating and macro fauna appearing, heat evolution and weight loss are small. Complex secondary reactions of condensation and polymerisation take place which give rise to the final end product, humus and the stable and complex humic acids.

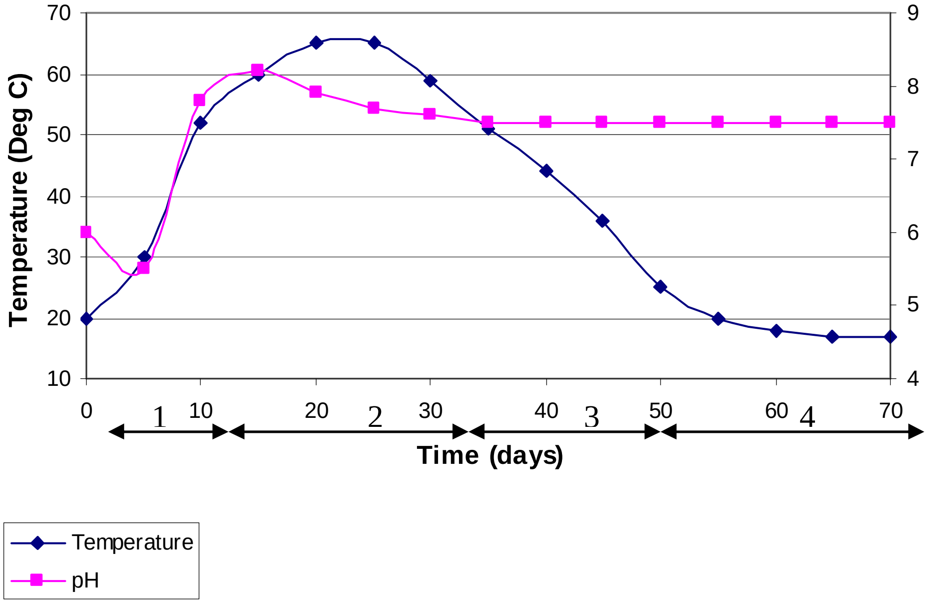

Figure 3: The temperature regime and pH variation during the typical stages of composting. Adapted from (Skitt 1979)

A further diversification of microbial species that can take place during composting is as a result of the oxygen concentration. Composting is an aerobic process, as the active microbial species require the presence of oxygen (see section 2.4.1). However, if the oxygen concentration is significantly depleted (<5% (Kulcu et al. 2004)) in even small volumes of the compost material, then anaerobic species will become active. These degrade waste materials using different reactions and can lead to emissions of methane, carbon monoxide, nitrous oxide, ammonia and volatile organic compounds (see section 2.5) (Hellebrand 1997; Hellman et al. 1997; Beck-Friis et al. 2000; Smars et al. 2001; Zeman et al. 2002; Sommer et al. 2004). For example, the different anaerobic and aerobic reactions of glucose are shown in Table 1. Glucose is one of the primary constituents of cellulose and hemicellulose; the major structural molecules used by plants (Haug 1980).

Table 1: Anaerobic and aerobic reactions of glucose (Crockett 2005)

Possible anaerobic fermentations of glucose	
Acetate	$C_6H_{12}O_6 \rightarrow 3CH_3COO^- + 3H^+$
Propionate, acetate, H_2	$C_6H_{12}O_6 \rightarrow CH_3CH_2COO^- 3CH_3COO^- + 2H^+ + CO^2 + H_2$
Butyric, H_2	$C_6H_{12}O_6 \rightarrow CH_3CH_2CH_2COOH + 2CO_2 + 2H_2$
Ethanol	$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$
Lactate	$C_6H_{12}O_6 \rightarrow 2CH_3CH(OH)COO^- + 2H^+$
Methanol	$C_6H_{12}O_6 + 2H_2O \rightarrow 4CH_3OH + 2CO_2$
Methane	$C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2$
Basic aerobic reaction	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

2.2. Alternative forms of composting

Composting is carried out at different scales, by a variety of techniques. The main categories of composting and the sources of organic wastes available for feeding them are listed in Tables 2 and 3, respectively. Although all the organic wastes listed in Table 3 could potentially be composted, there are limitations due to health, safety and environmental concerns, the physical and chemical requirements of the process being used and impacts on the quality of the resulting compost. Currently these limitations are only enforced with concern for health and environmental issues (see section 2.3.1), by legislation on waste management licensing (Environmental Protection Act 1990), licence-exemptions (Waste Management Licensing Regulations1994) and composting of animal by-products (Animal By-Products Order 1999 as amended). The UK is in a declining minority in the EU in its lack of statutory standards for finished compost products (The Waste and Resources Action Programme (WRAP) 2002). However, compost producers can choose to comply with voluntary industry and market-specific standards in order to help build customer confidence in compost products. In the UK, the British Standards Institution's 'Publicly Available Specification for Composted Materials' (PAS 100) sets out a minimum compost quality baseline which composters use as appropriate to the product types and markets targeted.

Table 2: The main categories of composting

Composting category	Compost material sources	Key points
Centralised composting	Large scale commercial composting fed from municipal sources such as parks and landscaping garden waste, civic amenity site garden waste and any separately collected household garden and kitchen wastes.	Legislature requires monitoring of the process and compost produced to control environmental and public health impacts. Transport intensive due to limits on proximity to the public and large amount and sources of waste. Varying levels of cost and equipment intensity depending on particular system used. Can produce marketable product.
Community composting	Medium scale volunteer based composting fed from locally generated sources of garden waste.	Low transport requirements due to close proximity to waste source. Possible social benefits to community. Not as strictly monitored as centralised composting and typically lower equipment efficiency due to smaller scale.
Supermarket composting	Medium scale composting to deal with waste fruit, vegetable and flowers produced by supermarkets such as Waitrose and Sainsbury’s in the GROW project.	Transportation requirements as produce must be shipped to farms from the supermarkets.
Farm composting	Medium scale composting dealing with wastes produced on farms including agricultural wastes, animal manure, food production wastes.	Close proximity to waste source.
Home composting	Small scale composting fed with fractions of household kitchen and garden wastes suitable for composting at that scale.	Proximity to waste source and very low costs with only the optional requirement of a home composting bin. No legislation or monitoring means poor management by individuals may lead to harmful emissions.

Table 3: Sources of organic waste

The domestic waste stream	The local Authority Waste Stream	The commercial waste Stream
Kitchen wastes Garden wastes	Municipal/park and landscape garden wastes Sewage sludge	Golf course and general commercial garden wastes Food leftovers Food processing and market wastes Manures Agriculture e.g. straw Abattoir and other animal by-product wastes Manufacturing processes e.g. furniture

2.3. Home composting

It is apparent from Table 2 that home composting is at a drastically smaller scale than any other form of composting. Also, as it is unique to each participating household in terms of input materials and process parameters, it is very difficult to monitor or analyse. For these reasons, home composting (Smith et al. 2003; Wheeler 2003) has not been subject to the rigorous analysis or environmental impact studies larger scale processes have been undergoing for decades (Haug 1980; Finstein et al. 1983; Hellebrand 1997; Regenstein et al. 1999; Zeman et al. 2002; Jackel et al. 2004; Hobson et al. 2005; Linzner et al. 2005). As participation in home composting grows, it is becoming increasingly important to account for the cumulative emissions which, among other things, can include powerful greenhouse gases such as methane, ammonia and nitrous oxide. Estimates of participation in home composting, as well as actual and potential rates of waste disposal through home composting, are discussed in the following sections. An important distinction should be made at this point, regarding the difference between actual waste disposal rates through home composting, and diversion from landfill. The analysis here is focused on waste disposal rates, for the purposes of experimental design and protocols, but these rates can not be considered equal to diversion as not all the waste that is home composted would otherwise have been landfilled. It could instead have been disposed of through various other routes including civic amenity sites, garden waste collections, community composting schemes or burning.

2.3.1. Estimating quantities of waste disposed of through home composting

Over a third of household waste is biodegradable (see Figure 4), so could theoretically be composted at home. As mentioned previously (section 2.2), however not all of the biodegradable components of this waste stream will be suitable for home composting. Although no legislation currently applies to home composting to enforce any restrictions on additions (unless livestock is kept under the Animal By-Products Order (1999)), there are many sources available to the public advising them on what to add if they do not learn by their own experience (See Figure 5). Estimates on the quantities of waste disposed of through home composting should, therefore, take these restrictions into account.

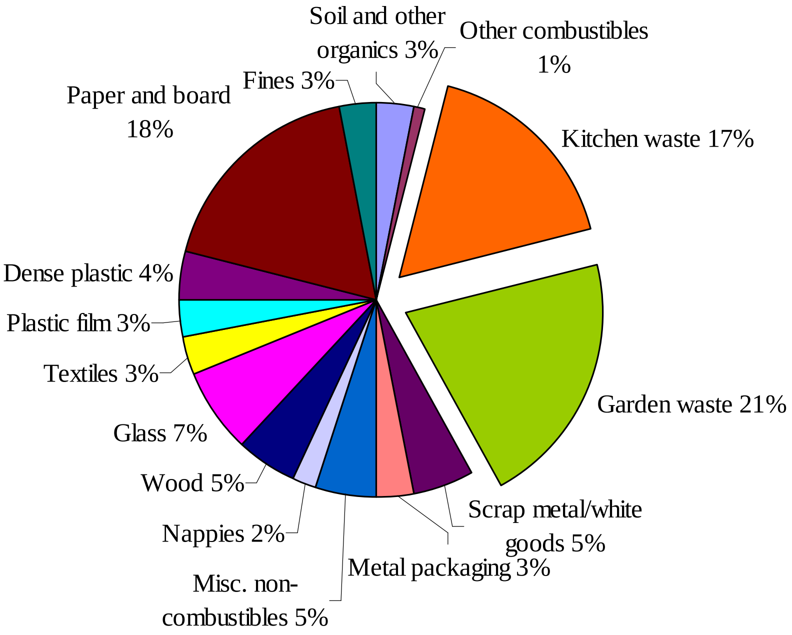

Figure 4: Analysis of household waste composition (Parfitt 2002)


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DO NOT COMPOST

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Letter from the Editor

Home Composting Hints

COMPOST MORE STUFF, MORE OFTEN

Compost in Cyber Space

TELL A FRIEND

Garden Makeover Ideas

Accessorise your compost bin

Figure 5: Publicly available composting leaflets (The Composting Association 2004; The Waste and Resources Action Programme 2006)

Materials can be unsuitable for two broad reasons:

1. <u>Health, safety and the environment</u>

Some organic materials such as those listed in Table 4 may carry the following health, safety and environmental risks (Stentiford et al. 1983; Trautmann et al. 2002; Coggins 2004; Waste online 2004):

- likely to cause odours – Materials rich in nitrogen, such as grass, food waste and manures can lead to emissions of NH_3 and VOC's which have very strong, unpleasant odours.
- attract pests such as rats and flies – Food wastes and manures will attract pests if there are sufficient quantities present
- may lead to the growth of bacteria, parasites, pathogens and viruses that are harmful to humans, animals or plants – animal products in any form including food wastes, manures and animal carcasses could carry harmful bacteria etc. that

could survive the composting process and be spread with the final material. This could lead to the contamination of grown food in gardens or arable land, nearby water sources and the soil potentially putting animals and people at risk of exposure. The same is true of plant materials carrying diseases but there is an added concern of perennial weeds and weed seeds being spread if they are added to compost.

- may lead to the build up of environmentally harmful chemicals in the compost – organic wastes can be contaminated with harmful chemicals from fertilisers, pesticides, traffic exhausts, household cleaning products and wastes. If these materials are composted the mass and volume loss during the process can increase the concentrations of the harmful chemicals. Again, this could lead to the contamination of grown food in gardens or arable land, nearby water sources and the soil potentially putting animals and people at risk of exposure.

The magnitude of the risks above depend very much on how well the compost process is managed and other factors such as the type and quantities of each feed component, the type of compost bin or heap, the bin location and the temperature the bin reaches during composting. The key composting parameter than can mitigate pathogen related problems is temperature. Different pathogens require various temperatures for different periods of time to ensure their destruction. Section 2.6.1 discusses the legislative requirements of different processes to ensure this destruction occurs for particular feed materials. Due to this complexity, and the difficulty of reaching and maintaining high temperatures at the home composting scale, advice given by the majority of relevant sources (different local authorities, master composter courses, leaflets, the Composting Association, environmental groups etc.) is to exclude all potentially hazardous materials from home composting.

Table 4: Materials unsuitable for home composting (Stentiford et al. 1983; Trautmann et al. 2002; Coggins 2004; Waste online 2004)

Materials with health, safety and environment risks to home composting
Dead animals Human and carnivorous animal (cats and dogs) excrement Meat cooked or uncooked Any cooked food Fish Oils and fats Dairy products Diseased plants Garden wastes contaminated with chemicals (from fertilizers, weed killers, paints on wood, etc.) Pernicious weeds Organic wastes contaminated with non-organic materials such as pieces of metal, glass, plastics and dusts.

2. <u>Balance of materials</u>

The composting process requires a balance of green and brown materials (See section 2.4.2) in order to perform well in terms of odours emitted, the time taken for composting and the quality of the compost produced. Therefore any materials present in excess will lead to either:

- Effort required by the composter to find additional materials from other sources such as farms or their community to balance those in excess
- Poor composting, possibly producing unwanted emissions (See section 2.5) and low quality compost (See section 2.6)
- The material requiring disposal by other means (e.g. Household garden waste collections, civic amenity sites, burning)

Paper and cardboard are materials that are typically available in excess, meaning only a very small proportion of them will be able to be successfully composted at home. Large woody materials such as thick branches, fence posts or tree trunks are also excluded due to the difficulty in composting such a large amount of one material and for their requirement for shredding or chipping prior to composting (see section 2.4.3). These considerations add significant difficulty to the estimation of potential waste diversion as it may not even be equal to the total amount of theoretically compostable household waste.

The factors discussed above mean that the large scale waste survey data available does not provide sufficient detail to accurately estimate home composting diversion. A few small studies have been performed to monitor individual household holds home composting additions for this reason but the data must be interpreted with care as variations may occur in urban/rural areas and/or with different socio-demographic characteristics. The data from one such study by Coggins (2004), using the definitions of compostable and non-compostable wastes in Table 5, can be seen in Table 6. This shows, firstly that the portion of non-compostable waste can be significant; there actually being more non-compostable than compostable garden waste in the inner urban group. Secondly, it demonstrates the wide variability that can be found between different groups. An in-depth review of the available data on compostable waste and actual home composting diversion is carried out in the next section.

Table 5: Definitions of compostable and non-compostable waste (Coggins 2004)

	Compostable	Non-Compostable
Garden	soft-prunings, grass, autumn leaves, green foliage	woody prunings, branches, fencing
Kitchen	peelings of fruit and vegetables, eggshells, nut shells, tea leaves and bags, cut flowers, plants	gravy, fat, meat waste+ bones, fish bones, cheese, rinds, nuts and seeds, hair + pet droppings

Table 6: Proportion of compostable waste from a study in Luton in October 1996 (Coggins 2004)

Waste category	Inner Urban	Outer Urban
Garden compostable	0.4kg (3.2%)	2.3 kg (14.5%)
Garden non-compostable	0.5 (2.9)	0.1 (0.6)
Total Garden	0.9 (6.1)	2.4 (15.1)
kitchen compostable	3.0 (22.5)	2.3 (14.5)
kitchen non-compostable	0.2 (1.6)	0.7 (4.5)
Total kitchen	3.2 (24.1)	3.0 (19.0)
Total putrescibles	4.1 (30.2)	5.4 (34.1)

2.3.2. Actual rates of waste disposal through home composting

The actual waste diverted by home composting from other sources of disposal is difficult to monitor satisfactorily for a range of reasons including:

- The intensive data collection and logistical issues required to monitor individual households.
- Significant variation in composition and quantities of waste across households and seasonally due to different eating habits and seasonal changes in garden waste.
- Variation in levels of participation at individual households over time due to social factors – enthusiasm for composting, need for compost, forgetfulness.
- The variable nature of Municipal Solid Waste makes monitoring reductions in collection volumes due to home composting extremely difficult.

For these reasons, waste disposal through home composting is currently excluded from local authority figures for diversion from landfill. The collated findings of a literature review of studies on compostable household waste and average home composting additions are shown in Table 7. The timescales and units of the reported additions vary widely so where necessary the figures were adjusted to give values in kg/yr and kg/week and grouped into either annual, winter, summer or unknown. Winter and summer were defined as 26 weeks long between Nov-Apr and May-Oct respectively. Total annual additions are reported with and without the inclusion of the Chartered

Institute of Pubic Finance and Accountancy (CIPFA) statistics as these include some very unreliable local council estimates of their household home composting waste disposal rates. The large variation in home composting additions and the limitations of small scale studies is very apparent from the data, with the maximum weekly addition being anywhere from 2 to 20 times the minimum as in the case of annual (CIPFA) total additions and the standard deviations varying between 20 to 60% of the average values.

The overall average annual addition was found to be 296 Kg/yr without the CIPFA data, and a much lower and less reliable 159 Kg/yr including it. Total additions were found to be larger in the summer period, presumably due to this period including the main growing season, when more garden waste is produced. This is not shown in the garden waste specific data, however, where the summer and winter additions are actually almost the same. This is almost certainly the result of a small and non-representative data sample however, as the total annual garden waste additions were much larger at 224 Kg/yr. It also does not reflect that the weekly summer addition had a much larger maximum weekly addition of 3.9 Kg compared to 2.6 Kg in winter. A comparison of the total and summed individual composition and seasonal additions, which should be the same in theory, is shown in Table 8. As already discussed the largest discrepancy occurs with the garden waste data, which has a summed weekly addition of 1.6 Kg but an actual annual value of 4.3 Kg. The other combined summer and winter additions agree very closely with the annual values, but the summed components again vary quite significantly from the overall totals, further illustrating the limited accuracy of the sampled data.

Table 7: Typical compost additions averaged from sources in the literature

	Timescale/ Season	**Average annual addition kg/yr**	**Average weekly addition kg/week**	**Weekly addition range Kg/week**	**Standard deviation Kg/week**
Average total compost additions	Annual	296	5.7	2.6-7.9	1.8
	Annual (CIPFA*)	159	3.1	0.5-9.0	1.8
	Winter	240	4.6	3.6-5.3	0.9
	Summer	357	6.9	5.1-8.3	1.6
	Unknown	259	5.0	2.3-8.1	1.9
Kitchen waste	Annual	118	2.3	1.6-3.9	0.8
	Summer	73	1.4	0.9-2.2	0.7
	Winter	141	2.7	1.4-5	1.1
	Unknown	96	1.8	-	-
Garden waste	Annual	224	4.3	0.5-5.6	1.9
	Summer	85	1.6	0.1-3.9	2.0
	Winter	86	1.6	0.4-2.6	1.0
	Unknown	239	4.6	3.6-5.6	1.4
Paper	Annual	12	0.2	0.1-0.7	-
	Summer	26	0.5	-	0.3
	Winter	48	0.9	-	-
	Unknown	12	0.2	-	-
Soil and other organic waste	Annual	25	0.5	0.2-0.8	0.4
	Annual	25	0.5	-	1.4
	Winter	27	0.5	-	-
	Unknown	15	0.3	-	-

*Including CIPFA statistics (Punshi 2000; Chartered Institute of Public Finance and Accountancy. Statistical Information Service. 2001; Mansell et al. 2001; Smith et al. 2001; Hogg et al. 2002; Parfitt 2002; Wheeler 2003; Williams et al. 2003; Bexley Coucil et al. 2004; Coggins 2004; Smith et al. 2004; Wheeler et al. 2004; Rodger et al. 2005)

Table 8: Compost additions from Table 7 summed from individual component waste streams and over summer and winter

	Timescale/ season	**Summed annual component addition kg/yr**	**Summed weekly component addition kg/week**	**Average weekly addition (Table 7) Kg/week**
Sum of average component waste streams	Annual	379	7.3	5.7
	Winter	210	4.0	4.6
	Summer	302	5.8	6.9
	Unknown	362	7.0	5.0
	Timescale/ season	**Average annual addition kg/yr**	**Average weekly addition kg/week**	**Average weekly addition (Table 7) Kg/week**
Combined summer and winter additions	Total additions	299	5.7	5.7
	Kitchen waste	107	2.1	2.3
	Garden waste	86	1.6	4.3
	Soil and other organic waste	26	0.5	0.5
	Paper	37	0.7	0.2
	Sum of components	256	5	5.7

2.3.3. Participation rates in home composting

The number of households participating in home composting has been estimated using data on the number of compost bins distributed by local authorities. This data is shown in Figure 6 and Figure 7, where it can be seen that participation is rising (though at an increasingly slower rate) and had reached 34% in 2000 with 2.25 million bins distributed by local authorities by 2004.

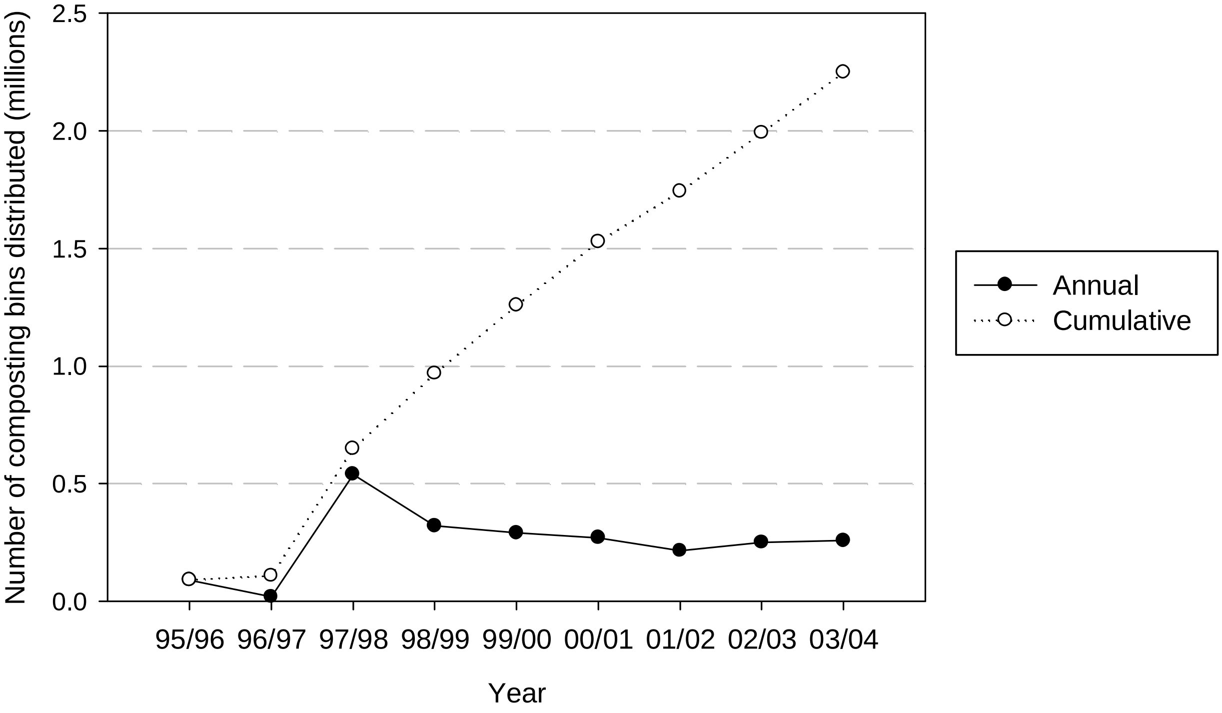


Figure 6: Distribution of home composting bins by local authorities in England 1995/96-2003/04 (Parfitt 2003; DEFRA 2005)

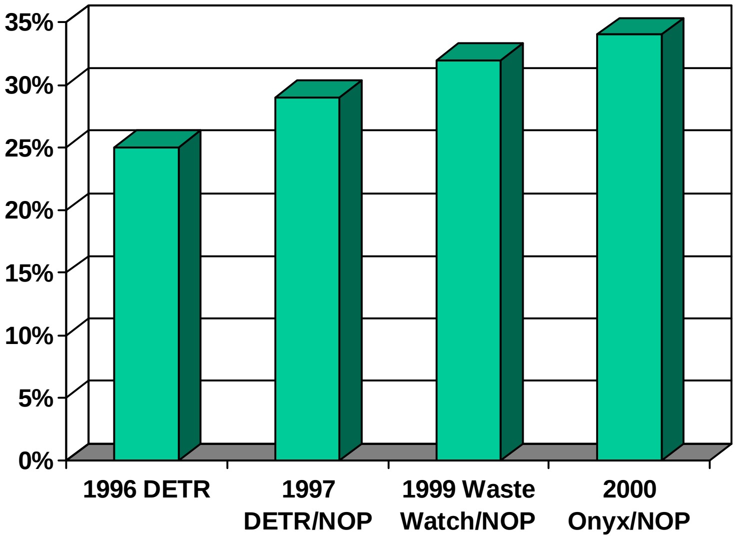


Figure 7: National participation in home composting 1996-2000 (Parfitt 2003)

Combining the typical waste disposal figures from section 2.3.2 with the number of bins distributed gives a very rough estimate of current diversion through home composting. This estimate does not take account of home composting activities taking place without council distributed bins and also assumes that all the bins distributed since 1995 are still in regular use. In order to estimate the diversion for 2008, it was assumed that bins continued to be distributed at the same rate as 2003/2004 up to 2007/2008, making the current total number of bins distributed 3.277 million bins. The results using the maximum, minimum and average household diversion estimates from Section 2.3.1 are shown in Table 9. Based on the average estimated household H.C. waste disposal rate, the total national diversion in 2008 is estimated to be 0.97 million tonnes. For comparison, the figures for total household waste arisings in England in 2006/07 were 25.8 million tonnes (DEFRA 2007). The WRAP home composting scheme target for the 2 year period from March 2004-2006 was to divert an additional 0.4 million tonnes of waste. WRAP estimated that by distributing more than an additional 1 million bins in that period they gave the capacity to divert around 0.275 million tonnes of waste over 2 years (Parfitt 2007).

Table 9: Estimates of total home composting diversion

Magnitude of estimate	Estimate of waste diverted through home composting Kg/hh/yr	Estimate of total waste diverted nationally in 2008 Millions of tonnes
Average	296	0.97
Maximum	468	1.53
Minimum	135	0.44

2.4. Key concepts and parameters: Background

A literature review has been performed on previous work into environmental emissions from composting, and home composting in particular. This section is intended to identify and investigate the key concepts that are relevant to the aims of the project, and to provide essential background information for the methodology development.

2.4.1. Oxygen and Aeration

Oxygen is essential for the metabolism and respiration of aerobic microorganisms (see section 2.1), and for oxidizing the various organic molecules present in the waste material (Epstein 1997). Oxygen in the air within the compost matrix is therefore consumed and replaced with the gaseous products of the composting process. Aeration refers to the processes by which oxygen is replaced in the compost matrix. In a compost pile, this can occur through two long-term processes and one short-term process:

<u>Bulk convective airflow</u>: This is the mass movement of air through pore spaces (see section 0), driven by an upwards buoyancy force present due to the density difference between the warm, moist interior compost air and the colder, less moist ambient air. The moisture content is important as water vapour has a considerably lower molecular weight than the oxygen and nitrogen gases it displaces. The saturation vapour pressure increases exponentially with temperature so it has an increasing effect at higher temperatures. Any carbon dioxide produced has an opposite effect, as its molecular weight is greater than either oxygen or nitrogen gases (Haug 1980; Epstein 1997).

<u>Molecular diffusion</u>: This is the gradual diffusion of molecules of oxygen through compost pore spaces driven by the concentration gradient from the low concentration within the compost matrix, to the higher concentration in the ambient air. Diffusion is significantly slower than convection; so much so that Haug (1980) reports it is insignificant except at very small compost volumes.

<u>Turning</u>: This refers to mechanically mixing or disturbing a compost pile so as to break up any clumps and compacted material. Turning causes a short term input of fresh air to the compost, but this is rapidly exhausted. With regard to aeration, the function of daily or weekly turning must be to assure that adequate free air space (FAS: see section 0) is

maintained (Haug 1980). If left unchecked, material compaction may cause FAS to decrease to the point where ventilation becomes inadequate. Periodic turning would decrease the unit bulk weight of the mixture, insuring the highest possible ventilation rate for the particular particle sizes in the mixture.

2.4.2. Carbon to Nitrogen ratio, C:N

Carbon and nitrogen are the two most important elements in the composting material, as the availability of one or the other is normally a limiting factor, with regards to microbial growth and hence composting activity. The availability of carbon and nitrogen in materials depends on their form, and does not necessarily conform to dry weight ratios. This is commonly an issue with high carbon, or “brown” materials, which are often derived from wood and other lignified plant materials, as increased lignin content reduces biodegradability. Particle size is an important factor, as small particles degrade more quickly than large particles of the same material; an optimum range of between 20-40mm has been reported (Trautmann et al. 2002). Shredding is therefore necessary to compost large woody materials. Nitrogen sources, or “green” materials, such as grass can give nearly instant availability that can exceed the assimilative capacity of the microbial community causing losses as ammonia gases and nitrates in leachate (Friends of the Earth 1993; Trautmann et al. 2002).

Composting microbes derive energy from degrading carbon compounds for growth and nitrogen for synthesising protein. Microbes use 30 parts by weight of carbon to each part of nitrogen, so material should have an available C:N ratio similar to this. Higher C:N ratios lead to progressively slower composting and lower ratios can lead to the release of ammonia and high nitrogen levels in leachate. The ranges recommended as acceptable in the literature vary between 20:1 to 40:1 with 30:1 typically described as optimal (Stentiford et al. 1983; Friends of the Earth 1993; Dickerson 2003; Petiot et al. 2004).

The final C:N ratio of the finished compost is also important in terms of the quality and benefits of the compost as a soil amendment. Stable soil organic matter has a C:N ratio of 12-15, which is the ideal range for finished compost. At higher values the nitrogen available to plants is reduced (Bary et al. 2002).

2.4.3. Porosity, air space and particle size

The properties of the composting matrix in terms of porosity or air space are important in a number of ways to the composting process and are also affected by several other factors. Since the microorganisms grow primarily on particle surfaces (Agnew et al. 2003), the substrate availability is determined by the surface area of the compost, which is dependent on the particle size. The particle size also affects the porosity, which determines how much water and air is available to the microorganisms (see sections 2.4.1 and 2.4.4). The continuity of the airspaces influences how easily air and water can flow through the material. The free air space also influences the heat and mass transport processes and therefore the microbial kinetics. The dependence of these properties on particle size is the reason shredding of large bulky materials such as branches is necessary (see section 2.3.1). All the properties mentioned so far are inherently difficult to measure directly; however another factor which is related to them but more easily measured is the bulk density.

The bulk density of compost is a measure of the mass of material within a given volume. It can be stated on a wet or a dry basis:

$$BD_{dry} = \frac{M_{dry}}{V_{wet}} \qquad\qquad BD_{wet} = \frac{M_{wet}}{V_{wet}}$$

Equation 2 **Equation 3**

The moisture content of the material should always be stated along with the bulk density to allow comparisons between materials. The bulk density influences the physical properties such as strength, porosity and ease of compaction. Due to its effect on porosity and air space it can be used as an approximate indicator of these parameters.

2.4.4. Moisture content

Water is both produced by and required for microbial activity, as it is necessary to support the metabolic processes of the microbes. Water provides the medium for chemical reactions, transports nutrients, and allows the microorganisms to move about (Agnew et al. 2003). If the moisture content is too high, the free air space and mechanical strength is reduced, which will lead to greater compaction and lower the porosity and aeration in the compost (see sections 2.4.1 and 2.4.3). Moisture is lost through leachate run-off, microbial reaction and as water vapour in the air. Water loss also contributes to temperature losses and is influenced by it. Optimum moisture content depends on the nature of the original materials but reasonable ranges are given as being between 40-65% with a preferred range of 50-60% (Epstein 1997; Krogmann et al. 2000; Beck-Friis et al. 2001; Agnew et al. 2003; Ward et al. 2005). The finished product should ideally have a moisture content in the range of 40 to 60 % by mass. Above 60%, the material may be clumpy and hard to spread on land with a lower organic matter per area applied. Below 40% the material may be dusty (Bary et al. 2002).

2.4.5. Temperature

Temperature is a key indicator in composting, as not only is it generated by the microbial decomposition of the organic matter, but it is also a determining factor of the decomposition rate (Trautmann et al. 2002). As the temperature increases, the activity of the bacteria increases and the reactions occur at a faster rate. The temperature is also linked to microbial succession by a relationship involving the feed substrates available and the temperature preferences of different microbial species (see section 2.1 and Appendix 1). Consequently if the temperature becomes too high (>65°C), fewer bacteria can survive so the decomposition rate falls. The temperature at any point during composting depends on the balance of heat generation by microbial action to heat losses through conduction, convection and radiation. This can be seen as a heat balance in Equation 4 (Fletcher et al. 2000):

$$Q_s = Q_{air\ in} - Q_{gas\ out} + Q_{react} - Q_{cond}$$

Equation 4

Where Q_s is the sensible heat change in the composting material, $Q_{air\ in}$ is the heat content of the inlet air, $Q_{gas\ out}$ is the heat content of the exhaust gases, Q_{react} is the heat generated by microbial reaction and Q_{cond} is the heat loss by conduction. Radiation has been considered negligible and ignored. The magnitude of the remaining values is interrelated with the other composting parameters.

2.4.6. pH and volatile fatty acids

The pH of compost material is dependent on the pH of the feed materials and the products of decomposition produced by microbial action. A typical pattern of pH variation under ideal conditions can be seen in Figure 3. Microorganisms have an optimum pH which they are most suited for, and at which their activity is most efficient. The microorganisms involved in composting have been found to prefer a pH of above 7 as it has been found that microbiological activity proceeds more slowly when the pH falls below this (Beck-Friis et al. 2001). It is believed that a high pH indicates an active composting process and that stability is indicated by a pH of 7.5 (Smidt et al. 2002; Smidt et al. 2005; Ward et al. 2005). The finished pH of compost should ideally be in the range of 5-8. Most plants prefer a pH of 6-7 and values below 5 or greater than 8 may injure them (Bary et al. 2002).

Fatty acids are products of anaerobic degradation. Their formation, breakdown and role in composting have only been briefly investigated but they are believed to be important in controlling biological activity and thereby gaseous emissions (Beck-Friis et al. 2001). This is presumably partly due to their influence on the pH of the composting environment, but as they are phytotoxic they can cause problems in cultivation (Eklind et al. 2000).

2.5. Gaseous emissions

The specific gaseous emissions produced during composting depend on the physical and chemical parameters of the materials and the associated active microbial species (see section 2.1). The following sections discuss the factors involved in, and the importance of, the known gaseous emissions possible from composting of organic household waste. When comparing different gases in terms of their impacts on climate change, it is common practice to compare them by their carbon dioxide equivalent, CO_2E, a quantity that describes the amount of CO_2 that would have the same global warming potential (GWP), when measured over a specified timescale. GWP is a measure of how much a given mass of a greenhouse gas is estimated to contribute to global warming relative to the same mass of CO_2, which is given a GWP of 1. For example, a gas with a global warming potential of 20 over a 100 year period would have 20 times the impact on global warming as the same mass of carbon dioxide emission over the following hundred years (Intergovernmental Panel on Climate Change (IPCC) 2001).

2.5.1. Carbon dioxide, CO_2

Carbon dioxide is the primary gaseous substance emitted during composting and can be regarded as a parameter for microbial activity where low emissions indicate a low activity (Hellman et al. 1997; Beck-Friis et al. 2001). It has been reported that about 30% of organic waste material can be decomposed to CO_2 within 2 months of composting and that the maximum emission rate occurs at the change between the mesophilic and thermophilic phases (see section 2.1) (Beck-Friis et al. 2000; Beck-Friis et al. 2001). Hellman, Zelles et al. (1997) and Zeman, Depken et al. (2002) state that in contrast to CO_2 emitted by fossil fuel combustion, CO_2 derived from plant matter degradation does not contribute to the Enhanced Greenhouse Effect (and thus to global warming) because it had been removed previously as CO_2 by photosynthesis from the atmosphere i.e. it is part of the “normal” “natural” cycle.

2.5.2. Methane, CH_4

Methane in the Earth’s atmosphere is an important greenhouse gas with a global warming potential of 25 over a 100 year period or 72 over a 20 year period. The average mole concentration of methane at the Earth’s surface in 1998 was 1.745 parts per billion (Intergovernmental Panel on Climate Change (IPCC) 2001). Methane is the product of the exclusive anaerobic processes of methanogenesis, performed by methanogens (Hellman et al. 1997). Emissions of methane from composting facilities in Germany were estimated to be $7.4\text{x}10^6$ $\text{tCH}_4\text{a}^{-1}$, which amounts to 0.31-0.44% of the total methane emissions in Germany (Jackel et al. 2004). Zeman, Depken et al. (2002), however, state that C/N ratios of garden organics are not likely to support methanogens, especially if aerobic conditions are well maintained. In addition, many prior experiments have shown that various compost materials can act as filter media for the biofiltration of methane (Nikiema et al. 2005). The biological degradation reaction of methane is given by:

$$CH_4 + O_2 \rightarrow xCO_2 + yH_2O + z\text{bacterial biomass}$$

Equation 5

Therefore both methane production and oxidation determine the net methane emission to the atmosphere. The oxidation is performed by methane-oxidising bacteria (MB). Phylogenetically MB belong to the Gammaproteobacteria (Methylococcacae) and Alphaproteobacteria (*Methylocystaceae* and genera *methylocapse* and *Methylocella*) (Jackel et al. 2004). Previous studies, for example in flooded rice fields (strong sources of methane), have shown that up to 90% of the CH_4 produced is oxidised before it can reach the atmosphere (Jackel et al. 2004). Under mesophilic conditions, composted material used as landfill cover material showed a methane-consuming potential, or increased the methane oxidation potential of the landfill cover soil. It has been found that methane is produced in compost only under high temperatures (Jackel et al. 2004).

2.5.3. Carbon monoxide

Hellebrand (1997) reported that carbon monoxide emissions over a composting experiment were about 0.04% of the initial carbon content of the green waste. Carbon monoxide is twice as effective as a greenhouse gas as carbon dioxide (IPCC 1996).

2.5.4. Nitrous oxide, N_2O

Nitrous oxide can either be a product of incomplete ammonium oxidation (nitrification) or of incomplete denitrification (Beck-Friis et al. 2000; Beck-Friis et al. 2001). Again, like methane, nitrous oxide contributes to an enhancement of the greenhouse effect but it is 270 times more effective than carbon dioxide (IPCC 1996). Several studies have shown that about 0.5% of nitrogen losses during composting of several wastes, including green wastes, occur through nitrous oxide in either gaseous form or in condensate (Hellebrand 1997; Beck-Friis et al. 2000; Beck-Friis et al. 2001).

Ammonium oxidizing bacteria are strictly aerobic bacteria, so are inhibited when the oxygen concentration is limiting and also when the temperature is over $40^{o}C$ (Beck-Friis et al. 2000). Denitrification can occur during mesophilic and thermophilic conditions and the process is repressed by O_2 as it is under anaerobic conditions that denitrifying bacteria use nitrous oxides as the terminal electron acceptor. Hellman et al. (1997) reported that during composting of household waste nitrous oxide emissions occurred during the first day when the temperature was rising and after 35 days when the temperature had fallen. Zeman et al. (2002) reported that most nitrous oxide emissions occurred during the final cooling stage of composting. Beck-Friis et al.

(2000) report nitrous oxide emissions at relatively high oxygen concentrations of 12%. An explanation provided for this is that compost particles may have an outer aerobic layer and an anaerobic core. The available substrates inside the core are soluble. From the core, the substrate diffuses into the outer aerobic layer where it is oxidised by an aerobic microbial population. Between the anaerobic and aerobic zones there is an area with an oxygen gradient, which could permit N_2O formation from both incomplete nitrification and denitrification.

2.5.5. Ammonia

Ammonia has a minor individual contribution to the greenhouse effect (Hellebrand 1997) and is also a strong cause of odours during composting. Beck-friis, Smars et al. (2001) reports that 24-33% of initial N lost over a composting experiment, was emitted almost entirely as ammonia. Over 85% of this, however, was found in the condensate, with the remainder in gaseous form.

2.5.6. Volatile Organic Compounds (VOCs)

Organic compounds can be volatilized during composting and represent major odour sources, groups include: fatty acids, ketones; aromatics; and other inorganic and organic sulphur compounds (Epstein 1997). Species and concentrations of VOC emissions monitored from MSW and biosolids operations have been found to be low and not to represent a significant hazard to workers. The feedstock is an important factor in their emission and also whether the materials are in anaerobic or aerobic conditions. For instance, compacted wet leaves produce a much stronger unpleasant fermentation odour than fresh dry leaves.

2.6. Compost quality, composition and standards

The end stage composition of composts, prior to spreading on land, is important in determining their benefits as a soil improver, but also any potentially negative environmental impacts and human, plant or animal health risks. For example, it is believed that the 2001 UK foot-and-mouth outbreak, and the classical swine fever outbreak in 2000, were caused by contaminated catering waste (DEFRA 2006). If similarly contaminated materials were used as composting feed, the resulting compost could also be contaminated. The factors contributing to the final composition are primarily the feedstock materials and their properties, but also the process parameters over all composting stages, particularly the oxygen concentration, pH, temperature and moisture content and their respective durations.

2.6.1. Legislative requirements

EU and subsequent national legislation exists to control the composting of feedstocks that may pose a risk to human and animal health. Under the UK Animal By-Products Order 1999 (as amended), it was illegal to allow livestock or wild birds access to catering waste which contained meat or products of animal origin, or which came from a premises handling meat or products of animal origin. This ban applied whether or not the catering waste had been treated. It therefore could not be used on land, effectively banning its use in compost and biogas treatment plants. Under the current Animal By-Products Regulations 2005 (Statutory Instrument 2347/2005), which came into force on 28 September 2005, approved composting and biogas premises can be permitted to handle certain low-risk animal by-products and catering waste which contains meat or which comes from a premises handling meat. In order to receive permission, these facilities must demonstrate that the appropriate materials are composted to one of several suitable standards, detailed in Table 10, with the following additional barriers:

(a) Raw material must be meat-excluded catering waste
(b) Materials must go through a second composting stage, using any of the conditions detailed in Table 10. For this second stage, windrowing does not need to be housed and can be done open (but the time/temperature and turning requirements remain the same as for housed windrows)
(c) Storage for a minimum of 18 days (this need not be in an enclosed system).

Composting plants must either use barrier (b), or both barriers (a) and (c). That is to say, there must either be two composting stages, or for meat-excluded catering waste only, one composting stage followed by storage.

Table 10: Minimum time/temperature and max particle size requirements (DEFRA 2006)

System	Minimum temperature	Minimum time	Maximum particle size
Composting (closed reactor)	60°C	2 days	40cm
Biogas	57°C	5 hours	5cm
Composting (closed reactor) or biogas	70°C	1 hour	6 cm
Composting (housed windrow)	60°C	8 days (during which windrow must be turned at least 3 times at no less than 2 day intervals)	40cm

If carried out purely as a method of waste disposal, then there is little further legislation on the composition or quality of composts. As a method of waste disposal, composting comes under the Waste Management Licensing Regulations 1994. According to these regulations, compost along with several other materials is exempted from waste management licensing, subject to certain conditions: a key condition, for example, is that no more than 250 tonnes of waste per hectare are spread on the land in any 12-month period.

2.6.2. Voluntary standards

If a compost product is intended to be used as a soil improver and particularly if it is to be sold as one, then its specific composition and quality as a soil improver is important. Although there are currently no legislative requirements for compost quality, there are a number of standards or codes of practice a compost producer can adhere to in order to improve public confidence in their product. These standards specify conditions in which composting should be carried out and the permissible concentration levels for a range of potentially toxic elements, physical contaminants, weeds and human pathogens. Some of the detailed specifications of three such standards are summarised in Appendix 3:

- Composting association standard PAS 100: BSI Publicly Available Specification launched in November 2002 and revised in 2005. This standard is required to obtain Composting Association certification.

- APEX: APEX was launched in summer 2002 by three of the UK's biggest waste management firms: SITA, Cleanaway and Onyx.

- Eco-label: Eco-label was launched in the early 1990s by the European Union to allow consumers to easily identify officially approved "green products". It specifies that soil improvers should derive from organic matter content provided by the processing of waste material, as long as materials of animal origin comply with community legislation. Sewage sludge is not permitted.

2.7. Leachate and condensate

During composting, depending on the feedstock and the composting process, leachate, condensate and runoff are generated. Leachate can be defined as water that percolates through the compost and exits at the bottom while condensate is water that evaporates from the compost and condenses on external surfaces such as building walls (Krogmann et al. 2000). In most composting piles, water moves to the bottom under the influence of gravity and creates leachate if the moisture content of the compost exceeds its water holding capacity. The maximum tolerable moisture content of coarser materials (wood and bark: 74 to 90%) exceeds the moisture content of finer, less structured materials (e.g. paper: 55 to 65%, food waste and grass clippings: 50 to 55%) (Krogmann et al. 2000). Evaporation is the major energy release mechanism during composting and in many cases the main fate of moisture during composting (Finstein et al. 1983). The mass transfer from biogenic waste to leachate can be divided into three categories (Krogmann et al. 2000):

- Hydrolysis of biogenic waste and biological degradation
- Solubilisation of soluble salts
- Entrainment of particulate matter.

The transfer of chemicals to leachate from compost could potentially cause leachate to become harmful to soil and water sources depending on the concentrations involved. Leachate can be of significant environmental concern in large scale composting for this reason, but due to the small scale of individual home composting activities, and the wide distance between them collectively, it is much less unlikely for home composting leachate to be of environmental relevance.

2.8. Alternative approaches to investigating home composting

Experiments to investigate home composting could be undertaken in several quite different ways. There are, however, basically four distinct approaches that can be taken, which have been defined here as:

2.8.1. Monitoring of in-situ home composting activities:

Members of the public are asked to volunteer to have their compost activities monitored. The researcher can then visit the participating households to take measurements and samples and the householder themselves can be utilised to take some measurements.

2.8.2. Home composting activities managed by the researcher

Home composting activities could be imitated by the researcher by composting a typical household's compostable waste stream under whatever household conditions were chosen, such as the size and type of compost bin, waste composition, feed rate, etc. A chosen number of compost bins could then be run simultaneously at a selected location and the researcher could take all measurements and samples to any schedule. The waste stream could come either by the researcher regularly collecting volunteering households' compostable waste to use at the experiment's location or specified compositions could be created from bulk sources of household compostable waste.

2.8.3. Laboratory-scale composting reactors managed to simulate home composting

A frequently used technique in composting research is to use laboratory scale reactors (Beck-Friis et al. 2001; Petiot et al. 2004). Although there are examples of very large reactors, over 1m^3 being built for research purposes, (Schwab et al. 1994; VanderGheynst et al. 1997), the more common case considered here is for smaller reactors, around 40L or less. The practice of using scaled down reactors has been developed primarily as a tool for studying the composting process within conditions existing in industrial plants but without on-site difficulties (labour consuming, hard to control, heterogeneous raw product, fluctuating weather conditions and preferential flow pathways). Various methods have been adopted to allow the researcher to set the composting parameters in a reactor to whatever conditions are desired. The technique, however, is not without its limitations and reproduction of the composting treatment at a laboratory scale is not simply a case of reducing scale (Petiot et al. 2004).

2.8.4. Home composting scale reactors managed to simulate home composting

Due to the small scale of most home composting activities compared with other targets of composting research, it is relatively simple to construct composting reactors of the same scale. It is therefore possible to perform well controlled and monitored experiments within a specially built reactor but without many of the difficulties involved in scaling processes down.

2.8.5. Direct comparisons between the alternative approaches

The tables below summarise the advantages and disadvantages of the alternative approaches by comparing the three key differences:

- In-situ householder composting vs. Managed composting experiments
- Non-reactor based experiments vs. Reactor based experiments
- Small-scale reactors vs. Large-scale reactors

Table 11: Comparison between in-situ householder composting and managed composting experimental methods

In-situ householder composting	Managed composting experiments
Measurements are taken directly from members of the public's home composting activities so are theoretically not dependent on any assumptions, interpretations or actions by the researcher.	The quality and value of the data collected depends on the accuracy of the researchers' assumptions and practices in setting-up and performing the experiments.
The number of households taking part in any research is only strictly limited by the frequency of visits required by the researcher and the associated time constraints. If the householders agree to participate actively a large amount of data can be collected such as waste additions and temperature.	The researcher must run each individual compost process including acquiring and supplying the feed waste stream so the number that can be run and adequately monitored at once will be constrained.

In-situ householder composting	Managed composting experiments
If a sufficiently large number of households are involved for the sample to be representative of the variety and differences in national composting activities then confident conclusions can be drawn from the data regarding national composting emissions and processes.	Physical and time constraints on the number of experiments that can be run simultaneously mean that the accuracy and value of any conclusions drawn from the collected data are dependent on the researcher's choice of experiments and their success in designing and carrying out the experiments based on the available survey data.
Due to the huge variation possible amongst different home composting activities a very large number of households would need to be involved to allow reliable interpretation of the collected data and then it is still vulnerable to geographical, social or other bias. Also detailed interpretation of the collected data would likely be hindered by the number of variables involved.	The researcher can use all available research and survey data about the household compostable waste stream and home composting activities to run the experiments under any chosen conditions, such as national averages, a specific range or conditions of special interest. Many variables can also be fixed for all experiments, allowing investigation of individual parameters and patterns to be identified within the data.
If a large number of households are involved then the measurement frequency of readings that can only be taken by the researcher will be significantly reduced due to the time constraints of travelling between them. Measurements are also restricted to either suitably accurate portable devices or the careful collection and transport of samples from all participating households to the analysis laboratory.	Working at one site allows the researcher to take measurements and samples from all experiments efficiently with a high frequency. At a suitable secure location it is also possible to keep expensive or sensitive equipment for frequent use with the added potential for collecting large quantities of data by data logging.
If the householders are utilised to make measurements then the quality of that data may be questionable due to its dependence on the methodology and proficiency of each householder which could vary significantly. Also measuring equipment must be supplied to each household adding to the project cost.	All measurements would be made by the researcher, ensuring much better consistency of method and technical proficiency.

In-situ householder composting	Managed composting experiments
The work depends on the participation of the public so may require monetary or other incentives and is vulnerable to the participants dropping out during the study.	As long as the feed waste stream for the experiments has a reliable and consistent source there is no external dependence.
The participants may alter their composting activities due to their participation in the study and hence give misleading data.	Any conditions designed into the experiments by the researcher can be consistently and reliably maintained.

Table 12: Comparison between standard H.C. bin and reactor based experimental methods

Standard H.C. bin experiments (household compost bin/heap etc.)	Reactor based experiments
Carrying out the experiments in conditions as similar as possible to the home composting activities they are designed to investigate improves confidence in the quality and relevance of the data with regards to the project aims.	Composting in a reactor as opposed to any form of typical home composting activity will, to varying degrees, inherently alter several composting parameters that may cause further differences in the process.
The relatively open system of typical home composting activities means designing a suitable monitoring methodology which can be correctly interpreted is not a straight forward task.	A reactor is a closed system which can be designed so that all inputs and outputs can relatively easily be collected, measured and quantified.

Table 13: Comparison between Laboratory-scale and Home composting scale experimental methods

Laboratory-scale reactors (<20L)	Home composting scale reactors (>100L)
Scaling down the process necessitates treatment of the waste materials to create a small particle size so that a consistent and homogeneous feed can be used. This makes it possible to make a feed material with a very accurate composition and moisture content but has other implications on the scaling effects.	At scales similar to typical home composting activities so waste does not need to be shredded very finely in order to produce homogeneous feeds which means conditions can be kept closer to those in home composting.

Laboratory-scale reactors (<20L)	**Home composting scale reactors (>100L)**
The scaling down of the process unavoidably alters many parameters of the composting material which could reduce the validity of relating the results to home composting. Some examples of the affected parameters are: air flow resistance, temperature generation, material heat coefficient, compaction/bulk density, nutrient availability.	A large scale reactor can be fed and managed identically to a typical home compost bin meaning relating the data collected from them to home composting activities can be done with some confidence. The only differences remaining being those caused by the forced rather than natural aeration and the physical separation from the surrounding environment, although these differences could still be significant.
It is possible to quite finely control the process conditions throughout the whole composting material due to the small scales involved, thereby allowing investigation of the emissions and processes occurring under specified conditions.	At larger scales, accurate control of the process conditions throughout the material is difficult to monitor or achieve successfully.
Experiments in small reactors enable the study of the process and emissions at conditions specified by the researcher. A draw back of their use in this project is the lack of data regarding how conditions vary in home composting activities. They lend themselves towards testing how specific conditions affect the process and emissions of different waste compositions and to identifying what conditions lead to potentially significant harmful emissions.	The aim of running a large scale reactor would be that, for a suitable airflow, the reactor would match the process conditions of a similarly run home composting process. The changes in parameters and emissions during the composting of a particular feed stream could therefore be monitored over the whole course of the process.

2.9. Previous research into home composting

In this section, any research specifically relating to the study of home composting processes and emissions has been reviewed with particular reference to methods used and any lessons that can be learnt. Investigations concerned purely with waste diversion have been excluded from this section but have been referred to in Section 2.3.2.

2.9.1. Home composting: Process, diversion and end-use

A significant piece of research was carried out at Imperial College London between 2000 and 2002 which has been the subject of at least three publications:

- A Practical Study on Organic Waste Diversion from Landfill by Home Composting (Smith et al. 2001).
- Small-scale composting of biodegradable household waste: process, diversion and end-use (Smith et al. 2004).
- Home composting: process, diversion and end-use (Smith et al. 2003)

The research consisted of 2 parts:

1. A questionnaire was distributed to almost 4000 properties to collect demographic and socio-economic data relating to participation in a home composting scheme.
2. 64 households were selected for detailed monitoring of their composting bins. Homeowners supplied with a 290L compost bin, weighing bucket, spring balance and compost thermometer. Amounts of kitchen, paper and garden waste placed in the compost bin and temperature were recorded by the householder. More detailed monitoring of temperature conditions and gas profiles using an electronic thermometer and gas sampling probe were performed by the researchers.

The following section examines and critiques the methods and results of the second part of the research.

Waste composition and temperature data collected by the householders

By utilising the householders to collect ongoing data, a large quantity of measurements over a long period of time were collected. The composition data has been included in Section 2.3.2 and the temperature data has been summarised in Table 14 below. Limitations in this type of data have been discussed in Section 2.8.5. The temperature data would possibly be more valuable were the frequency and timing of the measurements known in relation to material additions. Measurements made at the same time as a material addition will be made when the temperature is likely to be at its lowest, immediately before it rises. Infrequent measurements will not record the relatively fast temperature changes that occur during composting.

Table 14: Proportion of temperature readings taken in each range, adapted from (Smith et al. 2001)

	Proportion of temperature readings taken in each range		
	Psychrophilic range 0-20^{o}C	Mesophilic 20-45^{o}C	Thermophilic 45-70^{o}C
Summer (May-Oct)	20%	70%	10%
Winter (Nov-Apr)	95%	4%	1%

A summary of the findings on temperature and oxygen concentrations in relation to depth are given in Table 15 and the effects of several composting factors on the temperature, carbon dioxide and oxygen concentrations in Table 16.

These measurements were collected by the researchers so are likely to be more reliable than the householder data. Related data such as the frequency, quantity and relative timing of the waste additions would have provided further insight due to the relatively fast changes that can occur during composting. While almost no significant variation was found across any of the factors it is unknown what activity was occurring in the bins at the time of measurement. Depending on if measurements were made several days after a material addition or immediately following one, the results could be very different. The oxygen concentration data could be demonstrating this problem as most of the measurements show a high oxygen concentration within a very narrow range indicating low activity, except for just one result. This one result is far outside the range of any of the others, possibly because that compost bin had received a material addition very close to the measurement time while the others had not.

Table 15: Range of temperature and oxygen concentration values at different depths, adapted from (Smith et al. 2004)

	Range of values at each depth			
	10cm	20cm	30cm	40cm
Temperature °C	17-42	18-42	18-37	17-32
Oxygen conc. %	19-20.9 except one 16.0	18.0-20.9	18.5-20.9 except one 17.0	19-20.5 except one 15.5

Table 16: Effects of four factors on the composting process, adapted from (Smith et al. 2004)

	Garden size		Mixing		Earthworm inoculation		Accelerator	
	Large	Small	No	Yes	No	Yes	No	Yes
Temp (°C)	15.8	15.8	15.3	16.3	15.7	15.9	15.5	16.0
CO_2 (%)	0.53	0.34	0.54	0.29	0.39	0.43	0.42	0.40
O_2 (%)	19.8	19.9	19.7	19.9	19.9	19.8	19.8	19.9

Microbiological assessment

All 64 bins were tested for airborne *Aspergillus spp.* during physical disturbance of the composting material. The microbiological species present in compost vary significantly over the course of the process (See Section 2.1) and it is not clear how this could affect airborne concentrations of species such as *Aspergillus spp.* The values found (see Table 17), however, are significantly below the recommended tolerable concentration of 1000 cfu m^{-3}, or the exposure dose (>106 cfu m^{-3}) that may cause sensitisation (Milner et al. 1994). Further investigation may therefore be unnecessary, especially considering the low contact time most householders are likely to have with their compost.

Table 17: Concentration of *Aspergillus spp.* During physical disturbance of home compost, adapted from (Smith et al. 2004)

Statistic	Original colony count	Corrected colony number	*Aspergillus* concentration (cfu m^{-3})
Minimum	10.0	11.0	36.7
Maximum	30.0	37.0	123.3
Median	21.0	24.0	80.0
Mean	20.9	23.7	78.7

Vector attraction

Insect traps were placed inside and at distances of 1m and 2m from the compost bins and the traps were removed after periods of 1,3, 5 and 10 days. The largest numbers of flies were found within the bin and they decreased significantly at greater distances (see Figure 8). Using or not using lids on the compost bins was found to have no effect but a smaller garden size did cause a greater number of flies, thought by the author to be due to the proportionally greater presence of food waste.

This data is relevant to the social factors of participation and drop-out in home composting but less important in studying the environmental impacts. It could be of use in assessing potential health risks but the attraction of other pests, particularly rats could be more significant.

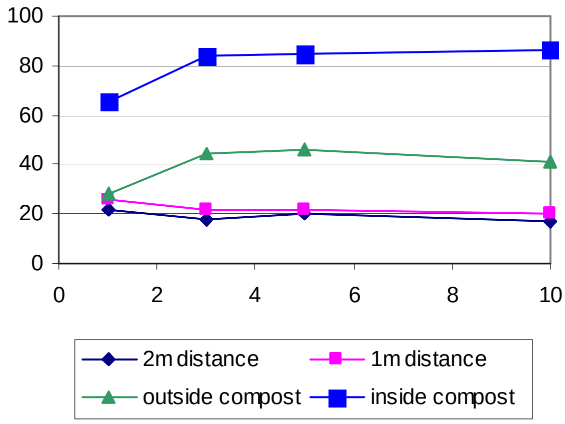


Figure 8: Mean number of fruit flies collected from compost bins, adapted from (Smith et al. 2004)

Compost quality

Samples of mature compost material from all bins were analysed for a suite of chemical determinants (Table 18) and were also subjected to a plant growth trial relative to peat and an unamended control. By testing composts produced by a statistically significant sample of home composters a good indicator of the range and average compost quality can be found. The effect of the four factors: garden size, mixing, earthworm inoculation and use of accelerators were analysed but no significant variation was found.

The report indicated that the home produced composts generally had higher contents of major nutrients than those typically reported for centralised composting. It also reported that this may be because woody plant remains of low nutrient status are generally excluded from home composting. A further point raised was that high variability in home composts may be related to the extent of fertiliser used by individual home owners and the associated nutrient content of their plant debris.

The results of the growth trial indicated that the home composts are effective replacements for peat based substrates for general horticultural use as well as soil improvers. The peat and control tests produced an average of 120 and 140 cumulative flowers per plant respectively while the home composts produced from between 148 to 215, a significant improvement. These results are significant in terms of environmental impacts; if home produced compost is able to replace peat, this can reduce the environmental damage done by removing peat and the transport emissions associated with its distribution for home use.

The chemical properties analysed do not cover all the properties typically required by compost standards or specifications. In the case of the PAS 100 specifications for soil improvers or fertilisers (See 2.6.2) for example, the following required parameters are missing:

- Pathogens (human)
- Potentially toxic elements
- Physical contaminants
- Phytotoxins
- Weed propagules

The researchers may have left out these analyses on the assumption that if householders follow basic advice on home composting these parameters should not pose any risk unlike in centralised composting with its less controlled waste stream.

Table 18: Chemical properties of home composts (Smith et al. 2004)

Parameter	Minimum	Maximum	Median	Mean
Dry solids (%)	17.2	75.4	33.3	30.2
Organic matter (% ds)	6.6	69.3	30.6	27.9
Total N (% ds)	1.12	6.07	3.19	3.32
Total P (% ds)	0.10	1.62	0.56	0.61
Total K (% ds)	0.42	4.15	1.45	1.59
Total Mg (mg Kg^{-1}ds)	128.5	625.7	242.3	276.4
pH	5.7	9.3	7.1	7.3
Conductivity (ms/cm)	462	1618	796	859
NO_3-N (mg Kg^{-1} ds)	8.81	96.9	35.8	41.4
NO_2-N (mg Kg^{-1} ds)	0.10	3.43	0.51	0.66
NH_4-N (mg Kg^{-1} ds)	0.87	37.7	14.9	14.3
Extractable P (% ds)	0.02	0.17	0.06	0.06

2.9.2. EA Home compost study

A study of home composting was commissioned by the Environment Agency in 2001 - 2003 and carried out by AEA Technology, the Open University and the University of East Anglia. At the time of writing the study is known to have been the subject of one publication and one unpublished report:

- EA Home compost study (Wheeler 2003)
- Life cycle assessment of home composting (Wheeler et al. 2004)

The study consisted of two parts:

- A literature and survey based investigation of how much and what types of wastes are composted at home
- A one year monitoring experiment of the home composting at 12 selected households.

The following section reviews and critiques the methodology and results of the study.

Household selection for monitoring experiment

The home composting activities of 12 households were monitored, selected by survey responses to cover the following variables:

- Four compost systems selected as representative of all systems in use:
- Unconfined heap
- Wooden self built, open structured composter
- Local authority supplied simple, unventilated container
- Plastic ventilated purchased unit
- Users classified as active or inactive based on volunteer description of their activity:
- Inactive – little or no material pre-treatment and did not turn the heap.
- Active – turned their compost more than once a year and attempted to balance or pre-treat the waste input.

The advantages and disadvantages of this type of investigation have been discussed in detail in Section 2.8.5.

Gas analysis

Methane and CO_2 analysis was carried out using a Geotechnical Instruments GA 94-1 gas analyser, shared between the households allowing approximately weekly analysis, possibly not a sufficient frequency to accurately assess composting gas emissions. VOC and ammonia measurements were made using diffusion tubes in four 1 month campaigns representing winter, spring, summer and autumn. In closed compost bins the headspace gas was analysed, while in the open systems a flux box method was used (see Section 2.12).

Carbon dioxide analysis gave a measured value in only 32 out of 112 readings, a surprisingly low number, possibly related to the frequency and timing of the measurements. The detection limit of the methane analysis equipment initially used was 0.1 volume %, which produced readings in only 2 out of 112 measurements. More accurate equipment was also used, although details are not given, which presumably produced the results in Table 19. The method for quantifying the emissions per unit mass of waste was based on the assumption of bulk convective flow as the gas exchange mechanism and the use of CO_2 emissions as a trace gas to estimate the gas flow rate. Due to the unverified assumption on the gas exchange mechanism and the low accuracy of the CO_2 emission estimates this method is of very limited reliability. The author states that a range of values was given due to the low concentrations and non-detect results. The concentrations of ammonia in winter and spring were in the range 50-600 ppb except for one result of 1800 ppb where the householder had added chicken manure.

Table 19: Gas emissions, adapted from (Wheeler 2003)

	CH_4 range (Kg/T waste)	NH_3 (Kg/T waste)
Average	2.32-206	23.6

Table 20: VOC emissions, adapted from (Wheeler 2003)

	Range of VOC emissions per Mg waste input (μg/T waste)
α-Terpineol	0.03-0.17
Pinene	0.15-0.57
Terpinene	0.20-0.61
d-Limonene	0.01-0.07
Limonene	20.00-72.64
Myrcene	0.55-1.86
Cymnene	1.63-6.22
Benzene	0.02-0.11
Toluene	0.03-0.16

Leachate analysis

Leachate collection was carried out using a collection tray at the base of the composting mass and the leachate was collected in a bottle which was monitored frequently (Figure 9). The total leachate generated will not be accurately measured by this method as some will escape beyond the edge of the tray. Further, it is unclear how much the presence of the tray will alter the behaviour of the composting process. It is highly likely to affect the airflow and moisture content throughout the bin, and potentially the movement of macroscopic life.

Table 21: Average generated leachate properties (Wheeler 2003)

	Volume generated (L/Mg)	pH	Ammonia (g/T)	Chloride (g/T)	COD (g/T)
Average	31.3	7.6	0.5	26.16	80

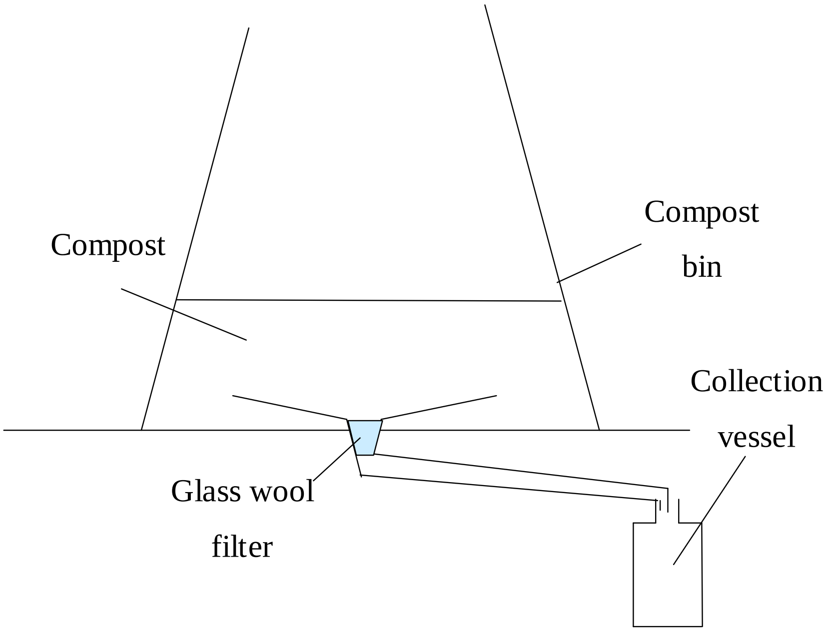


Figure 9 System used by Wheeler (2004) for collection of Leachate samples

Compost composition

The composition of the home composts produced by the householders were analysed for a selection of chemical elements. The selection includes most of the potentially toxic elements required by the PAS 100 specification but excludes mercury and zinc. As can be seen in Table 22 the findings of this study show that for these home composts the concentrations of potentially toxic elements are substantially below those required for PAS 100 specification.

Table 22: Home compost chemical composition compared to PAS 100 specifications (British Standards 2002; Wheeler 2003)

Element	Compost composition (g/T)	Limit required by PAS 100 specification (g/T dry matter)
Nitrogen, N	13502	-
Phosphorus, P	2439	-
Potassium, K	3432	-
Copper, Cu	13	≤200
Cadmium, Cd	0.47	≤1.5
Chromium, Cr	11	≤100
Nickel, Ni	7.1	≤50
Lead, Pb	34	≤200

2.9.3. Summary

The studies discussed in Section 2.9 have taken the approach of monitoring in-situ household composting activities, although in quite different ways, and have covered several areas of home composting research. Valuable data and lessons have been produced from the work but there is still room for further investigation particularly in some areas. Areas of research that have been covered in some detail already are: waste stream composition, microbiological assessment, vector attraction and compost quality and composition. The experimental approaches taken lend themselves well to these areas and the findings have shown that the microbiological health risks of home composting are low and the composts produced are able to perform well as a soil improver. Leachate collection and analysis has been performed in the second piece of research but further investigation could be performed testing different collection methodologies. The temperature and gas composition data could benefit from investigation by an alternative approach. More frequent and sensitive measurements may still give valuable data not covered by this work. A more controlled investigation of influencing factors may also be beneficial rather than the in-situ household behavioural trends adopted in the above work. The factors of garden size, mixing, earthworm inoculation, use of accelerators, bin type/heap and activeness were covered so perhaps other factors should be investigated, particularly in the case of earthworm inoculation and accelerator use which showed no significant effects.

2.10. Selection of experimental approach

It was apparent from the points discussed in section 2.8 and the research reviewed in Section 2.9 that an experimental approach monitoring in-situ household composting, as has been performed extensively in the past, offered the least benefits for the purposes of this project. Standard H.C. bin (Section 2.8.2) and reactor (Sections 2.8.3 and 2.8.4) based experiments offered contrasting advantages and disadvantages making the ideal approach to use both methods simultaneously. Not only would this allow utilization of the advantages of both techniques but it also offered the potential to make direct comparisons between the two systems run in parallel. In order to maximize the value of comparisons between the two systems it was chosen to run large rather than small scale reactors so as to minimize any differences.

Two different types of experiment systems were selected for study:

- The standard home compost bin system, managed to simulate selected home composting activities in specified conditions. This will enable the monitoring of composting processes closely matching those of a householder composting in similar conditions.
- Reactor based experiments at the same scale as H.C. bins, able to be run under almost identical conditions but built to allow control over certain parameters and accurate measurement of gas flow rates and emissions.

Sections 2.11 and 2.13 describe the design features of these experimental systems.

2.11. Home compost bin system

The remit of simulating home composting activities is a very large one, given the wide variety of systems and behaviours possible. Brief descriptions of some of the H.C. systems available to the public are provided in Table 23 and illustrated in Figure 10.

Table 23: Compost systems available for use in home composting

Compost system	Description
Tumbler	Consists of a drum mounted on a stand; they either tumble end over end, or around on their axis.
Basic H.C. bin	Possibly the most familiar type of compost bin, promoted and provided by most local authorities and also available from many water companies and garden centres. Sizes vary from 200L to over 700L, may or may not have access/inspection hatches and bases and come in a variety of colours.
Digester	Most common example is the 'Green Cone', consisting of a basket, buried in the ground with a double skin cone above ground. Difficult for rats to enter and utilizes worms to transfer broken down material into the surrounding soil. Does not produce removable compost but must be moved to another site every 1-2 years.
Green Johanna	Similar in shape to common open bottomed H.C. bin but of sturdier construction, fully sealed with a base place, preventing entrance by rats.
Wormeries	Worms can take part at certain stages in any composting process, however a system can be purpose built to utilize certain species of worms to decompose small quantities of kitchen waste.
Open heap or home made system	Material can simply be placed in a heap and composting will occur, though possibly at a slower rate depending on the size of the heap. Various levels of home made system can be built, from simply placing carpet over a heap for heat retention to large, multi-tiered or sectioned wooden constructions with lids and insulation.

Figure 10: Examples of H.C. systems available (Top: Left to right) Tumbler, open bottomed, Green Johanna (Bottom: Left to right) Digester, Wormery, Open heap

It is not known exactly how the type of compost system used affects the composting process and emissions and while this would ideally form a part of this study, only a certain number of factors can be investigated within the project time constraints. The majority of local councils that have promoted home composting have focused on plastic open bottomed H.C. bins, most likely because they offer the cheapest and simplest option other than unsightly open heaps or some home made systems. It is therefore reasonable to assume that these are the most common system as millions are known to be in use in the UK (DEFRA 2005; Scott 2005). At the time of setting up the experiments residents of several counties across the county were able to purchase Blackwall 220L compost converters at a discount price as part of the WRAP home composting scheme. These bins were therefore chosen as representative of typical open bottomed county council promoted compost bins, and therefore likely to be in common usage.

2.12. Monitoring emissions from an open system

Monitoring a relatively open system such as an open-bottomed compost bin presents several challenges. For gaseous emissions, when working with a closed system the outlet flow rate and composition can be measured from which the rates of emission of individual gasses can be calculated. In the particular case of an open bottomed compost bin, the air can enter and pass through the bin in several ways. The relative importance of the different air pathways will depend on the conditions in the bin. Possible air pathways are illustrated in Figure 11 and discussed in Table 24.

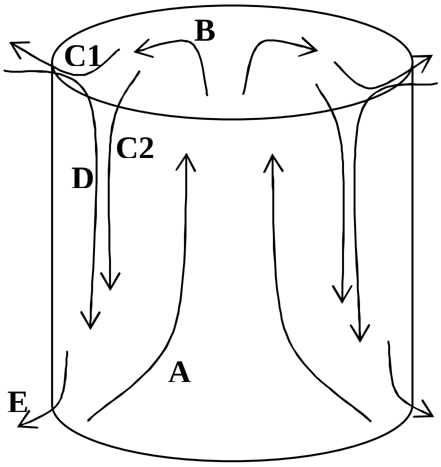


Figure 11: Possible air pathways for an open bottomed compost bin with clip on lid

Table 24: Air pathways from Figure 11

A	This is likely to be the principal air pathway, particularly during high activity and temperature periods. Fresh air will be drawn from the outer edge of the base and possibly through any hatches or grilles inwards and upwards by pressure differentials. Various degrees of mixing will occur with downwards moving air from pathways C2 and D. Air passing further into the matrix will have further to travel and suffer a greater resistance to flow. Differences in air composition throughout the compost matrix can therefore occur.
B	At the top of the bin there will be a headspace between the compost and the lid. Air leaving the compost matrix will mix and cool in this region.
C1	This is likely to be the main air outlet via space between the top of the bin and its lid. The rate of air exiting will depend on the pressure difference between the headspace air and ambient conditions and the area, shape and associated flow resistance of the space. As well as bulk movement of air molecular diffusion will occur through the gap, at a rate dependent on the size of the gap and on the internal to ambient concentration differentials.
C2	Air in the headspace not leaving by route C1 will cool relative to the compost air and may move back down into the compost matrix, most likely at the sides which will be cooler and offer less resistance to flow. Air moving by this route will mix to some extent with air moving by route A. Molecular diffusion will also occur back into the compost matrix from the top and sides dependent on the concentration differentials, air temperature and convective flow currents.
D	If there is not a high temperature in the bin and bulk convection movement is very low there may be free movement of air in as well as out through gaps with the lid, this is unlikely to be a significant amount however. Molecular diffusion will occur into the bin proportional to that entering via route C1.
E	Gases moving through route C2 that are not recycled back through route A may exit at the edges of the base or any hatches or grilles in the bin. Molecular diffusion can also occur via this route but there are unlikely to be high enough concentration differentials to drive any significant gas exchange.

This complex flow system makes quantifying gas emissions difficult as there is no specific gas outlet point at which to measure composition and flow rate. The simplest alternative for monitoring the gas composition is to sample from the headspace (B in Figure 11), which was the technique used in previous research ((Wheeler 2003; Smith et al. 2004). This method depends on the headspace gases being well mixed and representative of all gases exiting the compost system. Previous research has reported that stratification of gases is not a sampling issue in the headspace of vermicomposting units (Hobson et al. 2005) indicating that headspace gases are well mixed. Options for measuring or calculating the flow rate are discussed below.

Direct measurement or collection from the top of the compost unit

This would involve sealing the circumference of the lid, where there is the opening between it and the compost bin, and adding an outlet tube to the top of the unit. It could then be attempted to either measure the flow rate of gases through the outlet with a low-volumetric flow meter or collect them by means such as low-weight polythene bags for future measurement. The disadvantages of this method are:

- This method is based on the assumption that the overwhelming majority of gas exits the bin at the top by route C1 and not by route E on Figure 11.
- The changes in air flow caused by the alterations to the compost unit may have further effects on the composting process depending on the specific design.
- Sealing the lid onto the bin will cause practical difficulties in managing and feeding it.
- Most suitable and readily available flow measurement or collection systems offer some resistance to flow so will, to some extent, reduce the flow rate of gases exiting at the top. This further reduces the validity of the initial assumption.

Flux box method

Flux boxes are a method used for monitoring gas emissions from various waste management processes (Epstein 1997; Environmental Research and Education Foundation 2003; Hobson et al. 2005). The method involves an airtight container open at one end partly embedded in the gas emitting material (landfill/soil/compost) and the gas composition in the open space is monitored over a set time. The composition over time, area, volume and Fick's law of diffusion are then used to calculate the rate of emission of the component gases from the emitting material. The problem with this method for use in composting, identified by Epstein (1997) is that it assumes that molecular diffusion is the only method of gas movement into the box. Where temperature gradients and convection currents are present this assumption is not valid.

Pressure or temperature difference

The driving force for the bulk air movement from the headspace to outside the compost bin can be expressed in terms of the pressure and the temperature difference. It should, therefore, be possible to estimate the gas flow rate by measuring the conditions in the headspace and the ambient conditions. Difficulties arise however from the irregular outlet area, which is the space between the lid and the bin. The calculations would require estimation of the open area given by the space and the resistance to flow which would vary with the fitting and tightness of the lid and any moisture or particles in the space. Alternatively a similar approach to the direct measurement method could be made by sealing the space and adding a specified outlet but this would offer the same disadvantages discussed previously.

Theoretical estimate by mass balance

This method is known to have been used by EA Technology in estimating air flow rates through compost bins from their work discussed in Section 2.9.2 (Wheeler 2007). In this case, a mass balance was performed on carbon to estimate the mass of carbon lost annually in a particular process. By assuming that bulk convective flow was the gas transfer mechanism, the average annual carbon dioxide concentration in the headspace was then used to calculate the volume of air that would be required to maintain this concentration given the mass of carbon lost. This method allows estimation of air flow rates from some fairly simple measurements, however, the quality of the estimates produced are very dependent on the accuracy of the values used in the calculation and validity of the underlying assumptions. Previous work has been dependent on a limited data set and several significant assumptions, rather than case specific measurements, including:

- National averages to estimate the waste input composition
- Microcosm studies to estimate carbon released as CO_2

Reactor data comparison

A novel method proposed here is to estimate the equivalent air exchange rate in an standard H.C. system by comparing it to the forced aeration rate in a reactor system. This would involve running a number of reactors under different flow rates simultaneously to an otherwise identically run H.C. system. The estimate could be calculated in two ways, which can be carried out simultaneously. Firstly, by comparing the process conditions, particularly the carbon dioxide concentrations it would be possible to identify which flow rate most closely matches the H.C. system. The alternative method is to calculate the oxygen consumption in the reactor from the flow rate and the inlet and outlet oxygen concentrations. The reverse calculation can then be performed on the open system to estimate the equivalent air flow rate.

This experiment is dependent on two main assumptions; firstly that the composting parameters of the two systems remain approximately the same over the course of the experiment; and secondly that the oxygen concentration in the headspace is dependent only on the rate of exchange of air within the bins. The weaknesses in these assumptions stem from the following facts:

- The oxygen concentration is dependent both on the rate of consumption of oxygen and also the rate of air exchange.
- The air exchange in the open bins will be more dependent on the temperature and so activity within the compost due to its influence on convection.
- When the oxygen concentration is lower in the open bins the rate of diffusion of oxygen from external air into the bins will have a greater driving force and so will increase. Within the forced system however, the air exchange rate is constant and independent of all other factors; the rate of oxygen consumption being the only variable affecting the oxygen concentration (although this is dependent on other factors).
- The rate of oxygen consumption is dependent on how much of the compost has access to the air. In the forced system oxygen could potentially reach more densely packed parts of the compost or further into compost particles due to slightly higher pressure. This would result in a greater oxygen consumption rate even though the amount of compost was the same.

The degree of influence of the above facts is difficult to predict, but any effects should be observable through the measured parameters of the experiments. It is possible the influence could be insignificant relative to the unavoidable small variations in the feed compositions and physical properties. Further difficulties in imitating an open system with a closed reactor are discussed in detail in Section 2.13.

2.12.1. Summary

Numerous difficulties have been highlighted in quantifying the emissions from open home composting systems but a range of possible methods have been identified. Based on the above discussion it was decided to focus primarily on the reactor comparison and mass balance methodologies. Although the reactor comparison method involves several uncertainties, reactor based experiments have been shown to have their own merit. Running both systems readily enables comparisons and permits the generation of novel and potentially valuable results. Suitable tests and calculations could also to be performed where possible, in order to assess the future viability of the alternative methods.

2.13. Reactor based system

The purpose of the composting reactor is to allow composting at the same scales as in typical home composting but in a closed environment where the inputs and outputs can be accurately quantified and analysed. As comparisons were to be made with the open system it was desirable to imitate the composting process in a 220L open bottomed compost bin as closely as possible. The majority of previous work in the literature involving composting reactors is directed at simulating large scale processes at a much smaller scale (Michel Jr. et al. 1992; Hellebrand 1997; Smars et al. 2001), but despite this difference many of the design aspects are still relevant.

2.13.1. Temperature

As discussed in Section 2.4.5, the compost temperature is a function of the heat inputs, outputs and generation. Unlike in reactors at a laboratory scale, heat generation does not need to be externally augmented as the reactor is at the same scale as home composting. For heat generation to be similar to in a H.C. system, it requires the following properties to be comparable:

- Quantity and composition of composting material
- Size and types of microbial species present
- Process parameters with an influence on microbial activity

The inputs and outputs are determined by the temperature and flow rate of the inlet and outlet air, moisture evaporation, radiation from the sun and conduction through the container walls to the environment. Radiation, conduction and inlet air temperature are determined by the ambient conditions, so the weather and shade and also the container material properties. These can be controlled by the location of the composters and by using plastic reactors similar to the compost bins. The outlet air temperature and moisture evaporation will be determined by the composting material properties, process, temperature, humidity and air flow rate. Small differences in a reactor system from a parallel H.C. system could result in increasing variations and ultimately two very different processes. This would depend on how successfully the reactor simulated the H.C. system and the robustness of the process. Other unavoidable variations come from the open base of the H.C. system, putting the compost in contact with the ground, unlike in a reactor, and the differences in air flow which are discussed next in Section 2.13.2.

2.13.2. Aeration system

The most common configuration for aerating laboratory scale composting reactors is for the substrate to be enclosed in a vertical cylinder on top of a perforated plate with the purpose of ensuring better air distribution (Petiot et al. 2004). The other main configuration used involves a horizontal cylinder, with air blown or sucked into the headspace and distribution improved by mixing (Schwab et al. 1994). Clearly to simulate the air flow pattern through an open bottomed compost bin (Section 2.12) the first configuration is the most suitable. A complication in attempting to simulate the natural aeration occurring in home compost bins is that the air flow rate varies depending on the physical process conditions. The same problem has been encountered in the past when full-scale static pile or windrow composting has been simulated. Several researchers dealt with this by aerating reactors so that they only fulfilled oxygen demand and air was not forced through the matter (Mote et al. 1979; Sikora et al. 1983). It is possible that this approach could bring reactors closer to simulating home composting aeration but this can only be determined once it is known whether oxygen demand is met, exceeded or not reached. Due to the more complex and costly design that this approach would require it should, perhaps be more closely considered when more data is available. For the initial design, therefore the more common configuration of pumping air in under a perforated plate at a constant rate was chosen for its lower cost and simplicity of design and modelling.

2.13.3. Determination of suitable air flow rates

Several sources are available in the literature to make order of magnitude estimates of the flow rate range required to simulate home composting, including theoretical models and experimental data. One suitable model is that developed by Haug (1980) to model the natural ventilation of compost windrows. This is based on treating compost particles as spheres and the pore spaces as cylindrical pores between them. The presence of moisture in pores is ignored and to calculate the ventilation rate the buoyancy forces between ambient and internal air are balanced with friction losses, considering the effect of exit velocity negligible at low flow rates. A density difference of 0.22 g/L was assumed corresponding to a temperature difference of about 40^{o}C. The final model is shown below (Equation 6); the full derivation is available in Haug (1980). This was used to create Figure 12 with the added assumption of a bin diameter of 0.5m in order to convert the aeration rate into Litres per minute.

$$Q = 2.72 \times 10^{6} f \left(\frac{f}{1-f} \right)^{2} \Delta \rho r^{2}$$

Equation 6

Where Q = Aeration rate, $cm^3/sec\ m^2$

$\Delta\rho$ = density difference, g/L

r = particle radius, cm

f = FAS, fraction of total mixture volume

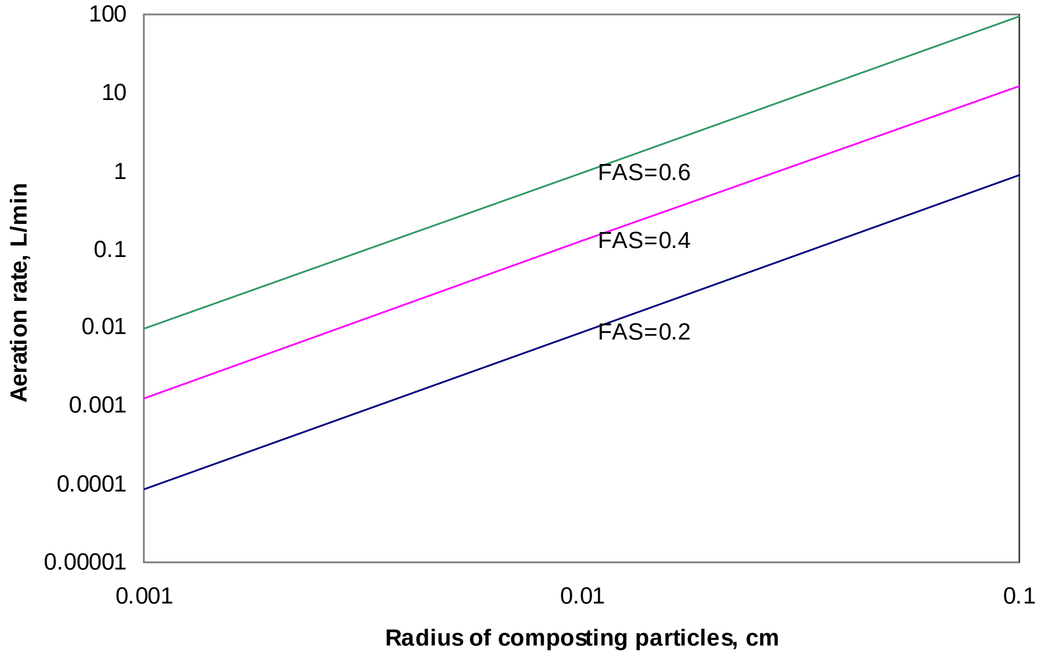


Figure 12: Natural aeration rates predicted by the Haug (1980) model

It should be emphasized that this is a greatly simplified model, designed to highlight the prime influencers of aeration and perhaps give order of magnitude estimates, not to predict actual values. There is an added complication in using this model for home composting as depending on the feeding regimen (See section 2.14) the free air space, average particle radius, temperature and humidity on which the aeration rate depends will vary throughout the bin with the maturity of the material. In relatively fresh material the particle diameter size in home compostable waste is likely to be at the 0.1cm order of magnitude or larger. Reported values for free air space of food and garden waste composts are between 15-30% (Agnew et al. 2003), although fresh material are likely to have higher values. For this case the aeration rate predicted by the model is in the range 0.1-5 L/min when the compost is around 40^{o}C above ambient conditions.

An alternative approach in estimating the required flow rate is to base it on the oxygen requirements of the waste material. Epstein (1997) reports a large number of oxygen consumption rates for different waste materials and temperatures from several sources. Values reported for materials similar to home compostable wastes are in the range 1 to

6 mg O_2/ g Volatile Solids/ Hour. This can be converted to Litres per minute by substituting appropriate values into Equation 7.

$$\frac{X}{1000 \times MM_{O_2}} \cdot \frac{M_{Vair} .100}{x_{O_2} \times 60} \times m . \frac{MC}{100} \cdot \frac{VS}{100} = Q$$

Equation 7

Where,

X = Oxygen consumption in mg O_2/g VS/hr

MM_{O2} = Molecular mass of oxygen, 32

M_{vair} = Molar volume of air, 24 L/mol at $20^{o}C$

x_{o2} = % O_2 in air, approx. 21%

m = mass of compost, g

MC = compost moisture content, %

VS = compost volatile solids, %

Q = Flow rate required to meet oxygen consumption, Litres per minute

Figure 13 shows the air flow rates required to meet the maximum and minimum oxygen demands based on Equation 7 for a range of parameters. Assuming fresh feed would provide the dominant oxygen requirements, a moisture content range of 60-80% with a volatile solids content of 70% was used and a compost mass between 10 and 30kg. The required flow rates are shown to be between 0.1 and 3 L/min, so similar to the previous result of 0.1-5 L/min.

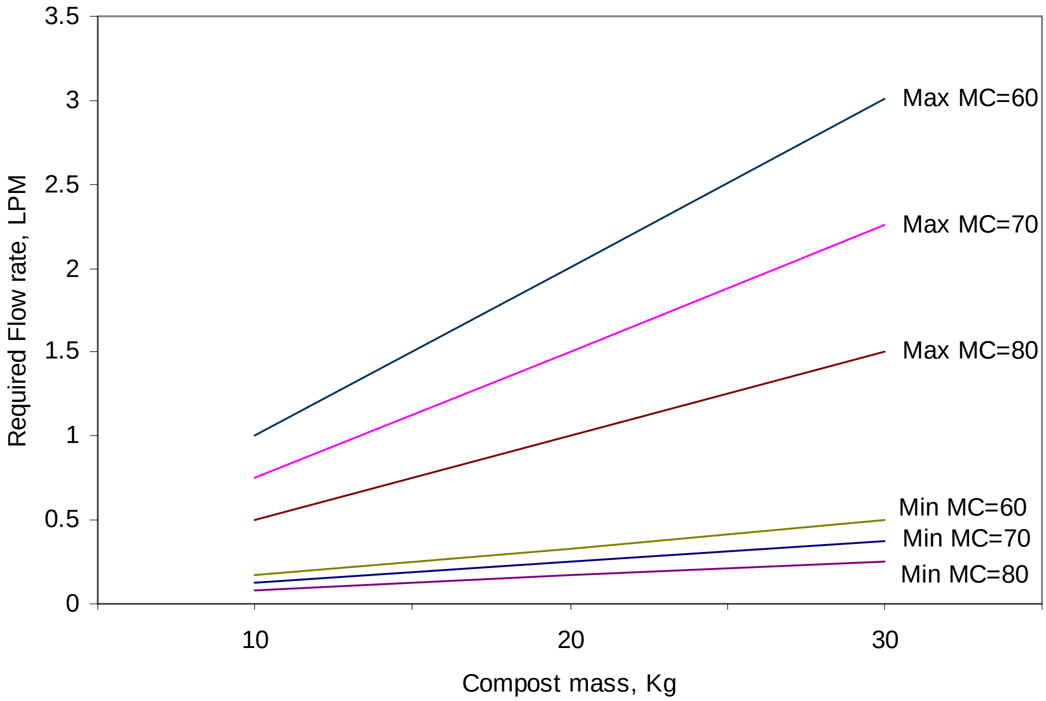


Figure 13: Required flow rate to satisfy the oxygen demand for different compost moisture content % with a minimum and maximum oxygen consumption of 1 and 6 mg O_2/g VS/hr respectively.

2.14. Feeding regime

In home composting there are a large variety of feeding regimens that can take place. If kitchen and other biodegradable household wastes are added this will be a daily or possibly a weekly regular feed to the bin. Garden waste will most likely be less regular and depend more on the growing season. If grass is composted this will be added at a frequency and quantity dependent on the garden size, growing season, type of grass and mowing frequency. Other garden wastes will be also be determined by what sources of garden waste/types of plants are present at the household. During the growing season it is possible some households will perform a lot of pruning etc. at one time and so add a large amount of material or even fill their bin in one go but the likely amounts or frequency of this behaviour is unknown.

The total emissions from a compost bin at any time will be a combination of the emissions from the degradation of each component; distinguished by their chemical and physical characteristics. These are determined by their original composition (fruit/grass/card/wood) and their state of degradation, which is determined by their age and the conditions (temperature, microbes present, activity of macroscopic life, moisture, pH, O_2 conc. etc.) over the period they have spent degrading. Although after many feed additions there will, in total, be a large amount of material present; if most of the activity in the degradation of a component occurs in the first one or two weeks then the bulk of the material will be relatively mature and less active. Only if the total emissions of the compost in the bin allow the concentrations to reach detectable levels will emissions be measurable.

For example if 2kg of fruit waste is added to the bin in a week long period it could be that under the conditions in the bin (temperature, oxygen concentration, moisture, pH etc.) the decomposition would produce 1 µg CH_4 per kg fruit waste. If this figure was combined with the total mass of fruit waste composted annually it may add up to a significant value. As it occurs in such small increments however, it is undetectable within the bin, leading to the incorrect conclusion that no harmful emissions are produced. The potential significance of this problem depends on the detection limits of the monitoring equipment used.

Monitoring the decomposition of much larger quantities of the relative materials or reducing the gas flow rate could cause emissions to reach detectable levels. The effect of both of these changes, however, is to reduce the airflow per unit mass through the material which would change the conditions of the process and so invalidate the results. Alternatively the minimum airflow at which emissions reach detectable limits could be investigated, giving an indication of how far the conditions in compost bins are from the conditions at which the emissions become significant. This experiment would require accurate control of the composting parameters.

The two methods of feeding home compost bins chosen to be investigated are:

- One large bulk feed (20+ Kg): This would encourage quicker composting at higher temperatures. Emissions would be more likely to reach detectable levels. The lid of the compost bin would not be removed for feeding which could affect the air composition. It is unlikely to be representative of typical home composting behaviour.

- Regular small additions (1-20 Kg): This is believed to be more common home composting behaviour. With regular small feeds, however, if the feeding is far apart then the decomposition of the material added may not produce enough emissions for them to reach detectable levels.

2.15. External environment effects

The external environment can influence home composting processes in a number of different ways, some of which are determined/influenced by the householder/composter and some of which are not. It is important to consider these in the design of H.C. experiments due to their impacts on repeatability and the interpretation of results. The factors considered most important or universally relevant are discussed below, but a more comprehensive review is provided in Appendix 2.

- *Heating effects* determined by the ambient temperature and strength and hours of sunlight which is also affected by shade from walls/fences and their orientation. Although it would be possible to artificially control heat inputs it would be very difficult to simulate typical ambient conditions and a complex and costly process. Insulating the experiments may help improve repeatability, but this may significantly reduce the similarity to typical composting.
- *Moisture content* will be influenced by the heating effects and to a lesser extent air humidity and surface drainage, dependent on whether the surface is concrete/paved or soil and its type and saturation. Home composters may also add water to their bins in order to improve the composting process.
- The presence of *macroscopic life* such as insects and worms that can perform/affect degradation processes are likely to be changed by the external environment, more so than microscopic life which will be more influenced by the feed materials and compost parameters. These are unlikely to have significant effects on gaseous emissions, except in the case of vermicomposting where very large numbers of worms are involved.

Due to the difficulty of controlling these parameters, the most appropriate approach is to record the ambient temperature and the moisture contents of the input materials so they are known for repeated experiments and the interpretation of the results. Carrying out experiments to observe the effects of insulation and adding water may also aid understanding in these areas. Performing the experiments on soil will at least allow macroscopic life to access the compost but it would be very difficult to ensure consistency or repeatability in this parameter.

3. Trial experiments

In this chapter the aims, methods and outcomes of trial experiments that were carried out are described. The experiments were conducted in order to gather some initial data, but primarily to assess the two chosen methodologies (Section 2.10):

- Experiments with standard H.C. bins, managed to simulate selected home composting activities in specified conditions. This will enable the monitoring of composting processes closely matching those of a householder composting in similar conditions.
- Reactor based experiments at the same scale as H.C. bins, able to be run under almost identical conditions but built to allow control over certain parameters and accurate measurement of gas flow rates and emissions.

3.1. Trial materials and methods

3.1.1. Standard naturally aerated home composting system

The bins used for these experiments were standard 220 l compost bins as supplied to the public (Blackwall Compost Converter 220 litres – black). The bins were open bottomed and the lids were modified to allow access to the headspace (the volume of air between the compost in the bin and the lid) without complete removal of the lid (see Figure 13). This meant that frequent gas sampling could be performed without the loss of headspace gases that would occur when removing the lid. As the headspace access tubes had valves, which were kept sealed except when collecting gas samples, the gas transfer mechanisms in the bins would be the same as when used by the public.

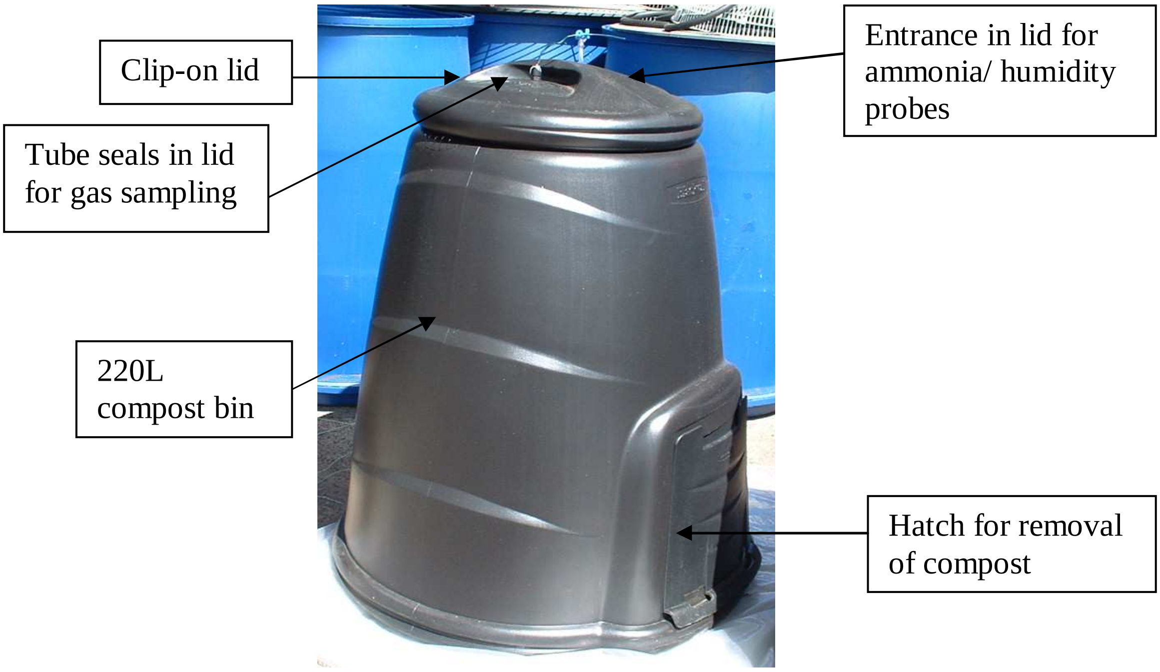


Figure 14: Standard naturally aerated home composting system

3.1.2. Forced aeration sealed composting system

This system was devised and designed in-house and consisted of a barrel with approximately 200 L capacity. The top and base of the barrel were removed and especially cut plastic covers were clamped in place over a neoprene gasket to keep the bin airtight (see Figure 14). A 10 mm diameter tube in the base was attached to a variable flow rate air pump (TetraTec 300). Air was allowed to exit through a tube in the lid of the bin to enable the air to flow through it without allowing any other air to enter other than that pumped in. Inside the bin, a perforated plate was held 5 cm above the base to support the compost whilst allowing free movement of air beneath it. The air flow rate through the bins was set by calibrating the air pumps to the desired flow rate using an air flow meter (Microbridge Mass Airflow Sensor AWM3000 series) before connecting the pumps to the bins.

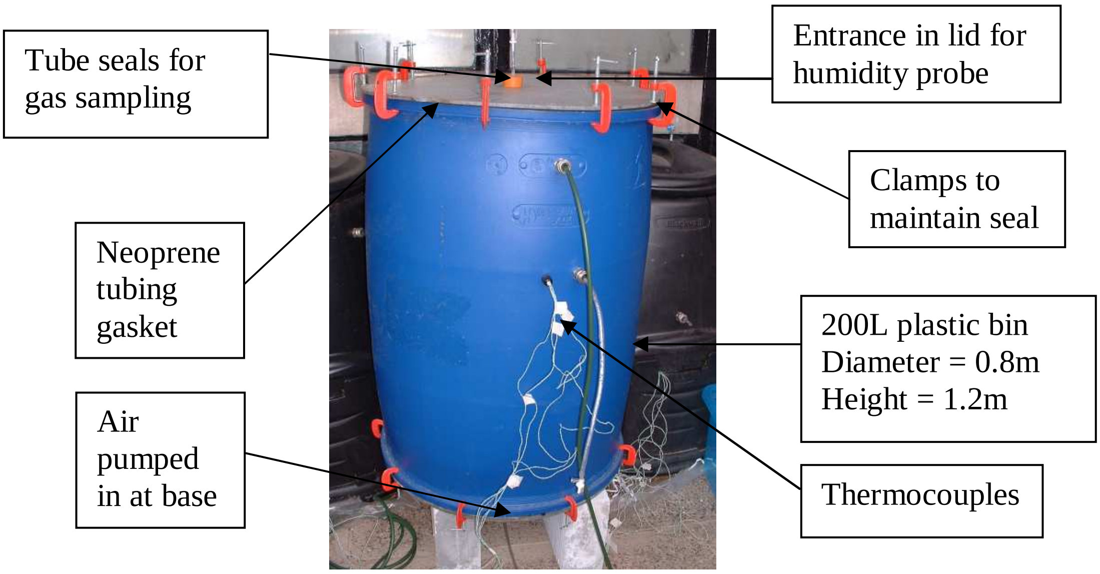


Figure 15: Sealed composting reactor system with forced aeration

3.1.3. Location/environment

Two outdoor locations at the University of Southampton's Highfield Campus were used for the experiments:

- Site one – Concrete surface, facing South-East, receiving sun in the morning and in shade during the afternoon.
- Site two – Grass and soil surface, also facing South-East, but in partial shade provided by surrounding trees throughout day.

Figure 16: (Left) Site one, location for the reactor system airflow experiments (Right) Site two, location for the H.C. system emissions experiments

3.1.4. Input materials

The feed materials used for the experiments and their sources are described below.

Fresh grass

Grass cut from the grounds of Highfield Campus was piled together at one location where it was left to compost. The grass was fed into the bins within 12-36 hours of being cut. As the grass was taken from large public grounds, some contamination with litter occurred - this was removed by hand. However, it is possible that some items were missed and that a limited amount of contamination passed into the compost bins.

Soft and woody prunings

Soft and woody prunings cut from different plants on the Highfield Campus were placed in a skip and collected for several weeks. The composition of materials collected in the skip therefore varied depending on the recent gardening work. The prunings were removed and shredded by a garden waste shredder to approximately 2-3cm in length prior to feeding into the compost bins.

Fruit and vegetable waste

Fruit and vegetable waste was collected from the Highfield Campus staff catering service. The waste included vegetable peelings and unusable parts of fruit and vegetables that were bruised or past their expiry date. The waste was collected daily and stored until the end of the week when it was fed into the bins; the waste therefore varied between 0-5 days old on feeding. This is representative of householders who store food waste in the kitchen and move it to their H.C. bin when there is enough waste, or once a week, but not of householders who add all food waste into their H.C. bins daily.

Card

Waste corrugated cardboard collected from the Highfield Campus was torn by hand into squares about 5 cm across before feeding to the compost bins. This was performed following typical home composting advice (The Composting Association 2004; The Waste and Resources Action Programme 2006).

3.1.5. Temperature

For bins located at site 1 (see Section 3.1.3), temperature was monitored at several points within the compost (Top, middle, bottom and side of the fresh feed addition) by using type K thermocouple wire attached to a datalogger (DT500, Datataker) to record the temperature at 5 minute intervals with an accuracy of ±0.1^{o}C. For bins located at site 2, where this was not possible, DS1921 I-button temperature dataloggers were used (see Figure 17). These had an accuracy of ±0.1^{o}C and were programmed to record the temperature at 10 minute intervals; the data was downloaded by connection to a PC every 4 weeks. They were placed in the centre of the fresh waste addition to capture the maximum temperatures reached.

Figure 17: DS1921 I-button temperature datalogger

3.1.6. Humidity

A humidity probe (Hygropalm Portable Humidity Temperature Indicator, Rotronic) was used to take humidity readings in the headspace of the compost bins (Method reference: Manufacturer instructions). The probe was calibrated with a 3 point calibration using Rotronic certified humidity standards of 35%, 95%, 10%. The accuracy of the probe at 22^{o}C is ±0.5%RH + 1.5% of reading. A hole in the H.C. bin or reactor lid, normally sealed with a rubber bung (See Figure 14 and Figure 15), was used to allow access to the headspace without allowing significant air exchange. It was found that between 5-15 minutes was required for a stable reading to be reached, with the reading moving increasingly slowly as it neared 100%.

3.1.7. Solids sampling technique

The task of obtaining a reasonably sized sample that is representative of the sampled portion presents a number of problems and emphasizes the need for using a standard sampling method. Growing media and soil improvers are very difficult to sample because of the variety and inhomogeneous nature of the materials involved (BSI - British Standards Institution 2000).

The sampling method for this study was to use a composite sampling strategy in which multiple individual or “grab” samples (from different locations) are physically combined and mixed into a single sample (see Figure 18) so that a physical, rather than a mathematical, averaging takes place (EPA - Environmental Protection Agency 2005). For a well-formed composite, a single measured value should be similar to the mean of measurements of the individual components of the composite (Fabrizio, et al. 1995). Collection of multiple composite samples can provide improved sampling precision and reduce the total number of analyses required compared to non-composite sampling. This form of sampling is recommended and used in the British Standards method for sampling from soil improvers and growing media (2000) and in other composting investigations (Eklind et al. 2000; Mohee et al. 2005).

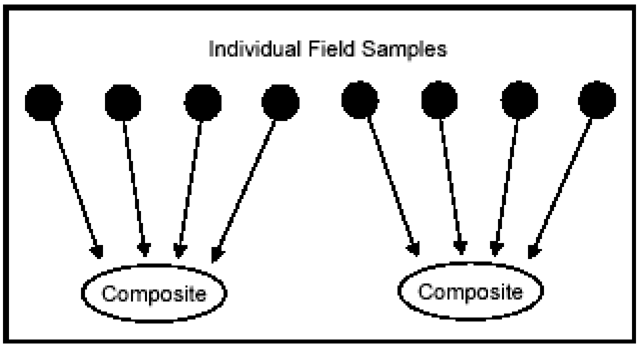


Figure 18: Forming composite samples from individual samples (EPA - Environmental Protection Agency 2005)

The British Standards method for sampling from soil improvers and growing media (2000) suggests the following formula for the number of sampling points, N:

$$N = 0.5 \times \left(V^{1/2}\right)$$

Where V is the nominal quantity of the sampled portion in m^3 and the minimum number of sampling points = 12. Eklind and Kirchmann (2000) pooled ten subsamples of about 250ml and Mohee and Mudhoo (2005) took four grab samples at four random locations from the middle of the composter and at the two extremities.

Adopting the British Standard method meant using the minimum number of 12 sampling points. These small component samples were removed by hand at random points from within the compost material and pooled in polythene bags to form one large sample of between 200-400g. This large sample was transferred to the laboratory within an hour and well mixed before sub-samples were removed for the various solids analyses. Samples were taken from the input materials at the start of experiments and from the compost products at the end of individual experiments.

3.1.8. Carbon dioxide and methane analysis

Gas analysis for carbon dioxide and methane was performed using a Varian CP 3800 gas chromatograph with a gas sampling loop using argon as the carrier gas at a flow of 50 ml min^{-1}. The GC was fitted with a Haysep C column and a molecular sieve operating at a temperature of 50 ^{o}C. The GC was calibrated using two standard gases containing 35% CO_2 and 65% CH_4 (BOC, Guildford, UK) and 1% of each component of CH_4, CO, CO_2 and H_2 in N_2 (SCOTTY gases). 5 replicate measurements of the standard gases were made; the accuracy of methane and carbon dioxide were found to be ±1.8% and ±1.0% and the precision of these measurements resulted in standard deviations of 1.3% and 1.4% (n=5) respectively. Five ml syringes were used to draw air samples from the compost bin headspaces or reactor outlet tubes and then sealed until analysis.

3.1.9. Elemental analysis

The total carbon and nitrogen values of the feed materials and composts were determined using a LECO CHNS-932 elemental analyser, following the manufacturer's standard procedures. Two certified natural reference materials provided by Elemental Microanalysis were used for calibration, composed of birch leaf (48.3% C, 2.1% N) and sediment (6.5% C, 0.5% N) with measurement uncertainties of 2.6% C and 0.07% N. 5 replicate measurements of the reference materials were made which resulted in standard deviations of 2.3% for N and 2.5% for C (n=5).

3.1.10. Moisture Content and Volatile Solids

TS and VS were measured gravimetrically using a fan-assisted oven (Vulcan-Hart, USA) at 105 ^{o}C and a muffle furnace (Carbolite, UK) at 550 ^{o}C using a balance with sensitivity ± 0.1 mg according to Standard Method BS EN 13040:2000 and 13039:1999.

The standard deviation of TS was ± 2.8% TS kg^{-1} wet weight and the VS was ±4.5%VS kg^{-1} wet weight based on typical measurements made throughout this work (n=5). According to the standard method a repeatability standard deviation for TS of composted coarse bark was 0.95% TS kg^{-1} wet weight (n=17) and for VS 1.29% VS kg^{-1} wet weight (n=18).

3.1.11. pH and Volatile fatty acids

The pH of the compost was measured using a weight ratio of sample to water of 1:5, mixing 60g of compost material with 300ml of distilled water. The resulting solution was shaken for 1 h at 20°C before analysis with a calibrated pH meter. A pH probe connected to a Jenway 3310 pH meter (Jenway, UK) was used. The pH meter was calibrated before use with buffer solutions (pH 4, 7 and 9.2, Fisher Scientific general purpose grade) which were made up weekly and stored in sealed jars. Between measurements, deionised water was used to clean the probe. The measurement was taken within a short period of sampling to avoid the evaporation of volatiles or evolution of dissolved carbon dioxide, both of which could alter the pH reading. The accuracy of the pH meter was ± 0.01 pH unit although according to the standard method 4500-H^+ (APHA 2005) under normal conditions expected accuracy of this method is ± 0.1 pH unit with a precision of ± 0.05 pH unit.

The use of a surface pH probe (Fisherbrand flat tip plastic BNC for surface pH measurements) was also tested for the rapid measurement of compost pH on-site using a portable pH meter. The probe was calibrated as for standard pH probes, using standard solutions of pH 7 and 4 or 9.2 as appropriate. Surface pH measurements were made in triplicate at different locations within the compost bins at the same time as the collection of a composite sample for standard pH measurement. The locations at which surface measurements were made were the upper surface, 20cm down, 40cm down and the bottom layer behind the hatch.

3.1.12. Leachate collection from open bins

A novel approach to collecting leachate from open compost bins was tested. A 75ml plastic container fitted with a 12cm diameter perforated lid and a filter medium (Figure 19) was placed into the upper compost in the bin and the fresh feed added over it.

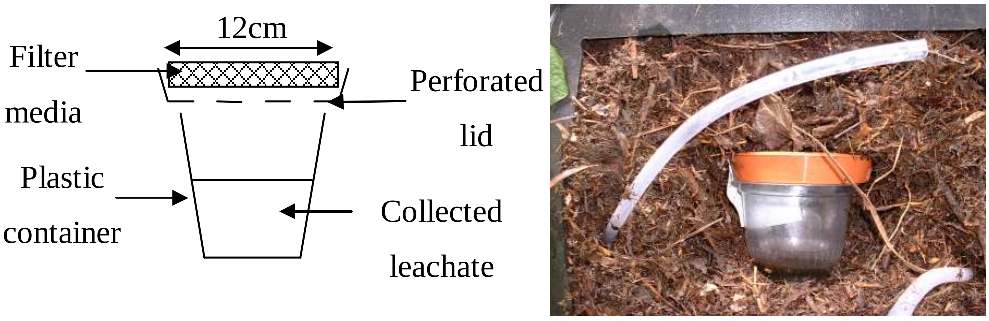


Figure 19: Leachate collection system

It was anticipated that leachate from the fresh compost would drain through the filter media into the container which could be removed after a set time and the leachate collected. As well as allowing leachate samples to be collected, this method had the potential to quantify the total produced, by scaling the quantity in the container with the ratio of the lid area to the cross-sectional area of the bin at the appropriate height. This would require, however, that the leachate drainage be equivalent over time across the compost cross-section, which may not be the case due its heterogeneous nature and any channelling that could occur.

3.1.13. Trial H.C. bin experiment protocols

These experiments were conducted using only the standard naturally aerated H.C. bins, located at site 2 (section 3.1.3), a standard garden environment as is typical of most home composting activities. In the initial trial experiments, five different feeds were used for five bins. The feeds were selected to represent the likely ranges of the most significant parameters affecting home composting. The compositions of the feeds are detailed in Table 25; the source and parameters of the component materials are described in Section 3.1.4. The mixture parameters were calculated from the individual components using a method of solving simultaneous equations (Trautmann et al. 2002). Kitchen waste was added weekly, while garden waste was added fortnightly. Temperature data was collected using I-button dataloggers (Section 4.3.1). The experiment was conducted for 4 weeks.

Table 25: Composition of the weekly feed given to the five open bottomed composting bins.

	Compost bin number and properties				
	1	2	3	4	5
Feed component	All components, turned	All components, not turned	Garden waste only, turned	Low C:N ratio, turned	Just kitchen waste, turned
	Mass of each component in weekly feed (Kg)				
Grass	6	6	6	6	-
Soft and woody prunings	1	1	2	-	-
Fruit and vegetable waste	2	2	-	2	3
Shredded cardboard	1	1	-	-	1
Total weekly feed	10	10	8	8	4
C:N ratio	25.4	25.4	28.4	17.3	30
Moisture content %	68.9	68.9	65.3	83.3	67.3

3.1.14. Trial reactor experiment protocols

This experiment was conducted using 5 sealed forced aeration reactors (Section 3.1.2) as well one standard open bottomed H.C. bins for comparison. Its primary purpose was to improve understanding of the air flow rates and mechanisms in home composting. Five sealed forced aeration bins and one naturally aerated bin were run. These were all fed with the same “garden waste only” composition used in Trial 1 (see treatment 3 in Table 25) at fortnightly intervals. The flow rates of the bins were set as 0.05, 0.15, 0.25, 0.35 and 0.45 litres per minute (L/min). These are at the lower range of the flow rate values estimated in Section 2.13.3 as higher values were thought less likely to occur. The flow rates were monitored regularly during the experiment using a portable flow rate meter at the gas outlet. The naturally aerated open bottomed H.C. bin run in parallel had the purpose of indicating if the flow rates used were in the correct range by observing which showed the most similarity in terms of the process parameters. The experiment was conducted at site 1 (section 3.1.3), where it was possible to securely install the monitoring equipment and experimental apparatus. The experiment was conducted for 4 weeks.

3.1.15. Trial insulation experiment

In order to reduce the uncontrollable influence of daily temperature fluctuations and shade effects on the compost bins, it was decided to test insulating and sheltering the bins. This was achieved using wooden fence panels to shelter the bins from the sun and a layer of loft insulation protected by plastic film to insulate them as shown in Figure 20. In the experiment 18 Kg of garden waste was first fed to a pair of non-insulated H.C. bins and a pair of non-insulated reactors and then repeated after insulating the bins and reactors.

Figure 20: Insulated compost bins

3.2. Trial H.C. bin experiment results

3.2.1. Temperature

The temperature profiles in the bins can be seen in Figure 21. The temperature data is summarised for feed additions 1 and 2 in Table 26 and Table 27 respectively.

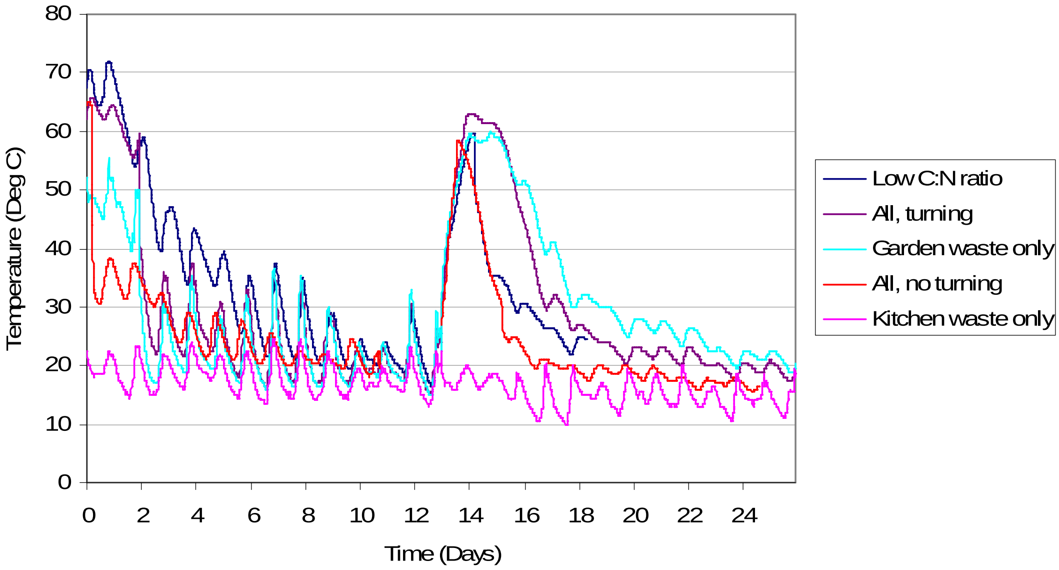


Figure 21: Temperature profiles in Trial Emissions H.C. bin experiments

Table 26: Temperature summary for trial H.C. bin experiment feed addition 1

	Low C:N ratio	All, turning	All, no turning	Garden waste only	Kitchen waste only
maximum	72	66	65	56	25
3 day average	59	50	35	39	19
14 day average	35	29	26	26	18

Table 27: Temperature summary for trial H.C. bin experiment feed addition 2

	Low C:N ratio	All, turning	All, no turning	Garden waste only	Kitchen waste only
maximum	60	63	59	60	21
3 day average	41	55	39	54	17
14 day average	35	31	24	34	15

3.2.2. Carbon dioxide concentration

The average carbon dioxide concentrations measured in the headspaces of the bins are shown in Table 28.

Table 28: Average headspace CO_2 concentrations in trail H.C. bin experiments

	Average headspace CO_2 concentration (%)	Standard deviation
All turned	5.9	0.6
Kitchen	0.3	0.0
Low C:N	5.3	0.5
All no turn	1.8	0.2
Garden	6.3	0.6

3.2.3. pH

The average results of compost pH measurements made as a solution and at the surface pH are shown in Table 29.

Table 29: Average pH in Trial Emissions H.C. bin experiments

Feed type	Approx C:N ratio	Solution pH	Surface pH
Garden and kitchen with turning	25:1	7.6	7.5
Garden and kitchen without turning	25:1	7.5	8.5
Low C:N	17:1	7.9	7.6
Garden only	28:1	7.5	7.7
Kitchen	30:1	7.9	7.9

A statistical analysis of the percentage error in the results and a comparison of the two methods is shown in Table 30 below. The average percentage error between the triplicate surface pH measurements is not particularly high at only 1.1%, which is actually lower than the error in the standard solution method at 1.5%. However, taking the solution pH as the true average compost pH, there is a much larger percentage error between the solution pH and surface pH measurements, with an average of 4.1% and a maximum of 13.7%.

Table 30: Percentage error in surface and solution pH measurements

	Average % error	Range % error
Surface pH triplicate measurements	1.1 %	0.0 – 4.9 %
Surface pH variation between locations	1.9 %	1.0 - 3.4 %
Solution pH triplicate measurements	1.5 %	1.0 – 2.0 %
Comparison of solution pH and surface pH measurement	4.1 %	0.1 – 13.7%

3.2.4. Humidity

As can be seen in Figure 22, all the measurements made were between 96 and 100%, but it is possible all readings would have reached 100% with an even longer stabilisation time.

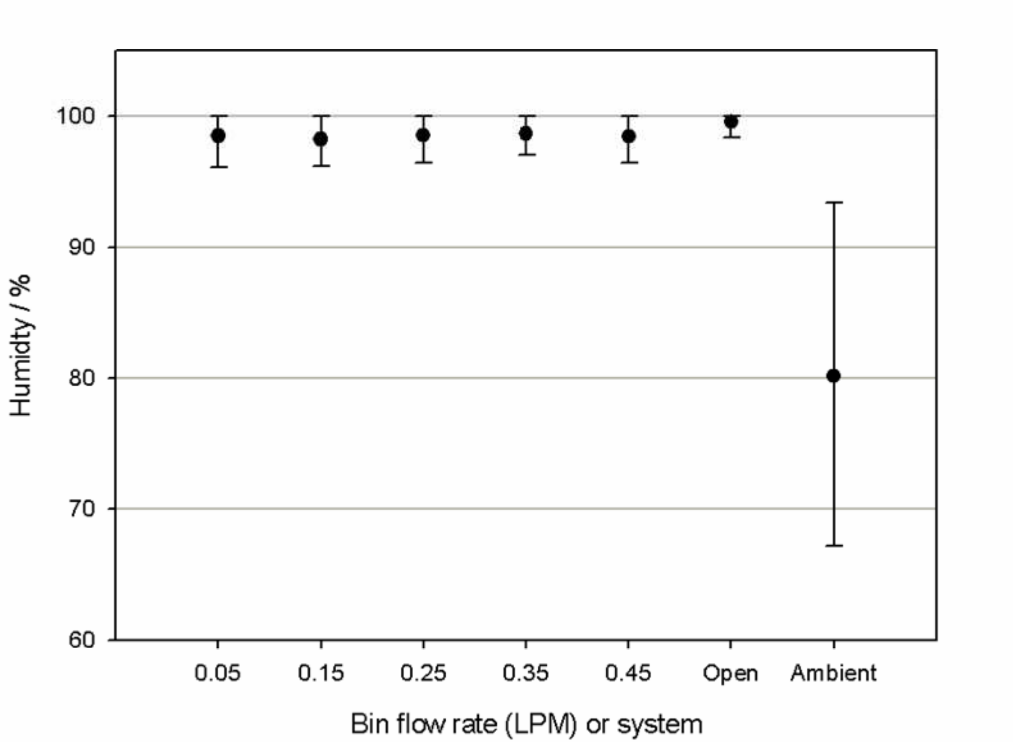


Figure 22: Range and average humidity observed in airflow bins

3.3. Trial reactor experiment results

3.3.1. Temperature

The temperature data is summarised for the different experiment treatments in Table 31. The temperature profiles can be seen in Figure 23.

Table 31: Trial reactor experiment temperature results summary

Reactor air flow rate	Temperature (^{o}C)			
	Max	Min	Average	Stdev
150	38.7	12.5	23.4	5.1
250	48.7	15.5	26.8	5.3
350	45.2	11.3	26.5	7.2
450	51.0	15.1	25.0	6.4
H.C. bin	55.7	13.9	27.2	9.9
Ambient	23.8	8.8	16.5	2.5

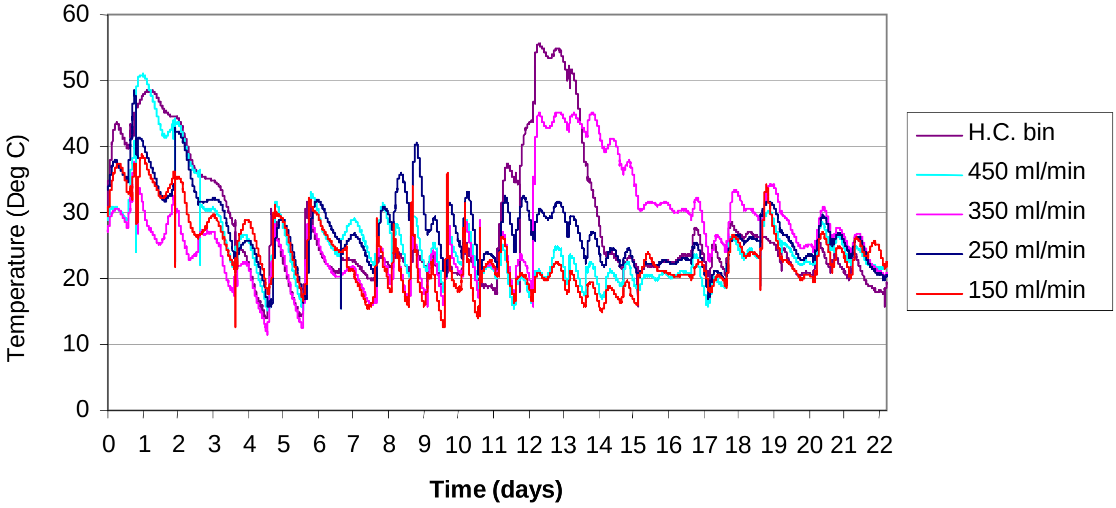


Figure 23: Trial reactor experiment temperature profiles

3.3.2. Carbon dioxide concentration

The average CO_2 concentrations for each reactor and the H.C. bin are shown in Table 32.

Table 32: Trial reactor experiment average CO_2 concentrations

Reactor air flow rate	Average headspace CO_2 concentration (%)	Standard deviation
0.05	19.5	2.0
0.15	17.0	1.7
0.25	9.6	1.0
0.35	9.9	1.0
0.45	11.9	1.2
H.C. bin	0.5	0.0

3.3.3. pH

The compost and leachate pH results are shown in Table 33.

Table 33: Trial reactor experiment compost and leachate pH results

Bin air flowrate (L/min)	Average pH of compost	Average pH of leachate
0.05	6.9	8.7
0.15	7.8	8.4
0.25	8.1	8.2
0.35	7.6	8.3
0.45	7.9	8.2
open	7.7	-

3.3.4. Humidity

The humidity measurements are summarised in Figure 24.

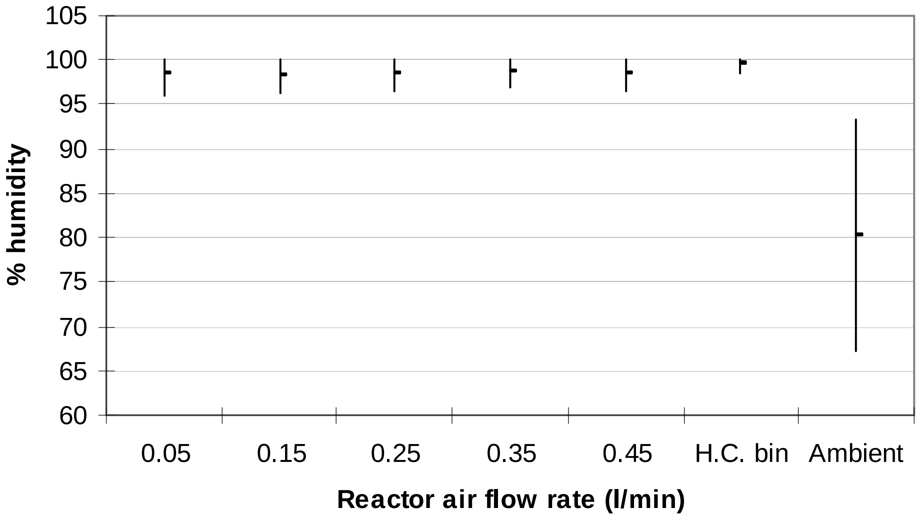


Figure 24: Trial reactor experiment humidity results

3.4. Trial insulation experiment

Figure 25 shows the temperature profiles resulting from a test carried out to observe the effect of insulation. It can be seen that two changes were caused in the bins:

1. Reduction in size of the peaks and troughs caused by the daily temperature fluctuations;
2. Removal of temperature differences at different locations in the bin.

What is not caused, however, is an increase in the maximum temperature reached as it is approximately the same in the cases with and without insulation.

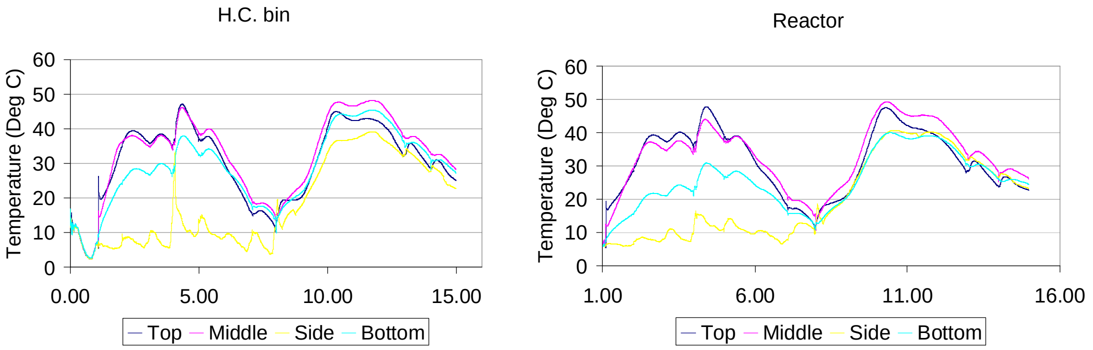


Figure 25: Temperature profiles of compost at the top, middle, side and bottom without insulation (0-7 days) and with insulation (8-21 days) in H.C. bins (left) and reactors (right).

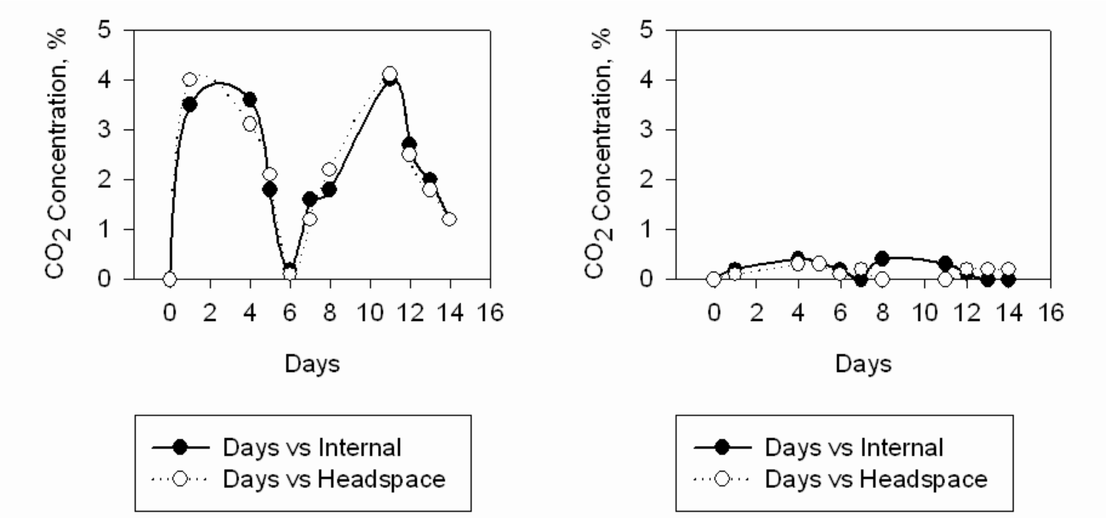


Figure 26: Trial insulation experiment CO_2 concentrations in the reactors (left) and H.C. bins (right)

3.5. Trial discussion

3.5.1. Temperature

The temperature results show that the maximum temperature was reached within 1-2 days of adding a fresh feed addition, after which the temperature fell rapidly getting closer to the ambient temperature. The maximum temperature observed was 72^{o}C which was sustained for less than an hour. The effect of ambient temperature can be seen to cause significant daily fluctuations in line with the rise and fall from day to night. It can be observed in the reactor experiment that the higher air flow rates reached higher temperatures, with the highest observed in the H.C. bin. In the H.C. bin experiments the kitchen waste feed reached a much lower temperature, mainly due to the much smaller feed size. The low C:N ratio produced the highest temperature, although only in the first feed addition and not the second, when the all components with turning treatment was higher. It can also be observed that turning the compost consistently resulted in higher temperatures.

3.5.2. Carbon dioxide concentrations

In the H.C. bin experiments the carbon dioxide concentrations show similar patterns to the temperature results. The kitchen waste treatment showed a very low CO_2 concentration at only 0.3% compared to 5-6% in the other treatments with turning and 1.3% in the treatment without turning. This very low CO_2 concentration from the kitchen waste treatment may not only be related to the smaller feed size but also the higher density of the feedstock, and hence the much larger headspace volume in this treatment. The headspace volume in a H.C. bin would logically affect the headspace CO_2 concentration measurement with the same emission rate. This feature was not considered previously but should be for future experiments.

In the reactor experiment, as would be expected there was a trend for CO_2 concentration to decrease with increasing air flow rate and it is lowest in the H.C. bin. The trend is not consistent however, with a very large drop between the 0.15 to the 0.25 l/min reactors, and an increase between the 0.35 and 0.45 l/min bins. As the feed for each reactor was as similar as possible such a significant difference was unlikely to be due to a different oxygen consumption of the waste. The most likely causes are:

- Drifting of the pump flow rate after it was initially set
- Significant failure of the sealing of the reactors allowing air to enter

Although the flow rate was monitored during the experiment by monitoring the outlet flow rate, this was found not to be an appropriate method. Despite the low resistance to flow of the instrument used, measurement of the outlet flow rate was difficult. Even the low resistance meant that after attaching the instrument to the reactor outlet there was a drop in flow rate and, due to the large reactor volume, up to 30 minutes was required for the flow to raise to a steady level, which must still have been lower than the original value. Presumably for this reason it was found that there was a marked difference between the calibrated flow rate and the measured value. Improving the reactor seals and adopting a system to monitor and adjust the pump flow rates continuously at the inlet should solve these issues.

3.5.3. pH

The pH for all except one compost sample is in the range 7.5 – 8.1 (see Table 33 and Table 29). (Ward et al. 2005) suggest that high pH levels can signify that active composting is still taking place and (Smidt et al. 2005) that a pH of 7.5 indicates stability. As the pH of all the composts is not very high it seems that the compost is mainly stabilising as the majority of the compost will have been at least several weeks old during sampling. Interestingly the compost that shows a pH below 7 is from the reactor that was given the lowest air flow rate. (Beck-Friis et al. 2001) state that volatile fatty acids are the result of anaerobic processes and strongly influence the pH of compost, causing it to be low when they are present. Therefore the lower pH of the compost with the lowest air flow rate may indicate a greater number of anaerobic processes taking place.

The differences between surface pH and solution pH measurements were found to be quite significant, with a maximum of 13.7%. Although the faster analysis of surface pH is advantageous this is of limited use in this home composting study for the following reasons:

- Measurement of surface pH requires removal of the compost bin lid which, if done frequently, will affect the gas composition. As pH measurements are of less significance to this study than gas composition measurements it is undesirable to make frequent pH readings to the detriment of the gas composition results.
- Common practice in the scientific community is to use the solution method, and the link with surface pH is not sufficiently well understood to compare the two measurements.
- From this preliminary work, the variation of pH between the locations monitored is quite low, at only 1.9%, not significantly higher than the measurement error.

At the small scale of home composting, therefore, the measurement of one composite sample by the solution method for the analysis of pH would seem to be sufficient.

3.5.4. Humidity

The results indicate that, due to the relatively enclosed nature of H.C. bins with lids and the high moisture contents of the waste inputs, the humidity is near 100% in the bin headspaces at all times within two weeks of a fresh feed addition. Due to the time required to carry out these measurements it seems unnecessary to continue with them in future experiments.

3.5.5. CH_4 analysis

No CH_4 was detected using the initial apparatus set up which had a sensitivity of +/- 0.5% which, it was realised, was far too insensitive to detect the concentrations of CH_4 that could be found in H.C. activities.

3.5.6. H.C. bin leachate collection

As a leachate collection method, this approach was found to be quite successful with at least small quantities of leachate found in all the containers. The amount collected, however, was highly variable with less than 5ml in some cases and the maximum 75ml in others. This indicates that as a quantitative tool it is inadequate due to the uneven leachate flow across the compost cross-section.

3.5.7. Insulation experiment

Insulating the H.C. bins and reactors had the desired effect of reducing the influence of daily temperature fluctuations but also removed the temperature gradients throughout the compost. The improvement in experiment repeatability is therefore offset by the difference from non-insulated H.C. activities.

3.6. Trial conclusions

The initial results of the trial experiments showed that the approaches adopted were viable but highlighted a number of improvements that could be made to improve future experiments. These conclusions can be summarised as follows:

- CH_4 analysis: A much higher sensitivity for CH_4 was required which could be achieved by using a different set up on a gas chromatograph.
- A portable infra-red gas analyser would improve the accuracy and speed of analysis of the headspace gas samples for CO_2. This would allow the analysis to be done at the H.C. bin or reactor taking the gas directly from the headspace, rather than transporting a sample to the lab. The analysis itself would also take only 30 seconds rather than up to 5 minutes.
- The air flow rates used in the reactor experiments proved to be significantly lower than the equivalent gas exchange rates in the H.C. bins from comparisons

of the CO_2 concentrations, so higher flow rates should be used in future experiments.

- Humidity was found to be almost 100% in all cases, showing that was no need to continue monitoring it in future experiments.
- The experiments could be improved by using mature compost material to reduce the headspace volume in the reactors and H.C. bins, which would also inoculate the composting process and make them more similar to H.C. bins used by the public.
- Surface pH analysis produces similar results to the solution method but is more variable, so the standard approach using the solution method should continue to be used.
- Adding in-line monitoring of the reactor air flow rate would ensure any drifting of the pump flow rate could be observed and corrected.
- The changes to the temperature profile throughout the compost caused by insulation are not worth the improvements to repeatability for the purposes of this project so this will not be used as standard for future experiments. It could still be used as an experimental parameter however, to observe the effects of a different temperature profile on the home composting process.

4. Materials and methods

The features of the trial methods which were kept in the second round of experiments are listed below, the details of which can be found in the previous section:

- 3.1.1 Standard naturally aerated home composting system
- 3.1.2 Forced aeration sealed composting system
- 3.1.3 Location/environment
- 3.1.5 Temperature
- 3.1.7 Solids sampling technique
- 3.1.10 Moisture Content and Volatile Solids
- 3.1.11 pH and Volatile fatty acids

The changes made to the methods are described in detail in the following sections.

4.1. Standard naturally aerated home composting system

The H.C. bins were unchanged from the trial experiment set-up described in Section 3.1.1.

4.2. Forced aeration sealed reactor composting system

Some alterations were made to the composting reactors from the trial experiments. As leachate was found to leak from the base of the some of the bins, it was decided to sacrifice the removable bases and seal their connection to the bins with silicone. Additional clamps were also added to the lid to ensure an airtight seal. Internal gas sampling tubes were added, consisting of a 10 mm plastic tube inserted through a seal in the bin, which was fed into the centre of the compost. The external part of the tube had a valve which was kept closed at all times, except when sampling the internal gas.

The air pump flow rate was again set by an initial calibration but in-line flow meters with controllable valves (MR Flow Meter 0.4-5 L/min, Key Instruments) were connected between the air pumps and the reactor inlets. This removed the time intensive measurement process and provided fast and responsive readings of the flow rate allowing more accurate adjustments to be made as required.

4.3. Input materials

Fresh grass cuttings and food waste were used as in the trial experiments but some additional materials were used as well in order to improve the material availability and similarity to typical home composting. The method of measuring out the input materials was also changed. Rather than weighing out each individual addition, the materials were added by volume in either 24L or 48L quantities. This was achieved by lining plastic containers of those volumes with plastic garden sacks and filling them with the appropriate waste stream. The filled plastic sacks were weighed prior to emptying them into the H.C. bins or reactors. This meant the exact input weight was known but a large number of bins could be fed much faster than if an accurate weight was needed. The downside of this method is inconsistency in the exact feed quantities due to unavoidable variation in the material packing density.

The new materials and their sources are described below. The material properties measured during the experiments and those reported in the literature are provided in Appendix 4.

Mature compost material:

100L of mature compost material was placed in the bottom of the H.C. bins and reactors for these experiments. The material was taken from the University of Southampton's Highfield campus garden waste compost site and had been composted in an open heap of primarily grass cuttings and leaves for between 6-12 months.

Municipal garden waste (MGW) from centralised composting site:

Wastes collected from civic amenity sites and from household collections of green waste in Southampton are taken to a centralised site for large scale composting. The material is shredded and kept outside. For the experiment this material was used as a "brown" material (see section 2.4.2) and was collected as soon as possible after the shredding process was completed.

4.4. Headspace depth

One of the parameters measured in the experiments was the depth of the headspace prior to starting the experiments by adding the first fresh feed addition and at the end of the experiment. Depth was measured by ensuring the upper layer of compost was approximately even and measuring the distance at the centre of the bin from the upper layer to a reference bar placed across the opening of the bin.

4.5. Internal mesh lining

A new protocol adopted for these experiments was the use of a mesh bag within the compost bins and reactors above the mature compost layer in the bottom of the bins (See Figure 27). This bag was constructed from pond netting with a $1cm^2$ mesh size, meaning that air and insect or animal life through the material was not affected. Fresh waste additions to the bins were put into the mesh bags. Due to the material particle size, compaction and self cohesion, when the experiments were finished it was possible to remove the waste separately from the mature layer in the base, with very little loss of material. This made experiment turn around time much faster and allowed the compost produced during an experiment could be easily removed and placed on scales for weighing.

Figure 27: Use of mesh bags in composting expermients

4.6. Gas analysis

For this round of experiments an Infra-Red gas analyser (Model GA 94A, Geotechnical Instruments, Leamington Spa, UK) was used to measure carbon dioxide. This instrument was calibrated by the manufacturer as per the recommended schedule and was operated by drawing in 300ml of air from the compost headspace over 30 seconds, at the end of which a reading for the percentage concentration of CO_2, CH_4 and O_2 was given. The accuracy of this device was ±1% for compositions between (5-15%) and ±3% for compositions above 15%. While acceptable for CO_2 this was not sufficiently sensitive to detect CH_4 in H.C. bins.

CH_4 analysis was performed using an FID Varian Star 3400 CX gas chromatograph with the column set to 60^oC. Due to the time taken to set up the Varian Gas Chromatograph (GC) to analyse compost gas samples for methane, only the later experiments were monitored using this technique. The GC was calibrated using samples of known CH_4 concentration from 5 to 500ppm. Compost gas samples were taken with a 20ml syringe from the compost headspace of open bottomed compost bins and from the outlet tubes of the sealed reactors. When sampling from the internal compost gas tubes (See section 4.2) the first three gas samples drawn were rejected to ensure the gas came directly from within the compost. Following gas collection the syringes were sealed and returned to the lab where the sample was transferred to a Tedlar bag. 10µL samples were drawn from the Tedlar bags for injection into the gas chromatograph. Samples were taken on alternate days, with the internal gas samples taken on one day and the headspace gases sampled on the following day.

Passive diffusion tubes were used for selected experiment treatments to sample for ammonia, nitrous oxide and volatile organic compounds. These were suspended in the headspace of the bins immediately following a fresh feed addition and were left for 14 days before removal and analysis by the external laboratory Gradko International Ltd.

4.7. Individual Experimental methods

Experiments were conducted under various feeding and bin management regimes and with different air flow rates in the sealed reactors in order to investigate specific home composting and experimental parameters. The methods used are described in the following sections. All the experiments can be considered to have the overall aims to:

- Quantify the range of gaseous emissions likely to be produced from home composting under a variety of conditions.
- Improve understanding of the relationships between composting process parameters and gaseous emissions.

4.7.1. Cumulative feeding H.C. bin experiment

The aims of this experiment were to quantify the importance of repeated feed additions relative to a single addition on the data collected and to investigate the parameters of feed size and composition, C:N ratio and temperature. A total of 10 H.C. bins were run for 70 days (from 11/4/06) on soil at Site 2 as 5 duplicate pairs. The bins were fed with one large feed addition (to acquire more data on the effects of feed size) followed by 4 similar smaller additions (see details in Table 34). The headspace depth in the bins before the first feed addition was measured as 0.57m and gas analysis (by IR) was performed for CO_2 only.

Table 34: Waste inputs and experimental justification for cumulative feeding H.C. bin experiments

	Feed addition 1 (Large addition)	Feed additions 2-5 (average)	Experimental justification
Garden waste	10.5Kg Grass + 10.8Kg MGW	4.8Kg grass + 7.1Kg MGW	A baseline pure garden waste feed with equal volumes of green and brown waste
Garden + kitchen waste	9.1Kg Grass + 12.2 Kg MGW + 3.4Kg KW	4.8Kg grass + 6.8Kg MGW + 3.4Kg KW	Added kitchen waste to observe its influence
Insulated	8.6Kg Grass + 12.6Kg MGW	4.8 Kg grass + 6.9 Kg MGW	An insulated bin to observe the influence of a higher temperature profile.
Large feed garden waste	18.2Kg Grass + 19.1Kg MGW	10.0Kg grass + 9.1Kg MGW	A large feed rate to observe its influence.
Garden waste Low C:N	18.5Kg Grass + 11.5Kg MGW	8.6Kg grass + 6.9Kg MGW	Twice the volume of green to brown waste to observe the effect of a lower C:N feed

4.7.2. Cumulative feeding reactor and H.C. bin comparison experiment

The aims of this experiment were to evaluate the approximate equivalent air flow through typical open bottomed H.C. bins under certain conditions as well as the success of simulating naturally aerated compost processes with forced aeration reactors. A total of 2 H.C. bins and 2 reactors were run for 70 days (from 11/4/06) on concrete at Site 1 as 2 duplicate pairs. The bins were fed with one large feed addition (to acquire more data on the effects of feed size) followed by 3 similar smaller additions (see details in Table 35). The headspace depth in the bins before the first feed addition was measured as 0.6m in the H.C. bins and 0.54m in the reactors. The reactor air flow rate was 700 ml/min and gas analysis (by IR) was performed for CO_2 only.

Table 35: Waste inputs and experimental justification for cumulative feeding reactor and H.C. bin comparison experiments

	Feed addition 1 (Large addition)	Feed additions 2-4 (average)	Experimental justification
Reactors and H.C. bins	18Kg Grass + 20 Kg MGW	7.9Kg grass + 10.3Kg MGW	A baseline pure garden waste feed with equal volumes of green and brown waste

4.7.3. Cumulative feeding H.C. bin experiment to measure methane

As the first cumulative feeding H.C. bin experiment (Section 4.7.1) took place without access to the more accurate G.C. methane detection method, a small follow up experiment was conducted in an effort to test if cumulative feeding was an important factor in methane production. The aim of this experiment was therefore to observe the importance of cumulative feeding in methane production. A total 2 H.C. bins were run for 36 days (from 30/4/07) on soil at Site 2 as a duplicate pair. The bins were fed with two feeds of grass and MGW, 14 days apart (see details in Table 36). The headspace depth in the bins before the first feed addition was measured as 0.62m and gas analysis was performed for CO_2 (by IR) and CH_4 (by G.C.).

Table 36: Cumulative feeding H.C. bin experiment to measure methane waste inputs

	Feed 1 (Kg)	Feed 2 (Kg)
Grass	7.7	10.5
MGW	10.8	9.7
Total	18.5	20.2

4.7.4. *Food waste experiment*

There were 2 stages to the food waste experiment. The first stage had the aim to measure the emissions from a food waste only feed. This was performed using reactors with a low air flow rate to enable the detection of lower emission rates. A total of 2 reactors were run for 42 days (from 20/3/07) on concrete at Site 1 as 2 duplicate pairs. The bins were fed with 6 feed additions, 7 days apart (see details in Table 37). The headspace depth in the reactors before the first feed addition was measured as 0.3m. The reactor air flow rate was 500 ml/min and gas analysis was performed for CO_2 (by IR) and CH_4 (by G.C.).

Table 37: Food waste experiment waste input composition

Food waste material	Mass in each feed addition (g)
Apples	480
Bananas	590
Broccoli	400
Carrots	440
Tea	240
Bread	370
Tomatoes	390
Total	**2900**

At the end of the first stage of the experiment the food waste material from the two reactors (17.7Kg food waste combined) was transferred to a single H.C. bin on soil at site 2 so that the reactors could be used for other experiments but the degradation of the food waste could continue to be monitored. The bin was monitored for 70 days (from 30/4/07), no further waste was added. Gas analysis was performed for CO_2 (by IR) and CH_4 (by G.C.).

4.7.5. *H.C. bin waste addition size experiment*

The aim of this experiment was to investigate the effects of feed size on the composting process and gaseous emissions. A total of 2 H.C. bins were run in 3 separate experimental runs each of 14 days (from 21/3/07) on concrete at Site 1 as duplicate pairs. The bins were fed with a single feed for each experimental run (see details in Table 38). Gas analysis was performed for CO_2 (by IR) and CH_4 (by G.C.).

Table 38: Feed size experiment waste inputs

Experimental run title	Feed addition
H.C. bin 10 Kg grass	9.9Kg grass
H.C. bin 16Kg grass	15.7Kg grass
H.C. bin 24Kg grass	24.1Kg grass

4.7.6. Reactor feed composition experiment

The aim of this experiment was to investigate the effects of feed composition on the composting process and gaseous emissions. A total of 2 reactors were run in 4 separate experimental runs for 14 days each (from 21/3/07) at Site 1 as duplicate pairs. The bins were fed with a single feed for each experimental run (see details in Table 39). The reactor air flow rate was 1.5 L/min and gas analysis was performed for CO_2 (by IR) and CH_4 (by G.C.).

Table 39: Feed composition experiment waste inputs

Experimental run title	Feed addition
1.5 L/min Grass	9.9Kg grass
1.5 L/min Grass + MGW (Higher C:N)	9.5Kg grass + 11Kg MGW
1.5 L/min Grass+ MGW (Lower C:N)	10.6Kg grass + 9.7Kg MGW
1.5 L/min MGW	25.8Kg MGW

4.7.7. Water addition and activity time experiment

The aims of this experiment were to investigate the influence of water addition on the home composting process and gaseous emissions, and also to observe the time taken for the gaseous emissions to fall below detectable rates. A total of 8 H.C. bins were run for 100 days (from 18/6/07) on soil at Site 2 as 4 duplicate pairs. The bins were fed with a single feed of 17.9Kg garden waste (10.4Kg grass + 7.5Kg MGW) and for each of the 4 pairs of bins an additional:

1. No water
2. 5L/fortnight water
3. 5L/week water
4. 10L/week water

Gas analysis was performed for CO_2 (by IR) and CH_4 (by G.C.).

4.7.8. Headspace volume experiment

The methodology in this and other home composting research has been to monitor the gas composition in a H.C. bin headspace. In interpreting this data it is necessary to consider all factors which influence the gas composition measurements. These include not only the rate of gas production and exchange with fresh air, but also the headspace volume. In order to investigate the effect of headspace volume on the measurements of headspace gas composition, the headspace volume was changed by putting different volumes of mature compost material at the bottom of the bins. A total of 4 H.C. bins were run for 14 days (from 30/4/07) on soil at Site 2 as 2 duplicate pairs. The bins were fed with a single waste addition of 18.5Kg garden waste (7.7Kg grass + 10.8Kg MGW). The headspace depth in the bins before the first feed addition was set to 0.4m in one pair, and 0.7m in the second pair. Gas analysis was performed for CO_2 (by IR) and CH_4 (by G.C.).

4.7.9. Gas transfer experiment

In order to investigate gas transport pathways through H.C. bins (See section 2.12), the different gas outlets in the bins were tested by sealing them to prevent any gas transport through them and observing the effects on the headspace CO_2 concentration. Sealing of the lid and hatch spaces was achieved by wrapping them in several layers of cling film. The following conditions were tested:

1. Unaltered standard H.C. bin
2. H.C. bin sealed around the join between the lid and the bin
3. H.C. bin sealed around the join between the lid and the bin with a rotameter flow meter (MR Flow Meter 0.4-5 LPM, Key Instruments) attached to an outlet tube in the lid
4. H.C. bin sealed around the join between the lid and the bin and around the hatch in the bin

5. Sealed composting reactor with the base removed leaving it open the bottom in contact with the ground (Section 3.1.2) - similar to sealed lid and hatch compost bin but, due to the greater weight of the barrel, with less space between the base and the ground.

A total of 4 H.C. bins and one composting reactor with the lid sealed but the base open and on the ground were run for 14 days (from 30/4/07) on soil at Site 2. The bins were fed with a single feed of 20.7Kg garden waste (6.7Kg grass + 14Kg MGW). Gas analysis was performed for CO_2 (by IR) and CH_4 (by G.C.).

4.7.10. Reactor flow rate experiment

The aim of this experiment was to investigate the influence of the air flow rate on the reactor composting process measurements. A total of 2 reactors were run in 3 separate experimental runs for 14 days each (from 17/4/07) at Site 1 as duplicate pairs. The air flow rate for the duplicate reactors in the three experimental runs was 0.5, 1.5 and 2.0 L/min. The reactors were all fed with a single waste addition of 9.9Kg grass and gas analysis was performed for CO_2 (by IR) and CH_4 (by G.C.).

5. Results

5.1. Cumulative feeding H.C. bin experiment

5.1.1. Temperature and CO_2 concentration profiles

Figures 29 to 33 below show the temperature and CO_2 concentration profiles for each individual treatment in the cumulative feeding H.C. bin experiment. The two profiles are shown alongside each other for the first 6 weeks, from which the strong link between the two can be clearly observed; with a rise in one matched by a rise in the other. The influence of the ambient temperature can also be seen, as the ambient daily temperature fluctuations cause similar fluctuations in the compost temperatures. Particularly at around 20-24 days, there is a sharp rise in ambient temperature followed by a rise in the compost temperature. This appears to cause a further period of composting activity, as in some of the treatments (Figure 28: Large feed garden waste for example) there is a rise in CO_2 concentration at the same time and the rise in compost temperature is sustained for several days.

The first feed addition in all the treatments was larger than the later addition, which is why the first temperature peak reaches a higher temperature than the others. Interestingly, the same is not true of the CO_2 peaks, and in fact it can be observed that the height of the peaks from one addition to another varies quite substantially even within the same experiment treatment. This could be because of a combination of several factors:

1. There may not actually be a significant increase in the composting activity rate despite the larger feed, and the higher temperature is due to a small increase in activity and the added insulation of the additional waste material.
2. The influence of headspace volume on the CO_2 concentration making an increased production rate difficult to detect (This is discussed further in Section 6.3)
3. The interaction of gas concentration and gas transfer by molecular diffusion meaning that a small increase is CO_2 production could be offset by an increase in the gas transfer rate (Gas transfer mechanisms are discussed in detail in

Section 6.8., where it is concluded that molecular diffusion is the dominant gas transfer mechanism).

4. Variation in the precise feed composition, packing density and free air space from one feed addition to another.
5. If the major route of gas transfer is the space between the bin lid and the compost bin (Gas transfer routes in H.C. bins are discussed in detail in Section 6.8., where it is concluded that this lid space is a major transfer route) then this could be strongly influenced by the exact position of the lid relative to the bin due to the imprecise, rough, and uneven features of the plastic components.

Other features that can be observed from the figures and the summary data in Table 40 are that larger feed sizes and lower C:N feed materials led to higher temperatures and concentrations of CO_2 (Discussed in more detailed in Sections 6.2.1 and 6.2.3). The insulated treatment results are not notably different from the similar garden waste treatment except for the smoother temperature profile due to the reduced influence of the ambient temperature.

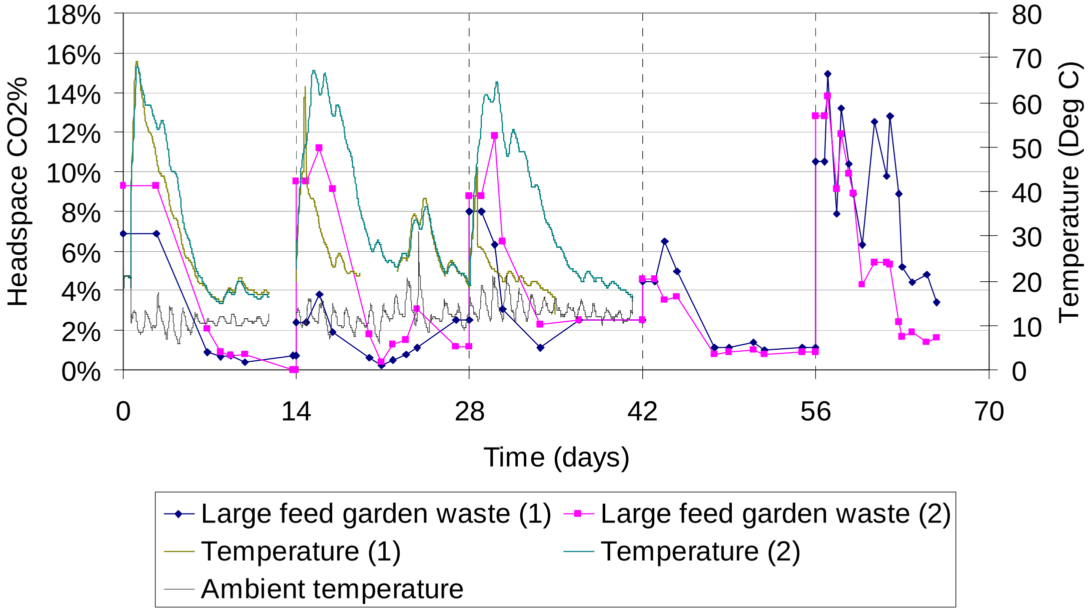


Figure 28: Large feed garden waste experiment temperature and CO_2 concentration profiles

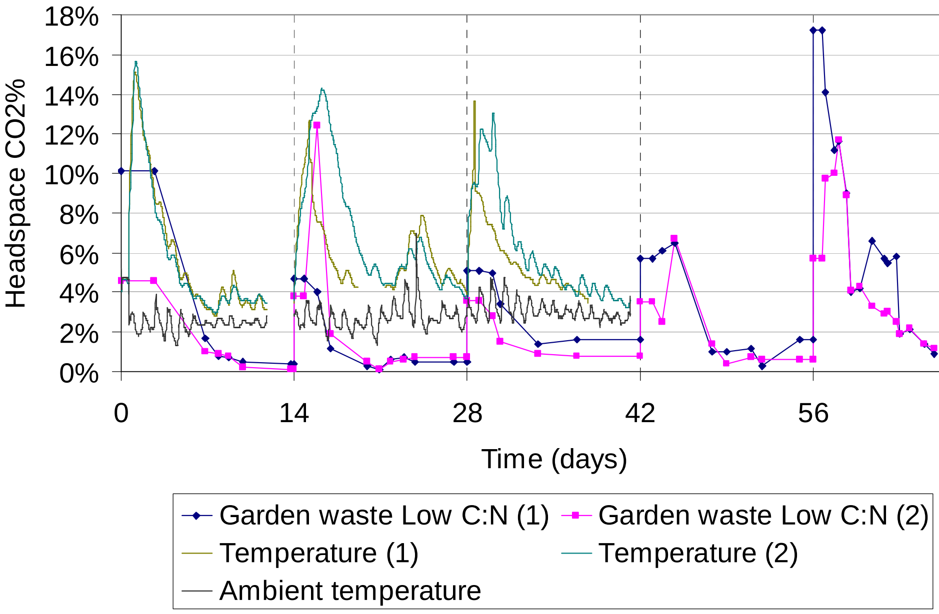


Figure 29: Garden waste low C:N experiment temperature and CO_2 concentration profiles

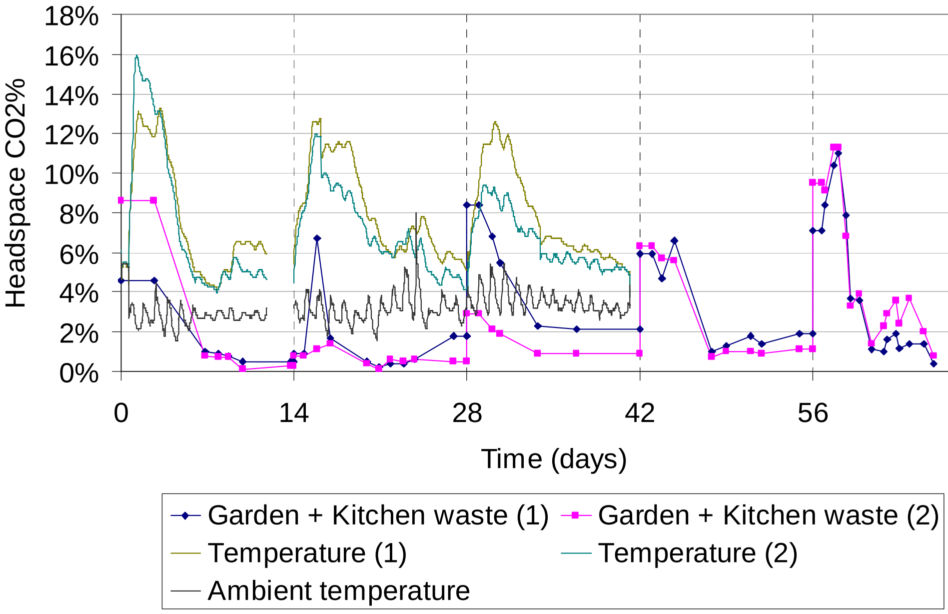


Figure 30: Garden and Kitchen waste experiment temperature and CO_2 concentration profiles

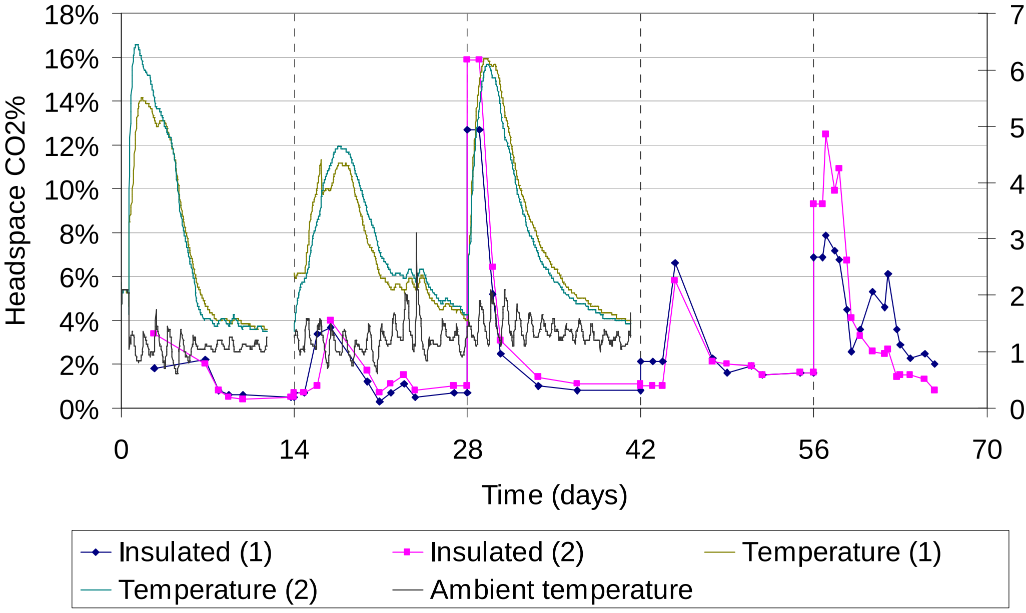


Figure 31: Insulation experiment temperature and CO_2 concentration profiles

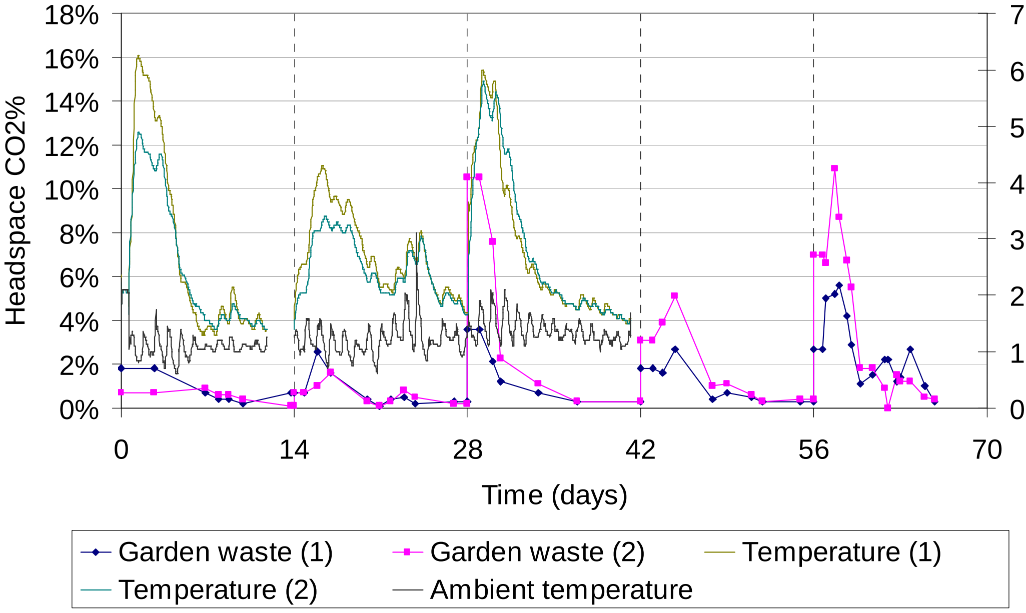


Figure 32: Garden waste experiment temperature and CO_2 concentration profiles

5.1.2. Physical measurements

The physical measurements of each of the treatments are summarised in Table 40. The feature of higher temperatures with the large feed addition but higher maximum detected CO_2 concentrations with the following smaller feeds can be seen. For example the garden waste treatment reached 63°C with only 1.9% CO_2 with a large addition but 60°C and 11.2% CO_2 with a smaller addition

Table 40: Cumulative feeding H.C. bin experiment results summary

Experiment title	Maximum CO2 concentration (%)	Maximum Temperature (°C)	pH	Final Weight (Kg)	Moisture Content (%)	Volatile Solids (%)
Garden waste (1st large feed addition)	1.9	63	7.3	15.2	44	61
Garden waste (additions 2-5)	11.2	60	7.8	8.8	47	53
Garden + kitchen waste (1st large feed addition)	8.3	62	7.5	15.3	43	53
Garden + kitchen waste (additions 2-5)	11.2	53	7.7	8.3	51	50
Insulated (1st large feed addition)	3.5	65	7.2	14.5	41	53
Insulated (additions 2-5)	11.1	62	7.9	8.9	53	56
Large feed garden waste (1st large feed addition)	9.7	69	7.0	26.7	44	63
Large feed garden waste (additions 2-5)	15.0	68	7.4	13.7	42	54
Garden waste Low C:N (1st large feed addition)	10.1	70	7.4	21.5	42	54
Garden waste Low C:N (additions 2-5)	17.2	53.5	7.7	11.1	43	46

5.2. Cumulative feeding reactor and H.C. bin experiment

5.2.1. Temperature and CO_2 concentration profiles

Figure 33 and Figure 34 below show the temperature and CO_2 concentration profiles for the duplicate reactor and H.C. bin comparative treatments. The visible relationship between temperature and CO_2 and the trends over time are identical to those discussed in Section 5.1.1. The more interesting features in comparing the two treatments are discussed in detail in Section 6.1 but it can be observed that the reactors reached much higher headspace CO_2 concentrations than the H.C. bins, while having quite similar temperature profiles. There was no feed addition at 42 days in order to observe longer term CO_2 emissions. It can be seen that CO_2 continued to be produced up to around 56 days, with concentrations of between 0.5-1% detectable in both composting systems. Another longer experiment was conducted to observe when this emission became undetectable (water addition and activity time experiment).

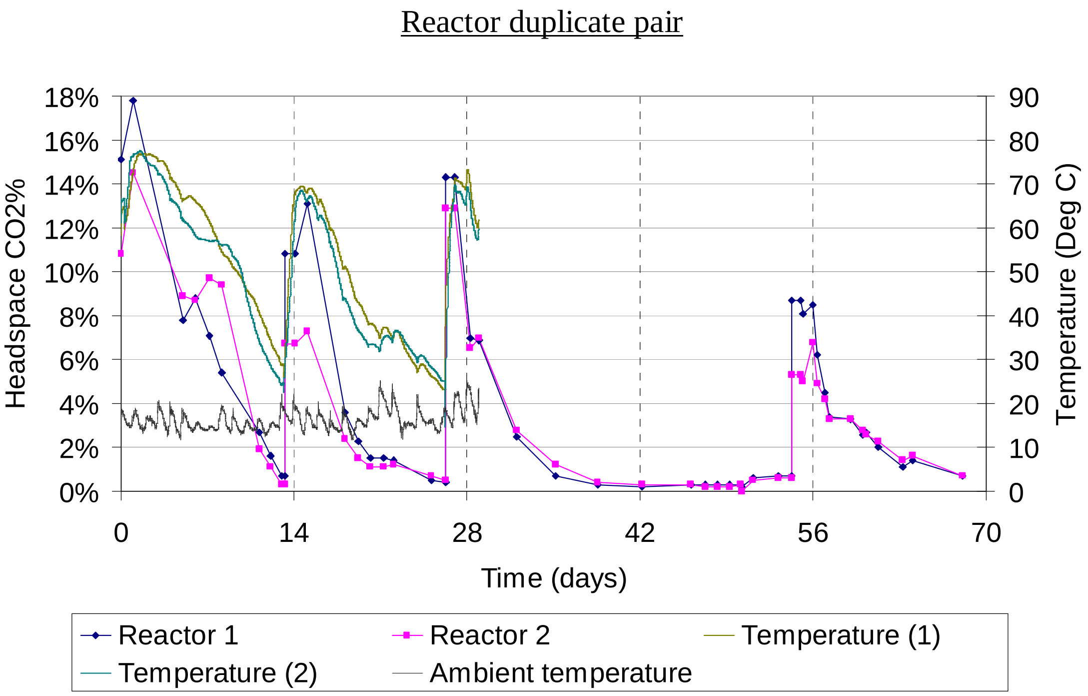


Figure 33: Temperature and CO_2 concentration profiles in the reactors

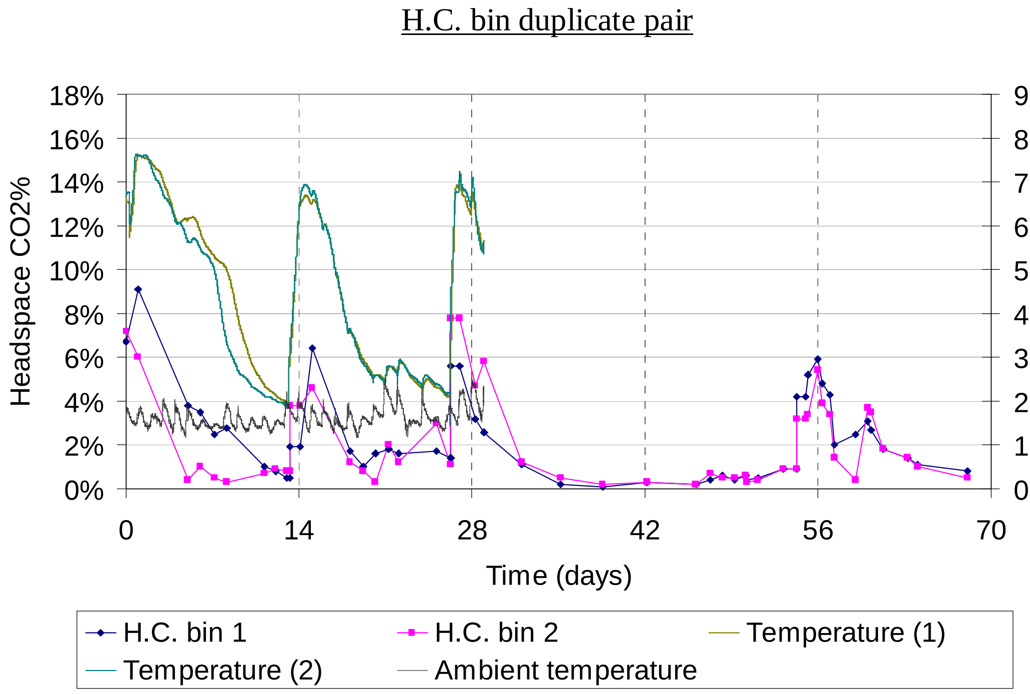


Figure 34: Temperature and CO_2 concentration profiles in the H.C. bins

5.2.2. Physical measurements

Table 40 shows the physical measurements of the two experimental systems, with the first large feed shown separately to the following three additions. For this experiment elemental analysis was only done at the end, which is why the large and small additions for each treatment have the same elemental composition.

Table 41: Cumulative feeding reactor and H.C. bin comparison experiment physical measurements

Experiment title	Reactor (1st large feed addition)	Reactor (additions 2-4)	H.C. bin (1st large feed addition)	H.C. bin (additions 2-4)
Maximum CO_2 concentration (%)	18.0	14.1	9.1	8.0
Maximum Temperature (^oC)	77.5	70.3	76.0	70.0
pH	8.3	8.0	8.2	7.9
Moisture Content (%)	49.2	57.7	42.7	52.1
Volatile Solids (%)	54.2	53.9	43.1	58.3

5.3. Cumulative feeding H.C. bin experiment to measure methane

5.3.1. Headspace CO_2 concentration profile

The CO_2 concentration profiles in Figure 35 below show that a higher CO_2 concentration was reached with the second feed than the first in duplicate 2, although not in duplicate 1. This variation is likely to be a result of the complex interaction of the composting activity, CO_2 emission rate, headspace volume and gas transfer processes under the influence of the area for gas exchange around the compost bin lids.

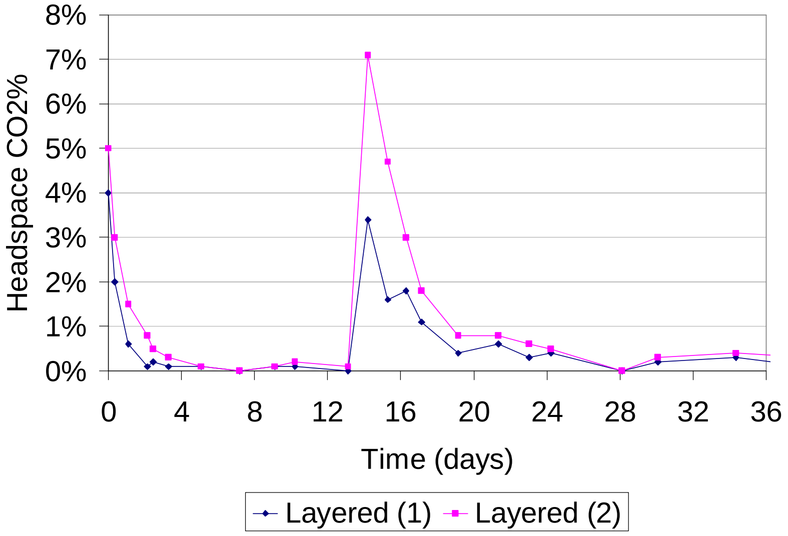


Figure 35: Headspace CO_2 concentration profile in cumulative feeding H.C. bin experiment to measure methane

5.3.2. Physical measurements

Table 42 shows the measurements made during the experiment. It can be seen that CH_4 was detected during the second addition but not the first, although at a very low concentration near the limits of detection. This is not very strong evidence that the layered feed addition, and the resulting oxygen depletion from the previous feed leads to CH_4 production. The fact that much higher CH_4 concentrations were detected from single feed additions in other experiments raises the question that the emissions detected here were a result of either the smaller headspace volume, or small uncontrollable differences in the waste properties and composting process.

Table 42: Physical measurements

Experiment title	Layered (1)	Layered (2)
Maximum CO_2 concentration (%)	3.5	7.0
Maximum CH_4 concentration addition 1 (ppm)	N.D.	N.D.
Maximum CH_4 concentration addition 2 (ppm)	7	5
pH	7.4	7.3
Final Weight (Kg)	12.7	13.8
Moisture Content (%)	49	49
Volatile Solids (%)	78	63

5.4. Food waste experiment

5.4.1. Headspace CO_2 concentration profiles

Stage 1

In the first stage of the experiment the CO_2 concentrations in the reactors shown in Figure 36 followed quite similar patterns, but differed by up to 3% points during some measurements. Unlike in the garden waste experiments where waste was added every 14 days, there is not the large peak in CO_2 emission followed by a gradual decline but rather a fairly steady concentration after the first week at around 3-5% CO_2. In other words, the more frequent small waste additions maintain a steadier rate of activity and CO_2 emission.

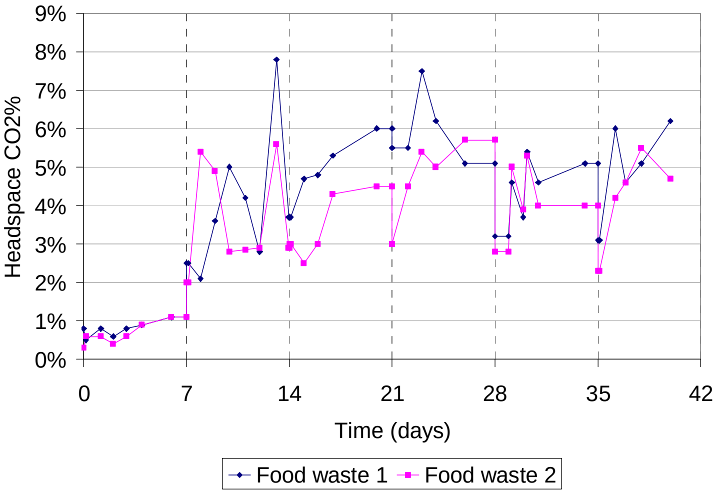


Figure 36: Food waste experiment stage 1 CO_2 concentration profiles

Stage 2

The CO_2 profile in the second stage of the experiment, where the partially composted food waste from the two duplicate reactor systems was pooled together and moved to a single H.C. bin, is shown in Figure 37. It can be seen that composting activity and emission of CO_2 continued for more than 70 days with concentrations of between 0.5-2.0%.

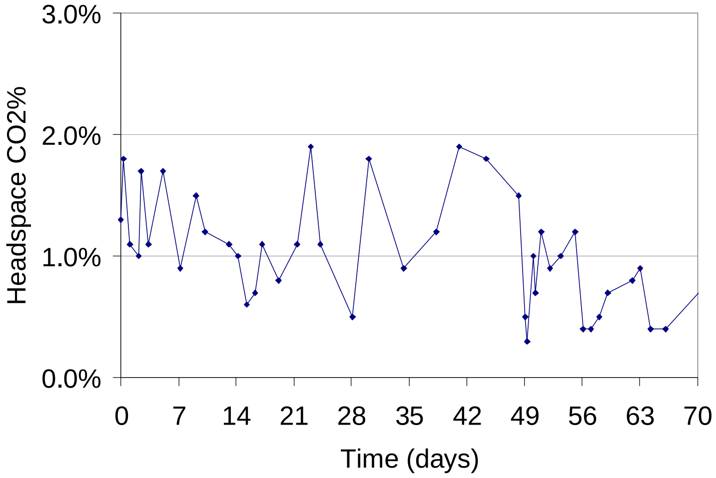


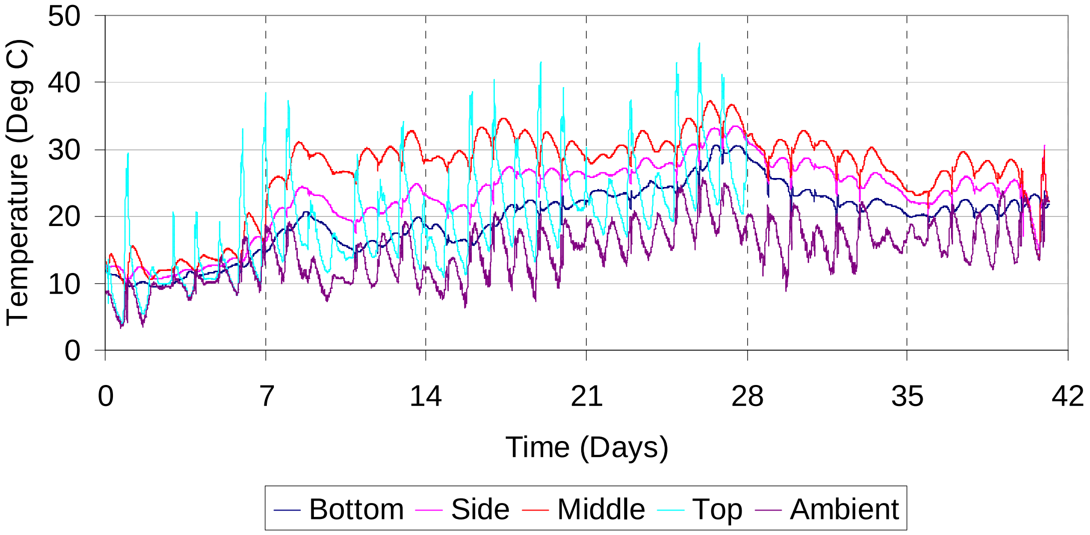
Figure 37: Food waste experiment stage 2 CO_2 concentration profile

5.4.2. Temperature profiles

The temperature profiles of the duplicate reactors in the first experiment stage are shown in Figure 38. As would be expected with a relatively small and high moisture content feed, high temperatures aren't reached but are typically around 30°C in the centre of the compost, about 10-15°C above ambient. The ambient temperature has a strong influence on the compost temperature, and there is a strong variation from the middle, side, bottom and top of the compost.

Stage 1

Food waste experiment (1)



Food waste experiment (2)

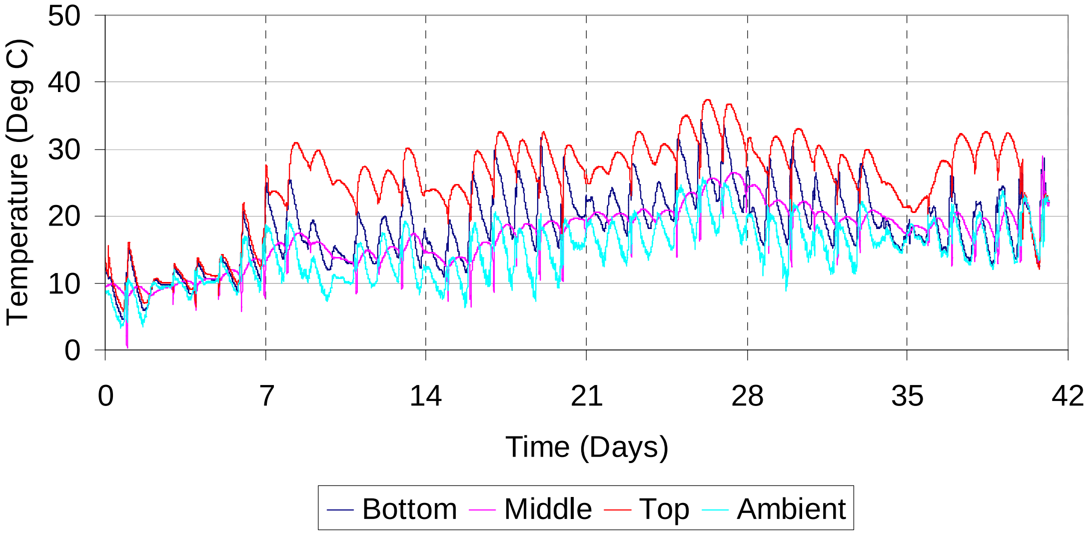


Figure 38: Food waste experiment temperature profiles in stage 1

5.4.3. Physical measurements

The food waste experiment measurements in Table 43 show that no CH_4 was detected in the first stage of the experiment, but was in the second stage. It may be that the forced air flow in the reactors flushed any CH_4 that was produced out before it reached detectable concentrations, but this didn't occur in the H.C. bin in the second stage. The CH_4 emission and anaerobic conditions that lead to it were likely to have been caused by the high density and moisture contents of the food waste, measured as 86% and 87% at the end of stage 1. This is discussed in detail in Section 6.9.1.

Table 43: Food waste experiment physical measurements (End of stage 1)

Experiment title	Food waste (1)	Food waste (2)
Maximum CO_2 concentration (%)	8.0	5.6
Maximum CH_4 concentration (ppm)	N.D. (29 in stage 2)	
Maximum Temperature (^oC)	46	37
pH	7.8	7.3
Final Weight (Kg)	8.9	8.8
Moisture Content (%)	86	87
Volatile Solids (%)	88	76

5.5. H.C. bin waste addition size experiment

5.5.1. Headspace CO_2 concentration profiles

The CO_2 concentration profiles in Figure 39 show that even large changes in the feed size may not have a significant impact on the CO_2 concentration measurements, despite the increase in CO_2 emission rate which must take place. An increase from 10 to 16Kg waste resulted in no significant change in the maximum CO_2 concentrations, with them both at around 3%. With 24Kg the concentration increased by less than 1% points, to 3.8%.

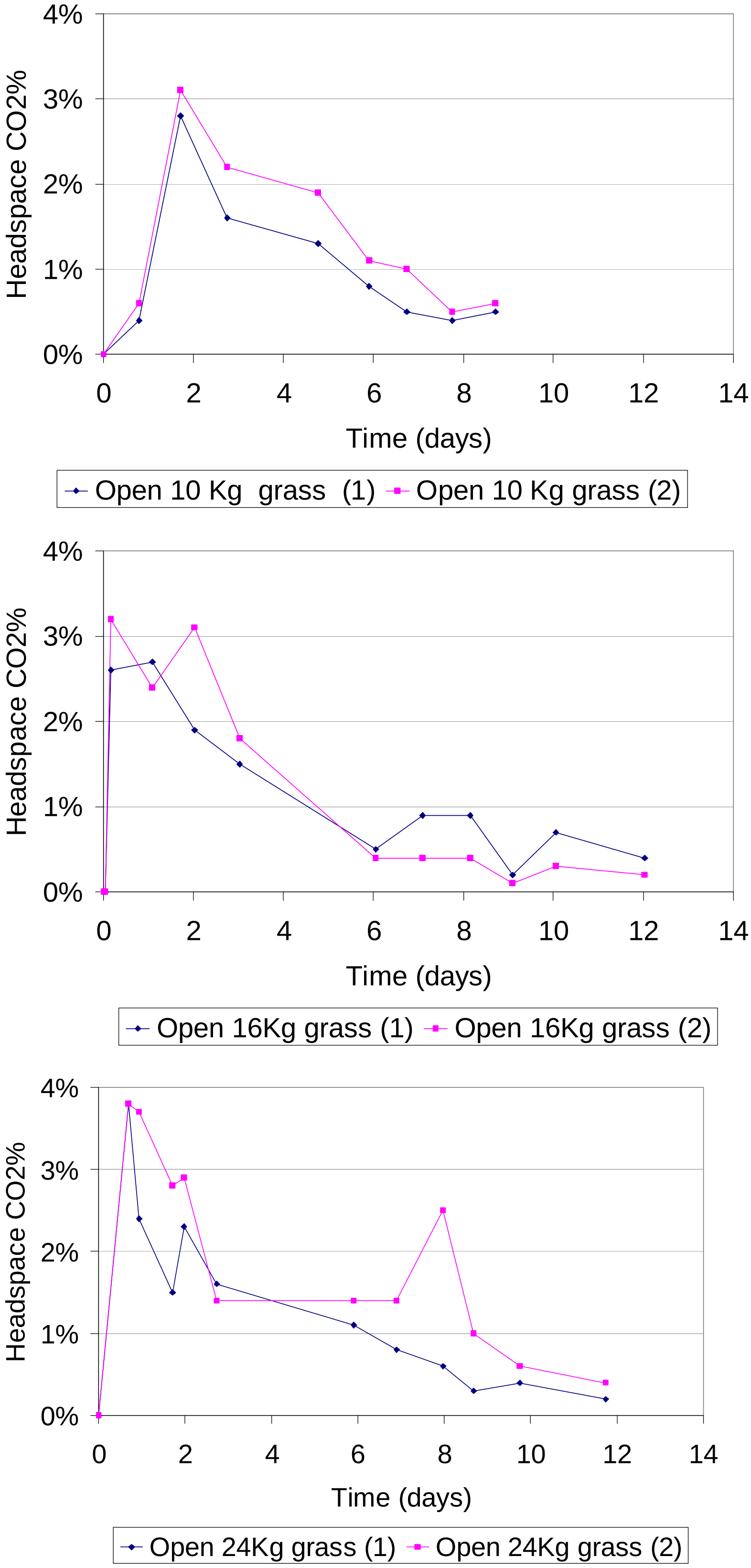


Figure 39: H.C. bin waste addition size experiment CO_2 concentration profiles

5.5.2. Temperature profiles

The temperature profiles of the three experimental treatments in Figure 40 to Figure 42 show that unlike the CO_2 temperature profiles, the feed size had quite a significant impact on the composting activity. With a 10 Kg feed, the maximum temperature reached was just over 50°C, while with 16 and 24 Kg feeds, it was over 70°C in both cases, at which point it becomes self limiting due to the requirements of the active microbes. In all cases there was a significant variation between the different points in the compost, with the highest temperatures in the middle of the compost and the lowest at the bottom. Ambient temperatures had a visible influence throughout the compost but much more so at the top where there was minimal insulation, and very little at the bottom where there was the maximum insulation.

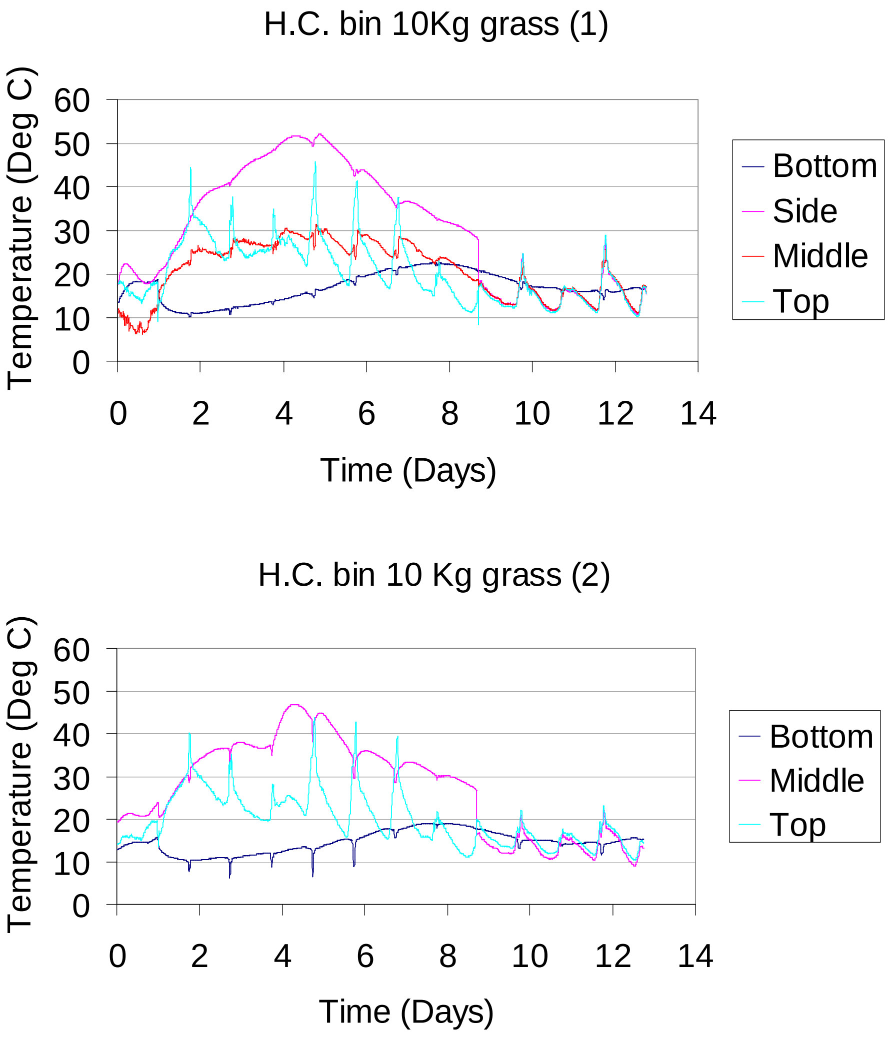
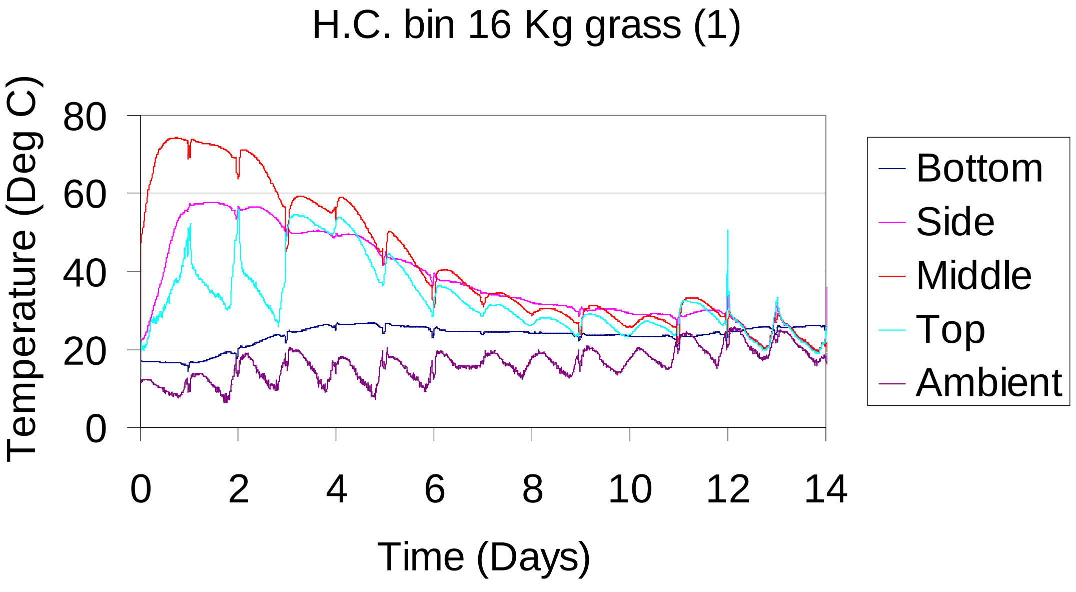


Figure 40: H.C. bin 10Kg grass temperature profiles



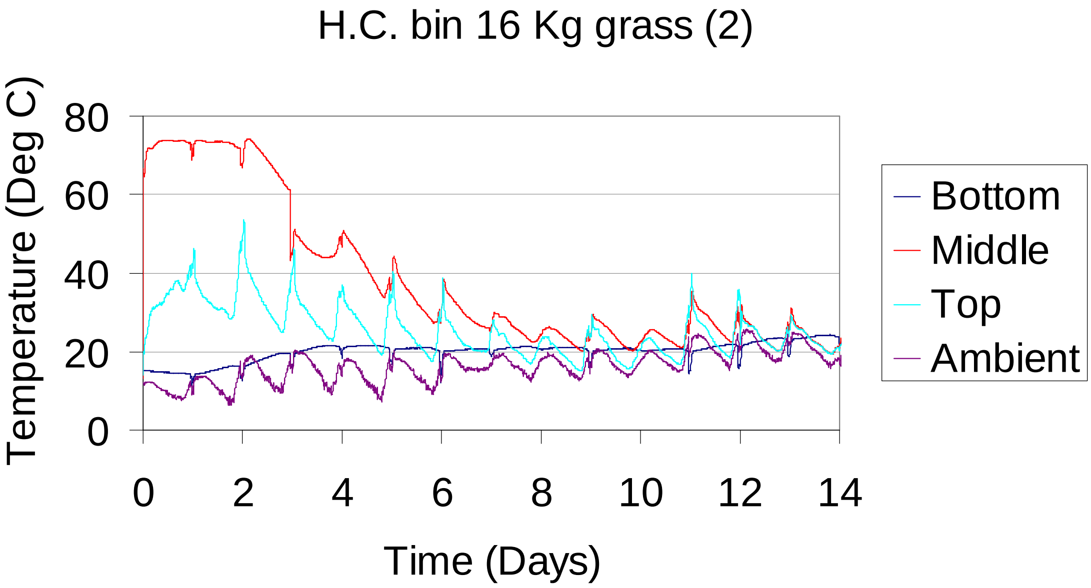
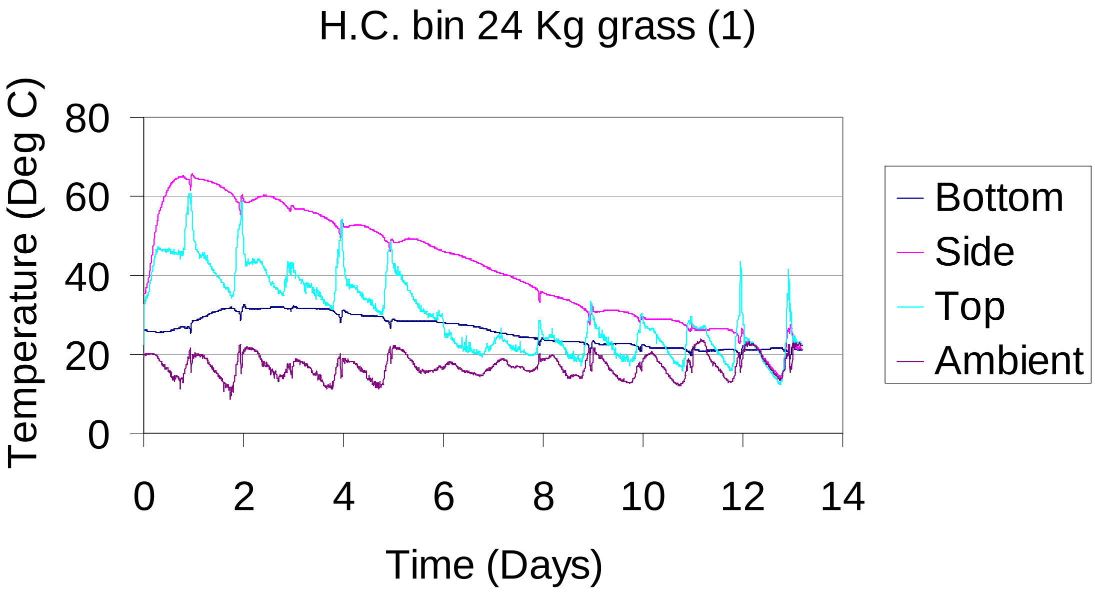


Figure 41: H.C. bin 16 Kg grass temperature profiles



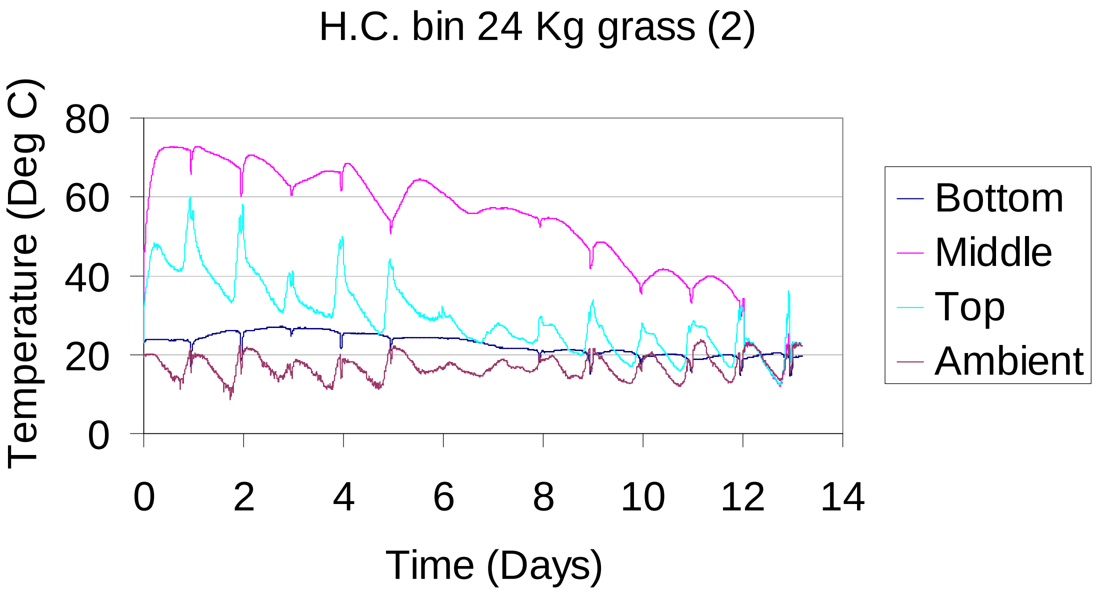


Figure 42: H.C. bin 24Kg grass temperature profiles

5.5.3. Physical measurements

The measurements in Table 44 reiterate the points already discussed regarding the small variation in CO_2 concentrations but more significant changes in temperature between the experiment treatments. It can also be noticed that the moisture contents of the 10Kg grass composts were much higher, around 65% at the end of the experiment than the 16Kg or 24Kg feeds, around 30-40% which is likely to be a result of the different temperatures reached and its influence on evaporation. A similar difference is visible in the pH with values of 8.4 - 8.5 in the 10Kg treatment but lower values from 7.5-8.0 in the 16 and 24Kg treatments.

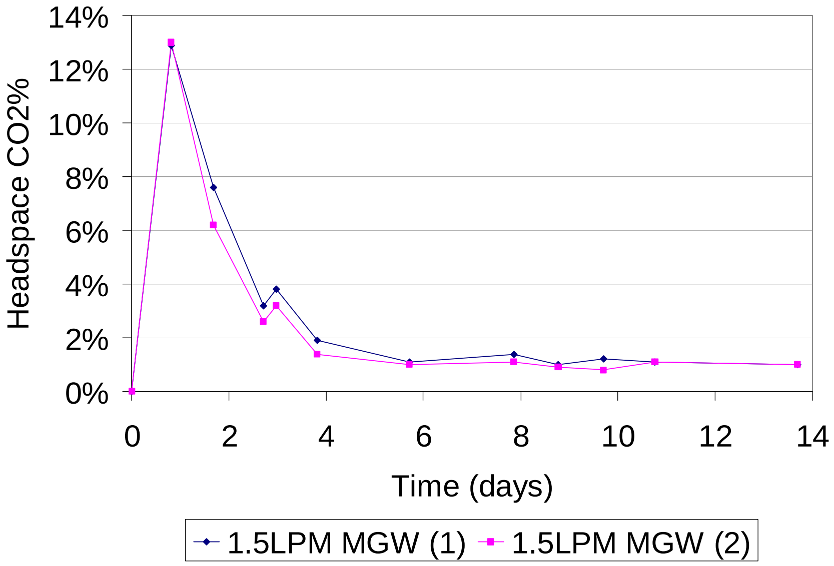
Table 44: H.C. bin waste addition size experiment physical measurements

Experiment title	Maximum CO_2 concentration (%)	Maximum Temperature (^oC)	pH	Final Weight (Kg)	Moisture Content (%)	Volatile Solids (%)
Open 10 Kg grass (1)	3.1	52	8.4	5.6	64	67
Open 10 Kg grass (2)	2.8	47	8.5	6.2	66	68
Open 16Kg grass (1)	3.2	74	8.0	10.0	28	79
Open 16Kg grass (2)	2.8	74	8.0	10.4	39	73
Open 24Kg grass (1)	3.8	66	7.9	14.9	29	62
Open 24Kg grass (2)	3.8	73	7.5	14.8	39	68

5.6. Reactor feed composition experiment

5.6.1. Headspace CO_2 concentration profiles

The different quantities of waste composted in the different treatments do not correlate with the observed maximum CO_2 concentrations reached. Both the highest and the lowest concentrations observed occurred in the similar grass and MGW waste treatments with 9 and 18% CO_2. The grass only feed reached almost 15% CO_2 despite having about half as much waste material, while the MGW only feed reached just 13% despite having more than double the waste feed. Grass should contribute more than MGW to the short term peak CO_2 emission as it is more readily compostable than the higher C:N ratio, more woody material (See section 4.3). A more detailed analysis of the impacts of waste composition on the composting process is provided in Section 6.2.1.



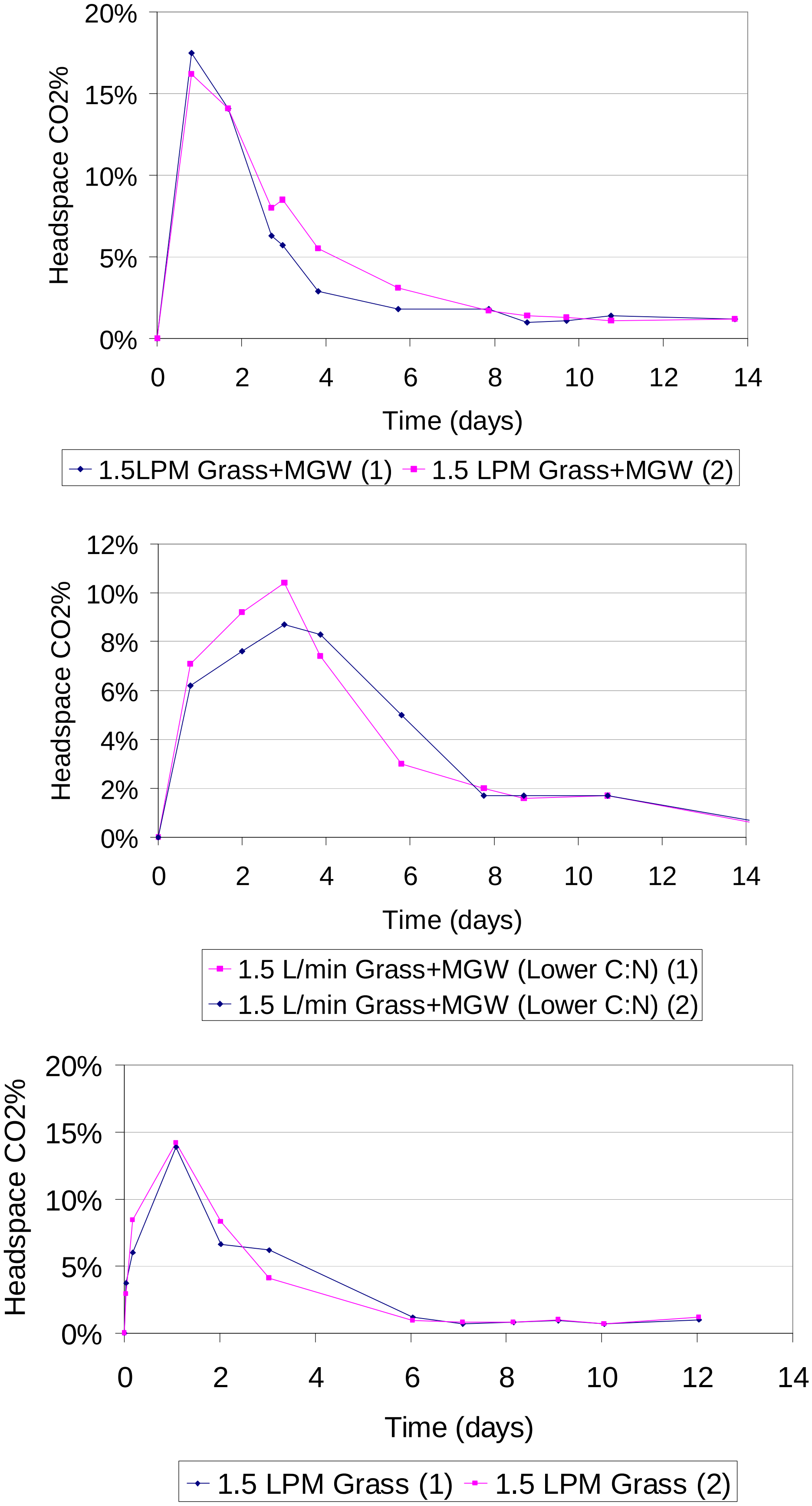


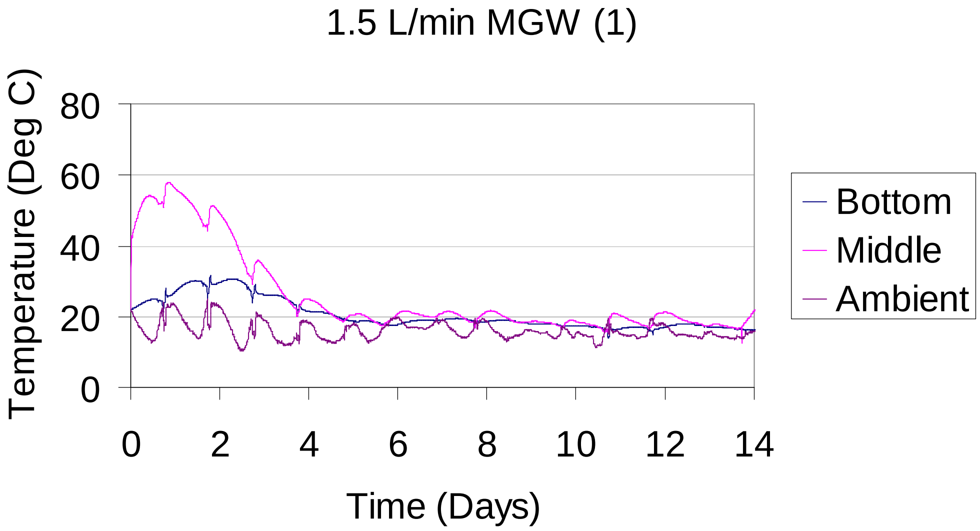
Figure 43: Reactor feed composition experiment CO_2 concentration profiles

5.6.2. Temperature profiles

The temperature profiles show a similar picture to the CO_2concentrations. The two grass+MGW treatments again gave both the highest (Figure 45) and the lowest (Figure 46) maximum temperatures despite having very similar feed materials. A potential cause could be the difference in ambient temperature, as the lower C:N treatment which reached lower temperatures and CO_2 concentrations had an ambient range of 12-18°C compared to 13-25°C in the high C:N treatment. At higher temperatures microbial activity is increased which leads to the production of more CO_2 and heat which reinforces the effect.

The MGW only treatment (Figure 44) also reaches the second lowest maximum temperatures at 66°C while the grass only treatment (Figure 47) reached 71°C. The grass only treatment also has a differently shaped profile to the others, with a shorter time at the peak temperature and a more rapid decline. This could be because of two factors:

1. The smaller volume of waste and different thermal properties meaning heat losses took place faster
2. The higher C:N ratio and more woody materials in MGW mean more time is needed for the composting process and microbial activity can be sustained for longer than with a grass only feed.



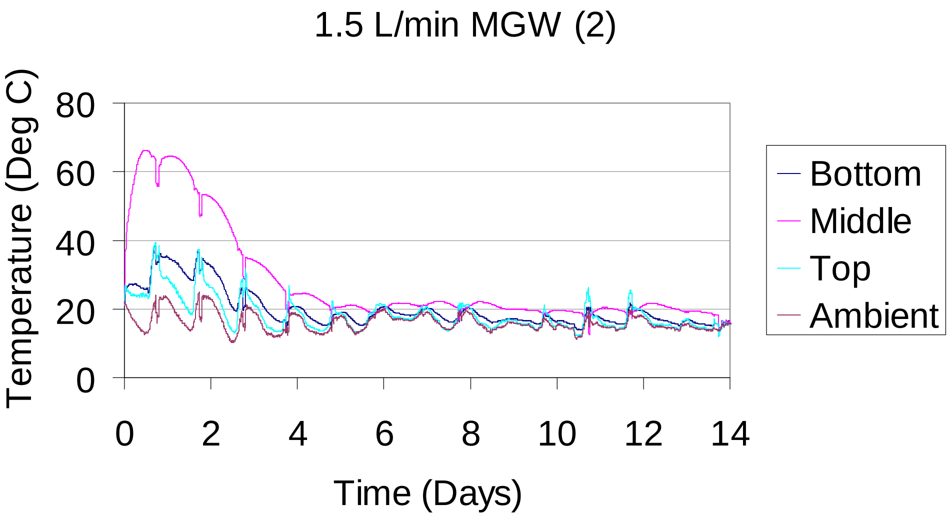


Figure 44: 1.5L/min MGW Temperature profiles

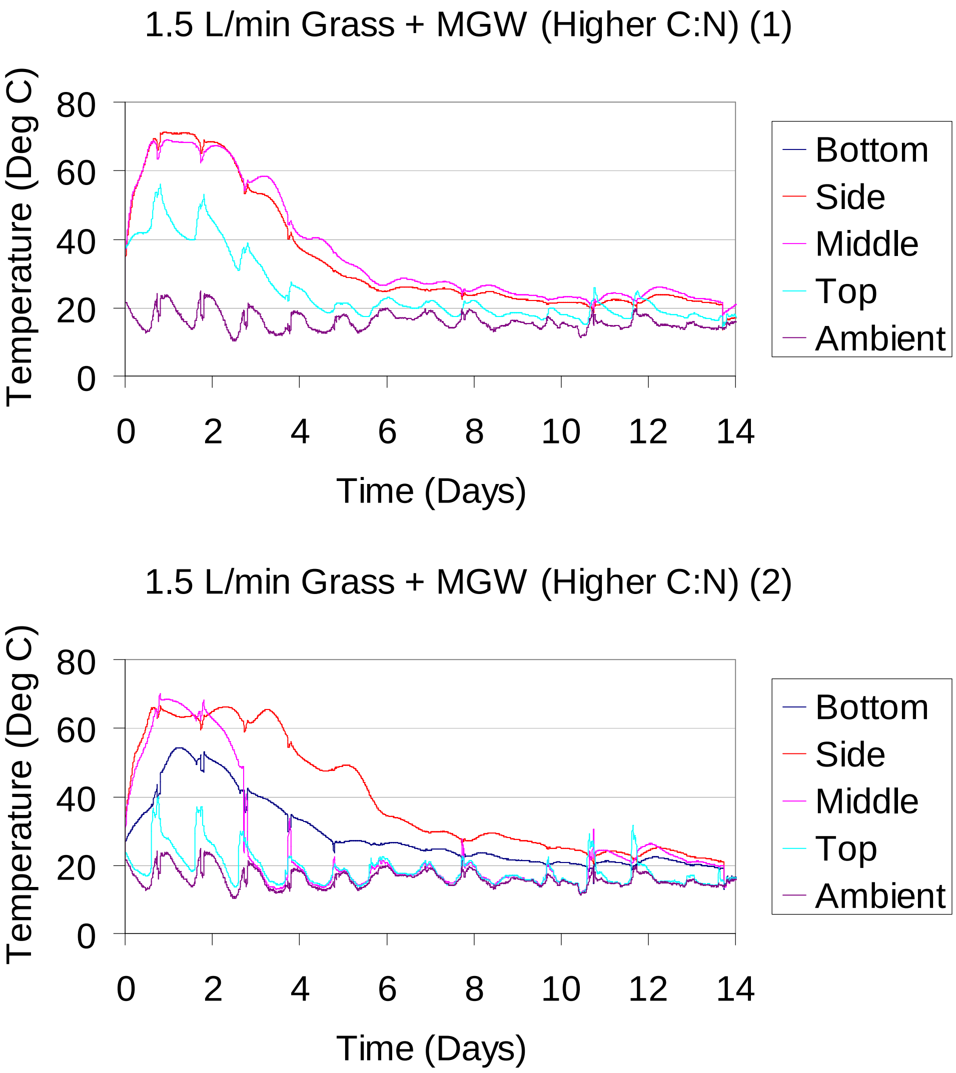
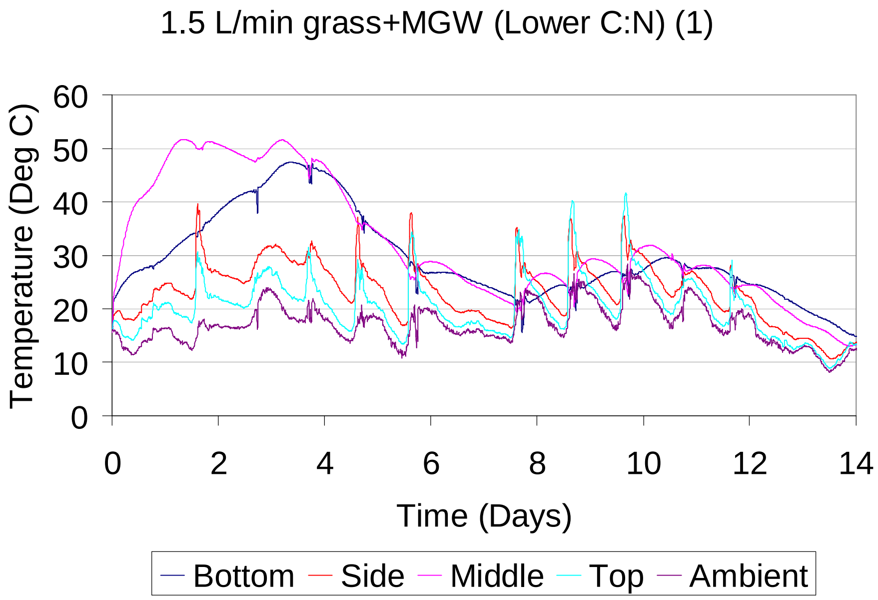


Figure 45: 1.5L/min Grass+MGW (Higher C:N) Temperature profiles



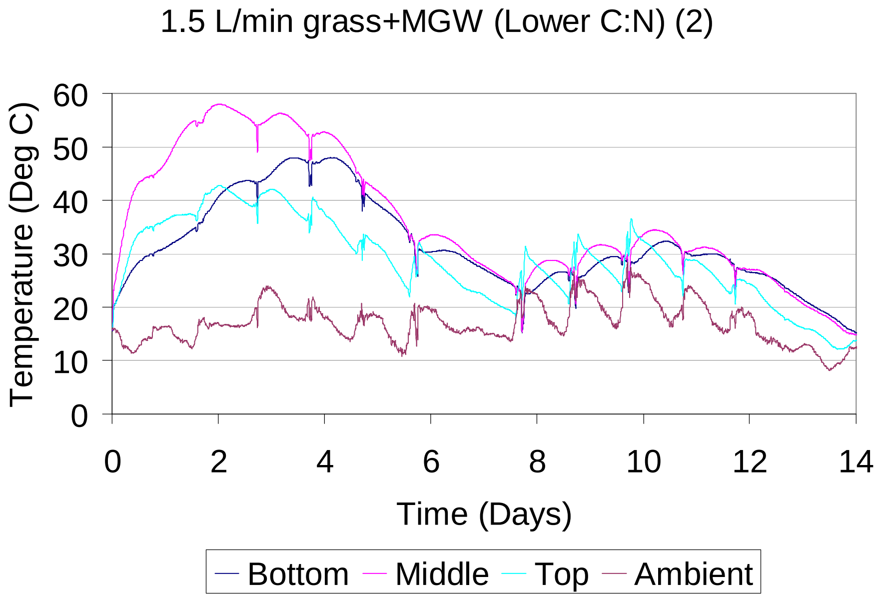


Figure 46: 1.5L/min Grass+MGW (Lower C:N) Temperature profiles

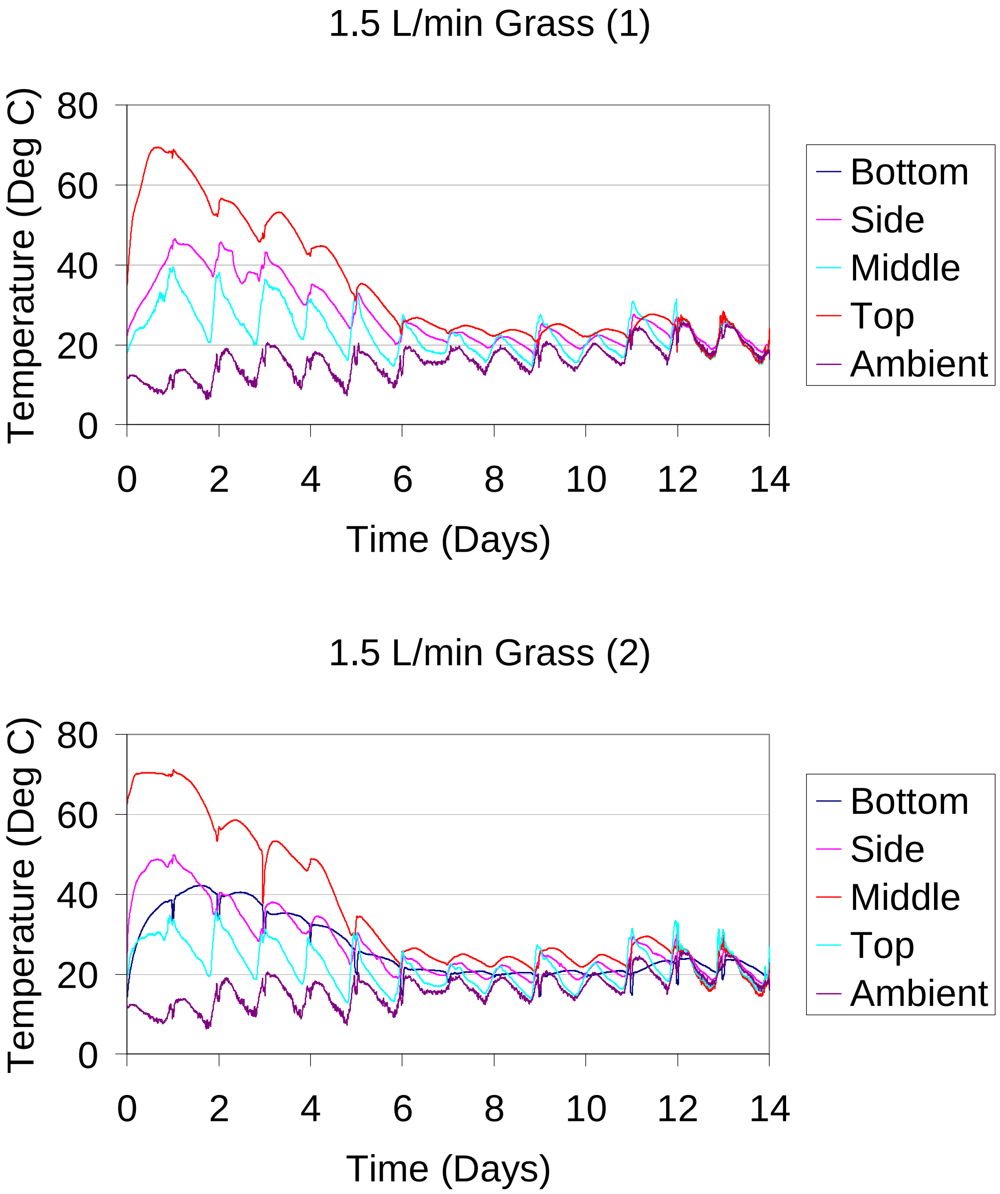


Figure 47: 1.5L/min Grass Temperature profiles

5.6.3. Physical measurements

The measurements shown in Table 45 reiterate the points discussed on the CO_2 concentrations and temperatures. Very little variation in the pH took place as can be seen in Table 46 with a range of 7.8 – 8.2 across all the treatments. A more detailed analysis of the impacts of waste composition on the composting process is provided in Section 6.2.1.

Table 45: Reactor feed composition experiment physical measurements (a)

Experiment title	Maximum CO_2 Conc. (%)	Maximum CH_4 Conc. (ppm)	Maximum Temp. (^oC)
1.5 L/min Grass (1)	11.3	N.D.	69
1.5 L/min Grass (2)	11.9	N.D.	71
1.5 L/min Grass + MGW (Higher C:N) (1)	9.1	N.D.	71
1.5 L/min Grass + MGW (Higher C:N) (2)	6.4	N.D.	70
1.5 L/min Grass+ MGW (Lower C:N) (1)	5.6	5	58
1.5 L/min Grass+ MGW (Lower C:N) (2)	7.8	5	52
1.5 L/min MGW (1)	5.9	N.D.	58
1.5 L/min MGW (2)	5.4	N.D.	66

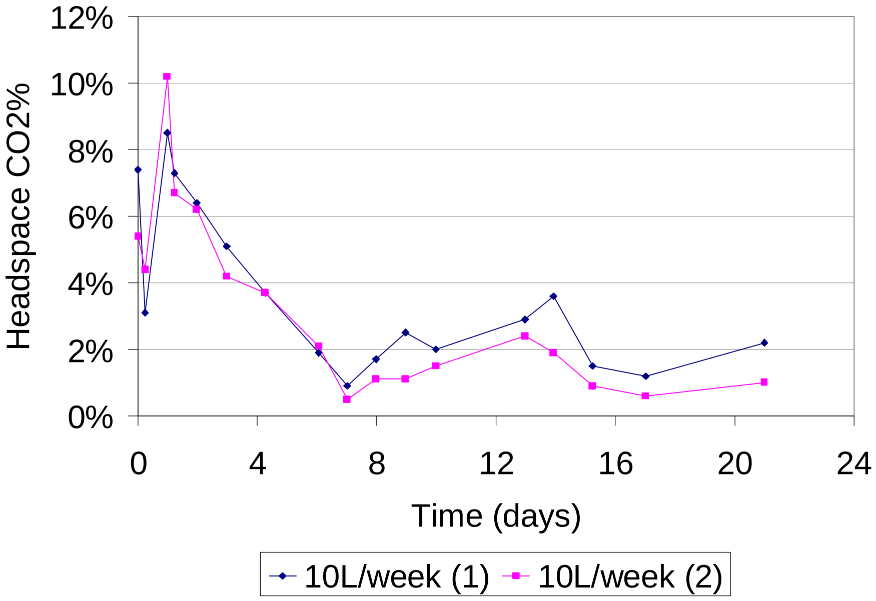
Table 46: Reactor feed composition experiment physical measurements (b)

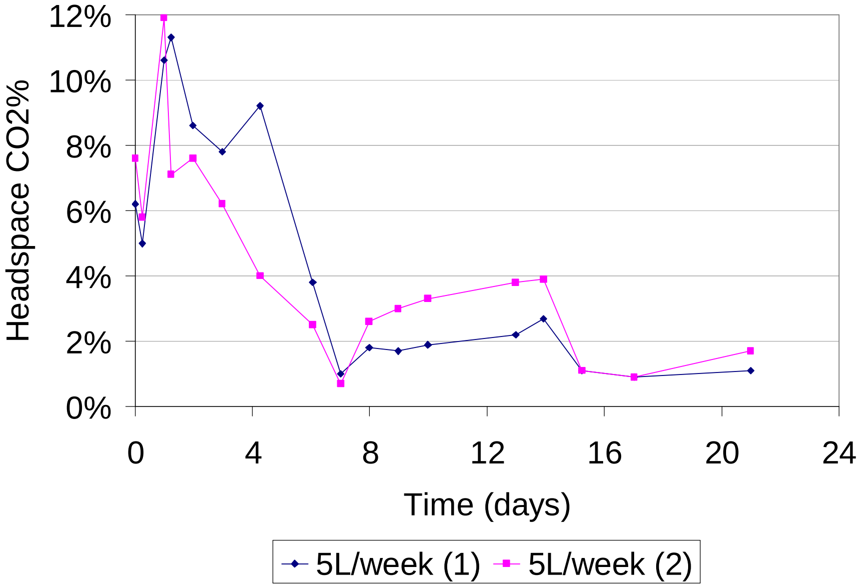
Experiment title	pH	Final Weight (Kg)	Moisture Content (%)	Volatile Solids (%)
1.5 L/min Grass (1)	8.0	7.0	40	80
1.5 L/min Grass (2)	8.0	7.1	46	72
1.5 L/min Grass + MGW (Higher C:N) (1)	7.8	17.6	51	67
1.5 L/min Grass + MGW (Higher C:N) (2)	8.0	16.9	52	65
1.5 L/min Grass+ MGW (Lower C:N) (1)	8.1	17.0	51	74
1.5 L/min Grass+ MGW (Lower C:N) (2)	8.2	17.5	57	77
1.5 L/min MGW (1)	7.8	23.8	46	64
1.5 L/min MGW (2)	8.0	23.3	49	59

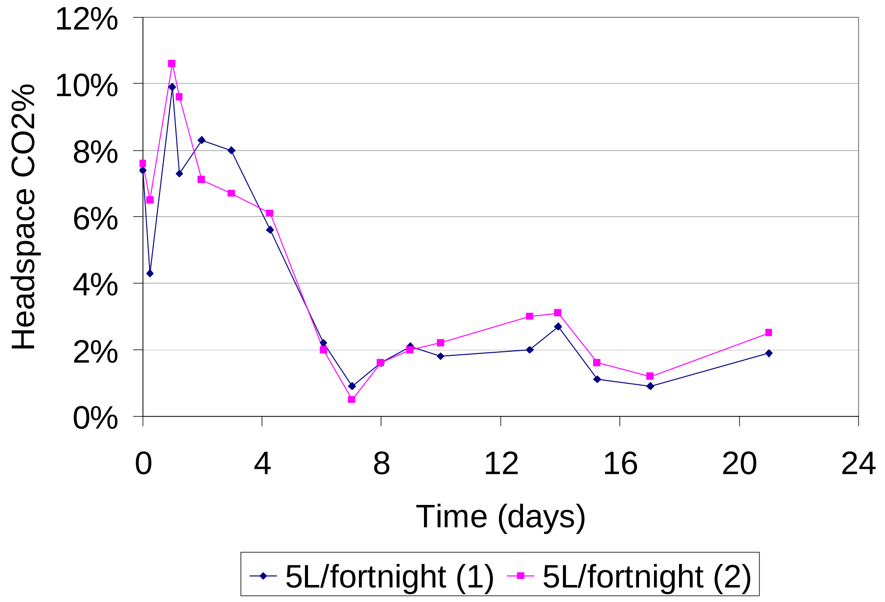
5.7. Water addition and activity time experiment

5.7.1. Headspace CO_2 concentration profiles

The CO_2 concentration profiles in Figure 48 show there was some variation between the different water addition treatments. The maximum concentration reached was between 8.5 for the 10L/week treatment and 11.9 for the 5L/week treatment. It can be seen that at 7 days, when water was added and the compost was turned, there was a rise in CO_2 emission. As this occurred in the 5L/fortnight and no water addition, which did not receive water at 7 days, this can be attributed to the turning process rather than water addition. The treatments with more water addition did reach higher CO_2 concentrations however, getting up to around 3-4%, but only 2% in the treatment without any water.







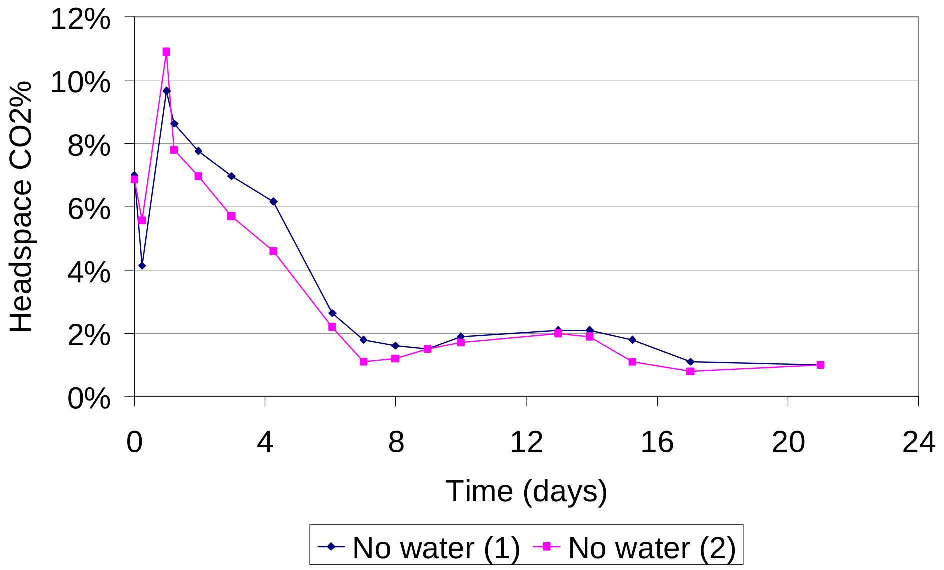


Figure 48: Water addition experiment CO_2 concentration profiles

5.7.2. Physical measurements

Water addition appears to have increased the production of CH_4 (see Table 47) with none detected when no water was added, but at least small amounts in all the other treatments and the highest recorded measurement in a standard H.C. bin of 280ppm in the 5L/week (1) system. This very high measurement in just one duplicate bin, may be a result of very specific conditions which are required for CH_4 production and can occur by chance if a high density, high moisture content pocket of compost exists which can become anaerobic (See section 6.9.1.) As would be expected, the measurements in Table 48 show that the moisture content of the composts with more water added were higher at 66% in the 10L/week treatment and only 55% in the no water treatment. The no water treatment also had a slightly higher pH of 7.1-7.2 compared to 6.6-6.8 in those with water added.

Table 47: Water addition and activity time experiment physical measurements (a)

Experiment title	Maximum CO_2 Conc. (%)	Maximum CH_4 conc. (ppm)
10L/week (1)	8.5	8
10L/week (2)	10.2	7
5L/week (1)	11.3	280
5L/week (2)	11.9	9
5L/14 days (1)	9.9	7
5L/14 days (2)	10.6	14
No water (1)	10.3	N.D.
No water (2)	11.3	N.D.

Table 48: Water addition and activity time experiment physical measurements (b)

Experiment title	pH	Final Weight (Kg)	M.C. (%)	V.S. (%)
10L/week (1)	6.6	10.8	66	52
10L/week (2)	6.6	10	65	49
5L/week (1)	6.8	11.3	65	54
5L/week (2)	6.7	10.1	63	45
5L/14 days (1)	6.6	9.7	56	56
5L/14 days (2)	6.7	9.8	55	54
No water (1)	7.1	9.7	54	56
No water (2)	7.2	10	55	52

5.8. Headspace volume experiment

The CO_2 concentration profiles in Figure 49 show how strongly the headspace volume influences the measurement, with much higher concentrations found with the smaller headspace volume throughout the experiments. The complex interaction of the gas transfer mechanism in the bins with the CO_2 emission rate is also demonstrated. During the peak emission in the first few days the concentration in the 40cm deep bin (small headspace) is 8-9% compared to 1-2% in the 70cm deep bin. In the later stage, however the difference is 1.1-1.3% compared to 0.1-0.2%. The influence of headspace volume is discussed in more detail in Section 6.3.

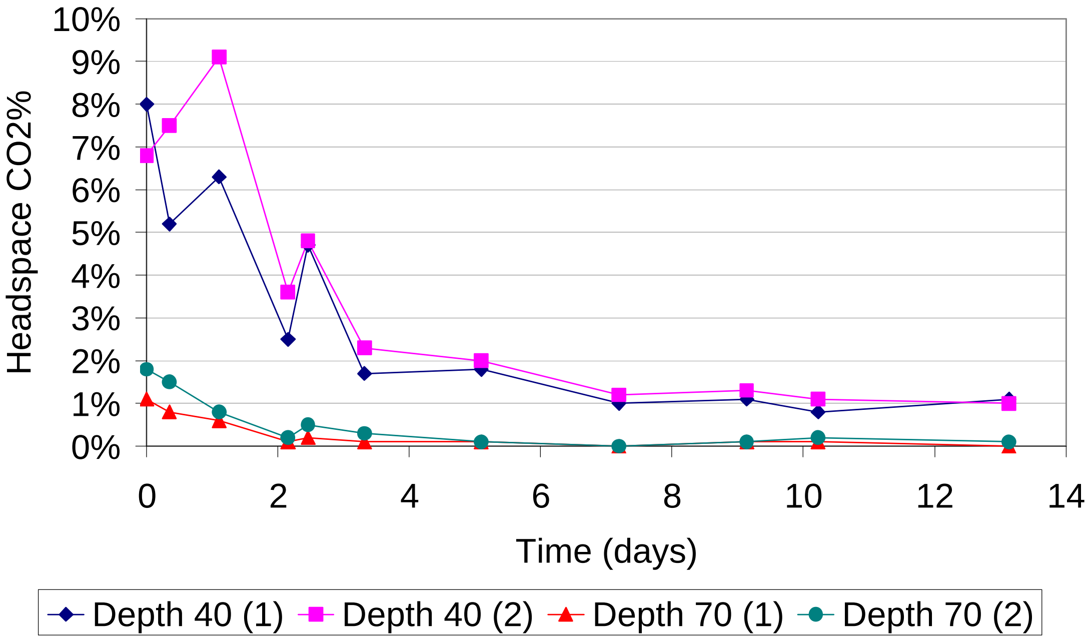


Figure 49: Headspace carbon dioxide concentration profiles of open compost bins with different headspace volumes

Table 49: Headspace volume experiment physical measurements

Experiment title	Depth 40 (1)	Depth 40 (2)	Depth 70 (1)	Depth 70 (2)
Maximum CO_2 concentration (%)	6.8	9.3	8.7	10.4
pH	7.4	7.4	7.4	7.4
Final Weight (Kg)	14.9	15.5	14.6	14.2
Moisture Content (%)	42	43	34	41
Volatile Solids (%)	64	66	68	59

5.9. Gas transfer experiment

The effects of sealing the various potential gas transfer routes on the headspace CO_2 concentration are shown in Figure 50. The results show that all the routes tested were important:

- Space between the bin and its lid;
- Space around the hatch;
- Space around the base as determined by the degree of contact with the ground – reduced with the barrel which weighs more

The fact that leaving an outlet with a very low resistance flow meter on an otherwise sealed bin did not enhance gas transfer and reduce the CO_2 concentrations has further implications on the type of gas exchange which is taking place. This is discussed in detail in Section 6.8.

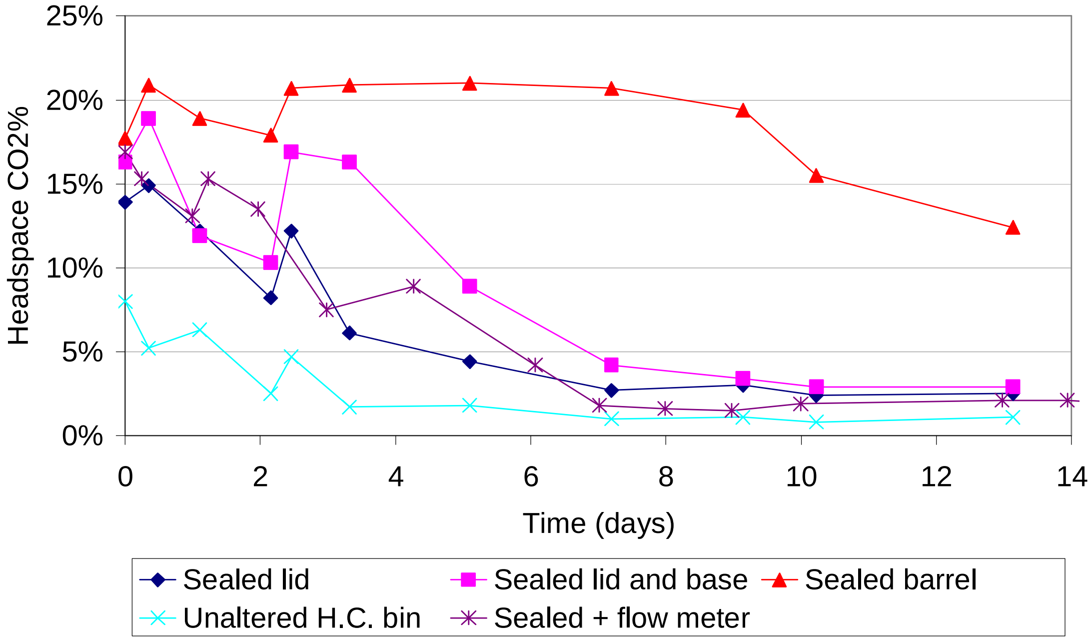


Figure 50: Headspace %CO_2 concentration profiles for differently sealed compost bins

5.9.1. Physical measurements

The increase in maximum CO_2 concentration with increasing restrictions on the gas transfer routes is shown in Table 50 with 8.6% in the unaltered bin and 18.9% with a sealed lid and hatch. This can be seen to have an effect on CH_4 production as 3 of the 4 differently sealed systems were found to have CH_4 concentrations significantly above the limits of detection, at 28 and 59ppm. The sealed system which maintained a very high CO_2 concentration for the duration of the experiment reached the highest single measurement of 460ppm CH_4.

Table 50: Average and maximum headspace %CO_2 concentrations in differently sealed H.C. bins

	Headspace %CO_2 concentration				
	Unaltered	Sealed lid	Sealed lid and base	Sealed +flow meter	Sealed barrel
Average	2.3	5.3	7.9	6.6	18.6
Maximum	8.6	14.9	18.9	16.6	20.9
	CH_4 concentration (ppm)				
Maximum	N.D.	28	N.D.	59	460

Table 51: Gas transfer experiment physical measurements

Experiment title	Unaltered H.C. bin	Sealed lid	Sealed lid and base	Sealed+flow meter (1)	Sealed+flow meter (2)
pH	7.4		7.2	7.1	7.2
Final Weight (Kg)	14.9	17.0	16.9	9.7	10.0
Moisture Content (%)	42	57	46	54	55
Volatile Solids (%)	64	64	59	56	52

5.10. Reactor flow rate experiment

5.10.1. Carbon dioxide concentration profiles

Figure 51 shows the CO_2 concentration profiles of the same grass only feed during composting in reactors with air flow rates of 0.5, 1.5, and 2.0 L/min. As would be expected, much higher CO_2 concentrations are found and maintained for longer with lower flow rates, the maximum in the 0.5L/min treatment was 18.9% compared to the lowest maximum of 7.3 % with 2.0L/min. It can be seen that the duplicates in the 0.5L/min treatment diverged quite significantly. This could have been due to problems with leachate water clogging the air inlet tubes in one of the duplicates, which has a greater effect at lower flow rates.

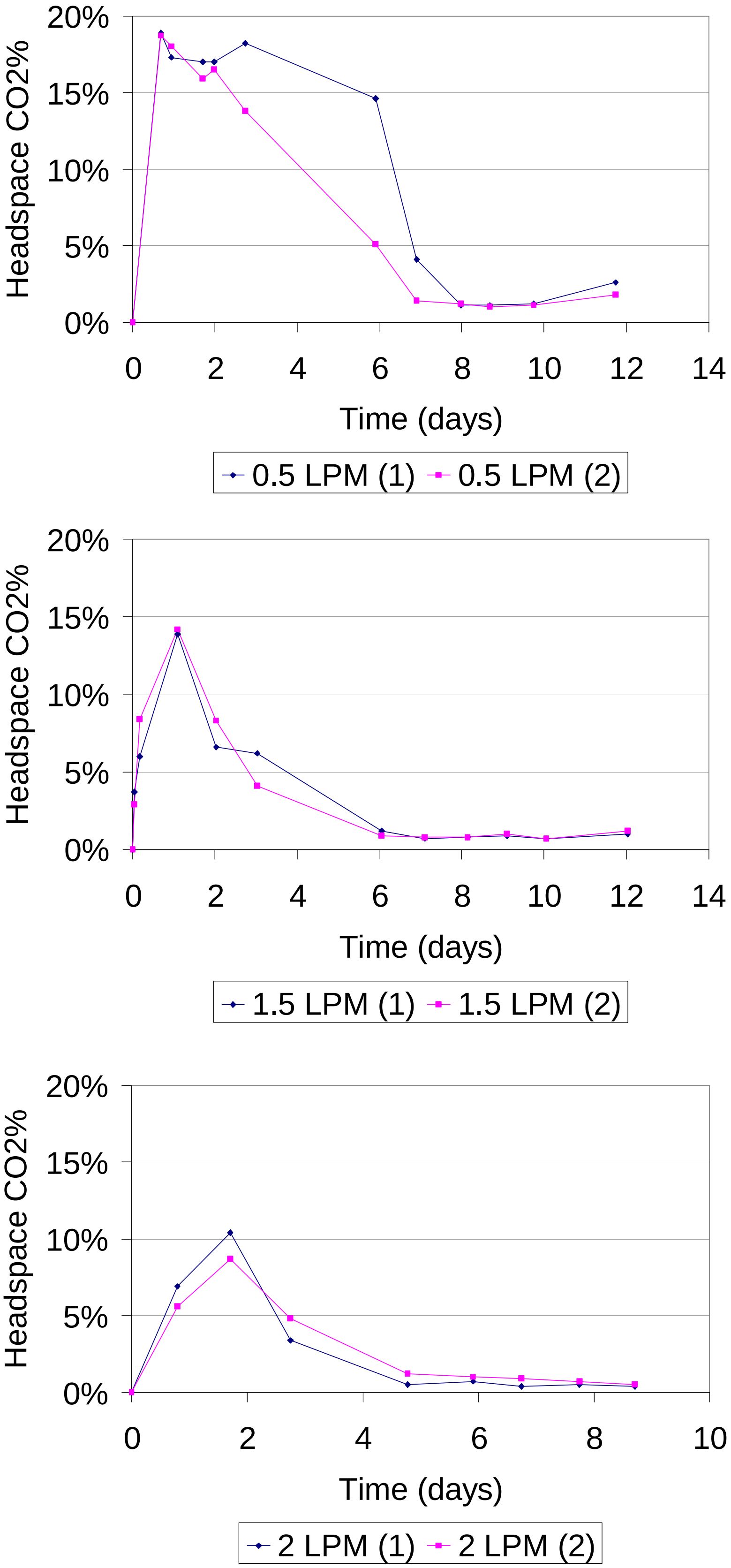
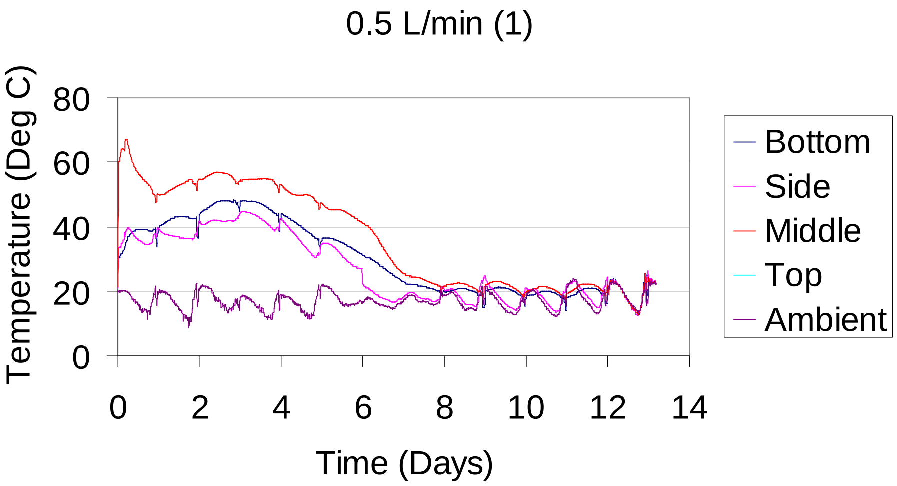
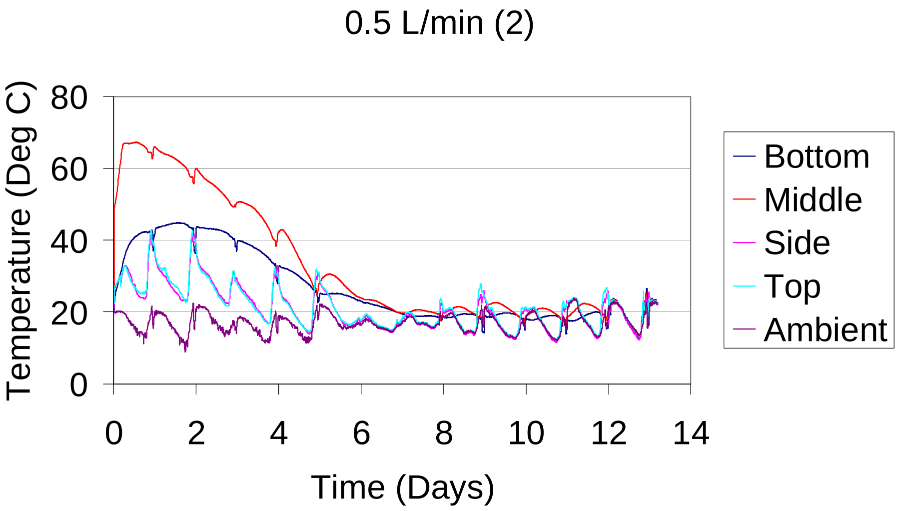


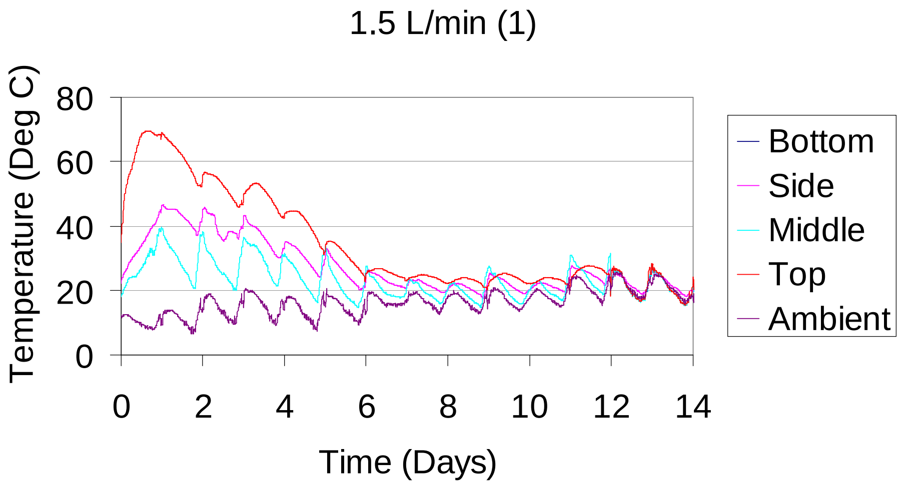
Figure 51: Reactor flow rate experiment CO_2 concentration profiles

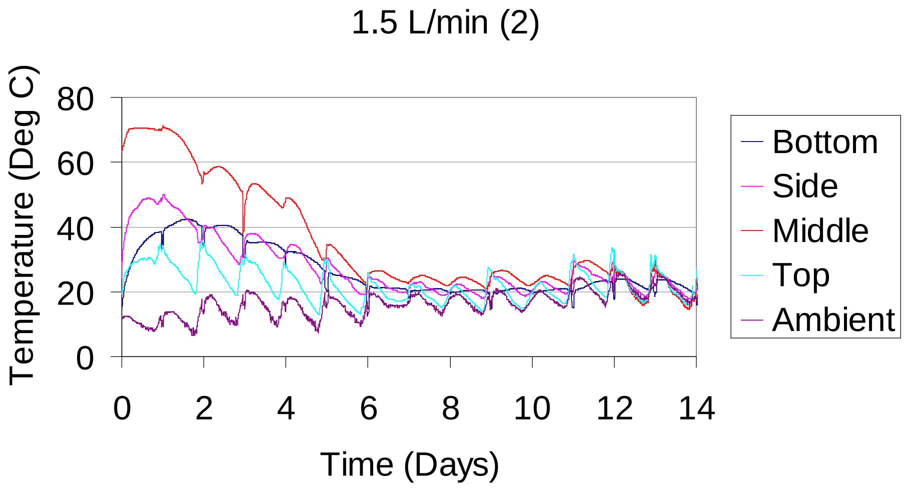
5.10.2. Temperature profiles

Figure 52 shows the temperature profiles of the different experiment treatments. As for the CO_2 results, the duplicate 0.5L/min treatments show quite different profiles. This could be further evidence of a mechanical problem with the gas flow rate in duplicate 1 as the kink in the profile after the first day could be due to a large reduction in air flow limiting the microbial activity and causing the two systems to diverge. The other feature that can be seen is that the 2.0L/min treatment reaches lower temperatures than the other unaltered systems. This could be caused by the higher air flow rate causing more heat loss from increased evaporation and input of colder air.






1.5 L/min (1)
Temperature (Deg C)
80
60
40
20
0
0
2
4
6
8
10
12
14
Time (Days)
Bottom
Side
Middle
Top
Ambient


1.5 L/min (2)
Temperature (Deg C)
80
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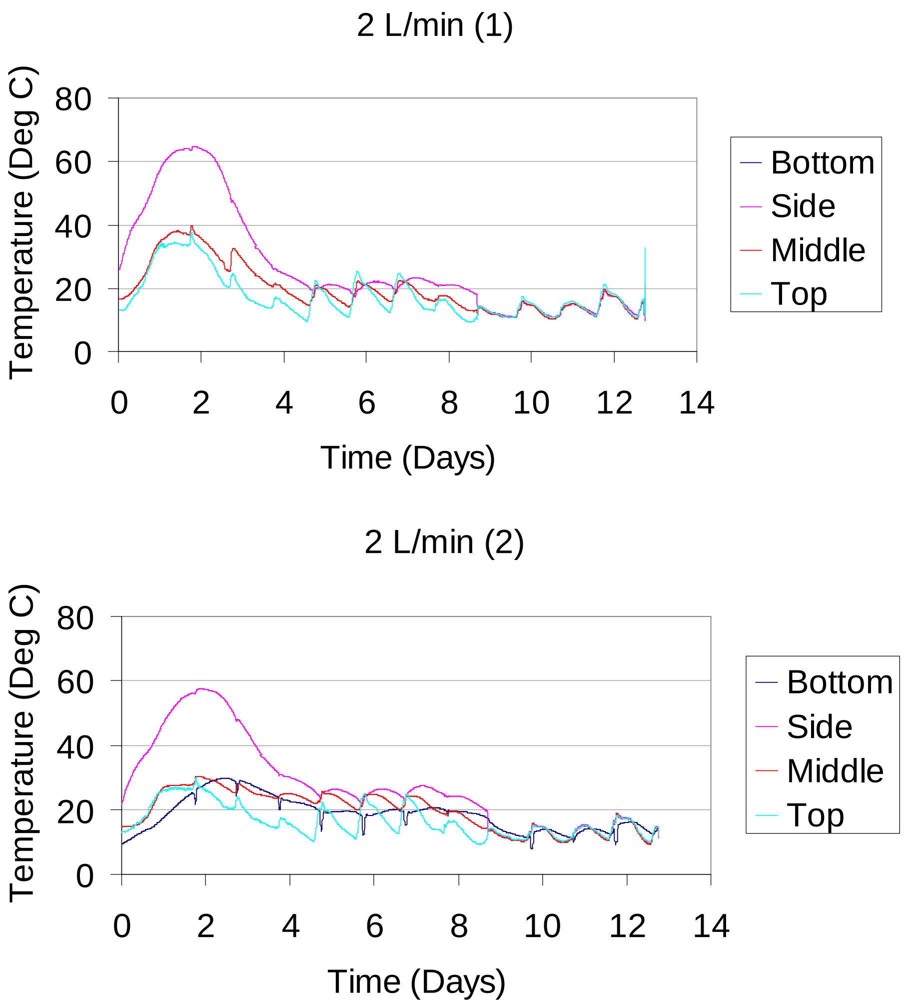

Figure 52: Reactor flow rate experiment temperature profiles

5.10.3. Physical measurements

The measurements in Table 52 reiterate the points discussed on CO_2 concentrations and temperature. It can also be seen that CH_4 was detected at a very low concentration in the 0.5L/min duplicate 1, which was the duplicate which may have had mechanical problems that reduced the inlet air flow. This would explain why anaerobic conditions were able to develop, and CH_4 was produced in this system but none of the others. The 2.0L/min treatment was found to have significantly higher moisture contents than the other treatments which can be explained by the lower temperatures that were reached and the reduced evaporation. This system also had a higher pH than the others, with 8.7-8.8 in the 2.0L/min treatment compared to 8.0-8.3 in the 0.5 and 1.5L/min treatments.

Table 52: Reactor flow rate experiment physical measurements

Experiment title	0.5 LPM (1)	0.5 LPM (2)	1.5 LPM (1)	1.5 LPM (2)	2 LPM (1)	2 LPM (2)
Maximum CO_2 concentration (%)	18.9	18.7	11.3	11.9	13.1	7.3
Maximum CH_4 concentration (ppm)	6	N.D.	N.D.	N.D.	N.D.	N.D.
Maximum Temperature (^oC)	67	67	69	71	65	57
pH	8.3	8.0	8.0	8.0	8.8	8.7
Final Weight (Kg)	6.7	7.3	7.0	7.1	7.2	7.3
Moisture Content (%)	41	38	40	46	68	65
Volatile Solids (%)	62	53	80	72	71	70
Gas flow rate (L/min)	0.5	0.5	1.5	1.5	2	2

6. Discussion

6.1. Comparison of reactor and compost bin systems

The experimental parameters of the reactor and H.C. bin experiments have been examined in order to ascertain if and how the different systems affected the composting processes taking place. The best experiments for comparison are those in which identical H.C. bin and reactor experiments were carried out in parallel. The three groups of suitable experiments are:

- Reactor flow rate experiment (Section 4.7.10)
- H.C. bin waste addition size experiment (Section 4.7.5)
- Cumulative feeding reactor and H.C. bin comparison experiment (Section 4.7.2)

The maximum CO_2 concentrations and temperatures reached as well as the properties of the finished composts from these experiments are illustrated for comparison in Figure 53 below. Looking at the maximum CO_2 concentrations, it can be seen that concentrations in the sealed reactors were always higher than in the open bins. Even at high flow rates of up to 2 Litres per minute, there was a maximum concentration of 9.6% CO_2 in the reactors but only 3.0% in the H.C. bins. This indicates that either the rate of gas exchange taking place in the H.C. bins was significantly higher than in the reactors or that the different systems caused differences in the composting processes. Regardless of the cause for this difference it is valuable to identify if there are other differences, potentially caused by the different gas compositions, to understand the validity of making comparisons between the two systems.

It can be seen in Figure 53 that there are some large differences in the other measured parameters as well. In most cases, however, the differences are within the standard deviations of the averaged measurements, as indicated by the raised bars. The most significant differences appear in the 10Kg grass feed experiments where the H.C. system had a 41% mass loss while the 3 duplicate reactors had 30, 29 and 27%. This is difficult to explain as it was not accompanied by corresponding differences in the moisture, volatile solids or carbon contents in which the 2 LPM reactors are actually very close to the H.C. bins.

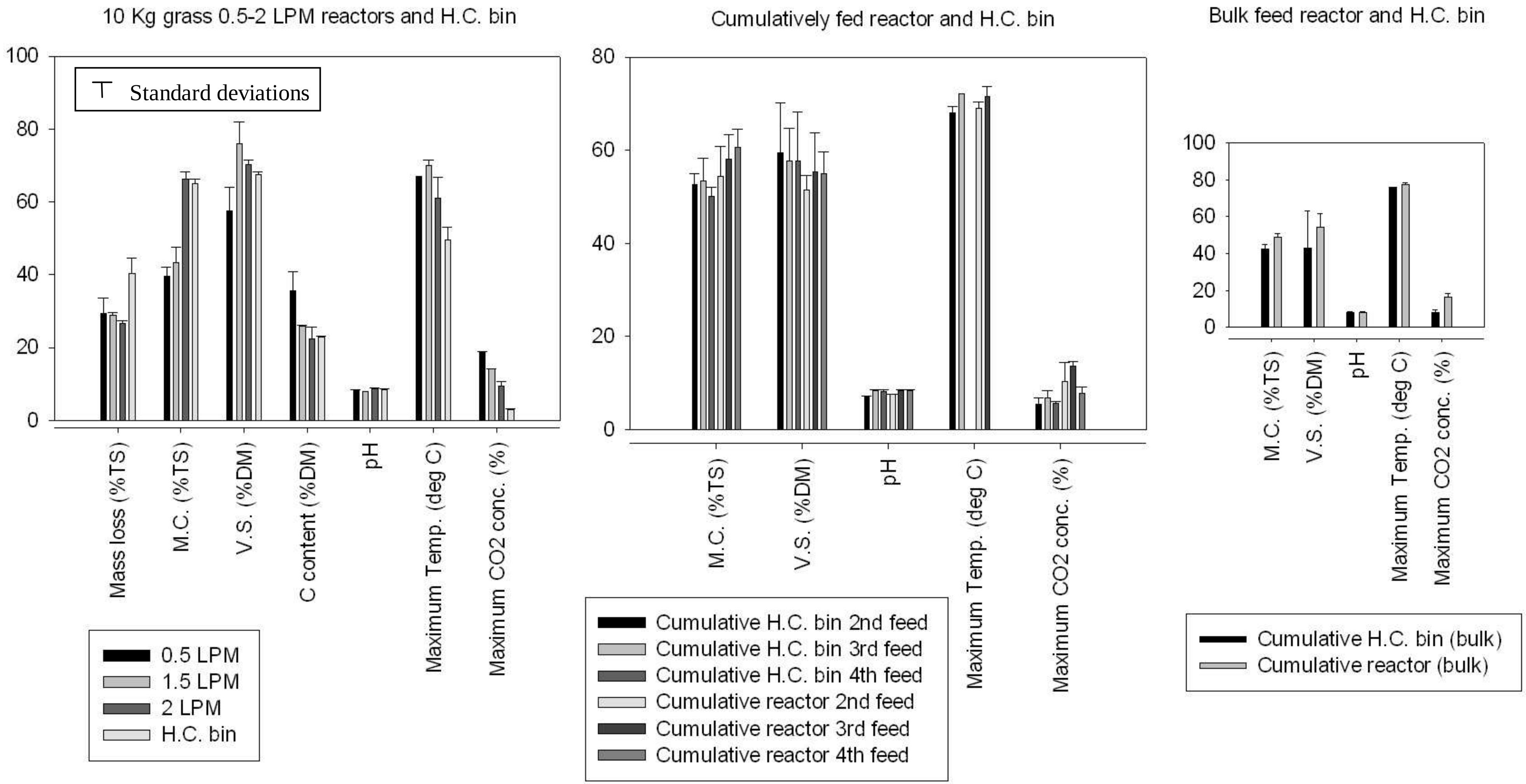

Figure 53: Comparison between Reactor and compost bin systems (bars indicate standard deviations)

The temperature profiles of the cumulative feed experiments, starting with the larger bulk feeds, are shown in Figure 33 and Figure 34 in Section 5.2.1. It can be seen that both systems follow the typical profiles, as discussed in Section 0, and reach very similar maximum temperatures of 77^{o}C and 76^{o}C. There does appear to be a difference in the rate at which the temperature falls between the two systems, with both H.C. systems dropping faster than the reactors in the first two peaks but not in the third. This could be related to a faster rate of gas exchange resulting in a faster intake of cooler air or due to the contact with the ground in the H.C. bins causing faster heat loss. By the third addition, which is the third peak, the larger volume of older material in the bin would reduce the impact of both these factors explaining why the effect is much less pronounced.

It is difficult to make confident conclusions as to the validity of comparisons between the two systems from this data due to the degree of variation within the individual experiments. The similarity between the temperature, M.C., V.S. and pH are encouraging as is the fact that, at least at higher air flow rates, the final parameters fall mostly within the experiment variations. It seems reasonable, therefore, to make use of the reactor system results in the analysis of H.C. systems but to ensure that the potential limitations are kept in mind when making the final conclusions.

6.2. Effects of home composting parameters

A number of different home composting parameters have been investigated experimentally during the project. In this section, the effects of varying these parameters on the composting process have been examined. The comparisons have been made between systems with minimal differences between them as much as possible. They are also mainly based on proportional differences, i.e. the proportion of input carbon lost, not just the total carbon lost. It was impossible, however, to perform enough experiments or account for all potentially relevant parameters and therefore only approximate comparisons can be made and this uncertainty should be kept in mind when interpreting the data. Another important point to note is that the comparisons can only be made for the first 14 days of composting as this is the time most of the experiments were run for. It was shown in Section 6.10 that this is the most active period of composting so the comparisons that can be made should still be relevant.

6.2.1. Compost feed composition

Figure 54 shows the affects of different feed compositions by grouping the experiments into categories based on whether their feedstock consisted of only food waste, grass, MGW or a mixture of grass and MGW. The properties of these feed materials are described in Appendix 4. The key observations are as follows:

- The food waste and MGW only categories consisted of one pair of duplicate reactors which can be seen in the very small error bars compared to the other categories which consisted of a larger number of different experiments. The large degree of variation within these categories reduces the accuracy of any conclusions that can be drawn.
- The materials are ordered in order of decreasing moisture contents and increasing C:N ratios. It can be seen that the materials with higher moisture contents and lower C:N ratios (those on the left) lost higher proportions of their mass, moisture contents and carbon contents. As discussed in Section 2.4, higher moisture contents and lower C:N ratios encourage more active composting, up to a point, although this is balanced with the quality of the finished product and the process emissions. Naturally materials with higher initial moisture contents will also have more moisture and mass as water that is readily lost.
- Except for the food waste category, higher maximum temperatures were observed with the lower C:N ratios. Again, this is because materials with a lower C:N ratio tend to be more readily compostable, leading to greater microbial activity and hence higher temperatures. The food waste maximum temperature was significantly lower than the other categories, due mainly to the much smaller feed size.
- Although there appears to be a trend for a fall in pH from left to right, the degree of variation is not significant with a range of only 7.9 to 8.2.

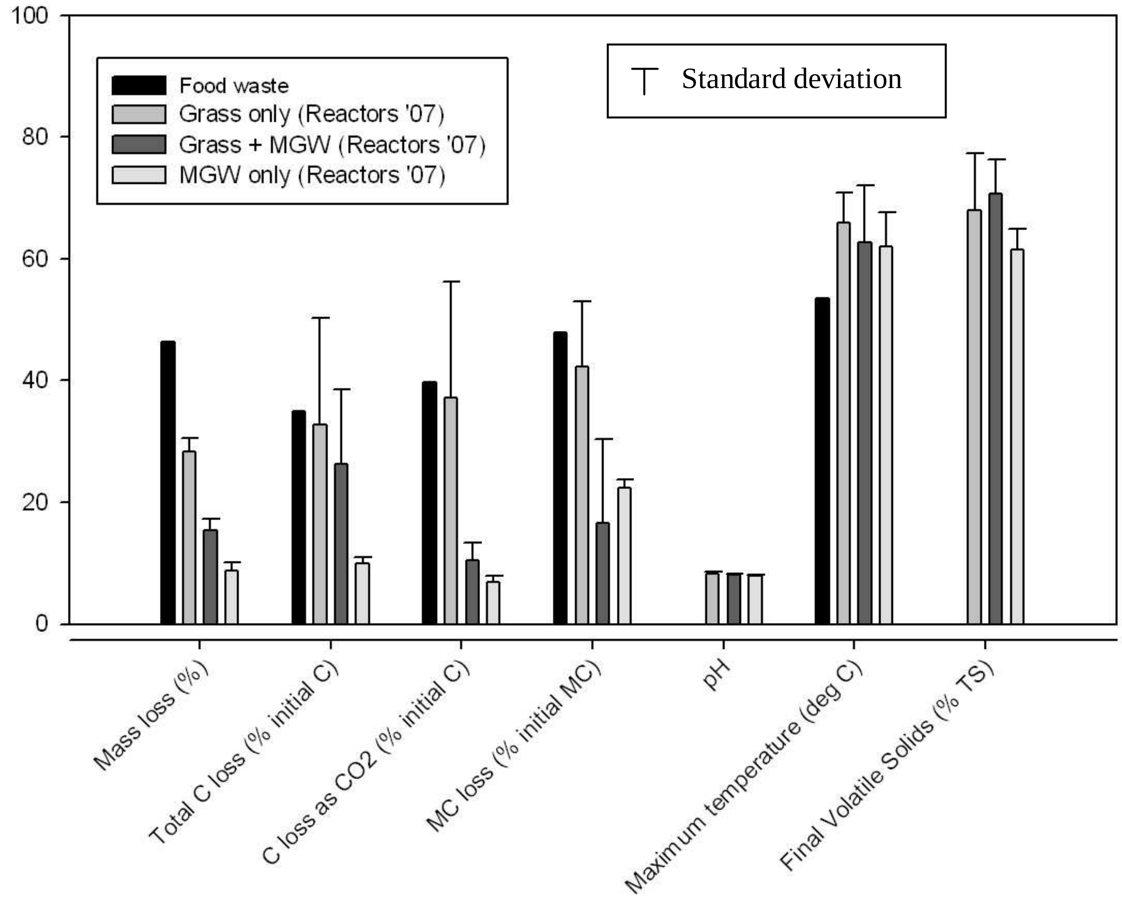

Figure 54: Effects of feed composition on composting parameters (bars indicate standard deviations)

6.2.2. Water addition

The results of an investigation into the effects of water addition (by the householder) are summarised in Figure 55. Four identical H.C. systems were run in duplicate with different additions of tap water at the start of the process and then on either weekly or fortnightly intervals:

- 10L water added weekly
- 5L water added weekly
- 5L water added fortnightly
- No water addition

The experiments are arranged within Figure 55 in order of decreasing water addition from left to right.

The key observations are as follows:

- The 10 L/wk and 5 L/wk experiments show lower mass losses than the other two experiments due to the greater mass of water held by the composts.
- The moisture losses were similar at additions of 5 L/wk and 5 L/fortnight but higher for 10 L/wk. This indicates that the compost was able to retain the greater volume of water added in the 5L/week compost compared to the 5 L/fortnight but not as much as was added at 10 L/week.
- The 10L/week and 5L/week showed significantly higher carbon losses as well as lower volatile solids contents compared to the other systems indicating greater degradation had occurred due to the added water.

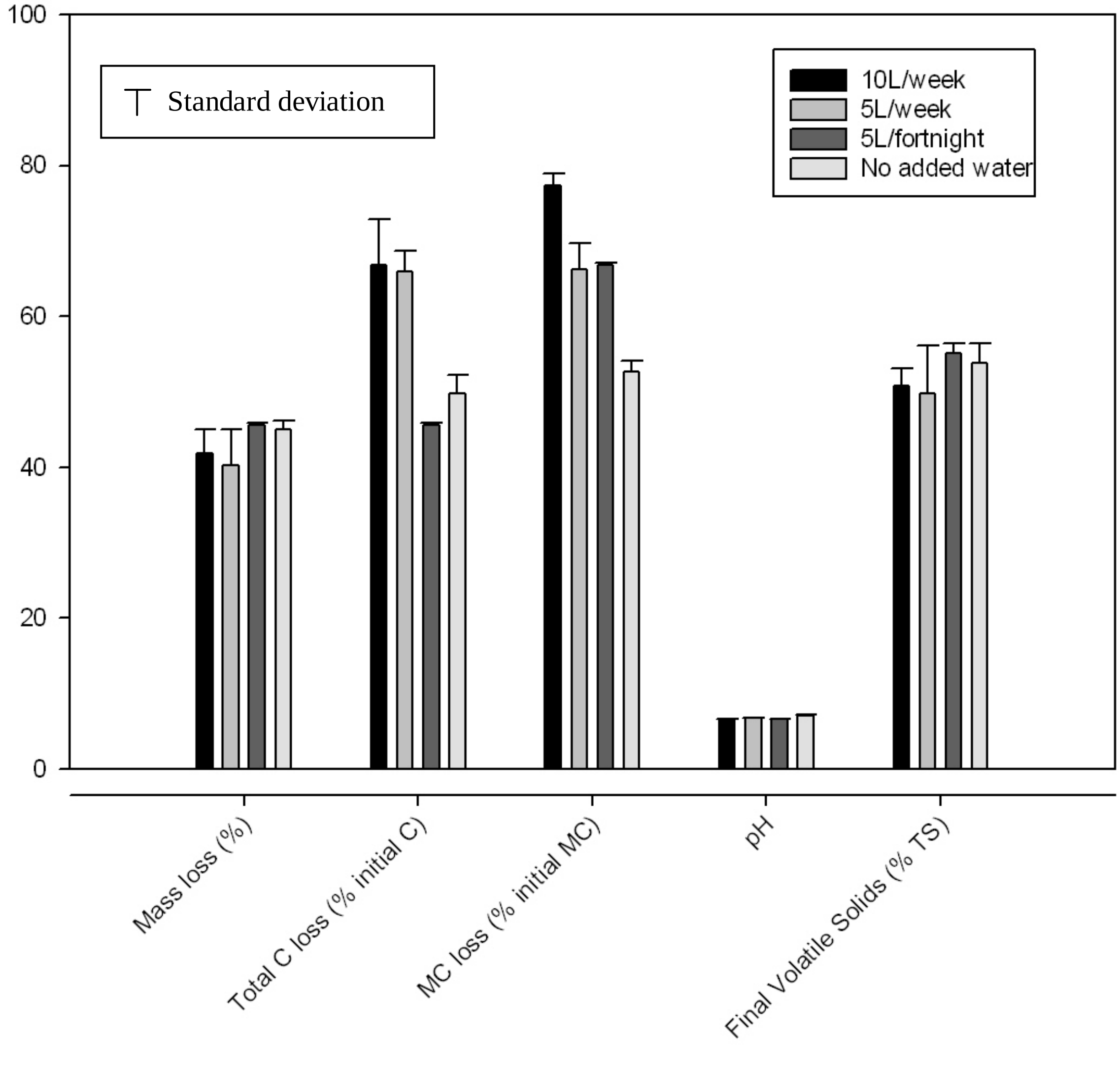

Figure 55: Effects of water addition on composting parameters (bars indicate standard deviations)

6.2.3. Feed addition size

In order to investigate the effects of the size of feed addition on the composting process, 10 duplicate experiments were repeated with at least a 50% increase in the feed size. The results of this investigation have been analysed by calculating the proportional difference of several key parameters between each linked pair of small and large feed experiments. So, for example, if an experiment had 20% mass loss with a small feed but a 40% mass loss when repeated with a larger feed, there would be a -50% difference. The advantage of this analysis is that it only compares experiments which are similar apart from in feed size but can then assess the overall difference between the small and large feed experiments. The mean and median of all the calculated proportional differences are illustrated in Figure 56. The key observations are as follows:

- There is very little difference in the mass lost with only very slightly more loss with smaller feeds.
- There are very large differences in the calculated total C losses and MC losses, although the standard deviations of these parameters are almost as large as the calculated values. The median values are also lower than the means indicating the true difference is likely to be smaller than indicated. Greater C losses could result from a smaller feed due to the improved aeration from reduced compaction and increase in outer surface area to total volume ratio. Lower MC losses in smaller feeds would most likely be related to lower temperatures and the effects on evaporation.
- The maximum temperature was 15% lower on average in the smaller feeds, although again there is a large standard deviation but the median is larger than the mean in this case. Higher temperatures would be caused by the greater microbiological activity in a larger mass of waste, which would enhance this activity leading to higher temperatures and rates of decomposition as is indicated by the higher total C losses in the larger feeds. Larger feeds would also lose less heat due to the reduced surface area to volume ratio but greater moisture content losses would remove more heat. Higher temperatures in the larger feeds also further explain their greater moisture content losses due to the enhanced evaporation.

- The pH was very slightly higher in the smaller feeds, but by an insignificantly small amount relative to the measurement error.

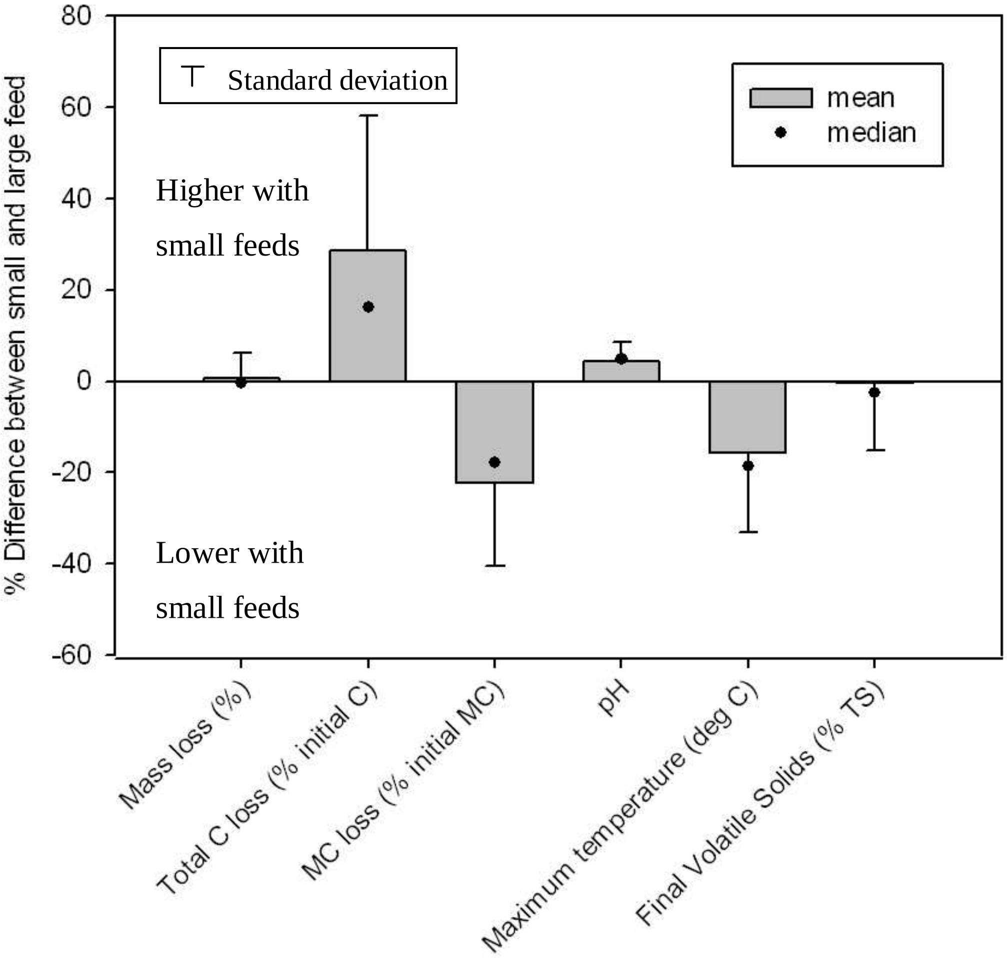

Figure 56: Proportional differences in key composting parameters caused by size of feed addition (bars indicate standard deviations)

6.3. Importance of headspace volume

The results of the headspace volume experiment in Figure 49 (Section 5.8) and summarised in Table 53 clearly show that a reduced headspace volume causes CO_2 measurements to be significantly higher with a maximum of 9.1% in a 40cm depth and only 1.8% in a 70cm depth. This result demonstrates the significant importance the headspace volume has when interpreting H.C. bin gas composition data.

Table 53: Average and maximum headspace %CO_2 concentrations in open compost bins with different headspace volumes

	Depth 40cm (1)	Depth 40cm (2)	Depth 70cm (1)	Depth 70cm (2)
Average headspace %CO_2 conc.	2.1	2.6	0.2	0.3
Maximum recorded %CO_2 conc.	8	9.1	1.1	1.8

6.4. Carbon dioxide concentrations in home compost bins: Overview

Due to the decomposition of compost material over time and the dynamic relationship between activity, temperature, moisture content and microbial population, the rate of emission of carbon dioxide is at its highest in the first days following a fresh feed addition. This is reflected in the carbon dioxide concentration profiles found in Chapter 5, which tend to rise quickly from an initially low concentration to peak after 1-2 days, after which they fall over another 1-2 days to a fairly stable lower concentration.

The concentrations of carbon dioxide detected in standard open bottomed compost bins over the 14 days following a fresh feed addition for a total of 75 individual additions are summarised in Table 54 and Figure 57 below. The results are split into the maximum, 3-day average and 14-day average concentrations in order to distinguish the different phases discussed above. As would be expected with the wide range of parameters used, there is significant variation across the experiments, as indicated by the relatively high standard deviations in Table 54 and the height of the box plots in Figure 57. The maximum detected value was extremely high at 17.2% CO_2. This occurred in the Large garden waste feed experiment (See Section 4.7.1) experiment after several previous feed additions, when there was almost no headspace volume remaining. The median of the maximum observed values was still relatively high, at 6.5% CO_2, with the 3 and 14 day values increasingly lower, at 4.7% and 2.2% respectively.

Table 54: Summary of headspace CO_2 concentrations in 14 days following a feed addition in H.C. bin experiments (n=75)

	Headspace CO_2 concentration, %		
	Maximum detected value	3-day average	14-day average
Median	6.5	4.7	2.2
Mean	6.9	5.2	2.3
Standard deviation	3.9	3.1	1.2
Range	0.9 - 17.2	0.5 - 12.8	0.1 - 6.6

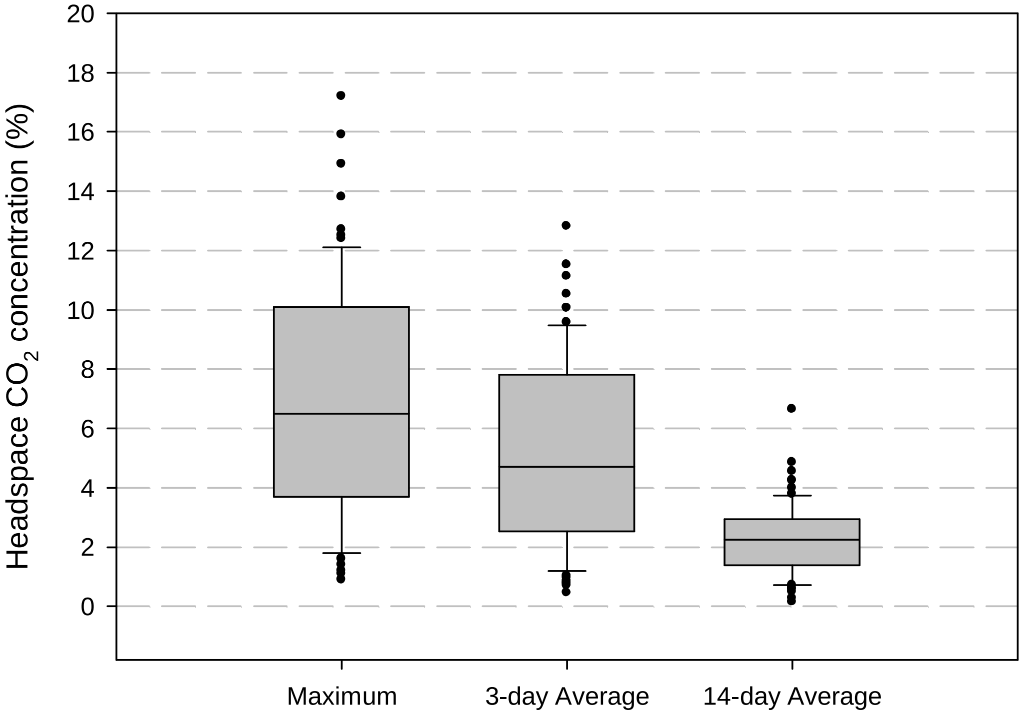

Figure 57: Box plots of maximum, 3-day average and 14-day average headspace CO_2 concentrations in 14 days following a feed addition in H.C. bin experiments (n=75)

As a large number of interrelated parameters influence the CO_2 concentration, its relationship with any individual parameter is complex and extremely difficult to analyse. Despite this fact, the simple linear correlation of CO_2 concentration with some of the potentially more significant factors was tested, including the size of the feed addition and the headspace volume. The headspace volume was calculated from the compost depth using the calculation in Appendix 6. The calculated correlation coefficients, and the strengths of the relationships, as indicated by r^2, are shown in Table 55. The plotted data using the maximum CO_2 concentration is shown in Figures 58 to 61. A positive linear correlation was observed, as anticipated, with larger feed additions leading to greater CO_2 emissions and headspace concentrations. The large range of experimental conditions and their complex interaction, however, means the strength of the linear relationships is very low, with values of r^2 at or below 0.1. It can be seen that more positive correlation exists with the maximum, followed by the 3-day average values. For example, the total feed addition correlation for the maximum, 3 and 14 day average concentrations is 0.21, 0.19 and 0.08 respectively. This is unsurprising considering that over 14 days the CO_2 concentration tends towards a similar low value, whatever the initial conditions. The results in Table 55 also show that there is a more positive correlation if the grass addition is considered individually, which has a value of 0.36, when compared to the total or individual MGW feeds, which have values of 0.21 and 0.23. The r^2 value is also higher for the grass addition at 0.13, compared to 0.04 and 0.05. This difference can be explained by the fact that the grass component is the most readily compostable, and therefore the dominant contributor to CO_2 emission. It was thought that taking account of the headspace volume would increase the correlation, but the results show there is actually little difference. The correlation with the maximum concentrations has a similar value of 0.23, although the 3-day average value is slightly higher at 0.3 compared to 0.19 without accounting for the headspace volume.

Table 55: Comparison of correlation coefficient for CO_2 concentration versus Feed additions and Total feed addition / Headspace volume

Correlated parameter	CO_2 concentration	Correlation coefficient, r	Coefficient of determination, r^2	P-value
Total feed addition (Kg)	Maximum	0.21	0.04	0.519
	3-day average	0.19	0.04	0.082
	14-day average	0.08	0.01	0.103
Grass only addition (Kg)	Maximum	0.36	0.13	0.038
	3-day average	0.26	0.07	0.003
	14-day average	0.25	0.06	0.028
MGW only addition (Kg)	Maximum	0.23	0.05	0.304
	3-day average	0.19	0.03	0.054
	14-day average	0.12	0.01	0.115
Total feed addition / Headspace volume (Kg/L)	Maximum	0.23	0.05	0.296
	3-day average	0.30	0.09	0.054
	14-day average	0.11	0.01	0.019

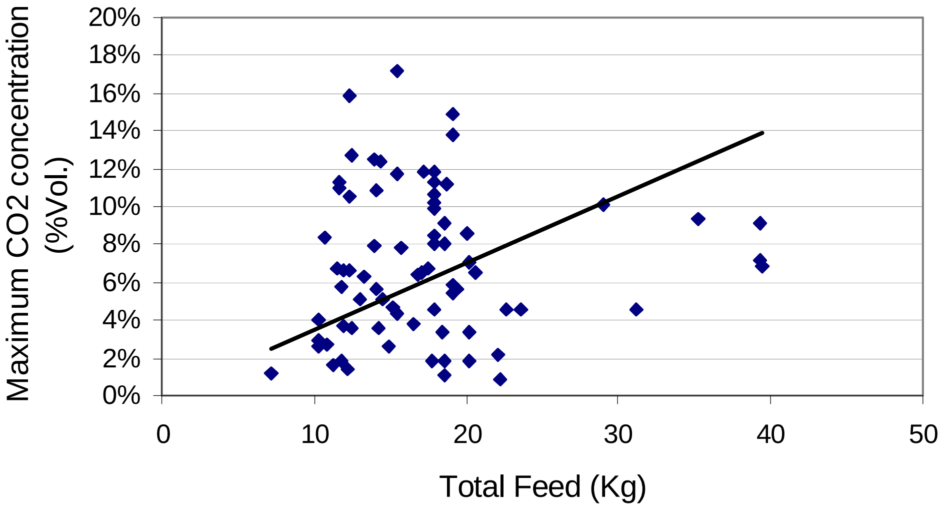

Figure 58: Maximum CO_2 concentration versus Total feed addition

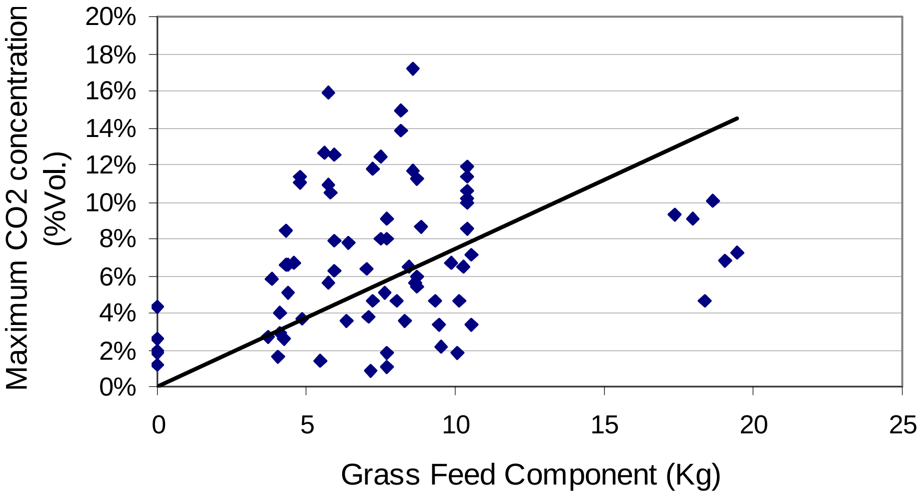

Figure 59: Maximum CO_2 concentration versus Grass feed component

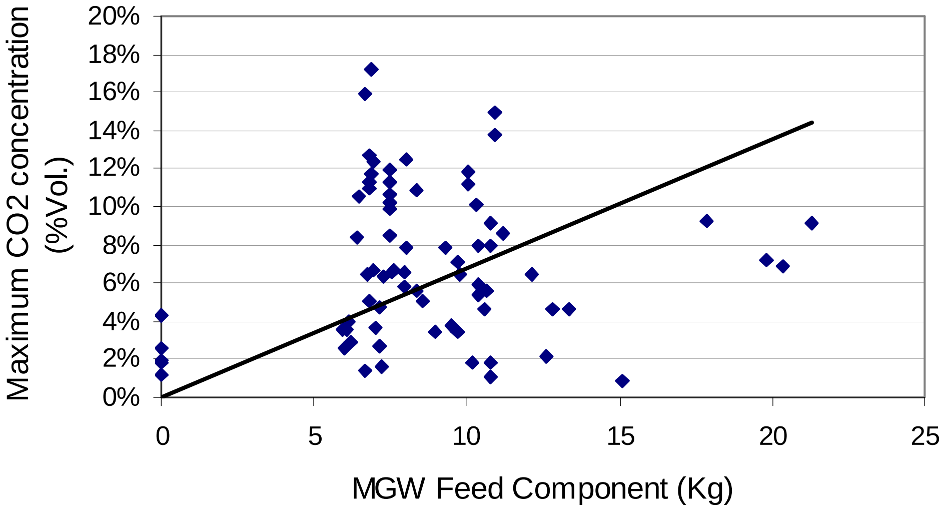

Figure 60: Maximum CO_2 concentration versus MGW feed component

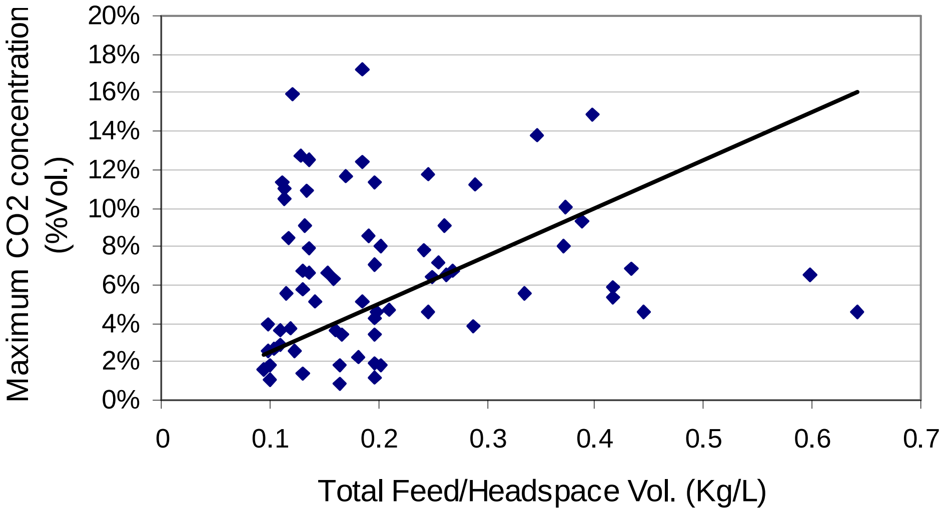

Figure 61: Maximum CO_2 concentration versus Total feed divided by the headspace volume

6.5. Compost temperatures during home composting: Overview

The temperature profiles found in Chapter 5 show very similar characteristics to the CO_2 concentration profiles, except for the influence of the ambient temperature, which can cause matching compost temperature fluctuations, particularly at lower compost temperatures. The average and range of temperatures, measured for a total of 75 individual additions, are summarised in Table 56 and Figure 62, split into the maximum, 3-day average and 14-day average values. As for the CO_2 concentrations, discussed previously in Section 6.4, there are large ranges and standard deviations due to the variety of conditions tested. The absolute maximum value observed was 74^{o}C, and the average maximum 51^{o}C. The average 3 and 14 day averages were 40^{o}C and 28^{o}C respectively. The linear correlations between the maximum and average temperatures and the feed addition mass are shown in Table 57. Due to the lower number of parameters involved, when compared to the CO_2 concentration, the correlation is substantially more positive, with an r value of 0.59 for the maximum temperature, compared to only 0.21 for maximum CO_2 concentration. Although still not highly significant, the strength of the correlation is also much higher for the maximum temperature, at 0.34, compared to 0.04 for CO_2 concentration.

Table 56: Summary of temperatures detected throughout all conducted composting experiments

	Temperature, ^{o}C		
	Maximum detected value	3-day average	14-day average
Average	51	40	28
Standard deviation	17	15	8
Range	14-74	9 – 71	10 - 53

Table 57: Linear correlation of temperature (^{o}C) with total feed addition mass (Kg) (n=75)

	Temperature versus total feed addition		
	Correlation coefficient, r	Coefficient of determination, r^2	P-values
Maximum	0.59	0.34	0.16
3-day average	0.44	0.19	0.60
14-day average	0.24	0.06	0.25

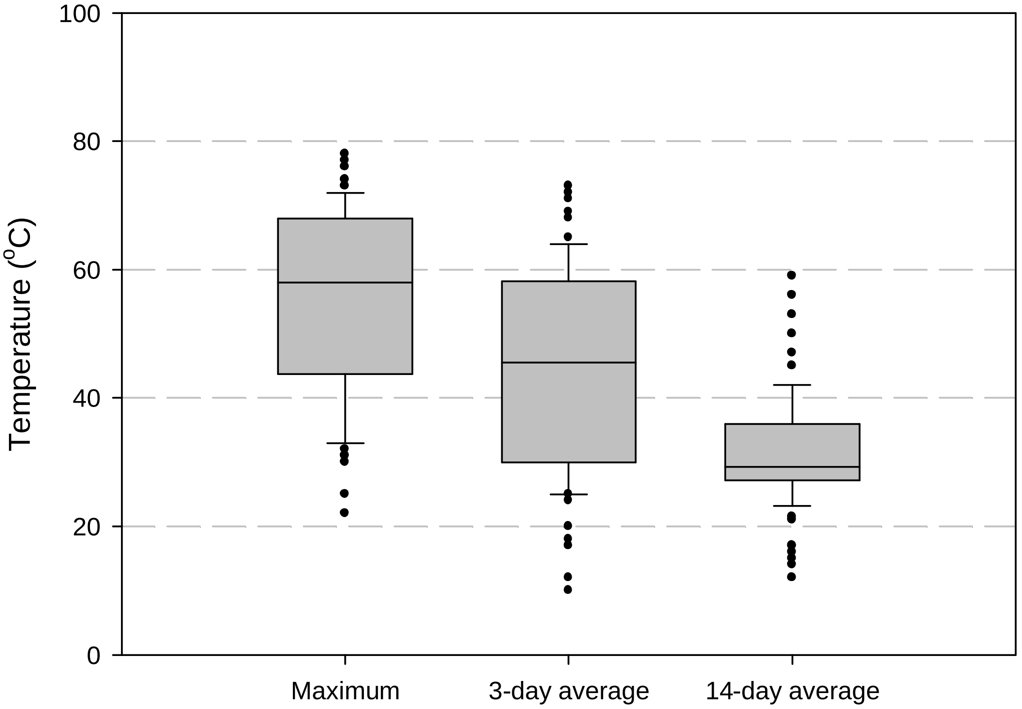

Figure 62: Box plots of maximum, 3-day average and 14-day average compost temperatures

6.6. Leachate production

The daily volume of leachate collected from each composting reactor is shown in Figure 63. The values given are the average volumes from duplicate bins. No leachate was collected for the first 28 days after starting the reactors, presumably due to the mature compost present at the bottom of the reactors, which the leachate took time to drain through and more significantly absorbed any leachate produced until it was fully saturated. The time needed for the leachate to drain through the mature material after saturation is indicated by the 1-2 day delay between a rise in leachate production and a feed addition. The total leachate produced for each fortnightly feed addition was assumed to be equal to the volume emitted from the start of the first peak following feeding to just before the next. The total leachate productions and measured parameters are indicated alongside their corresponding feed compositions in Table 58. As would be expected the feed materials with higher moisture contents showed the greatest leachate production, with a high of 0.45 L/Kg for food waste down to 0.04 L/Kg for MGW. Total solids were at only 1-2% for all the feeds and the total carbon in the liquid fraction was between 230-440 mg/L. The leachate pH ranges from the different feeds were quite similar at between 7.1 and 8.2 so either neutral or slightly alkaline.

Table 58: Total leachate production and properties for a range of feed additions

Figure 63 reference	Compost feed	Production (L/Kg waste)	Total Solids (%)	pH range	Total carbon (mg/L)
1	9.9 Kg grass	0.20	1.2	7.2 – 7.7	230
2	9.5 Kg grass + 11.0 Kg MGW	0.09	1.1	7.1-8.2	240
3	10.5Kg grass + 9.7 Kg MGW	0.09	1.3	7.1-7.5	220
4	5.5 Kg food waste	0.45	1.7	7.4 – 7.7	310
5	25.8Kg MGW	0.04	2.0	7.2-7.8	440
6	2 week old 9.5 Kg grass + 11.0 Kg MGW	0.02	1.1	7.3-7.5	380

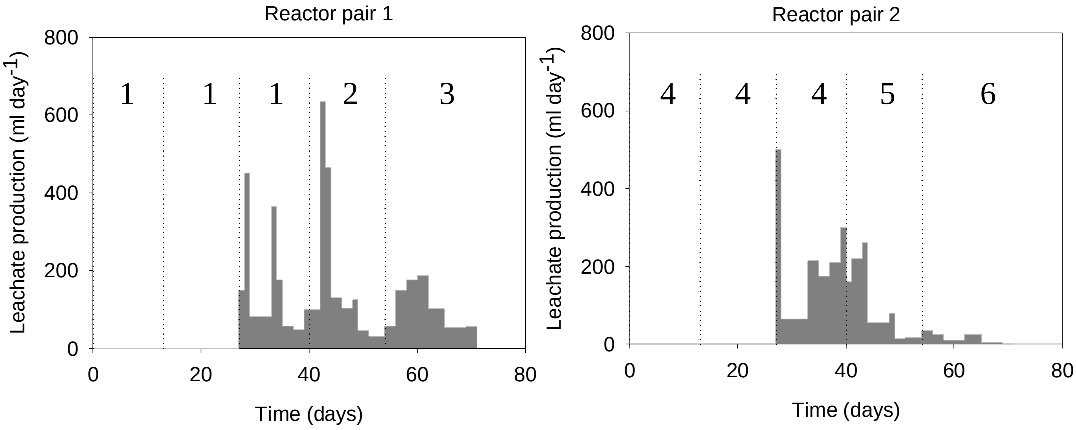

Figure 63: Time averaged daily leachate production (Feed additions indicated by dashed lines, numbers 1-6 refer to feed compositions in Table 58)

6.7. Compost quality

Final composts from the cumulative feeding H.C. bin experiment (Section 4.7.1): Large feed garden waste, Garden waste Low C:N and Garden + kitchen waste bins were analysed for water extractable nutrients and potentially toxic elements as an indicator of the quality of home produced composts. Analysis was carried out by an external laboratory approved by the Composting Association for conducting PAS 100 analysis. Table 59 shows the results of the water extractable nutrients analysis and Table 60 the potentially toxic elements compared to the PAS 100 limits. All the tested composts have lower concentrations of potentially toxic elements than required by the PAS 100 standards. This analysis and the concentrations of water extractable nutrients confirm previous work that show home produced composts are safe and beneficial as soil improvers (Wheeler 2003; Smith et al. 2004). Plant growth tests performed by Smith and Jasim (2004) found several home composts performed better than tested commercial products.

Table 59: Water extractable nutrients in three tested composts

	Mass of extractable nutrient in Dry Matter (mg/kg)		
Parameter	High load	Low C:N ratio	With kitchen waste
Phosphorus as P	248	325	448
Potassium as K	4513	6712	7600
Calcium as Ca	355	398	347
Magnesium as Mg	53	57	55
Sulphur as S	319	568	508
Boron as B	4.0	4.6	5.0
Copper as Cu	0.4	0.5	0.5
Iron as Fe	23	26	26
Manganese as Mn	8.4	6.2	5.5
Molybdenum as Mo	0.2	0.4	0.5
Zinc as Zn	9.3	10.3	10.6
Sodium as Na	559	687	755

Table 60: Potentially toxic elements in three tested composts

	Element mass in dry matter (mg/kg)			
Parameter	High load	Low C:N ratio	With kitchen waste	PAS 100 upper limit
Cadmium as Cd	0.7	0.6	0.6	1.5
Chromium as Cr	12	8.8	11	100
Copper as Cu	47	36	37	200
Lead as Pb	93	69	82	200
Mercury as Hg **- less than**	0.5	0.5	0.5	1
Molybdenum as Mo	2.5	2.1	3.3	N/A
Nickel as Ni	8.4	5.8	7.8	50
Zinc as Zn	164	170	152	400

6.8. Gas exchange mechanisms in home compost bins

As discussed in Section 2.12, understanding the gas exchange mechanisms taking place in home composting systems would be an important step towards quantifying emitted gases. In this section, experimental data that provides insights into this area have been analysed and the conclusions and implications discussed.

The primary mechanism for gas exchange from home composting systems was thought to be bulk convective flow, with air drawn in at the base and exiting through the top (See Section 2.12). With this in mind, sealed composting reactor experiments were conducted with air pumped in at the base and allowed to exit at the top as described in Section 3.1.2. If the initial premise were correct, it was hoped it would be possible to identify the rate of gas exchange in open bottomed H.C. bins by identifying the air flow rate in sealed reactors at which the process parameters of the two systems were the most similar.

The relevant experiments carried out to enable these comparisons were:

- Cumulative feeding reactor and H.C. bin comparison experiment (4.7.2)
- H.C. bin waste addition size experiment (4.7.5)
- Reactor flow rate experiment (4.7.10)

The key results, reported as averages of the duplicate experiment pairs are summarised in the Tables 61-63 below.

Table 61: Comparison between CO_2 concentrations in reactor and compost bin experiments

Cumulative feeding reactor and H.C. bin comparison experiment	H.C bin maximum CO_2 concentration (%)	Reactor maximum CO_2 concentration (%)
(1st Large feed)	16.2	8.2
(Average across 4 smaller feeds)	10.5	6.0

Table 62: CO_2 concentrations in Reactor experiments fed 9.9Kg grass

Air flow rate, L/min	Reactor maximum CO_2 concentration (%)
0.5	18.8
1.5	14.1
2.0	9.6

Table 63: CO_2 concentrations in H.C. bin experiments

Waste input, Kg grass	H.C bin maximum CO_2 concentration (%)
9.9 Kg	3.0
15.7 Kg	3.0
24.1 Kg	3.8

Looking at the maximum CO_2 concentrations, it can be seen that concentrations in the sealed reactors were two or even three times higher than in the H.C. bins. Even at a high flow rate of 2 Litres per minute, the CO_2 concentration was 9.6% compared to only 3.0% in the equivalent H.C. bin. There are several possible explanations for this:

1. The composting processes taking place in the two systems are substantially different causing dramatically different rates of production of CO_2. The composting parameters of the two systems have been closely compared in Section 6.1. Although process differences were observed between the systems, it was concluded they were not to the extent to cause significant differences in CO_2 production.
2. Different headspace volumes between the two systems caused the headspace gas concentrations to be different. The significance of this factor is discussed in Section 6.3 but as the initial material depth in both systems was kept approximately the same this factor is not likely to have caused the large differences observed.

3. The convection driven rate of gas exchange from the H.C. bins was significantly higher than the flow rates used in the sealed reactors. While higher convection driven flow rates are possible according to theoretical models (See Section 2.13.3) they do not match experiment observations. The exiting gases from the reactor outlets were easily observable from the physical sensation of gas flow and droplets of moisture spitting outwards. Although the gas outlet route from H.C. bins would be the space between the lid and bin rather than a single outlet it seems unlikely that there would be no noticeable signs of such a high rate of gas flow.
4. The rate of air exchange from the H.C. bins was significantly higher than the in the sealed reactors but was by primarily by the mechanism of molecular diffusion rather than convective flow.

To gain further evidence for which of the above explanations was correct, an experiment was carried out in order to gain a greater understanding of the gas transport pathways through the H.C. bins (Section 4.7.9). The importance of each potential gas outlet in the bins was tested by sealing them to prevent any gas transport and observing the effect on the headspace CO_2 concentration.

The results can be seen in Section 5.9 in the carbon dioxide concentration profiles in Figure 50 and the average and maximum concentrations in Table 50. It is readily apparent that, despite its small area, the space between the lid and bin is an important gas transport route in home compost bins of this nature as is the space created around the bin hatch. While this was not unexpected, these results are interesting as they give a quantitative indication of the importance of the pathways. The average CO_2 concentration was more than doubled by sealing the lid and more than tripled by sealing the base as well. The fact that the sealed barrel produced even higher concentrations indicates that the closer contact with the ground caused a further reduction in gas transport, reducing it to near zero, based on the time it took for the concentration to fall below the maximum possible of 20.9%. It could, therefore be assumed that gas transport at the base also plays a significant role in gas transport in H.C. bins, though presumably not as significant as when the other openings are sealed. Based on the apparent affect of sealing the bin lid area, if bulk convective flow were a significant transport mechanism, it would be expected that some flow would be detected through the flow meter of the third system tested. Despite the relatively low detection limits of the meter, however, at under 0.4 Litres per minute, there was no flow detected at any time. This is very strong evidence that molecular diffusion is the dominant gas transport mechanism in home compost bins.

To summarise, the primary conclusions from this data are that:

- Small openings around compost bin hatches or other openings present in different models, as well as around the base do play a role in gas transport.
- Molecular diffusion is the dominant gas transport mechanism

These conclusions have strong implications for the methodology used to quantify the gas emissions from gas concentration data (See section 2.12).

In order to check this conclusion theoretically, a simple numerical model has been used to investigate whether diffusion is able to account for the observed rates of mass transfer. The simplified model is based on a constant rate of diffusion of CO_2 through a stagnant layer of air at the interface between the headspace gases and ambient air. This assumes that there is no bulk movement of air into or out of the bin and therefore the layer of air at the interface is stagnant. The air flow experiments discussed previously found no evidence of bulk gas flow taking place but did not rule it out entirely. The model can therefore at best be used as an order of magnitude indicator of the contribution of diffusion to the mass transfer of CO_2 from H.C. bins and not for making accurate predictions. If the subscripts 1 and 2 refer to the two sides of the stagnant layer and the subscripts A and B refer to CO_2 and air respectively, then the rate of diffusion through a stagnant layer is given by Equation 8 (Coulson et al. 1999).

$$N_A = -\frac{D}{RTx}\left(P / P_{BM}\right)\left(P_{A2} - P_{A1}\right)$$

Equation 8

Where,

N_A = Molar flux of CO_2, kmol/m^2s

D = Diffusivity of CO_2 in air, m^2/s

T = Temperature, K

P = Pressure, kN/m^2

P_{A1} = Partial pressure of CO_2 in headspace, kNm^{-2}

P_{A2} = Partial pressure of CO_2 in ambient air, kN/m^2

x = stagnant layer of air thickness, m

P_{BM} = Logarithmic mean value of $P_{B,}$

The use of this equation in determining the rate of diffusion through a circular interface around a H.C. bin lid in Kg CO_2/s is described in detail in Appendix 8. Three key parameters in the model whose values are either uncertain or variable were shown to be:

- The thickness of the stagnant layer of air (<1mm)
- The concentration of CO_2 in the H.C. bin headspace (<15%)
- The width of the gas interface area around the circumference of the bin (<1mm)

The actual rate of CO_2 emission can be calculated for the reactor system experiments using the method described in Appendix 7. The average rate of CO_2 emission over the first 14 days of composting and the maximum rate for the first 24 hours calculated for the reactor experiments are shown in Table 64 and Table 65. It can be seen that the maximum rate of emission in the first 24 hours was 0.54 Kg CO_2/day and 0.18 Kg CO_2/day averaged over the first 14 days.

Table 64: Average rate of CO_2 emission calculated from composting reactors

Experiment title	Average rate of CO_2 emission over first 14 days (Kg CO_2 / day)	Standard deviation
0.5 LPM	0.09	0.02
1.5 LPM	0.13	0.03
2 LPM	0.18	0.06
1.5 LPM Grass + MGW	0.07	0.02
1.5 LPM Grass + MGW	0.12	0.04
1.5 LPM MGW	0.08	0.01
Food waste	0.09	0.01

Table 65: Maximum rate of CO_2 emission during first 24 hours from composting reactors

Experiment title	Average rate of CO_2 emission over first 24 hours (Kg CO_2 / day)	Standard deviation
0.5 LPM	0.25	0.00
1.5 LPM	0.46	0.02
2 LPM	0.54	0.22
1.5 LPM Grass + MGW	0.26	0.06
1.5 LPM Grass + MGW	0.31	0.08
1.5 LPM MGW	0.22	0.01
Food waste	0.20	0.01

Based on the diffusion gas transport model parameters described in Appendix 8 and a stagnant layer thickness of 1mm, CO_2 concentration of 15% and interface width of 1mm, the mass transfer rate is found to be approximately 0.4 Kg CO_2/day: very close to the maximum observed emission rate. Based on these parameters, therefore it is apparent that diffusion could theoretically be the sole mechanism for gas transfer from home compost bins. The influences of the three key parameters, identified above, on the model are illustrated in Figure 64. The Figure shows that if the actual values of the stagnant layer thickness or interface width are very different from the estimated values then the diffusion model soon becomes invalid. At one extreme, the potential emission rate becomes too low to account for the observed CO_2 concentrations and production rates. At the other extreme the potential emission rate is so high that, at the production rates observed in the reactor systems, there would be no build up of CO_2 within the bin headspaces, which was not the case. If the basis of the model is assumed to be valid, however, then the previous fact provides a further use of the Figure based on the following two points:

- Significant CO_2 build up was observed within the H.C. bin experiments
- An approximate maximum gas emission rate of around 0.5 (or 1.0 to be more certain) Kg CO_2/day is known from the reactor experiments

Based on these two points, it can be assumed that the region of the Figure where the emission rate rises above the maximum observed rate, (all of the region above 1.0 Kg/day or from the black shaded region and above) does not occur. This information can be used to improve the use of the diffusion model in estimating the rate of emission of detected trace gases as has been done in Section 6.9.1.

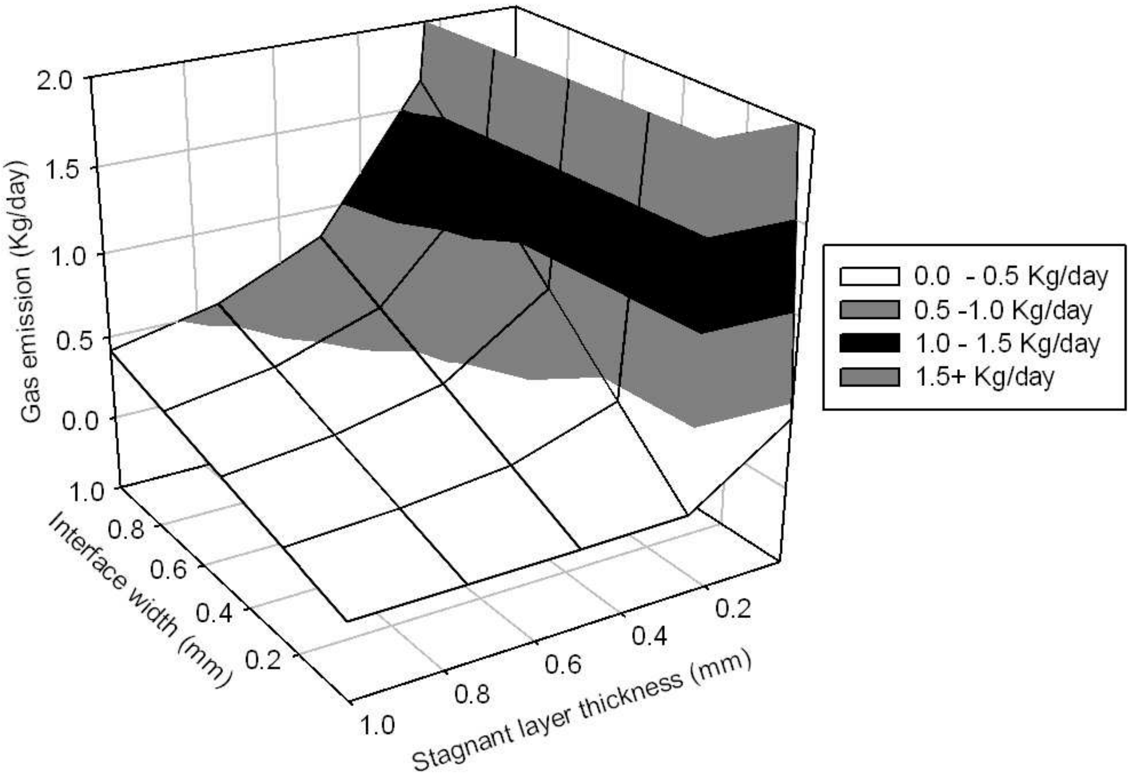

Figure 64: Rate of gas emission based on diffusion transport model with a headspace CO_2 concentration of 15%

6.9. Trace gas emissions: Overview

6.9.1. Methane emissions

The gas chromatography and sampling methods used for CH_4 analysis are described in Section 4.6. While the method used offered good sensitivity, the accuracy was limited with an average residual error from the calibration data of ±30%. The lowest calibration standard available was air, which had an average CH_4 concentration of approximately 2 ppm (Intergovernmental Panel on Climate Change (IPCC) 2001). The method accuracy at this concentration was only sufficient to distinguish CH_4 concentrations from air of above 5 ppm. Any measurements below this threshold were therefore assumed to have the same CH_4 concentration as air. Only a few of the conducted experiments gave measurements above this threshold, the details of which are given in Table 66. As would be expected, the highest concentration found was in one of the sealed airflow test experiments (see section 6.8) where a concentration of 460 ppm was found, but the highest value found in an unaltered naturally aerated compost bin was 260 ppm internally and 90 ppm in the headspace. Overall, the results show raised emissions of methane to be quite variable with no clearly consistent pattern. The majority of the experiments that showed raised emissions were near the top of the CO_2 concentration ranking but not in all cases and not including several of the highest ranking experiments. This may be related to differences in the air flow in the forced aeration reactors from the standard naturally aerated compost bins. An unaltered naturally aerated compost bin does not enter the CO_2 ranking until after 14 sealed or forced aeration experiments. The forced aeration experiments which show raised CH_4 emissions are at the very bottom level of detection with CH_4 concentrations of only 5 or 6 ppm, despite very high CO_2 concentrations. There are two likely explanations for this:

- Methane production is occurring in the forced aeration reactors but the methane is removed from the system before it can build up to higher concentrations. In the naturally aerated systems, where diffusion is believed to be dominant, methane may not leave the system as quickly so can reach measurable concentrations. As concentration difference between the inside and outside of the bin is the driving force for gas transport by molecular diffusion, it is possible for the CO_2 to be lower but the CH_4 concentration to be higher in a compost bin compared to a sealed reactor due to the different driving forces present.

- Methane production is lower in the forced aeration reactors because, despite the higher CO_2 concentrations when compared to the H.C. bins, the oxygen that is present is able to penetrate more deeply into compost particles due to the higher air pressure and different flow system. There are therefore fewer zones that are sufficiently anaerobic for methane production to occur.

In most cases, both duplicates in an experiment showed similar methane emissions but there are some where only one showed raised emissions, as in the case of the 5L/week experiment, where one of the pair gave a much higher measurement than the other. This could be a result of the sampling procedure; the duplicate bins were sampled on alternate days, meaning a short duration of raised CH_4 emission could be missed in one of the bins, while it was captured in the other. Another possibility is that very specific conditions are required for CH_4 emission, such as a very compressed, moist and high temperature region within the compost and this only occurred in one of the bins, due to variations in material packing and structure.

Table 66: Details of experiments showing raised CH_4 concentrations in headspace or internal gases

Experiment title	Method section	Maximum headspace CO_2 concentration (%)	CO_2 concentration ranking /49	Maximum recorded methane concentration (ppm)	
				Headspace	Internal
Sealed barrel	4.7.9	20.9	1	4	460
0.5 L/min (1)	4.7.10	18.9	3	6	6
Sealed+flow Meter (1)	4.7.9	16.9	7	13	59
Sealed+flow Meter (2)	4.7.9	16.6	8	7	12
1.5 L/min Grass+MGW (Lower C:N) (2)	4.7.6	16.2	9	5	5
Sealed lid	4.7.9	14.9	10	28	28
5L/week (2)	4.7.7	11.9	15	5	9
5L/week (1)	4.7.7	11.3	16	86	280
5L/fortnight (2)	4.7.7	10.6	17	14	5
10L/week (2)	4.7.7	10.2	20	7	7
5L/fortnight (1)	4.7.7	9.9	21	5	7
1.5 L/min Grass + MGW (Lower C:N) (1)	4.7.6	8.7	23	5	5
10L/week (1)	4.7.7	8.5	25	5	8
Layered (2)	4.7.3	7.1	28	5	5
Layered (1)	4.7.3	3.4	35	4	7
Food waste (stage 2)	4.7.4	1.9	43	29	12

*Bracketed numbers refer to bin 1 or 2 of each experiments duplicate bins

Figure 65 shows the internal and headspace concentration measurements against composting time. The scale is reduced so that, although the few higher concentrations measured made are not visible, the details for lower concentrations are. It can be observed that, when raised concentrations were found, particularly in the headspace, they were predominantly in the first 1-3 days of composting. In the internal gases higher concentrations were found over longer periods, up to 15 or 20 days. The exception to this pattern was the food waste compost in the open bin. The details of this experiment can be found in Section 6.2.3. It consisted of a bulk feed of 18Kg of food waste that had been built up by small weekly additions in duplicate forced aeration reactors. After 6 weeks at the end of the airflow test the composting material was transferred to a standard compost bin for further long term measurements to be made. Despite no methane having been detected during the airflow experiments, methane was detected at this time and consistently for the following 90 days. The key feature of this feed material, in terms of methane production, is likely to be its physical structure and moisture content, causing there to be very little free air space within the material for oxygen to enter and flow through. Despite its relatively small volume therefore, a large proportion of the internal mass was likely to be anaerobic while the surrounding gases were high in oxygen content.

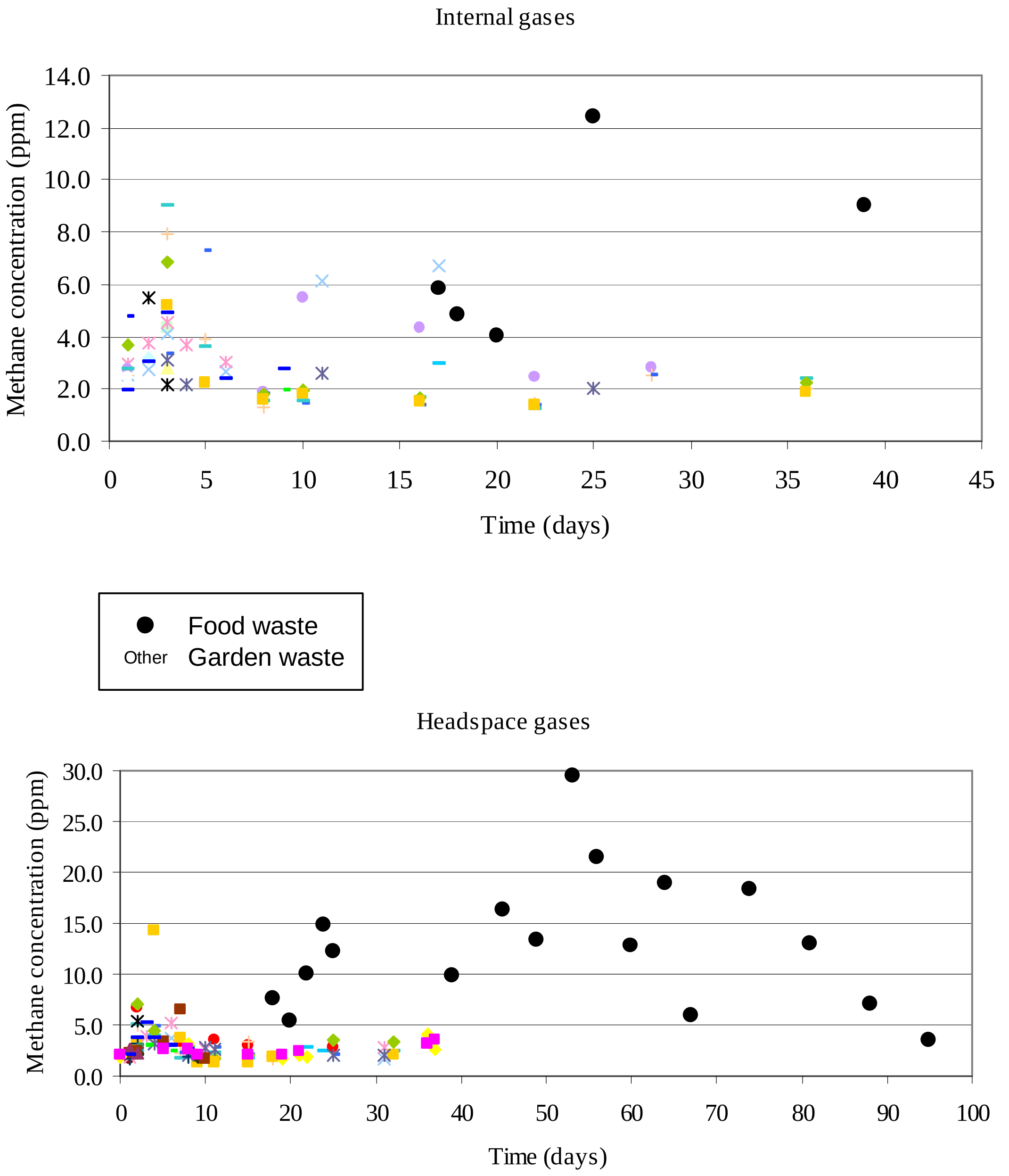

Figure 65: Internal and headspace methane concentration measurements relative to composting time for all monitored experiments

In order to quantify the rate of emission of CH_4 from the H.C. experiments performed it is necessary to use the diffusion gas transfer model described in Section 6.8 and Appendix 8. Three scenarios are considered in order to convert the model result into an annual rate of CH_4 emission from home composting:

1. The simplest and most widely observed example where no CH_4 is produced during home composting activities.

2. A realistic but worst case scenario, with the highest observed headspace CH_4 concentration of 86ppm, emitted constantly, but only, throughout the first 24 hours of composting following a feed addition. Assuming relevant feed additions are added every two weeks during the growing season which is assumed to last for 26 weeks of the year.
3. An absolute worst case scenario with the maximum observed concentration of 86ppm CH_4 emitted constantly throughout the year.

The results of applying the model to scenario 2 are displayed in Figure 66. Based on the analysis of CO_2 emission rates, performed in Section 6.8, the darker region of the Figure can be ignored. This gives an upper limit of the CH_4 emission as around 0.002 Kg CH_4/year/household. Converting these values into equivalent-Kg CO_2 on a 20 and 100 year basis by multiplying them by the global warming potential of CH_4 (Section 2.5.2) gives the results shown in Table 67. It can be seen that the additional impacts from CH_4 emission from home composting are in fact very low, with only 0.14 Kg equiv.-Kg CO_2/hh/year estimated as the realistic worst case scenario and 4.3 Kg equiv.-Kg CO_2/hh/year as the most extreme potential emission.

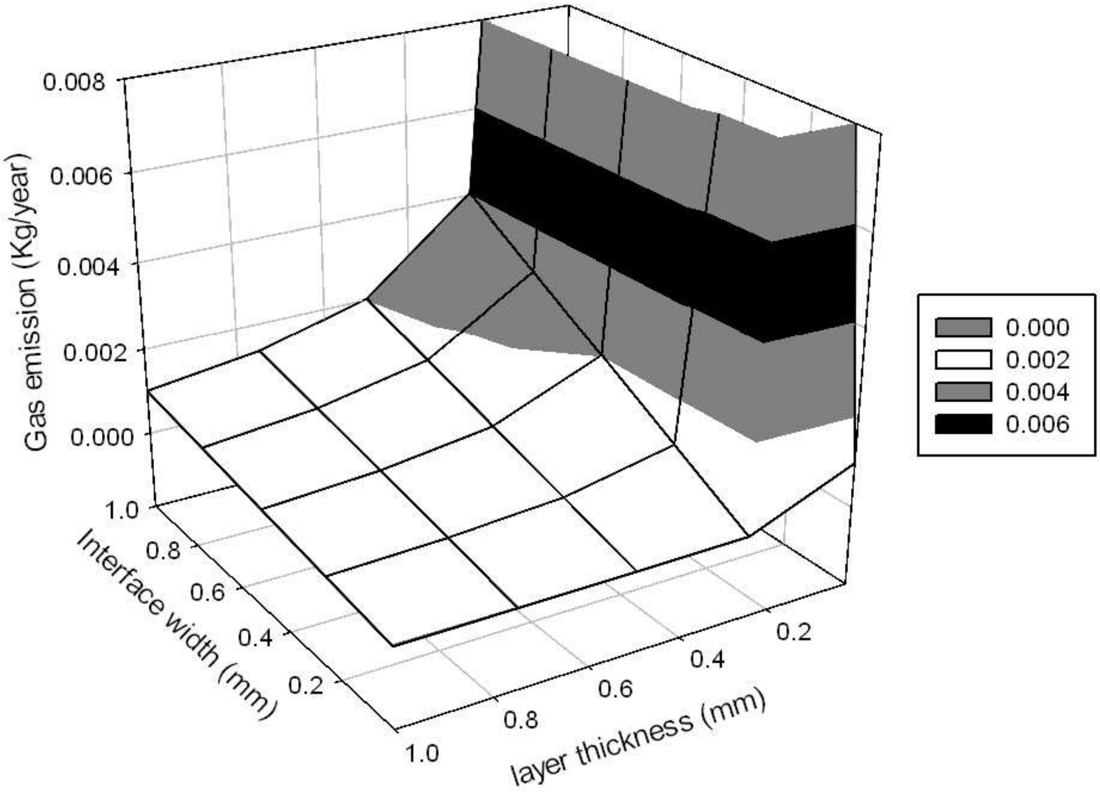

Figure 66: Rate of emission of CH_4 based on diffusion transport model (scenario 2)

Table 67: Upper limits of CH_4 emission

	Upper limit of CH_4 emission (equiv.-Kg CO_2)			
	20-year basis		100-year basis	
	Scenario 2	Scenario 3	Scenario 2	Scenario 3
Per household per year	0.14	4.3	0.05	1.5
Per tonne of waste Lower limit[1]	0.35	11	0.13	3.8
Per tonne of waste Upper limit[2]	1.4	43	0.5	15

[1] Based on 400 Kg waste/household/year [2] Based on of 100 Kg waste/household/year

6.9.2. Ammonia, nitrous oxide and volatile organic compounds

Concentrations of ammonia and nitrous oxide measured by passive diffusion tube analysis are shown in Table 68 and volatile organic compounds in Table 69. The results are for an average concentration over an exposure time of 14 days immediately following addition of the fresh feed material. Supply and analysis of the diffusion tubes was provided by Gradko International Ltd. NH_3 is only found at trace concentrations in the atmosphere so the concentrations found in the compost headspace gases show that NH_3 emission is occurring. Calculation of an approximate average rate of emission per Kg feed material for the forced aeration experiments is demonstrated in Appendix 7. For the given experiment parameters and if it is assumed that, for a repeating fortnightly feeding schedule, the rate of emission does not change significantly over time (discussed in Section 6.10) it is possible to estimate the emission per tonne of feed material, which is also given in Table 68. It can be seen that the highest rate of emission calculated was 15.5 g NH_3/T feed for a grass only feed. This is likely to be at the upper range of emission for most home composting feeds, as grass is a high in nitrogen content material, and one of the most common feed materials. Although kitchen wastes can also have high nitrogen contents, for the composition used in this study, the emission of ammonia per tonne of feed was less than 10% of that for the grass only feed. It is also interesting to note that the open bin experiment “Low C:N” produced a similar concentration of NH_3 as the forced aeration experiment with a grass only feed.

This must be considered with respect to the gas transport mechanism through open compost bins, which is discussed in Section 6.8.

The N_2O concentrations (Table 68) in the monitored compost bins were found to be lower than the concentration in the atmosphere. These analyses were performed by an external laboratory on two separate sets of samples from different experiments, both giving the same result. This most likely indicates that microbiological or chemical activity is taking place under the composting conditions in the experiments tested that consumes N_2O and none that produce it.

Table 68: 14 day average NH_3 and N_2O concentrations from passive diffusion tube analysis

	Feed material/ 14 days	Concentration of NH_3 (ppm)*	Emissions of NH_3 g/T feed	Concentration of N_2O (ppm)
0.5 LPM (1)	9.9 Kg grass	21.6	15.5	0.001
0.5 LPM (2)	9.9 Kg grass	16.7	12.0	0.007
Food waste (1)	5.5 Kg food waste	0.8	1.0	0.058
Food waste (2)	5.5 Kg food waste	0.5	0.65	0.055
Garden waste low C:N	15.5 Kg grass + MGW	14.1	-	0.004
Ambient air (1)		-	-	0.134
Ambient air (2)		-	-	0.129

*blank subtracted (Uncertainty ± 7 %)

The results of the VOC analysis, shown in Table 69, indicate raised concentrations of some VOCs but still at very low concentrations and none of significant environmental or health concern with normal exposure times. Both pinene and limonine were also found in the EA Home composting study discussed in Section 2.9.2.

Table 69: Volatile Organic Compound concentration

VOC compound	Concentration in compost headspace gases (ppb)	Concentration in air (ppb)
Limonene	95	-
Phellandrene	76	-
Pinene	35	-
Disulfide, dimethyl	30	-
3-Carene	21	0.4

6.10. Importance of cumulative, layered feed additions

Repeated feed additions layered on top of each other over time are likely to occur in most home composting activities. This is very time consuming to simulate experimentally as it can only be achieved by feeding materials repeatedly over many weeks. It would be advantageous if each feed addition could be considered individually, which would be possible if the previous feed additions had only a negligible impact on the overall composting process and emissions, except through the headspace volume (See Section 0). This would be dependent on the relative activity and emissions of the older material compared to the most recent feed. This has been investigated in two ways. Firstly, by monitoring the time taken for the emissions from an individual feed to fall to the extent where they are no longer detectable. This was performed as part of an investigation of the impacts of water addition (Section 4.7.7) and involved running 6 compost bins with a feed of 17.9 Kg garden waste until the headspace carbon dioxide concentration dropped below the detection limits of 0.1%. The carbon dioxide concentration profiles, seen in Figure 67, show that it took 100 days for the emission of CO_2 to reduce to the point where the concentration fell below this detection limit. The concentration for the vast majority of this time, however, was at most 2.0% and more often below 0.5% depending on the water addition and turning frequency. It may be the case, therefore, that despite the long period of continual emission, the presence of older material does not make a significant contribution to overall bin emissions when fresh waste material is added. This would be dependent on the age of the older material and the size and composition of the fresh waste feed.

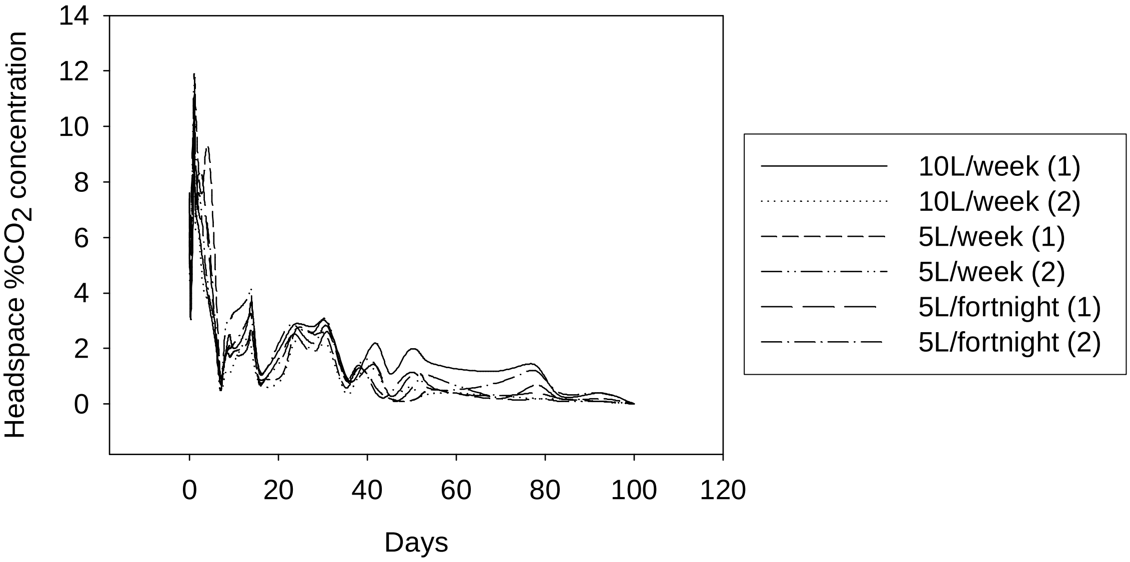

Figure 67: Headspace %CO_2 concentration profiles of compost bins with different water additions

The second set of relevant data comes from several experiments conducted with a repeating feed addition. Six pairs of open bottomed compost bins and one pair of sealed composting reactors were run under slightly different conditions for 12 and 10 weeks respectively with feeds of between 10 and 20 Kg/14 days. The specific experiment details are described in Sections 4.7.1 and 4.7.2. The feed additions occurred every two weeks, determined by the availability of fresh grass cuttings, but fitting with the likely frequency of home garden waste additions. The %CO_2 concentration profiles for these experiments are shown in Figure 68. It can be seen in these profiles that there is a significant degree of variation from one feed to another. A quantitative analysis was carried out, to show if there was a notable increase in concentration from one feed to the next, on the 14-day average, initial 3-day average and maximum CO_2 concentration during each bin's fortnightly feed decomposition. A drawback of these data is that the headspace volume was not kept constant, as it is reduced by each additional feed, and this has been shown to influence headspace concentration measurements (Section 0). Bearing this in mind, the results, summarised in Table 70, show that there appears to be a slight increase in CO_2 concentration from one feed to the next. Considering the correlation of the calculated slopes, however, as well as the contribution from reducing headspace volume, the small increase could not be considered a significant trend. It seems reasonable to assume, therefore, that for fortnightly feeds of between 10-20Kg the composting emissions of each feed can be considered individually.

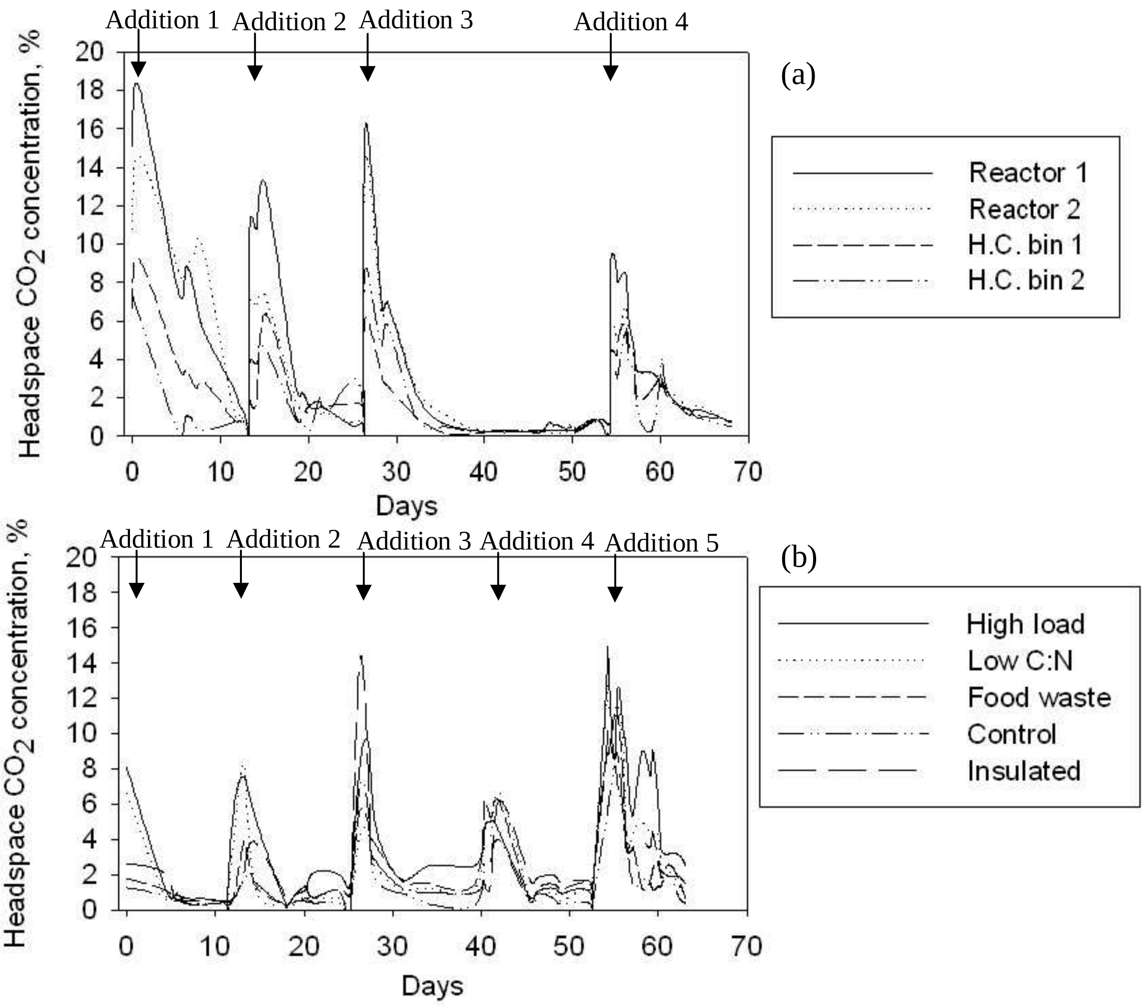

Figure 68: Headspace %CO_2 concentration profiles of compost bins with repeated feed additions (a) Airflow experiment, parallel reactor and H.C. systems (b) H.C. system emissions experiment

Table 70: Analysis of trends in %CO_2 concentration in repeated feed additions

	Maximum recorded %CO_2 concentration		3 day average %CO_2 concentration		14 day average %CO_2 concentration	
	Slope (%CO_2/day)	r^2 value	Slope (%CO_2/day)	r^2 value	Slope (%CO_2/day)	r^2 value
Average	0.07	0.36	0.06	0.5	0.03	0.55

6.11. Comparison of home and centralised composting

There are several ways to approach a comparison between home and centralised composting, particularly depending on the level of complexity involved. Considering the variability of feedstock materials, available forms of centralised composting and existing uncertainties within the research field, an exhaustive comparison is clearly beyond the scope of this work. A first comparison at a very basic level would be useful in producing initial quantitative data and indicate the relative importance of more detailed work. For this purpose a literature review has been carried out for data on the impacts of centralised composting in terms of Kg CO_2-equiv. emissions and climate-relevant trace gases (CH_4, N_2O).

The simplest approach is to assume that the centralised composting process is sufficiently well managed that no climate-relevant trace gases are emitted and the additional GHG emissions are caused by transportation and processing burdens. Values from several sources in the literature on these emissions are shown in Table 71. A further simplification is to assume that the amount of CO_2 directly emitted from the composting of the waste would ultimately be the same whether by home or centralised composting. This leaves the only additional burdens from home composting as the emission of any climate-relevant trace gases and the production of the compost bin. A detailed life cycle assessment of a Green Cone food waste digester was performed by Environmental Research & Consultancy (Knipe 2007). The Green Cone digester is a more complex and larger structure than more common open bottomed H.C. bins so its lifecycle emissions are likely to be higher than many alternative bins. It can still be used as a reasonable approximation for a “typical” home compost bin, particularly as a worst case scenario. The estimate of the anthropogenic greenhouse gas emissions just from the lifecycle of the cone were calculated as 253.5 tonnes of CO_2E/year. Accounting for the variation in Kg waste composted per household per year and the trace gas emissions calculated in Section 6.9.1 as shown in Table 72 below gives a total anthropogenic emission from home composting of between 2.9 – 11.5 Kg CO_2E/T_w. The values for the trace gas emissions are based on the realistic worst case scenario. Much lower values or even zero emissions were observed to be more common experimentally, but a much larger sample base would be required to estimate the actual proportions of home composting activities resulting in trace gas emissions. It can be seen, however, that only around 12% of the total GHG emissions are made up of the trace gas emissions, even using the worst case scenario. The relative impact of variation in this value is not, therefore highly significant to the total value.

Considering the complex and diverse nature of centralised composting operations estimates of the anthropogenic GHG emissions they cause vary greatly depending on the specific operations and methods used to analyse them. This is reflected in the small sample of estimates shown in Table 71 which range between 20 to 55 Kg CO_2 equivalent per Tonne of waste composted. Taking even the lowest estimate of 20 Kg CO_2E/T_w, however, the emissions from centralised composting operations are still almost double the very worst case scenario for home composting of 11.5 Kg CO_2E/T_w. When it is considered that this is also based on the, largely invalid, assumption that there are no climate relevant trace gas emissions from centralised operations it becomes clear that home composting is far superior to centralised composting in terms of GHG emissions. Making comparisons between home composting and other, non-composting forms of waste management is significantly more difficult due to the added complexities of avoided energy and materials, and carbon sequestration. Quite detailed analyses of these issues have been performed within certain constraints by Knipe (2007) and AEA Technology (2001).

Table 71: Anthropogenic GHG emissions from transport and processing machinery in centralised composting

Included activities	GHG emissions ($Kg\ CO_2E/T_w$)	Source
Food waste collection, processing and product delivery	49.7	Lifecycle assessment of centralised food waste composting facilities (Knipe 2007)
Waste collection, processing and product delivery	55.9	A study of the Viennese biowaste management system (Linzner et al. 2005)
Open composting transport and energy use in collection, processing and product delivery	21	Report for the European Commission on waste management options in the EU (AEA Technology 2001)
Closed composting transport and energy use in collection, processing and product delivery	26	Report for the European Commission on waste management options in the EU (AEA Technology 2001)
Waste transportation excluding collection	19.2	Review of Environmental and Health Effects of Waste Management: Municipal solid Waste and Similar Wastes (Enviros Consulting Ltd et al. 2004)

Table 72: Total anthropogenic GHG emissions from home composting

	Estimated range[3] of GHG emissions ($Kg\ CO_2E/T_w$)	Percentage of total (%)
Trace gas emissions (CH_4)[1]	0.35-1.4	12
Lifecycle of compost bin[2]	2.5-10.1	88
Total emission	2.9-11.5	100

[1] Realistic worst case scenario (Section 6.9.1) [2] (Knipe 2007) [3] Based on 100-400 Kg waste/hh/year

6.12. Mass balances and total national CO_2 emissions from home composting

A meaningful and useful mass balance for home composting activities is difficult to create due to the highly varied nature and conditions of each home composting process and feed addition. It is possible to estimate average inputs and outputs for a particular sample of home composting processes but the accuracy of these estimates is only as good as the size and suitability of the sample population. The majority of experiments performed over the course of this project were only run for a short time making them of limited use for total mass balance calculations. The results from the selection of experiments which were run for over 100 days (See Section 4.7.7) are summarised in Table 73 alongside those from the study by Smith et al. (2004) based on a sample of 64 households (See section 2.9.1) monitored over 2 years.

An alternative approach is to use data from other composting studies, based on either larger scale composting systems or laboratory scale microcosm studies. As discussed in Section 2.8.3 there is significant uncertainty over the accuracy of applying data from laboratory scale studies to larger scale systems and the relevance of data available in the literature is limited by the particular feedstock and experimental conditions used. Bearing these limitations in mind, however, laboratory studies are still a useful source of information and were used by AEA Technology (Wheeler 2003; Wheeler 2007) to identify the following assumptions for use in a home composting mass balance:

- 48.91% of input carbon is released as CO_2 based on microcosm studies
- Average home composting waste input composition 21% Carbon (%DM), 60% moisture

Table 73: Mass balance data

	Average values from Smith (2004)		18 Kg Grass + MGW composted for 100 days (Average 4 duplicate H.C. bins)	
	Input %	% lost	Input %	% lost
Total mass	100	57.8	100	45
Moisture content	65	56.5	63	52.7
Dry matter	35	60.0	37	31.9
Carbon (% DM)	-	-	40	57

The total annual CO_2 emissions from home composting can be calculated from mass balance data and the following additional factors:

1. Analysis of home composting leachate samples (Section 6.6) indicated that only around 0.5% or less of input carbon is lost through leachate (Appendix 9).
2. Trace gas analysis (Section 6.9) showed that only negligible amounts of carbon are emitted in any form other than CO_2
3. Based on points 1 and 2, it is reasonable to assume that the total input carbon lost during composting is emitted as CO_2.
4. The mass of waste home composted in 2008 was estimated in Section 2.3.3 to be 0.97 Million tonnes of waste/year.
5. The anthropogenic GHG emissions from home composting from the production and distribution of compost bins is 7.4 Kg CO_2E/T_w based on an average of 296 Kg waste composted/household/year (Sections 2.3.3 and 6.11)

The estimates of the total CO_2 emissions calculated using the mass balance data from the literature (Wheeler 2003; Wheeler 2007) and measured values (Table 73) are shown for comparison in Table 74.

Table 74: Estimated annual total, anthropogenic and biogenic CO_2 emissions from home composting in the UK in 2008

	Mass of waste composted	Biogenic Equiv.-CO_2 emissions	Anthropogenic Equiv.-CO_2 emissions	Total Equiv.-CO_2 emissions
	(Thousands of tonnes/yr)			
Literature	970	146	7	153
Measured	970	300	7	307

7. Conclusions

The experimental approaches adopted and results gathered and analysed during this project have led to a number of novel conclusions. Within the original scope of the work, the four primary objectives laid out in Chapter 1 have all been satisfied. The first of these, was to identify and compare the available techniques for measurement and analysis of the emissions from home composting in order to find the most accurate and reliable methodology. Using theoretical analysis and previous published research, the methods and techniques available were reviewed in detail, highlighting their individual advantages and disadvantages. A review of the factors relevant to home composting was also performed, particularly on the size and composition of typical waste additions, analysed from a range of sources, which were grouped together to create a detailed summary (Section 2.3.2). With the main emphasis of the project on quantifying the potential for environmentally significant gaseous emissions the most appropriate methods were selected as experimenter managed systems using both ordinary home compost bins as well as compost bin scale reactors with controlled air flow. Suitable experimental apparatus and protocols were designed, tested and refined based on the results of the literature review and trial experiments (Section 3). A number of lessons were learnt in the course of this process that will be of value to future studies and in interpreting existing data, particularly the following:

- With regard to temperature and gas composition measurements the monitoring frequency and timing relative to feeding and turning has a large impact on the results. In the first few days following a feed addition, daily monitoring is essential, and hourly monitoring would be beneficial (Sections 6.4 and 0).
- Ambient temperature fluctuations over the course of a single day have a significant influence on compost temperature which could have an impact on the results from studies using the public where the timing and geographical location of measurements could be different (Section 0).
- Measurements of headspace gas composition were shown to be highly dependent on the headspace volume, making this an important additional factor when headspace gases are to be used as a measured parameter.
- Evidence from gas concentration data and rates of emission calculated from the reactor experiments indicated that the primary gas exchange mechanism in home compost bins was diffusion rather than bulk convective flow (Section 6.8). This

is important in determining appropriate methods to quantify gaseous emissions from headspace gas concentrations.

- Based on the assumption that the rates of CO_2 emission were not significantly different between the reactor and H.C. bin systems, a model of gas diffusion through a stagnant layer of air was applied to H.C. bins to produce quantitative estimates of the upper ranges of emission rates of trace gases such as methane (Section 6.8).

The use of controlled reactor system experiments produced valuable data on rates of CO_2 emission that was instrumental in understanding the gas exchange mechanisms in home compost bins. It was difficult to judge, however, due to limitations in the sample size and the degree of variation between even duplicate experiments, how differences in the reactor and H.C. systems affected the composting processes. The apparent importance of diffusion in the H.C. systems caused significant differences in the gas composition measurements, with typically higher concentrations of CO_2 but lower concentrations or no detection of trace gases in the reactor systems (Section 6.8).

The second project aim was to assess the potential for environmentally harmful emissions from home composting. Trace gas analyses carried out on H.C. headspace gases (Section 6.9) found no detected emissions of N_2O but emissions of NH_3 of up to 15.5 g/T feed. Volatile organic compounds were detected at only very low concentrations, with the most concentrated being limonene at 95 ppb, and none of significant environmental or health concern. Emissions of methane were detected but only in a small number of cases, typically in the first 2-3 days following feed addition, and at very low concentrations. The highest single detected concentration was 86ppm within the compost bin headspace with a simultaneous concentration of 280 ppm within the internal compost matrix. A food waste only feed was observed to behave differently from larger garden waste feeds with consistently higher methane concentrations of between 5-30 ppm detected for almost 100 days after the last feed addition. This was likely to be caused by the physical structure and moisture content of the food waste, causing there to be very little free air space within the material for oxygen to enter and flow through. Despite its relatively small volume therefore, a large proportion of the internal mass was likely to be anaerobic while the surrounding gases were high in oxygen content.

The third project objective was to add to the body of knowledge within composting science, regarding the relationship between key factors, including temperature, CO_2 emission, pH, moisture content and feed properties. A number of composting parameters were investigated during the project (Section 6.2) and the trends identified in the data matched existing knowledge on the influence of the tested parameters. The variability inherent in composting processes and limitations in the number of experiments that could be performed limited the number and types of conclusions that could meaningfully be drawn. An important point that was highlighted was the degree of influence of the composting parameters, including the feed composition and size and process management, on H.C. performance. Large differences were observed in CO_2 production, mass balances and temperatures reached with relatively small changes in composting parameters. Estimates of an overall mass balance for home composting under select conditions were calculated and compared with other estimates from the literature (Section 6.12). On the basis of these values the total, biogenic and anthropogenic equivalent CO_2 emissions from home composting in the UK in 2008 were calculated. Total emissions were estimated to be between 150 to 300 thousand tonnes/yr, with 7 thousand tonnes/yr from anthropogenic sources.

Analyses of the physical chemical properties of selected mature composts showed that they were of sufficient quality to pass the PAS 100 specification for composted materials. This confirmed previous work in the literature finding home produced composts could be used as safe and beneficial soil improvers (Section 6.7). Leachate production was quantified as between 0.04 to 0.45 L/Kg waste depending on the feed composition. The properties of compost leachate will vary significantly with the compost feed materials. Although not within the scope of this project, compost leachate has been analysed in other research and home compost leachate specifically by Wheeler (2003, 2007). Considering the composition and rates of emission of home composting leachate, the environmental impacts are likely to be negligible as long as standard advice on which waste materials to compost is followed.

The final aim of the project was to compare the environmental impacts of home composting with those of centralised facilities. The total equivalent emissions of anthropogenic climate relevant gases from home composting activities and centralised composting were compared using the results of the gas analysis performed and data from the literature (Section 6.11). For home composting, the factors included in the analysis were the emission of climate relevant trace gases, which only included methane, and the lifecycle of a typical compost bin. For centralised composting the transport and processing emissions from a range of facilities calculated by several different sources were used as estimates. The experimental evidence indicated that only very specific conditions in home composting would lead to emissions of methane, and therefore nationally emissions are likely to be very low. In order to make a more robust comparison, however, the estimated realistic worst case scenario for methane emission was used. This made the estimate of the total anthropogenic greenhouse gas emissions from home composting as between 3 and 12 Kg CO_2E/T_w with almost 90% coming from the lifecycle of the compost bin. Emissions from centralised facilities however were between 20 and 56 Kg CO_2E/T_w, at least more than double that for home composting. This comparison makes it quite clear that, in terms of emissions of Kg CO_2E/T_w home composting is significantly superior to centralised options.

7.1. Recommendations for future work

The aims of the project were all successfully achieved, although limitations exist in the confidence of the conclusions drawn, due to the large degree of variability observed in the results and the relatively small sample sizes. Due to the time taken for methodology development and the labour intensive nature of the experiments this was an unavoidable constraint without substantially limiting the scope of the project. With regards to comparisons between home composting and other forms of waste management, such as centralised composting, more data may not be of great value due to the scale of the difference indicated by this work. Even using a worst case scenario the emission of anthropogenic climate relevant trace gases accounted for only around 10% of the total emissions from home composting, and this value was less than half of the best case estimates for centralised options. Emissions of relevant gases occurring in home composting would therefore need to be a great deal larger and more frequent than those found here in order to affect the conclusions. The risk of this is further reduced considering that the experiments conducted in this work were chosen in order to account for likely composting activities that would lead to the greatest emissions. Whilst further data collection would improve the confidence in the conclusions, the necessity for this is at least reduced. With the methods and lessons developed during this project, however a fairly simple but well designed and intensive project of data collection from home composting activities by the public could provide substantial benefits, particularly the following:

- A larger sample of gas composition measurements, identifying the frequency and concentrations of methane and nitrous oxide measurements would improve the confidence in and accuracy of total emissions calculations and enable the proportion of activities resulting in their emission to be accounted for.
- Further data on the properties of feed additions, management practices and their relative frequencies could enable more accurate mass balances to be performed accounting for different scenarios and their proportions within the public's composting activities.

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Appendix 1. Species diversity of the dominant microorganisms isolated during different composting phases

Table 75: Species diversity of the dominant microorganisms isolated during different composting phases (Ryckeboer et al. 2003)

	Species isolated at 25°C		Isolated at 55°C
Isolation days: composting phase	*Prokaryotes (no. of strains)**	*Fungi (no. of strains)**	*Prokaryotes (no. of strains)**
Day 0: starting material	*Bacillus amyloliquefaciens (1)* *Bacillus cereus (1)* *Bacillus licheniformis (1)* *Bacillus pumilus (11)* *Bacillus subtilis (4)* *Paenibacillus lentimorbus (1)*		*Bacillus pumilus (5)* *Bacillus sphaericus (1)* *Geobacillus stearothermophilus (1)* *Bacillus subtilis (2)* *Geobacillus thermoglucosidasius (1)* *unidentified bacilli (14)*
Day 13: thermophilic phase	*Bacillus badius (1)* *Bacillus licheniformis (4)* *Bacillus sphaericus (1)* *Brevibacillus agri (1)* *Paenibacillus macerans (1)* *Paenibacillus pabuli (2)*		*Bacillus sphaericus (1)* *unidentified bacilli (12)*
Days 27–48: cooling phase	*Bacillus cereus (2)* *Bacillus licheniformis (1)* *Bacillus sphaericus (1)* *Cellulomonas cellulans (4)* *Pseudomonas alcaligenes (3)* *Rhodococcus rhodochrous (1)* *unidentified bacilli (1)* *other unidentified bacteria (4)* *streptomycetes (6)*	*Aspergillus candidus (2)* *Aspergillus sp. (3)* *Dactylaria sp. (1)* *Mucor sp. (5)* *Scopulariopsis sp. (1)* *Trichothecium sp. (1)* *Verticillium sp. (1)* *unidentified (4)*	*Paenibacillus lentimorbus (1)* *unidentified bacilli (9)*

	Species isolated at 25°C		Isolated at 55°C
Days 55–85: maturation phase	*Bacillus licheniformis (1)* *Bacillus oleronius (1)* *Bacillus sphaericus (4)* *Brevundimonas diminuta (1)* *Cellulomonas cellulans (5)* *Flavobacterium mizutaii (2)* *Paenibacillus polymyxa (2)* *Paracoccus denitrificans (8)* *Pseudomonas alcaligenes (1)* *Rhodococcus rhodochrous (4)* *unidentified bacilli (1)* *unidentified bacteria (18)* *streptomycetes (13)*	*Acremonium sp. (1)* *Aspergillus sp. (7)* *Cephaliophora sp. (1)* *Geotrichum candidum (2)* *Gliocladium roseum (1)* *Mucor sp. (7)* *Scopulariopsis brevicaulis (2)* *Trichothecium sp. (4)* *Verticillium sp. (1)* *unidentified (14)*	*Bacillus badius (1)* *Bacillus pumilus (3)* *Bacillus smithii (1)* *Geobacillus stearothermophilus (3)* *Geobacillus thermoglucosidasius (3)* *Paenibacillus macerans (2)* *unidentified bacilli (19)* *other unidentified bacteria (2)*

*Bacteria were isolated on days 0, 13, 34, 62 and 85; streptomycetes on days 34, 42, 62 and 85; fungi on days 27, 34, 41, 48, 55, 62, 69 and 85.

Appendix 2. Home composting process variables

Table 76: Review of home composting process variables and experimental parameters and comments on their significance and the likely frequency of specific options in home composting

Process variables	Comments
• **Bin size and type**	
o Common plastic open bottomed	Open bottomed, usually 200-700 litres in size
o Tumbler	Free standing rotating bin typically 150-200L
o Digester	Consists of a basket buried in the ground and an upper cone above ground. Material pulled into soil by worms but difficult for rats to access.
o Green Johanna	Similar to common plastic open bottomed type but higher cost fully sealed system with base plate preventing any access by pests.
o Wormery	Utilizes the digestive processes of worms by creating an ideal environment for 500-1000 of certain species (*tiger worms or dendras*) that are suited to digesting kitchen waste.
o Open heap	An unconfined heap of piled up waste
o Home-made box/insulation	Numerous home-made systems of various size including very large insulated structures to small mesh containers.
• **Moisture content**	Depends on feed, any control measures, site ground, weather, temperature
o Uncontrolled	Probably common but unpredictable
o Controlled	Advised but probably less common
▪ High	Leads to anaerobic conditions, probably fairly uncommon
▪ Low	Reduces activity probably quite common

▪ Ideal	Advised, maximises activity
▪ Average	Unknown – either controlled near ideal or uncontrolled which will have a wide range and variance and could change significantly over the term and long term
• **Material feed rate**	Dependent on household properties, can vary significantly over short term and long term
o High frequency	Daily – typical for household waste
o Low frequency	Typical for garden waste
o High quantity	Large households/gardens, good attitude
o Low quantity	Small households/gardens, bad attitude
o Average	Only estimates available but large range and variance. Effect of a constant feed against the varying feed rate that will realistically occur unknown but probably not significant.
• **Bin flow system**	
o Plug flow	Typical, not well mixed, layers, remove compost when ready at base
▪ Rate of material removal	When ready? Rate varies with demand and readiness
o Batch	Turning, well mixed
▪ One bulk feed	Large gardens, less common
▪ Fed until bin full then left	Less common, perhaps left over winter and ready after?
o With compression as bin fills	Probably typical
o Without compression as bin fills	Probably less common
• **Initial Material in bin**	
o None	Typical start but only until bin has filled
o Bin always full or partially full	Typical after initial starting phase
▪ Level of fullness	Dependent on relationship between feeding, removal and rate of composting
• Always full	Typical with compression
• Fractionally	If high rate of composting and removal

full and varying	
▪ Maturity range of material	Dependent on relationship between feeding, removal and rate of composting
• All mature	If batch and old, not typical
• Range from mature to fresh with varying proportions	Typical, hard to reproduce in short time, high variance, unknown range
• Part mature, Part partially mature	Similar to range so similar to typical, effect of difference not known
• **Site ground material**	Effects drainage and ingress of macroscopic life
o Concrete	Probably less common but does occur
o Soil	Probably most common
▪ Properties of soil	Effect not known, range not known, hard to control.
o Enclosed - tumbler	Probably less common but does occur
• **Turning frequency**	
o High	Enhances composting, probably uncommon
o Low	Slower composting, more chance of anaerobicity, common
o Never/very infrequent	Slower composting, much higher chance of anaerobicity, common
o Minimum optimum	Turning when temperature drops off, enhances, uncommon
o Typical	Unknown, will change over time, wide variance
• **Turning method/efficiency**	
o Manual mixing	Mixing with a tool or by emptying and refilling, common
o Tumbling	Probably less common
o Thorough	Complete mixing of all bin material, probably less common, precludes plug

	flow system
o Not thorough	Slight mixing/breaking up of material, more common
o Mixing just of upper material	Probably common, required for plug flow system
• **External temperature**	
o Controlled	Not used, effects difficult to accurately predict, hard to achieve satisfactorily
▪ High	Hinders composting if too high, uncommon
▪ Low	Slows composting, probably quite common dependent on bin management, location, time of year etc.
▪ Ideal	Probably very uncommon, certainly without daily rise and fall
▪ Average	Wide range and variance, unknown and dependent on many variables, possible to estimate for specific circumstances
o Uncontrolled	Dependent on location, shade, weather, time of year, annual variation
▪ Hours of sunlight	
• High	Enhances composting unless temp goes too high
• Low	Slows composting
• Ideal	Maximum unless temp going too high
• Average	Wide range and variance, unknown and dependent on many variables, possible to estimate for specific circumstances
▪ Strength of sunlight	
• High	Enhances composting unless temp goes too high
• Low	Slows composting
• Average	Wide range and variance, unknown and dependent on many variables, possible to estimate for specific circumstances
o Insulation	

▪ Used	Probably quite uncommon, will retain heat, enhance composting, reduce rapid changes from sunlight?
• Type/properties	Not known
▪ Not used	common
• **Feed composition/C:N ratio**	Significant variation in short term and also believed to show seasonal trends over long term. Data available but large range and variance.
o Just garden	Probably most common
o Just household	Probably quite uncommon
o Garden and household	Common
▪ More household	Very large household, very small garden probably quite uncommon except outside growing season or with very inactive gardener who will rarely compost
▪ More garden	Regular gardener probably common with limits above
o High C:N ratio	Too many brown material like paper/card, woody prunings, slows composting, probably low emissions. Probably quite uncommon except in winter
o Low C:N ratio	Too many green materials: mainly grass, kitchen waste, green prunings. Leads to N_2O and NH_3 emissions, possibly to anaerobicity. Probably quite common especially in spring.
o Ideal C:N ratio	Advised, enhances composting, probably quite common.
o Average C:N ratio	Will vary with time as feed does, can be estimated from survey data but large range and variance
o Components used to make up garden and household waste ▪ See feed components	If overall proportion garden/household and C:N ratio kept constant individual components may still alter the trace elements present which could affect the

	microbial activity and the chemical composition of the final compost.
• **Feed particle size – shredded, chopped, torn, scrunched**	
o Small	Advised, enhances composting, if too small leads to anaerobicity, probably quite common
o Large	Not advised, slows composting, reduces emissions, probably quite common as requires less effort
o Ideal	Small but not too small and with some larger to enhance air flow. Not known exactly and probably quite uncommon
o Typical	Not known
• **Bulking agents**	
o Used	Enhances composting and reduces emissions if used correctly, probably quite uncommon
▪ Type	Not known
o Not used	Common
• **Earthworm inoculation**	
o Used	Enhances composting if done correctly, dependent on phase, temperature, material and type of worm. Required to get worms if not on soil. Probably uncommon
▪ Type of worm	Various, typical should be that found in normal soil
o Not used	Common, worms should enter bins on soil anyway
• **Accelerator**	Enhances composting in theory. Can be chemical or a rapidly composting material such as nettles. Probably quite common. Effectiveness not known but probably not highly significant.

Appendix 3. Compost standard specifications

PAS 100

Among the criteria set by the Composting Association standard for final compost quality are:

Table 77: Selection of PAS 100 limit levels of defined parameters

Parameter	**Upper limit**
Human pathogens	
Salmonella s.p.p.	absent in 25g sample
E. coli	1,000 CFU/g
Potentially toxic elements (mg/kg dry matter)	
Cadmium	1.5
Chromium	100
Copper	200
Lead	200
Mercury	1
Nickel	50
Zinc	400
Physical contaminants	
Glass, metal and plastic larger than 2mm	0.5% of total air-dried sample by mass (of which less than 0.25% of total air-dried sample is plastic)
Stones and other consolidated mineral contaminants larger than 2mm	7.0% of total air-dried sample by mass
Weed contaminants	
Weed propagules	5 viable propagules per litre
Phytotoxins	
Plant tolerance	20% below control

APEX

The following analysis should be undertaken on the finished compost on a monthly basis for elements and once a quarter for other parameters and impurities in order to meet the Apex specification:

Table 78: Selection of APEX limit levels of defined parameters

Parameter	**Upper limit**
Human pathology	
Salmonella s.p.p.	Absent in 25g sample
E.coli	1,000 CFU/g
Elements (mg/kg dry matter)	
Cadmium	2
Chromium	130
Copper	150
Lead	200
Mercury	2
Nickel	50
Zinc	300
Arsenic	8
Boron	1
Chloride	850
Sodium	200
Physical contaminants	
Glass, metal and plastic larger than 2mm	Absent
Stones, smaller than 2mm	Absent
Other contaminants	
Weed seeds	Absent
Plant pathogens	Absent
Herbicides, fungicides, insecticides	Absent

Other Apex specifications for finished compost, to be checked every month, are:

Table 79: Further monthly tests for APEX specification

Parameter	**Upper limit**	**Lower limit**
pH	7.5	8.5
Electrical conductivity	750 µS/cm	1,200 µS/cm
Organic matter	30%	40%
C:N ratio	15	20
Nitrogen	0.7%	1.0%
Ammonia-N	1mg/l	5mg/l
Nitrate-N	15mg/l	120mg/l
Phosphorus	25mg/l	40mg/l
Potassium	0.5% or 650mg/l	0.7% or 1,200g/l
Magnesium	10mg/l	30mg/l
Free carbonate	Trace	Trace
Moisture content	35%	45%
Bulk density	450g/l	550g/l

Eco-label

To qualify for Eco-label standing, a product must not contain more than the following concentrations of elements, in terms of dry weight:

Table 80: Selection of Eco-label limit levels of defined parameters

Parameter	**Upper limit**
Human pathogens	
Salmonella s.p.p.	Absent in 25g sample
E.coli	1,000 CFU/g
Elements (mg/kg)	
Cadmium	1
Chromium	100
Copper	100
Lead	100
Mercury	1
Nickel	50
Zinc	300
Arsenic	10
Molybdenum	2
Selenium	1.5
Fluorine	200

Nutrients

In addition, when used at the recommended rates of application, it is recommended that Eco-label products exceed the maximum nutrient loadings of:

- 17g/m2 total nitrogen
- 6g/m2 phosphate
- 12g/m2 potassium oxide

Nuisance

The Eco-label specifies that products should not:

- Have persistent or offensive odours after being applied to the soil.
- Contain fragments of glass, wire, other metal or hard plastic.
- Introduce weed seeds or vegetative reproductive parts of aggressive weeds.

Fitness for use

Finally, the Eco-label specifies that product packaging must bear the following information:

- A description of the purpose of the product and limitations to its use. The suitability of the product for particular plant groups should be stated.
- Recommended conditions of storage and a 'use by' date.
- The major feedstock, including the sector from which the product has been manufactured (e.g: food processing, paper, etc).
- The recommended rate of application, expressed as kilograms or litres per square metre of ground per year.
- Guidelines on safe handling and use.

Appendix 4. Feed material properties

The material properties measured during the experiments and those reported in the literature are summarised in Table 81 below. The measured values were made using the techniques described in Sections 3.1.10 and 3.1.7 performed on samples taken from each batch of feed material. The literature values were taken from a range of sources for each material.

Table 81: Feed material properties measured during this project and from the literature ((Northeast Regional Agricultural Engineering Service (NRAES) 1992), (Kulcu et al. 2004), (Eklind et al. 2000), (Epstein 1997), (Michel Jr. et al. 1992), (Ward et al. 2005))

	% C		C:N ratio		Moisture content (%)	
	Range	Average	Range	Average	Range	Average
Literature values						
Grass	42 to 58	49	9 to 25	15	73 to 82	78
MGW	24 to 45	34	17 to 32	25	30 to 70	50
Food waste	35 to 56	46	11 to 40	23	69 to 87	79
Measured values						
Grass	31 to 58	41	16 to 18	17	55 to 82	62
MGW	40 to 50	43	15 to 50	27	30 to 52	42

Appendix 5. External laboratory test results

Table 82:Water extractable nutrients

	In dry matter				**Method**	**Plant**
Parameter	High load	Low C:N	Food	**Units**	**Reference**	**significance**
NH_4-N (ammonium-N)				mg/kg	BS EN 13652	Primary nutrients
NO_3-N (nitrate-N)				mg/kg	BS EN 13652	
NH_4-N plus NO_3-N				mg/kg	Calculated	
Phosphorus as P	248	325	448	mg/kg	BS EN 13652	
Potassium as K	4513	6712	7600	mg/kg	BS EN 13652	
Calcium as Ca	355	398	347	mg/kg	BS EN 13652	Secondary nutrients
Magnesium as Mg	53	57	55	mg/kg	BS EN 13652	
Sulphur as S	319	568	508	mg/kg	BS EN 13652	
Boron as B	4.0	4.6	5.0	mg/kg	BS EN 13652	Trace nutrients
Copper as Cu	0.4	0.5	0.5	mg/kg	BS EN 13652	
Iron as Fe	23	26	26	mg/kg	BS EN 13652	
Manganese as Mn	8.4	6.2	5.5	mg/kg	BS EN 13652	
Molybdenum as Mo	0.2	0.4	0.5	mg/kg	BS EN 13652	
Zinc as Zn	9.3	10.3	10.6	mg/kg	BS EN 13652	
Chloride as Cl				mg/kg	BS EN 13652	
Sodium as Na	559	687	755	mg/kg	BS EN 13652	

1 Water extractable values are a measure of nutrient concentrations immediately available to plants.

Table 83: Potentially toxic elements

	In dry matter						
Parameter	High load	Low C:N	With Food	**PAS 100 upper limit**	**Unit**	**Pass or Fail**	**Method reference**
Arsenic as As	N/D	N/D	N/D	N/A	mg/kg	N/A	
Cadmium as Cd	0.7	0.6	0.6	1.50	mg/kg	**Pass**	BS EN 13650
Chromium as Cr	12	8.8	11	100.00	mg/kg	**Pass**	BS EN 13650
Copper as Cu	47	36	37	200.00	mg/kg	**Pass**	BS EN 13650
Fluoride as Fl	N/D	N/D	N/D	N/A	mg/kg	N/A	
Lead as Pb	93	69	82	200.00	mg/kg	**Pass**	BS EN 13650
Mercury as Hg **- less than**	0.5	0.5	0.5	1.00	mg/kg	**Pass**	BS EN 13650
Molybdenum as Mo	2.5	2.1	3.3	N/A	mg/kg	N/A	BS EN 13650
Nickel as Ni	8.4	5.8	7.8	50.00	mg/kg	**Pass**	BS EN 13650
Selenium as Se	N/D	N/D	N/D	N/A	mg/kg	N/A	
Zinc as Zn	164	170	152	400.00	mg/kg	**Pass**	BS EN 13650

Table 84: Physical properties

	As received (fresh)				In dry matter				
Parameter	High load	Low C:N	With food	**Unit**	High load	Low C:N	With food	**Unit**	**Method Reference**
Bulk Density[1]	574	535	527	g/l	226	194	199	g/l	BS EN 12580
Dry Matter	N/A	N/A	N/A		39.3	36.2	37.7	% m/m	BS EN 13040
Moisture	348	341	328	g/l	N/A	N/A	N/A		BS EN 13040
	60.7	63.8	62.3	% m/m	N/A	N/A	N/A		

Appendix 6. Conversion of headspace depth to headspace volume in H.C. bins

In order to convert the measured headspace depth into the headspace volume the compost bin was assumed to fit the bottom half of a cone as in Figure 69. In this way it is possible to define an equation to calculate the compost headspace volume in a conical bin for any compost depth where the bin height, base diameter and top diameter are known. The derived equations are listed in Table 85 below.

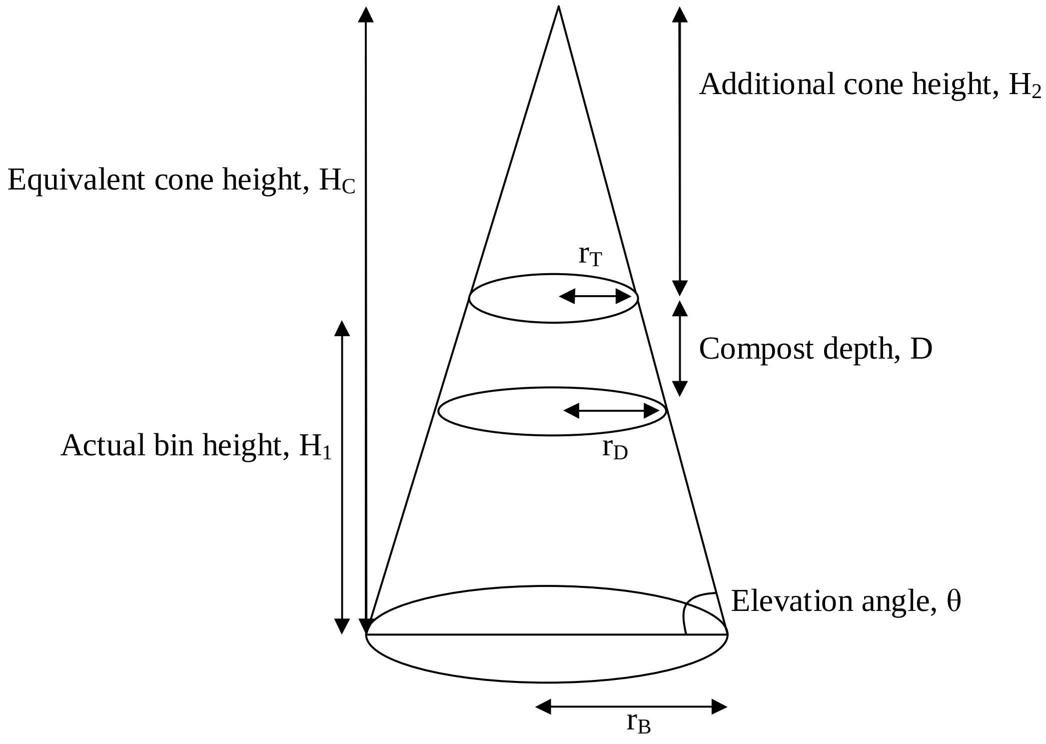

Figure 69: H.C. bin represented as bottom section of a cone

Table 85: Equations necessary for the calculation of headspace volume from compost depth

Volume of a right angled cone	$\frac{\pi}{3} r^2 h$
Elevation angle, θ	$\arctan\left(\frac{H_1}{r_B - r_T}\right)$
Equivalent cone height, H_c (m)	$r_B \tan\theta$
Bin radius at depth D, r_D (m)	$\frac{(H_2 + D)}{\tan\theta}$
Compost bin volume, V_B (m^3)	$\frac{\pi}{3}\left(r_B^2 H_C - r_t^2 H_2\right)$
Headspace volume, V_H (m^3)	$V_B - \frac{\pi}{3}\left(r_B^2 H_c - r_D^2 (H_2 + D)\right)$

Appendix 7. Calculation of gas emission rate from concentration data and forced aeration flow rate

The calculations used to estimate the mass flow rate of an emitted gas from the gas concentration and inlet air flow rate of a composting system are detailed in Table 86 below. The assumptions used in these calculations are that:

- There is negligible difference in the moles of gas entering and exiting the system.
- The inlet air is at standard temperature and pressure.
- The ideal gas law applies

Table 86: Calculation of gas emission rate from concentration data and air flow rate

Inlet air flow rate, Q (m^3hr^{-1})	Set parameter
Experiment duration time, t (hr)	Set parameter
Mass of feed addition during experiment, M (Kg)	Set parameter
Volume of air entering system during experiment, V (m^3)	$V = Q.t$
Average concentration of gas x over time t, c_x (ppm)	Measured parameter
Average concentration of gas x over time t, C_x (%)	$C_x = \frac{c_x}{10000}$
Emitted volume of gas x at standard temperature and pressure, V_x (m^3)	$V_x = \frac{V.C_x}{100}$
Ambient air pressure, P (KPa)	101.325 (Standard atmospheric)
Ambient air temperature, T (K)	293.15 (Standard ambient)
Gas constant, R ($m^3Kpa(Kgmol.K)^{-1}$)	8.315
Molecular mass of emitted gas x, mm_x ($gmol^{-1}$)	CH_4 = 16, NH_3 = 17, CO_2 = 44
Average mass of gas x emitted during time t, M_x (Kg) from Ideal gas law	$M_x = \frac{P.V_x.mm_x}{R.T}$
Average mass of gas x emitted per Kg feed material, Q_x (Kg x/Kg feed)	$Q_x = \frac{M_x}{M}$

Appendix 8. Calculating the rate of diffusion of CO_2 through a stagnant layer of air

If the subscripts 1 and 2 refer to the two sides of the stagnant layer and the subscripts A and B refer to CO_2 and fresh air respectively, then the rate of diffusion through a stagnant layer of air is given by Equation 8 (Coulson et al. 1999).

$$N_A = -\frac{D}{RTx}\left(P / P_{BM}\right)\left(P_{A2} - P_{A1}\right)$$

Equation 9 Where,

N_A = Molar flux of CO_2, kmol/m^2s

D = Diffusivity of CO_2 in air at 298 K and atmospheric pressure, m^2/s

T = Temperature, K

P = Pressure, kN/m^2

P_{A1} = Partial pressure of CO_2 in headspace, kNm^{-2}

P_{A2} = Partial pressure of CO_2 in ambient air, kN/m^2

x = stagnant layer of air thickness, m

P_{BM} = Logarithmic mean value of P_B, kN/m^2

In the case of diffusion through a circular interface around a compost bin lid the conversion to Kg CO_2/s is achieved by Equation 10:

$$M_A = N_A . m_A . S$$

Equation 10 Where,

M_A = Mass transfer of CO_2, Kg/s

m_A = Molecular mass of CO_2

S = Mass transfer surface area, m^2

The steps in carrying out the calculation and the necessary assumptions are as follows:

- Diffusivity, D of CO_2 in air at 298K and atmospheric pressure is 16.4x10^{-5} m^2/s (Coulson et al. 1999). The actual diffusivity would vary with the temperature and pressure of the stagnant layer of air but this value has been used as a simplifying assumption due to uncertainty of these parameters and the availability of diffusivity data.
- Temperature, T and pressure, P of the layer of air have been assumed to be 298K and atmospheric pressure (101.3 KN/m^2). The actual values would be a function of the compost headspace and ambient air temperatures and pressures.
- The partial pressures of CO_2 at the two sides of the stagnant layer are given by Equation 11:

  $$P_i = C_i.P$$

  Equation 11

  Where,

  P_i = Partial pressure of gas mixture component i, KN/m^2
  C_i = Fraction of component i in gas mixture
  P = Gas mixture pressure

  The mixture pressures at both sides of the layer are assumed to be atmospheric pressure (101.3 KN/m^2). The concentration of CO_2 at side 2, the fresh air side, was assumed to be negligible. The concentration at side 1, in the headspace would depend on the composting system conditions. The maximum value observed experimentally was 17.2% or 0.172 as a fraction of the mixture.
- P_{BM} is the logarithmic mean value of the partial pressure of the non-CO_2 gas mixture across the stagnant layer of air. The partial pressures at points 1 and 2 are given by Equation 11 where $P_{B2} = 1$ as there is negligible CO_2 and $P_{B1} = 1 - P_{A1}$. The logarithmic mean is calculated by Equation 12:

  $$P_{BM} = \frac{(P_{B2} - P_{B1})}{\ln(P_{B2} - P_{B1})}$$

  Equation 12

- The thickness of the stagnant layer of air would depend on the physical properties of the compost bin. The presence of a stagnant layer of air around the lid is itself uncertain, disregarding its thickness but assuming its existence the thickness would most likely have an upper limit of a few mm.
- The surface area of the interface at which the mass transfer takes place is theoretically determined by the circumference of the bin at the height where the lid closes around it and the width of the space between them. For the H.C. bins used in this project the circumference is 1.0m. The width of the opening, however, is difficult to define as the lid is stretched and clamped around the bin meaning space is only created by the unevenness and inflexibility of the contact surfaces meaning the actual width will vary around the circumference. As a simplifying assumption a constant value can be used with an upper limit of around 1mm.
- The molecular mass of CO_2 is 44 g/mol

Appendix 9. Estimation of carbon losses by leachate

Carbon losses through leachate emitted during composting can be estimated using the following parameters:

(Approximated from Table 58, Section 6.6)
Leachate production per Kg waste = 0.1 L/Kg
Leachate Total Solids = 1.5 %
Leachate liquid fraction carbon content = 300 mg/L
(Approximated from national household waste analysis database, Wheeler 2007)
Waste solids content = 40%
Waste solids carbon content = 21%
(Assumed similar to waste solids)
Leachate solids carbon content = 21%
Leachate density approximately 1 Kg/L

Total C in leachate liquid fraction per Kg waste = $0.1 \times 0.0003 = 0.00003\,\mathrm{Kg}$,
Total C in leachate solids fraction per Kg waste = $0.1 \times 0.015 \times 0.21 = 0.000315\,\mathrm{Kg}$,
Total C lost in leachate per Kg waste = 0.00003 + 0.00315 = 0.000345 Kg,
Waste input C per Kg waste = $1 \times 0.4 \times 0.21 = 0.084\,\mathrm{Kg}$,
Fraction input C lost in leachate = $\frac{0.000345}{0.084} \times 100$ = 0.41 %