QUALITY ENHANCEMENT OF COMPOST USING VERMICOMPOSTING AND AIR SEPARATION

Thesis submitted for the degree of Doctor of Philosophy

By

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September 2007

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ABSTRACT

European and National legislations in the UK have created a tremendous pressure on the waste management industry for a major expansion of the composting industry over recent years. Also, with the greater awareness of the health and environmental safety within the community, compost producers are forced to provide an authenticated form of quality compost to the consumers. The work presented in this thesis focuses on quality enhancement of mature green-waste derived compost using vermicomposting and air separation techniques.

A vermicomposting trial was conducted for a period of 18 weeks by utilising re-hydrated mature green-waste compost produced at Carmarthenshire Environmental Resource Trust (CERT) composting facility as a feedstock. It was found that a minimum average compost mass reduction of 16% was observed by using an average mass throughput of 32.6 kg m^{-2} $week^{-1}$. The greatest reduction in volatile solids was observed only during the initial stages of the trial. However, no significant reduction was noted towards the end of the vermicomposting process, when worm mass had reduced to approximately 1.3 kg/m^2.

Replicated growth trials on coriander and tomato were conducted using two commercially available multipurpose composts and five waste-derived composts. It was found that commercial composts showed better plant growth when compared to waste-derived composts. This was followed by another set of growth trials undertaken with lettuce, using pure worm casts (VC), green waste compost (FS) and mixtures of the two i.e. 50/50 and 20/80 (VC:FS, v/v) mix. Results showed that plant biomass production was optimal with 20/80 (v/v) mix, whilst VC and FS yielded poor plant growth. In general, the vermicomposting process did not result in an increased availability of nutrients or potentially toxic elements, the only exception being Zn.

Characterisation studies were also conducted on unscreened mature compost samples to identify the physical contaminants followed by laboratory and commercial scale air separation trials. Of the coarser fraction from Bryn Pica compost, 1% of plastic film was found. The laboratory air separation trial showed that at the minimum average air velocity of 4.24 m/s, 100% plastic film was removed along with 73% of <10 mm CERT compost. During the commercial scale trial, it was found that following screening, the <25 mm fraction would meet the physical contaminant limits of the BSI PAS-100:2005 standard. The 'Komptech Hurrikan' removed 91% of the light materials from the compost oversize (>25 mm). The air jig trial showed promising results and that, in less than 2 minutes, various sizes of stones were separated from the compost stone mix sample.

DEDICATION

I dedicate this thesis to my beloved uncle, Mr. Muhammad Asif Jah. He was Assistant Director in Geological Survey of Pakistan when he was honoured with the British Government Foreign and Commonwealth Office (FCO) Scholarship for PhD in the field of Geology at Cambridge University in September 1986.

He successfully completed his research and was due to submit his PhD thesis but unfortunately he met sudden death due to lung failure and expired on 13th July 1991 in Cambridge. He is buried in Peshawar, Pakistan which was his home town.

Department of Earth Sciences, Cambridge University has placed a bench in memory of Mr. Muhammad Asif Jah. This thesis is a tribute to his hard work and dedication towards accomplishment of his dreams which remained unfulfilled. God bless him and give him highest place in Jannah (Ameen).

ACKNOWLEDGEMENTS

First and foremost, I thank Almighty ALLAH from the depth of my heart for His guidance and blessings, which have been an unfailing source of strength, comfort and inspiration in completion of this work.

I am grateful to my academic supervisors, Prof Keith Williams and Prof Tony Griffiths, for their continuous support and excellent advice throughout this project. I consider myself very fortunate to have worked with them. I am also thankful to the board of Carmarthenshire Environmental Resources Trust for allowing me to conduct research at their site and to Grant Scape (formerly known as EB Nationwide) for funding this work through the Landfill Tax Credit Scheme.

I would like to thank all my friends, colleagues and staff within the Centre for Research in Energy, Waste and the Environment at Cardiff: Dr Guy Hewings, Dr Richard Marsh, Late Dr Tom Wollam, Jeff Rowlands, Ravi Mitha and Chris Lee for their endless support and help.

I would like to express the deepest appreciation to Prof Davey Jones at School of Agricultural and Forest Sciences, University of Wales, Bangor, who continually and convincingly conveyed a spirit of adventure and excitement in regard to the growth trials and research conducted at Bangor. Without his guidance and persistent help this research would not have been possible. I would also like to thank Dr John Anderson at the School of Chemical and Environmental Engineering, Nottingham University, who allowed me to use the air jig test rig during the air separation trials.

I would also like to thank and acknowledge my parents, friends and family for their unfailing support, encouragement, sacrifices and patience throughout the completion of this project.

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LIST OF ABBREVIATIONS

ABPR	Animal By-Product Regulation
AM	Arbuscular Mycorrhizal
AEC	American Earthworm Company
ANOVA	Analysis of Variance
BMW	Biodegradable Municipal Waste
BREW	Business Resource Efficiency and Waste
BSI	British Standards Institution
BS	British Standards
C	Degree Celsius
C:N	Carbon to Nitrogen ratio
C:P	Carbon to Phosphorus ratio
CERT	Carmarthenshire Environmental Resource Trust
CWM	Carmarthenshire Waste Management
C_2Cl_4	Tetrachloroethylene
DEFRA	Department for Environment, Food and Rural Affairs
EPA	Environmental Protection Agency
EC	Electrical Conductivity
EU	European Union
FS	Feedstock
H_2O_2	Hydrogen Peroxide
HCl	Hydrochloric Acid

HNO_3	Nitric Acid
HF	Hydrofluoric Acid
HPDE	High-density Polyethylene
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrophotometer
ISO	International Standard Organisation
KCl	Potassium Chloride
KOH	Potassium Hydroxide
LDPE	Low-density Polyethylene
MSW	Municipal Solid Waste
MRF	Material Recovery Facilities
NRAES	Natural Resource Agriculture and Engineering Service
NH_4	Ammonium
NO_3	Nitrate
NH_3	Ammonia
NA	Not available
NO_2	Nitrite
ND	Not Detected
ORP	Oxidation Reduction Potential
PAS	Publicly Available Specification for Composted Product
PTE's	Potentially Toxic Elements
PGR's	Plant Growth Regulators
PET	Polyethylene Terephthalate
PVC	Polyvinyl Chloride

RDF	Refused Derived Fuel
RP	Redox Potential
ROM	Run-of-Mine
SPAD	Soil Plant Association Development
VCU	Vertical Composting Units
VC	Pure Vermicompost
WAG	Welsh Assembly Government
WET	Wales Environment Trust
WRAP	Waste and Resource Action Program

NOMENCLATURE

UNITS	DESCRIPTION
CFU g^{-1}	Colonies Forming Units
mg N kg^{-1}	Concentration of nitrogen
µS cm^{-1}	Electrical Conductivity
µm	Micrometer
µmol photons m^{-2} s^{-1}	Power
nm	Wavelength

CHAPTER 1 INTRODUCTION

1.1 PREAMBLE

This chapter presents a generic overview of the waste management issues, legislations in-place, developments of compost quality standards and potential markets for composted products. Drivers for the research along with the aims and structure of the thesis are also presented.

1.2 THE MUNICIPAL WASTE ARISINGS

The United Kingdom (UK) in the year 2005/06 produced 35.1 million tonnes of total municipal waste, of which only 9.4 million tonnes was recycled/composted. It can be seen in Figure 1.1, that a large quantity (73%) of municipal waste was not recycled/composted during the same time period (2005/06), however, the rate of recycling and composting has shown a significant increase from 6% (1.9 million tonnes) in 1996/97 to 27% (9.4 million tonnes) in 2005/06 (Defra, 2007). This shows that the composting industry has grown tremendously in recent years and now there is a need to develop an industry-wide understanding of this sector in order to help composters to produce defined and certified quality compost, which is a key factor for developing the future market.

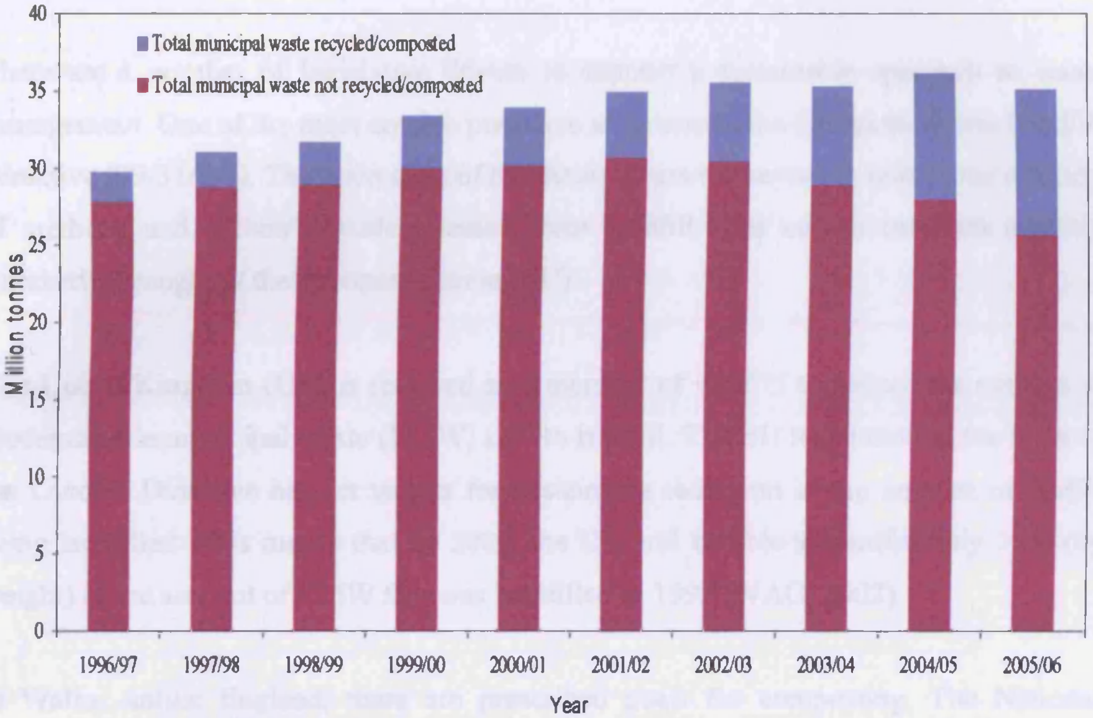


Figure 1.1 The UK municipal waste arisings from 1996/1997 to 2005/2006
(Data from Defra, 2007)

According to Friends of the Earth Trust, UK (2002), municipal solid waste (MSW) collected by the local authorities every year was composed of 60% biodegradable material, while the Welsh Assembly Government reported a figure of 64% (WAG, 2002). Biodegradable waste commonly consists of kitchen waste, green-waste, paper and cardboard. If this portion of municipal waste is sent to landfill, it will decompose anaerobically and release methane as a by-product (a potential greenhouse gas). There are many other issues associated with landfilling of biodegradable waste such as production of leachate, propagation of pests and pollution of soil and air. This also leads to the waste of potential recyclable goods and the refuse-derived fuels (RDF). However, by adapting composting /anaerobic digestion and effective kerbside organic collection schemes, the amount of biodegradable waste sent to the landfill can be reduced significantly.

1.3 THE WASTE MANAGEMENT LEGISLATIONS

There are a number of legislative drivers to support a sustainable approach to waste management. One of the most notable pressures at present is the European Union Landfill Directive (99/31/EC). The main aims of the directive are to prevent or reduce the quantity of methane and carbon dioxide released from landfill sites and to establish uniform standards throughout the European Union (EU).

The United Kingdom (UK) is required as a member of the EU to reduce the amount of biodegradable municipal waste (BMW) sent to landfill. The EU legislation in the form of the Landfill Directive has set targets for sustainable reduction in the amount of BMW being landfilled. This means that by 2020, the UK will be able to landfill only 35% (by weight) of the amount of BMW that was landfilled in 1995 (WAG, 2002).

In Wales, unlike England, there are prescribed goals for composting. The National Assembly for Wales, has set a target of at least 15% of the country's total municipal solid waste to be composted by 2010 (WAG, 2002). This equates to approximately 0.35 million tonnes of biodegradable material, representing a threefold increase on current composting practices, if the amount of municipal solid waste continues to rise at 3% per annum. The Composting Association, UK, conducted a survey on the state of composting and biological waste treatment in the UK in 2004/05. It indicated that across the UK, this industry has grown significantly, increasing from 1.97 million tonnes in 2003/04 to 2.67 million tonnes in 2004/05, representing a 35% increase and more than two-and-a-half times the amount of waste composted in 2000/01 (Gilbert, 2006). This shows that the UK composting industry is heading in the right direction. However, in order to meet EU Landfill Directive targets, it will have to increase the amount of waste processed drastically.

1.4 COMPOST QUALITY ASSURANCE

With the drive to meet the EU Landfill Directive targets, many local authorities are using the composting process to remove the biodegradable fraction from the waste stream. The quality of the compost must be a function of the collection mechanism and input material. However, to actually meet the Landfill Directive many authorities have realised that organic waste other than green waste will need to be collected to meet the composting target, like those for instance, that are set by The Welsh Assembly Government (WAG). Furthermore, with several outbreaks of large-scale animal diseases in the UK, the government has introduced an additional regulation called the Animal By-Product Regulations (ABPR, 2003). This has forced the compost producers to develop processes such as in-vessel composting other than the traditional windrow composting to treat BMW.

The quality issues are fundamental to the acceptance of the composted products in the market place and therefore quality assurance is of crucial importance. Hence, a more defined understanding of the critical parameters is required. However, in order to meet this perceived need, The Compost Association, UK and Waste and Resources Action Programme (WRAP), UK have funded the British Standard Institution (BSI) to produce the compost quality standard "Publicly Available Specification" (PAS-100) for composted materials and growth related parameters, which was updated in 2005.

In early 2007, the Business Resource Efficiency and Waste (BREW), WRAP and the Environment Agency, UK developed a Compost Quality Protocol in consultation with the industry and other regulatory stakeholders. This Quality Protocol sets out control procedures for the production and the use of quality compost from source-segregated biodegradable wastes such as food waste and green waste. The main aim is that by following standards in the protocol, compost producers will no longer have to class their end-product as waste-derived compost and it will not be subjected to further waste regulations. This practice will increase consumer confidence and will also protect the environment and human health (Gilbert, 2006). It is thought that the launch of the Quality Protocol is likely to encourage further growth in the production of composted product and will increase the use and purchase of quality compost.

1.5 MARKETS FOR COMPOSTED PRODUCTS

There is a strong connection between quality assurance and markets for composted products and their intended application. Developing markets for composted product is a key issue and is dependent on establishing consumer confidence as well as manufacturing the correct grade that is suitable for the specific sector, therefore, along side quality, understanding of the range and size of the potential markets will be vital to the commercial compost producers.

However, market analysis over recent years suggests that both producers and users have the opinion that sustainable recycling of organic wastes demands clear regulation regarding what is the required material to recycle and how it should be managed and controlled. In order to provide a guideline, The Composting Association, UK (2003), published a recommended range for different compost parameters (pH, electrical conductivity, moisture content, organic matter content, particle size and carbon to nitrogen ratio) for potential markets and end-user groups. This activity was carried out in conjunction with The Composting Association, UK, BSI PAS-100. The Waste and Resource Action Programme, UK (WRAP, 2003) has also published a series of guidelines for the use of compost in various market sectors and The Welsh Assembly Government (WAG, 2002) indicated the realistic estimates of achievable market penetration for composted products in Wales, which are defined alongside the UK total potential markets. For example, in the UK the combined market for the agricultural and horticultural sectors is up to 11 million tonnes, of which about 129,000 tonnes is in Wales (Ali et al. 2005). This tends to be the bulk market sector with a price of up to £10 per tonne and is seen as the low value end of the market. In Wales, it is expected that 30,000 tonnes of compost will have to be produced in excess from source-segregated green and organic material by 2010. This will produce over 150,000 tonnes of saleable compost product, so clearly there will be a need to maintain a balance between supply and the potential demand.

The vermiculture and vermicomposting sector is one that is attracting much attention both at the national and global scale as an alternative waste treatment system (Eastman et al. 2001). In Wales, the potential estimated market for vermicompost is 30,000 tonnes per annum (WET, 2002). The market acceptance of vermicompost is greater than that of compost, apparently based on its better visual aspects (Subler et al. 1998, Ndegwa and Thompson 2000 and Tognetti et al. 2005), higher nutrient content and increased microbial activity (Mulogoy and Bedoret 1989, Logsdon, 1994 and Ganeshamurthy et al. 1998).

1.6 THE RESEARCH DRIVERS

In the UK, most municipal green waste is composted using the traditional windrow method. However, a lack of research exists with regards to its quality improvement. Therefore, this research has been undertaken to assess if quality could be enhanced using vermicomposting and air separation techniques of mature green waste compost.

1.7 AIMS AND THESIS STRUCTURE

The objective of this research was to examine if value could be added to the mature green waste compost using both biological and physical techniques, with particular reference to vermicomposting and air separation. Commercially sold, mature green-waste compost (<10 mm, particle size) produced at The Carmarthenshire Environmental Resource Trust (CERT) composting facility located in West Wales, UK, was utilised as a test product.

Chapter 2 presents a comprehensive review of relevant literature carried out on the composting process followed by an in depth analysis of the vermicomposting process and air separation techniques including air classification and air jigging.

Chapter 3 presents materials and methods utilised during the vermicomposting and plant growth trials. It also describes the methodology used for the compost contaminant characterisation along with the laboratory and commercial scale air separation techniques.

Chapter 4 contains the various results obtained during vermicomposting process and discusses the findings.

Chapter 5 highlights results on the replicated growth trials on coriander, tomato using various composted product. It also presents and discusses the results of lettuce growth trial.

Chapter 6 provides results obtained from compost contaminant characterisation studies on unscreened mature compost samples to identify the physical contaminants.

Chapter 7 summarises the various conclusions that may be drawn from the study and provides recommendations for further research.

CHAPTER 2 LITERATURE REVIEW

2.1 PREAMBLE

Quality assurance is fundamentally important in the composting process and appropriate compost quality should be among the primary goals of composting facilities. While, much work has been done on the production and use of compost, this literature review outlines approaches to enhance the quality of compost by giving a general overview of composting and an in depth review of vermicomposting and air separation techniques. It concludes by analysing the importance of these techniques for the separation of a major portion of the physical contaminants from the resulting compost to get a better-quality end product.

2.2 COMPOST QUALITY

The physical and chemical characteristics of composts depend primarily on the type of feedstock utilised. The presence of physical and chemical contaminants can have a negative impact on the quality and the marketability of the end-product. In the UK, under the current guidance of the Waste and Resource Action Program (WRAP) and under the umbrella of BSI Publicly Available Specification (PAS-100:2002) for composted material updated in 2005 (BSI PAS-100:2005), compost producers are required to meet the limits of various important parameters as stated in Table 2.1. Also, as people in a community gain greater awareness of the health and environmental safety issues associated with compost production and use, compost producers are likely to come under increasing pressure to provide an authenticated form of quality assurance to the consumers.

Table 2.1 Minimum compost quality requirement to meet BSI PAS-100

Parameter	Upper Limits	Method
Human Pathogens (Indicator species) Salmonella spp	Absent in a fresh sample of 25g	ABPR 2003, Schedule 2, Part II or BS EN ISO 6579
Escherichia Coli	Less than 1000 CFU g^{-1}	BS ISO 11866-3
Potentially Toxic Elements (PTE's)	All Units mg kg^{-1} dry matter	
Cadmium (Cd)	≤ 1.5	BS EN 13650 (aqua regia extractable)
Chromium (Cr)	≤ 100	BS EN 13650 (aqua regia extractable)
Copper (Cu)	≤ 200	BS EN 13650 (aqua regia extractable)
Lead (Pb)	≤ 200	BS EN 13650 (aqua regia extractable)
Mercury (Hg)	≤ 1	BS ISO 16772
Nickel (Ni)	≤ 50	BS EN 13650 (aqua regia extractable)
Zinc (Zn)	≤ 400	BS EN 13650 (aqua regia extractable)
Stability/maturity	16 mg CO_2/g organic matter/day	ORG0020
Plant response	Plant germination and growth test: Reduction in germination of plants in amended compost as % of germinated plants in peat control (20 %). Reduction of plant mass above surface in amended compost as % of plant mass above surface in peat control (20%).	According to annex D BSI PAS-100:2005
	Description of any visible abnormality (No abnormality present)	
Weed seeds and propagules	Germinating weed seeds or propagules re-growth shall not exceed a mean of 0 per litre of compost	According to annex D BSI PAS-100: 2005
Physical contaminants Total glass, metal and plastic and any 'other' non-stone fragment >2 mm	$\leq$ 0.5% m/m of air-dried sample, of which $\leq$ 0.25% is plastic	According to annex E BSI PAS-100: 2005
Stones Stones >4 mm in grades other than mulch	$\leq$ 8 % m/m of air-dried sample	According to annex E BSI PAS-100: 2005
Stones >4 mm in 'mulch' grade	$\leq$ 16 % m/m of air-dried sample	According to annex E BSI PAS-100: 2005

Adapted from the Publicly Available Specification (BSI-PAS100:2005) for composted materials, The Composting Association, UK, Standards.

2.3 GENERIC OVERVIEW OF COMPOSTING

2.3.1 DEFINITION

A number of researchers have defined composting differently. Golueke (1972) defined composting as the biological decomposition of the organic constituents of waste under controlled conditions. This allows for a large number of descriptions to be applied to composting systems, including the technological basis, management regimes and temperatures. According to Haug (1993), composting is the biological decomposition and stabilisation of organic substrates under circumstances that allow the development of thermophilic temperatures as a result of biologically-produced heat.

In composting, various micro-organisms including bacteria (actinomycetes) and fungi (moulds and yeast) break down organic matter into simpler substances. Studies directed by Bryson (2003) stated that there are currently about 5000 known types of bacteria and 70,000 types of fungi. The effectiveness of the composting process depends on the environmental conditions present within the composting system i.e. oxygen, temperature, moisture, organic matter and the size and activity of the microbial population. The composting process also results in the release of carbon dioxide (CO_2), water and heat as by-products (NRAES, 1992).

2.3.2 FACTORS AFFECTING COMPOSTING

Polprasert (1989) explained that the succession in temperature during composting is due to a series of events. Composting is regarded as having initially a thermophilic phase during which there is a rapid temperature increase, with temperatures reaching the range of 45 °C to 85 °C. As the rate of microbial activity declines, the thermophilic phase is replaced by a lower-temperature phase (the mesophilic phase) in which temperatures are in the range of 20 °C to 45 °C. The growth rates of micro-organisms that carry out composting are generally divided into two categories (thermophiles and mesophiles) based on temperature tolerance. Strom (1985) investigated the effect of temperature on a diversity of species within a composting system and concluded that the temperatures above 60 °C had a marked detrimental effect, whereas Droffener et al. (1995) showed that, even in composts sampled at temperatures above 60 °C, the bacteria strains that had been classed as mesophiles were identified, implying that these bacteria have the ability to survive and possibly reproduce, even at elevated temperatures.

Composting can operate at oxygen levels as low as 10%, which is about half the normal concentration in air. Metcalf and Eddy (2002) stated that the composting process can be inhibited at oxygen levels below 10% and in order to ensure that the material is composting, it may be necessary to supply air to the system. Below 10% oxygen, the system tends to become anaerobic and it may produce methane (Druilhe et al. 2002) and cause problems with odorous gases and the formation of leachates that can contaminate ground water.

The moisture content has been shown to affect the other properties of the composting materials as well. Mears et al. (1975) showed that both the thermal conductivity and specific heat capacity of compost are linearly proportional to its moisture content. Organic materials have a wide range of moisture contents but the range for composting, expressed as a percentage of total weight is 50 to 60 % (w/w) moisture. Levels below 45% will inhibit microbial growth, while excess water, above 70 %, will inhibit the flow of air (Edwards et al. 1998). Furthermore, moisture content and the fragment size of the composting materials will collectively determine the free air space in the mass and therefore determine the availability of air and its flow patterns. Small particles have the advantage of increasing the surface area that is accessible to the microbes but if the particle sizes are too small, air flow will be inhibited. The best range of particle size has been shown to be between 3 and 50 mm in diameter, depending on the type of material and its bulk density (Edwards et al. 1998).

In composting, the microbes use carbon for energy and nitrogen for protein synthesis. The microbes can do their work when the average C:N ratio is approximately 25:1 but the ideal ratio for composting has been found to be 30:1 (measured on dry weight basis) (Edwards et al. 1998). This ratio governs the rate at which the microbes decompose organic waste, because with higher carbon content, the process will take longer and nitrogen becomes limiting. Conversely, if excess nitrogen is present, ammonia may be formed, creating an odour problem. Most organic materials do not have an ideal C: N ratio. Therefore, to accelerate the composting process, it may be necessary to alter the ratio (Stentiford and Lasaridi 2000).

2.3.3 COMPOSTING METHODS AND TECHNOLOGIES

2.3.3.1 Windrow Composting

Windrow composting consists of placing the mixture of raw materials in long, narrow piles known as windrows. These are generally 3 to 6 m wide and 3 to 4 m high and they are agitated or turned on a regular basis using a front-end loader or windrow turner. The size of the windrow depends on the bulk density of the material to be composted and on the equipment to be used for turning. Windrows aerate primarily by natural or passive air movement, i.e. convection and gaseous diffusion. However, aeration is affected significantly by the particle size and porosity of the material comprising the windrow. Therefore, in order to effectively aerate a typical-sized windrow, it is important to determine the porosity of the material (NRAES, 1992). Windrows made from materials that have lower bulk densities, such as green waste, can be larger than a wet, dense windrow that is comprised of manure or other mixed feedstocks. Both initial mixing and frequent turning of the windrow can supplement the oxygen for the microbes, re-establish the desired porosity and release trapped heat, water vapour and other gases. Additionally, turning and mixing reduces the potential for pockets of anaerobic decomposition in areas that are too moist or too rich in nitrogenous substrate (McClintock, 2004). Furthermore, turning and mixing exposes all material equally to the air, releases hot gases and disperses the moisture that accumulates in the core of the windrow. Thus, in this way, all of the material is composted evenly. In addition, raw materials are blended well and particle sizes are reduced, which increases the surface area (NRAES, 1992).

2.3.3.2 Static Pile Composting

The simplest form of the static pile system of composting consists of a stacked pile of shredded organic waste that is left to decompose by means of natural biological breakdown (Wright, 2002). The substrate can be mixed with a bulking agent, such as woodchips, which provides structural stability to the material and maintains air voids without the requirement of periodic agitation (Haug, 1993). Therefore, no agitation or mixing/turning is required during the compost cycle once the pile is on the batch basis. The static pile may be improved by using a water pipe system situated on top of the pile, over which a flexible, non-porous cover is placed. These modifications help to reduce the natural convection of air through the waste material, which helps to maintain the elevated temperatures and maintains adequate moisture content. In turn, this facilitates greater process control and increases the rate of decomposition. Aerated static piles involve the introduction of a network of perforated pipes placed at the bottom of the waste material or laid in the flooring beneath the pile. Forced aeration is introduced at a controlled rate to aid aerobic decomposition and maintain temperature (Tyrrel et al. 2001).

2.3.3.3 In-vessel Composting

In order to meet the targets of the European Landfill Directive (European Commission, 1999), biodegradable and/or difficult wastes (catering waste) would need to be diverted from landfills. Furthermore, with several large-scale outbreaks of animal diseases in the UK, the government has introduced an additional regulation called the "Animal By-

Product Regulation" (ABPR, 2003), which has forced local authorities to employ new technologies. In-vessel composting is one such technology that has the potential to meet these targets. The term 'in-vessel composting' has been adopted to cover a wide range of composting systems, from enclosed halls to tunnels and containers. The common feature is that the material being composted is contained so as to allow a higher degree of process control such as forced aeration rather than just aeration by mechanical turning (Edwards et al. 1998). In-vessel systems control and accelerate decomposition by creating ideal conditions for the microbes by bringing the compost mixes up to the optimum temperature as quickly as possible. Prior to 2003, there were a number of in-vessel composting systems available but little data were available for choosing the appropriate system for a given application (Walker et al. 1986). In-vessel systems can be categorised broadly into five different types according to their design and structure (Edwards et al. 1998), i.e. containers, silos, agitated bays, tunnels, enclosed halls and rotary composting systems.

Container systems range from transportable metal containers to static concrete boxes. Their capacities range from 30 to 80 cubic metres for transportable containers and up to 180 cubic metres for static containers (Edwards et al. 1998). The modular nature of these systems allows a wide range of compost volumes to be processed. Transportation enables containers to be stored at separate sites and some container systems can be stacked to reduce the space required. Some containers process in batches and some in a continuous flow. Continuous flow systems use mechanical agitation of the waste and are usually loaded by a conveyor belt, while batch systems are usually loaded and unloaded with a front-end loader. Notton (2005) and Hewings (2007) monitored a batch containerised in-vessel composting system in order to see if this technology could be applied to meet the Animal By-Products Regulations. These systems were investigated using green waste, citrus waste and catering waste in different combinations. Myrddin (2003) calculated that the throughput of the containerised vessel varied from 17 and 46 kg m^{-2} $week^{-1}$. Notton (2005) showed that the containerised vessel, even with insulation added, did not reach a temperature high enough to meet the ABPR (2003) targets and concluded that in order to achieve the required standard of sanitisation, an appropriate aeration and process control would be essential.

Silos or vertical composting units (VCU) can be divided into dynamic and plug flow types. Dynamic silos operate in batches and agitate the waste with paddles or augers. High mixing rates allow this system to manage wet wastes, provided an amendment material, such as wood chips, is added. In plug flow systems, waste is stacked into a tower and descends under its own weight as the composted material is removed at the base. This type is used for drier wastes because there may be a danger of compaction with wet wastes. Some silos may include a second curing reactor to mature the compost, rather than using a windrow system. Myrddin (2003) compared a variety of in-vessel composting systems using manufacturer's data for capacity, footprint and residence time within the composters. It was found that the highest throughput, in kilograms m^{-2} $week^{-1}$, was achieved by a vertical composting unit. However, the area required for maturation of the compost post-treatment was not included in this calculation.

Agitated bays consist of rows of rectangular beds, in which the compost is retained between the two walls. A turning and shredding machine either straddles the walls or, where there are a number of bays, runs along a rail at the top of the walls. The machine mixes the compost and deposits it further along the bay. Both approaches provide aeration and move the compost through the system in a continuous flow. In addition to this, forced aeration can also be provided through ducts in the floor. The agitated bed reactor can be operated in either plug flow mode or batch operation mode. In the batch operation mode, the vessel is loaded with raw waste and bulking agent, processing takes place and the vessel is emptied.

Concrete tunnels operate either as 1) continuous flow systems in which the compost is pulled through the tunnel on a mat or 2) batch systems in which the compost is loaded and unloaded through the same entrance by a conveyer or front-end loader. Forced aeration is provided through ducts in the floor. A recent adaptation of the tunnel concept is the bag system. High-tensile strength polythene is used to create a tunnel. Shredded waste is packed into the tunnel, which gradually unfurls as the loading equipment moves forward. Aeration is supplied by tubing laid inside the tunnel and venting pipes are attached to valves in the tunnel walls or roof.

In enclosed halls systems, materials are composted on the floor of the hall and are usually contained in one long bed. The whole composting process tends to occur in the same hall, with a large bucket wheel being used to turn and move the material through the system. Aeration is achieved with either positive or negative pressure. In positive pressure systems, the air from the reception area is forced through the compost and is also re-circulated within the composting hall and exhausted to a biofilter. The negative pressure system sucks the air through the compost and passes it to a biofilter that limits the air movement directly into the environment. Both types of halls have the overall effect of reducing pressure in the building as a whole.

In-vessel rotary composting is simply defined as composting in a slowly rotating drum (see Figure 2.1). The drum is usually heat insulated on the external diameter. In a rotary composter, a wide range of organic waste, such as poultry manure, dead poultry, cow manure and pig manure, can be mixed with the green waste or MSW to adjust the carbon to nitrogen (C:N) ratio. Water can also be added to balance the moisture content of the process.

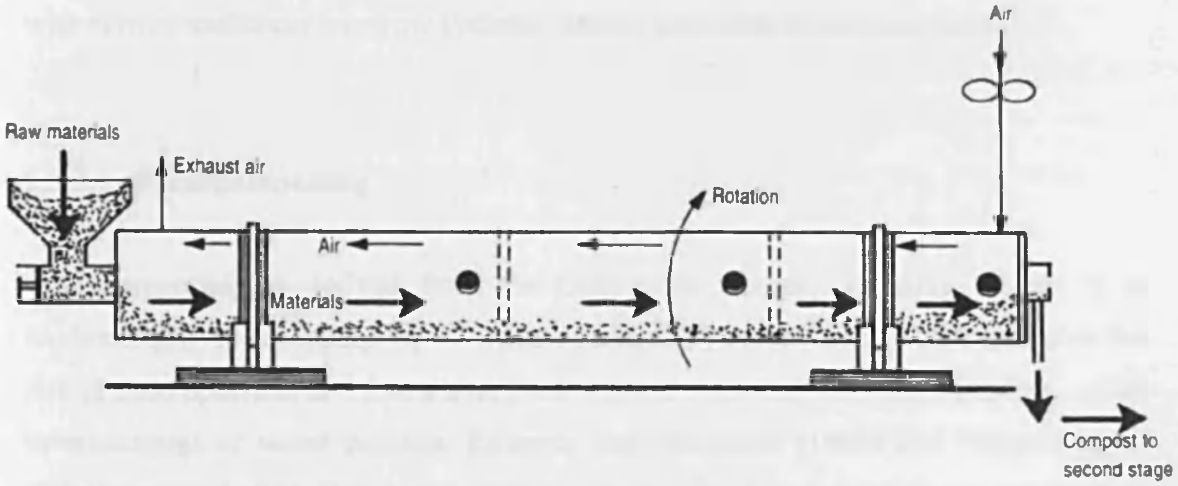


Figure 2.1 Rotating drum composter (copied from Bedminster Bioconversion)

In practice, the rotating vessel is usually a component of the complete process. It includes sorting, shredding, treatment (reactor), screening and reloading. Generally, these are used as a pre-treatment process, where additional maturation and screening processes are required. The process can be continuous or batch and aeration is undertaken using natural or forced systems. Some vessels are inclined at an angle to achieve better mixing and to avoid an uneven pocket that could interfere with the aeration process. The speed of drum rotation is slow, typically four turns per hour. Typical residence time is three days, assuming the temperature regime requirement has been met, after which the material is unloaded and stockpiled for at least another two or three weeks for stabilisation using either windrowing or static piles. Thereafter, a further period of maturation is required.

Ali et al. (2004) carried out a detailed comparison of rotary in-vessel composting systems. Processing capacities of the systems were calculated using data available from manufacturers as well as three-week stabilisation in a windrow with dimensions of $2.5 \times 5 \times 15$ m. It was found that the throughput ranged between 150 to 200 kg m^{-2} $week^{-1}$. Therefore, it was concluded that the rotary in-vessel systems, compared to other in-vessel technologies, had higher throughputs and are the fastest type of composting available today, likely due to the short residence time. Further detailed analysis is required to see if this system would comply with the current ABPR (2003). However, the rotary in-vessel system does offer a considerable potential to meet a range of regulations, when combined with current traditional windrow systems, thereby providing operational flexibility.

2.3.3.4 Vermicomposting

Vermicomposting is derived from the Latin term 'vermis', meaning worms. It is fundamentally the consumption of organic material by earthworms, which enhances the rate of decomposition and forms a nutrient-rich and microbial-active end product, called vermicompost or worm castings. Edwards and Neuhauser (1988) and Ndegwa et al. (2000) reported that that worm cast is an excellent soil conditioner since it is homogenous, has desirable aesthetics, reduced level of contaminants and enhanced water-holding capacity. For many years, earthworms have been used as a source of decomposing organic wastes and improving the composition of the soil. A large numbers of businesses throughout the world are successfully employing vermicomposting technology and marketing vermicompost as an excellent soil enhancer to farmers and gardeners. The breeding and production of earthworms and the use of worm casts have become vital components of the waste recycling industry worldwide. For example, Japan imports millions of tonnes of earthworms per year for conversion of organic wastes into vermicompost. Vermicomposting is set to emerge as an important waste management tool. Composting worms serve as natural bioreactors and they can conduct their work throughout the year, as long as the environmental conditions remain within favourable limits. For improved performance, it is necessary that organic feedstock and conditions allow the worms to reproduce successfully and to endure changes in climate and moisture. Providing appropriate conditions, vermicomposting appears to be a relatively simple solution to the management of certain compostable organic wastes.

2.4 VERMICOMPOSTING IN DETAIL

2.4.1 TEMPERATURE

Temperature values and changes in temperature will affect the success of all of the activities of vermicomposting process, which is a bio-oxidation and stabilisation process of organic material that, in contrast to composting, involves the joint action of earthworms and micro-organisms (Dominguez et al. 1997). Compost worms are the agents of turning, fragmentation and aeration of waste, resulting in the production of a homogeneous and stabilised humus-like product. They cannot tolerate temperatures above 35 °C (Edwards, 1995) and as a consequence, the microbial processes are not the same as conventional composting in which the optimal temperature range is 45-65 °C (see Section 2.3.2). Vermicomposting does not achieve high temperatures but sometimes, prior to adding the worms, a thermophilic stage is used to kill insects and pathogens (Frederickson et al. 1997).

In the literature, there is a wide range of species that have proven to be effective as composters but the range of species actually studied is limited. The study conducted by Appelhof (1997) explained that red worms (*Eisenia fetida*) feed most rapidly and convert waste best within the temperature range of 15-25 °C. It was further added that they can also work at temperatures as low as 10 °C but temperatures at or below 0 °C and above 30 °C are lethal for them. Sherman (2000) also suggested that vermicomposting using red worms should take place at mesophilic temperature (13-30 °C) and that getting piles too hot will drive worms away. This was further affirmed by Tognetti et al. (2005), who claimed that temperatures above 30 °C can eradicate the worms. Moreover, the vermicomposting process temperature is not high enough to kill pathogens acceptably and hence the product does not pass the U.S. EPA's rules for pathogen reduction as reported by Alidadi et al. (2005) using *E. fetida*.

Various researchers have reported that the choice of species for use in vermicomposting depends largely on temperature. Ashok Kumar (1994) stated that *E. fedita*, *Eudrilus eugeniae*, *Perionyx excavatus* and *P. sansibaricus* are better suited to the southern region of India than to the northern areas because of the low temperature in summer. Another research project in India (Shanthi et al. 1993) also used three species of earth worms, namely *Metaphire posthuma*, *Eisenia* Species and *P. excavatus* in the degradation of vegetable waste. They suggested that *P. excavatus* was able to withstand greater ranges of moisture and temperature than other species and thus was the best suited for use in vermicomposting. In contrast to this, some researchers (Reinecke et al. 1992, Edwards and Bater, 1992, Loehr et al. 1985) argued that *E. fetida* had a wider tolerance for temperature and moisture. Moreover, Reinecke et al. (1992) added that *E. fetida* can tolerate temperatures as high as 42 °C and as low as 5 °C when compared to *E. eugeniae* and *P. excavatus*. Edwards and Bater (1992) observed that the highest growth rate of the worms occurred at 30 °C and 85% moisture content and that the maximum number of cocoons hatched at 20 °C, which was considered optimum growth temperature for *E. fetida*. Similarly Loehr et al. (1985) contributed that *E. fetida* is an appropriate specie to be used in the vermi-stabilisation process, since it had the greatest overall reproductive capacity, the best production of cocoons and the best growth rate in the temperature range of 20 to 25 °C. It was also reported that, by using aerobically digested sewage sludge, the same temperature range (20-25 °C) appeared best for reproduction and growth of *Dendrobaena veneta, Eudrilus eugeniae, P. excavatus* and *Pher hawayana,* as well. Further investigations conducted by Edwards et al. (1998) showed the effect of temperature and various organic feedstocks on the growth and reproduction of *P. excavatus*. Their results showed that increasing the temperature up to 30 °C accelerated the growth rate and reduced the time to sexual maturity with 50% of the clitellate earthworms forming after four weeks of experimentation. In addition to this, the highest reproduction rates occurred at 25 °C with a feedstock of both cattle solids and sewage sludge.

Frederickson et al. (1997) also stated that the optimum range for culturing *D. veneta and E. fedita* is considered to be around 15 to 25 °C. Somewhat similar results were obtained by Fayolle et al. (1997), which showed that 10, 15, 20 and 25 °C temperatures were suitable for growth and cocoon production of *D. veneta* and suggested that, at 10 °C, this specie has a very long life cycle. They further explained that with an increase in temperature from 10-15 °C to 20-25 °C, development time was considerably reduced.

Vermicomposting systems operating at lower ambient temperatures of 6.3 ± 2.3 °C showed lower earthworm reproduction rates, when compared to those operating at the moderate temperature of 13.7 ± 0.8 °C, where significantly increased worm reproduction rates have been identified by Frederickson and Howell (2003). They further added that vermicomposting is the joint action of earthworms and the aerobic micro-organisms that flourish and decompose the waste at these lower temperatures (mesophilic conditions). Hence, it is common with vermicomposting systems to apply waste frequently in form of few centimetres thick layer to reactors, containing earthworms in order to prevent thermophilic conditions and to help keep the waste aerobic.

2.4.2 MOISTURE CONTENT

Feedstock moisture content is one of the critical factors to consider during vermicomposting, especially when deciding what proportions of various materials (feedstock) are to be mixed. An appropriate moisture content is also necessary to support the metabolic processes of the microbes. Earthworms breathe through their skins, which must be moist for exchange of air and excretion of waste to take place. If necessary, one can add water to dry bedding and feed. Appelhof (1997) suggested that too much moisture present as stagnant water in the reactor can reduce available oxygen and cause worms to drown. According to some researchers (Edwards, 1995 and 1998, Neuhauser et al. 1988, Kaushik and Garg, 2003), in order to achieve optimum conditions, moisture content should be maintained within the range of 70-90% (w/w). However, studies conducted by Frederickson et al. (1997), and Bansal and Kapoor (2000) successfully performed vermicomposting by using lower moisture contents of 66 ± 2% and 60%, respectively.

It seems likely that, in order to maintain optimum moisture conditions during vermicomposting of different materials, moisture content can be altered by adding either water or mixing certain types of materials (e.g. sawdust, cardboard) to the feed material. Suthar (2007), Garg et al. (2006) and Maboeta and Rensburg (2003) vermicomposted biodegradable waste, partially composted waste, woodchips and sewage sludge in different combinations and maintained moisture contents of 65-70%, 55-60% and 70% respectively, by periodically sprinkling the mixture with an adequate amount of water. In contrast to this, Marsh et al. (2005) used a mixed feedstock of aquaculture sludge and cardboard for regulating the moisture content from 95% to 80%. However, Alidadi et al. (2005) adjusted the moisture content of the sewage sludge (80%, w/w) to 60% by adding sawdust prior to vermicomposting.

Research has also been conducted to observe the effects of moisture content on various earthworm species. Muyima et al. (1994) suggested that maintaining moisture content in a range of 77-79% suits *D. veneta*, whereas, *E. eugeniae* and *P. excavatus* performed better within the range of 80-82% and at 81.8%, respectively. It was further noted that since *E. fetida* can tolerate lower moisture levels, between 65-75%, it is most successful for the vermicomposting process. In contrast to this, Loehr et al. (1985) used *E. fetida* to vermicompost aerobically digested sewage sludge and suggested that when the moisture content is kept within the range of 84-91%, it performed better and showed enhanced overall reproductivity after 20 weeks of breeding study. However, Dominguez and Edwards (1997) examined the growth of *E. andrei* in a mixture of pig manure and maple leaves at different moisture levels (65, 70, 76, 80, 85 and 90%) and reported a direct relationship between moisture content and growth rate. Furthermore, their results showed that the maximum growth occurred at a moisture content of 85%.

2.4.3 FEEDSTOCKS

Earthworms will consume animal manures, compost, food scraps, shredded or chopped cardboard or paper, almost any decaying organic matter or waste product. However, excellent feeds are horse, rabbit, swine, dairy, or steer manures, whereas, poultry manure is not recommended as it is too high in nitrogen and mineral matter (Edwards, 1998 and Slocum, 2002). Many researchers (Loehr et al. 1985, Maboeta and Rensburg 2003 and Alidadi et al. 2005) have studied the use of earthworms to digest sewage sludge.

Recent studies (Sharma et al. 2005) showed that a variety of organic solid wastes, including domestic, animal, agro-industrial and human wastes can also be vermicomposted. It was suggested that the first step in vermiculture is to select suitable feed materials for earthworms, which can be nitrogen-rich material such as cattle dung, pig manure, poultry manure, or some other organic material such as leguminous agro-waste with a C:N ratio of less than 40. Similarly, Marsh et al. (2005) used mixed aquaculture effluent and cardboard. They reported that maximum growth of *E. fetida* was observed by increasing the percentage of aquaculture sludge up to 50 %, equating to a

C:N ratio of 98:1. In contrast to this, Ndewga and Thompson (2000) claimed that an optimum C:N ratio of 25:1 is more suitable for the growth of *E. fetida*.

Suthar (2007) utilised different biodegradable waste categories (crop residue, farm-yard manure consisting of cattle excreta, discarded cattle feedstock, vegetable market waste and household waste) amended with animal manure in different ratios to evaluate the efficiency of *P. sansibaricus* for vermicomposting. They reported an increase in organic C, total N and available phosphorus and potassium after vermicomposting of all used substrates. Moreover, their study indicated that the end product had a lower C:N ratio, when compared to the initial ratio. Similarly, Garg et al. (2006) mixed kitchen waste, agro-residue and institutional waste separately with the cow dung and soil in the ratio of 6:3:1 (dry weight basis). Furthermore, the mixture was partially decomposed for 15 days, followed by vermicomposting using *E. fetida* for 85 days. Their results showed lower organic carbon and pH in the product and suggested that this was due to the production of CO_2. However, an increase in the electrical conductivity, along with total N, P and K, was also reported and it was concluded that the worm casts obtained from the textile industrial waste had the highest N and P content, when compared to the institutional waste, agro-residue and kitchen waste.

A study conducted by Elvira et al. (1998) indicated that paper mill sludge usually has a nitrogen deficiency that precludes effective vermicomposting so in order to obtain an appropriate C:N ratio and to provide an inoculum of micro-organisms, a mixture of nitrogen-rich organic waste is usually required. A study was conducted on the life cycle of *D. veneta* by Fayolle et al. (1997) at four different temperatures (10, 15, 20 and 25 °C) with horse manure, brown peat mixture and aerobic paper sludge as feed materials. It was claimed that worms fed on paper sludge (C:N ratio 45) showed a two-fold increase in growth rate and cocoon production compared to those fed on horse manure (C:N ratio 25) because of the difference in the C:N ratios of the sludge and the horse manure.

Atiyeh et al. (2000c), Kaushik and Garg (2003) studied vermicomposting of cow manure using *E. andrie* and *E. fetida*. They reported a reduction in the C:N ratio from 36 to 21 and 69 to 26, respectively and linked this to a rapid breakdown of carbon compounds (reduction in CO_2) and mineralisation of nitrogen (increase in total nitrogen content) during vermicomposting. Pittaway (2001) composted pig manure both with and without *E. fetida* and observed a volume reduction of 12 % and a reduction in the amount of organic carbon with worms. Moreover, it was shown that no increases in available P, N, and K were observed and it was suggested that this might be due to the fact that sorghum was fed to the animal as a feed material.

Loh et al. (2005) studied the growth and reproduction of *E. fetida* using cattle and goat manures. They were of the view that cattle manure provided a better environment for the earthworm to grow and produced a higher value of vermicast than goat manure because the C:N ratio in cattle manure was higher than in goat manure. Bansal and Kapoor (2000) analysed vermicomposting of mustard residue and sugarcane trash mixed with cattle dung and reported a significant reduction in C:N ratio and an increase in mineral N after three months. In light of all the above discussion, The Composting Association, UK (2004), concluded that earthworms will process more waste and reproduce more quickly when fed with fresh, finely-shredded organic materials containing a carbon-nitrogen (C:N) ratio in the range of 15:1 to 35:1.

Research conducted by Wright (2002) indicated a maximum mass reduction of 86% during vermicomposting of fresh biodegradable materials (fruit and vegetables) and newspaper. However, a mass reduction of 49% was attained when composted, biodegradable, newspaper and green-waste were utilised as feed materials. This clearly demonstrates that the type of feedstock is crucial in controlling the vermicomposting process.

Work has also been done on comparing (Short et al. 1999) and combining vermicomposting and windrow composting (Frederickson et al. 1997) to attain the maximum benefits by combining thermophilic and mesophilic processes and to assess optimum time periods in each method (Nair et al. 2006). Haimi and Huhta (1986) suggested that vermicomposting as a secondary treatment after the traditional theomorphic phase is not a good option, since the nutritional value of the feed for worms would drop rapidly. Short et al. (1999) compared the use of both systems to process and stabilise waste paper sludge. They used *D. veneta* to process waste paper sludge using a stocking density of 4 kg m^{-2} and maintained at 20.8 °C for eight weeks followed by a four-week stabilisation period. Paper sludge (five tonnes) was also windrowed and maintained at a temperature of 50-60 °C for the first four weeks and at 30-40 °C thereafter for 12 weeks. They reported that windrow composting resulted in a larger overall nitrogen loss (70%) compared to vermicomposting (41%). Frederickson et al. (1997) suggested the benefit of a combined system to process green waste is to enhance rates of stabilisation along with the production of earthworms and vermicompost. They measured the reduction of volatile solids after vermicomposting pre-composted green waste for a period of eight weeks. They found that vermicomposting reduced volatile solid content up to 12% compared to the windrowed compost for the same time period. Nair et al. (2006) used a combination of thermophilic composting and vermicomposting to improve the treatment and efficiency, to assess the optimum time period required in each method to produce good quality compost. They used a combination of feedstock, which included 58% grass clippings, 24% shredded paper and 18% kitchen waste (lettuce, cabbage, oranges, tomatoes, mandarins, pears, apples and broccoli). The thermocomposting was carried out in a tumbler bin and a temperature of 55 °C was observed on the second day, the temperature stabilised at 25 °C after 10 days. They reported a mass reduction of around 80%. Initially, the moisture content of the material was in the range of 80-85% and after the process it was 70%. The overall results showed that the combination of nine days of thermocomposting followed by 2.5 months of vermicomposting was helpful in waste stabilisation, pH, moisture control and mass reduction. In addition to the above information, it was further suggested that vermicomposting had also reduced the concentration of pathogens.

2.4.4 STOCKING DENSITY

Stocking density is another parameter that has a significant influence on vermicomposting. It refers to the initial weight of worm biomass per unit area of reactor/ bedding. In the literature, various researchers have used a wide range of stock densities for their studies. Frederickson et al. (1997) observed a significant reduction in growth and reproduction of *E. andrei* with an increase in stocking density. During further studies Frederickson (2001) also estimated that the working density should range between 1 to 4 kg m^{-2}. Short et al. (1999) employed a density of 4 kg m^{-2} and Elvira et al. (1998) used 0.56 kg m^{-2} of stock density. Another research undertaken by Wright (2002) on vermicomposting of a combination of substrates (fruits, vegetables, shredded newspapers, green waste and composted biodegradables) used 3 kg m^{-2}, whereas Roberts (2005) vermicomposted in-vessel pre-composted green waste and biosolids using *D. veneta* at a stock density of 5 kg m^{-2}.

At present, there is little knowledge about how stocking density regulates population growth rate and to what extent. According to Frederickson (2005), optimum reproduction rate occurs at stock densities <1 kg m^{-2}. Therefore, stock density may not be limited to certain factors. However, Dominguez and Edwards (1997) claimed that early sexual maturity of earthworms occurs at higher stock densities. Moreover, a stocking density of eight *E. andrei* worms per 44 g dry matter of pig manure was found to be optimal for sexual development. Similarly, Gajalakshmi et al. (2001) explained that a high stocking density and a feed rate of 950 g for 250 worms per 3-litre (L) container produced 6.5 times more castings per unit reactor volume as compared to 750 g feed for 200 worms per 4 L.

Loh et al. (2005) suggested that in vigorously growing worm beds, feeding is required every 3-5 days with an optimal stocking density of 1.6 kg m^{-2} along with a feeding rate of 0.75 kg feed per day (Ndegwa et al. 2000). They further added that overfeeding must be avoided as it can lead to excessive fermentation in the bed and cause the worms to shrink and eventually die. Appelhof (1997) recommended the use of a worm to garbage (biodegradables) ratio of 2:1, based on the initial weight and on the average daily amount of garbage fed to the worms (e.g. 225g of garbage daily for 500 g of worms). However, Bansal and Kapoor (2000) employed 100 mature earthworms to vermicompost 10 kg (dry weight) of crop residue with 7:3 ratio of cattle dung in cemented pits (60 × 60 × 90 cm) at a moisture content of 60%.

2.4.5 PHYSICAL AND CHEMICAL CHARACTERISTICS

2.4.5.1 Physical Characteristics

Vermicomposting is a relatively low-cost method for treating organic waste, which involves earthworms to fragment the waste residuals by passing it through their grinding gizzards (Edwards and Neuhauser 1988, Hand et al. 1988). During this process, earthworms actively break up the waste substrate, accelerate the rate of decomposition of organic matter and alter the physical and chemical properties of the material, leading to a reduction in waste volume and the production of a stable compost product (Hartenstein and Hartenstein 1981 and Albanell et al. 1988). Vermicomposts are finely-divided, peat-like materials with high porosity, aeration, drainage and water-holding capacity (Edwards and Burrows 1998, Atiyeh et al. 2000a,b). They contain most nutrients in plant available forms, e.g. nitrates, phosphates, exchangeable calcium and soluble potassium (Edwards 1998) and have large surface areas that provide microsites for microbial activity and for the strong retention of nutrients (Sharma et al. 2005). Edwards (1998) and Ndegwa et al. (2000) reported that worm cast is an excellent soil conditioner since it is homogenous and has desirable aesthetics, a reduced level of contaminants, enhanced microbial activity and the propensity for holding more nutrients over a longer period. According to Chaoui et al. (2003), earthworms can improve soil porosity and thus provide a better growth medium.

Chan and Heenan (1995) discussed that worm cast has a composite structure. It was added that typically it is made of 210-500 µm units in diameter, which are comprised of smaller, spherical sub-units (50-100 µm). Moreover, they reported that casts were significantly more stable and higher in total nutrients than soil aggregate of the same size. In addition to this, it was further stated that porosity in the casts was created by spaces between the sub-units, which were composed of very densely-packed clay/silt-size particles.

2.4.5.2 Nutrients transformation

According to Mulongoy and Bedoret (1989) and Ganeshamurthy et al. (1998), earthworms enhance the nutrient availability through casting. It is believed that the passage of the ingested material through the worm's guts may increase microbial activity in the casts and thus the availability of the nutrients. Many studies (Edwards and Burrows 1998, Atyieh et al. 2002a, Chaoui et al. 2003) have shown that the use of earthworm casts can serve as an alternative to fertiliser and results in the slow release of nutrients for the plant's uptake.

Buchanan et al. (1988) stated that vermicomposts have more available nutrients per weight than the organic waste from which they are produced. Furthermore, Pramanik et al. (2007) argued that vermicomposting allows obtaining an organic source of nutrients for the crop, which are physically, nutritionally and bio-chemically improved over compost in relatively less time. They also suggested that it is important to determine the characteristics and extent of organic C, N, P, K, humic acids, micro-organism and enzymatic activities in order to determine the dynamics of vermicomposting. Similarly, Albanell et al. (1988) indicated that in comparison to the feed material, vermicompost possesses a reduced salt content, greater cation exchange capacity and increased content of total humic substances.

It has also been reported that the increase in nutrient content is attributed to accelerated mineralisation of organic matter after vermicomposting (Atiyeh et al. 2000c and Kaushik and Garg 2003, Loh et al. 2005). Tripathi and Bhardwaj (2004) reported that *E. fetida* showed faster and higher decomposition rates, mineralisation of nutrients and breeding than did *Lampito mauritii*, when fed on kitchen waste plus cow dung. They also claimed that worm castings had an increased concentration of nitrogen, phosphorus and potassium and they observed reductions in C:N and C:P ratios after 150 days of vermicomposting as compared to the control. Bansal and Kapoor (2000) studied vermicomposting of mustard residue and sugarcane trash mixed with cattle dung using *E. fetida* in a 90-day experiment. They reported a significant increase in Zn and observed changes in the total P, K and Cu contents in the final product.

Research conducted by Decaens et al. (1999) demonstrated that in fresh casts, ammonium ion (NH_4^+) concentrations were very high (234 to 294 mg/g dry weight) and suggested that this is due to mineralisation of waste in the earthworm's guts. It was reported that during the first week of cast aging, NH_4^+ levels decreased while, due to rapid nitrification of casts, the ammonia (NH_3) level increased. After two weeks, the levels of both NH_4^+ and NO_3^- were stabilised, probably due to the protection of the organic matter in the dry casts. It was further stated that it is most likely due to CO_2 fixation or macro-faunal activities in the casts that organic C increases during casts aging.

The casts are also rich in humic acids, which condition the soil and have a perfect pH balance and plant growth factors. According to Atiyeh et al. (2002b), plant growth regulators (PGR's) and other plant growth influencing materials such as auxins, cytokinins and humic substances produced by the micro-organisms are present in vermicompost. Similarly, Sharma et al. (2005) explained that humic substances can occur naturally in mature animal manure, sewage sludge or paper mill sludge but the amounts of these substances and the rates at which they decompose are increased dramatically by vermicomposting.

2.4.5.3 Microbial activities

The literature has less information on microbial activities than on other contents. However, it is widely believed that vermicompost greatly exceeds conventional compost with respect to levels of beneficial microbial activity. Much of the work on this subject, which was led by Professor Clive Edwards (Subler et al. 1998), was done at Ohio State University.

The digestive system of earthworms consists of a pharynx, an oesophagus and a gizzard, followed by an anterior intestine that secretes enzymes and a posterior intestine that absorbs nutrients (Sharma et al. 2005). During progress through this digestive system, there is a dramatic increase in the number of microorganisms by as much as a factor of 1000 (Edwards, 1999). The casts excreted by earthworms contained significant quantities of polysaccharides, which stimulate microbial activity and induce changes in the structure of the intrinsic microbial community (Edwards and Bohlen 1996).

The burrowing and casting activities of earthworms contribute to the activity of soil micro-organisms (Edwards and Bohlen 1996) and nutrient enriched earthworm casts serve as a good source that supports microbial growth (Lee, 1985). However, Edwards (1998) suggested that vermicompost is rich in diverse microbial populations, particularly fungi, bacteria and actinomycetes. It is believed that bacteria are of minor importance in the diet, whereas algae are of moderate importance, while both protozoa and fungi are major sources of nutrients. Worms produced under sterile conditions could live on individual cultures of certain bacteria, fungi and protozoa but they grow best on various mixtures of micro-organisms (Sharma et al. 2005). The total microbial load in the different regions of the guts of worms has also shown more intense colonisation of microbes in the anterior part of the intestine than the other parts.

Kale (1993) and Edwards (1999) argued that microbes, which transform nutrients into forms readily taken up by plants, are diverse due to the mesophilic transformation of organic matter. Vermicompost contains larger microbial populations than thermophilic compost, leading to greater potential for odour reduction and nutrient mineralisation.

Groups of soil microorganisms that live in very intimate contact with roots are the arbuscular mycorrhizal (AM) fungi. These fungi are known to assist the plant in uptake of nutrients and to improve plant growth (Douds et al. 2005). It has also been demonstrated that vermicomposts can stimulate root elongation and lateral root emergence and mycorrhizal association (Kale et al. 1987 and Cavender et al. 2003).

2.4.6 EFFECTS OF COMPOST AND VERMICOMPOST ON PLANT GROWTH

The pioneering effort by the father of oligochaetology, Darwin (1881), summarised some 40 years of intimate research into earthworm behaviour and reported that earthworms prepare the ground in an excellent manner for the growth of fibrous-rooted plants and for seedlings of all kinds.

Plant growth studies conducted by Atiyeh et al. (2000a,b and 2002a) on the use of vermicompost as an amendment to the potting mix, showed that even a relatively small concentration could enhance plant growth. It was reported that by using only 10 % (v/v) of pig manure vermicompost in the container mix, the dry weight of the French marigold, tomato seedlings and tomato fruit yield increased significantly (31 %) over those of the plants grown in the control media. It was also suggested that poor plant growth was observed, when the proportion was above 60 % (Atiyeh et al. 2000b and Subler et al. 1998). Other research by Chaoui et al. (2003) has suggested that worm casts can serve as a naturally-produced, slow-release source of plant nutrients. Kale et al. (1992) and Subler et al. (1998) claimed that the presence of plant growth regulators (e.g. hormones) and/or symbiotic microbes (e.g. mycorrhizas) in the worm cast could also be responsible for the improvement in plant growth in vermicompost. In support of this, indole acetic acid has been isolated from the humic fraction of vermicompost (Canellas et al. 2002, Arancon et al. 2003). Other plant growth regulators have also been isolated from soils supporting high earthworm populations and an increase in plant growth in pot trials has been attributed to the presence of plant growth hormones, such as cytokinins and auxins (Krishnamoorthy and Vajranabhaiah 1986).

Recent investigations by Atiyeh et al. (2002a,b) and Arancon et al. (2004b) concluded that this plant growth improvement is due to the worm cast's humic acid content and is independent of mineral nutrient changes, which occur during the vermicomposting process. Moreover, it was also reported that pure vermicompost had an overall negative effect on the growth of plants as compared to the growth of control plants. It was explained that this retardation in plant growth and productivity was due to high salt concentration in the pig manure vermicompost (11.76 m mhos/cm) or poor porosity and poor aeration of the medium (Atiyeh et al. 2002a).

Subler et al. (1998) reported that the differences between the vermicompost and compost treatments on leaf chlorophyll concentration occurred within one week of its germination and suggested that these differences were diminished as the plant grew. Whereas, Galli et al. (1992) observed an increase of 30 % in protein synthesis in lettuce seedlings following the application of vermicompost and showed that no differences were recorded in the presence of compost. They also suggested that an increase in soil productivity, which cannot be explained by mineral nutrients alone, is often recorded when composted organic wastes are supplied to croplands. However, the situation is more complex. Studies carried out at the University of Wales, Bangor by Jones (2004) and Cavender et al. (2003) suggested that plant responses to vermicompost are species specific.

Recent studies conducted by Edwards et al. (2006) investigated the effects of aqueous vermicompost extracts or teas on the germination and growth of tomatoes. They also studied the effect of cattle waste vermicompost teas on disease suppression. The teas were produced by placing one litre of vermicompost in four litres of aerated water for 24 hours. Then the tea was drained off and placed in containers for use in greenhouse trials. They used a range of concentrations of vermicompost tea with a dilution ratio of 0.5 to 10 % and applied it twice a week for eight weeks. The results showed an enhanced germination and growth of tomatoes and the authors suggested that this is due to teas from cattle manure. It was also suggested that vermicompost teas could possess the same chemical and microbiological characteristics as vermicomposts and that, during the brewing process, soluble mineral nutrients, beneficial micro-organisms, humic and fulvic acids, plant growth hormones (such as auxin) and plant growth regulators could be responsible for the enhanced growth. It was further added that the mineral nutrient in vermicomposts cannot be the reason, as all treatments had nutrient added, whereas, this enhancement of tomato plants could have benefited from either growth hormones or the hormones that had been adsorbed onto humic acids during vermicomposting passing into the teas and the micro-organism. Therefore, it was concluded that a low application rate of vermicompost teas certainly enhanced the growth due to low plant growth regulators or hormones but a higher application rate depressed the plant growth. Moreover, it was observed that tomato plants infected with *verticillium* wilt showed disease suppression by the use of vermicompost teas with a dilution of 0.5 to 10%. Other research conducted by Arancon (2004a) in the same context also showed a suppression of disease on a range of plants including *Pythium* on radishes and *Rhizoctonia* on cucumbers in the green-house. They suggested that 5-10 tonnes acre^{-1} application rate of vermicompost derived from paper waste and food scraps suppressed *Verticillium* wilt and *Rhysitorium* on strawberries, *Phomopsis* and powdery mildew on grapes and bacterial rot on cucumbers. Therefore, it was suggested that this was purely microbial since these effects disappeared after sterilisation of vermicomposts.

Wright and Upadhyay (1998) reported that earthworms play a vital role in preventing soil erosion and soil aggregates formation directly as well as indirectly by transmitting the arbuscular mycorrhizal (AM) fungi, which are involved in water stable aggregate formation. Some of the researchers (Kale et al. 1987, Subler et al. 1998 and Cavender et al. 2003) suggested that the growth of symbiotic microbes (e.g. mycorrhizas) stimulates root growth and increases the plant's ability to uptake added inorganic nutrients.

2.4.7 WORLDWIDE DEVELOPMENT OF VERMICOMPOSTING

The composting sector of the waste industry is rapidly developing worldwide because of the need to restrict the landfilling of biodegradable wastes in favour of promoting more sustainable waste management practices. Many different approaches are being used to process large volumes of organic residuals with earthworms, ranging from relatively simple land- and labour-intensive techniques to fully automated high-technology systems.

Vermicomposting has been adopted worldwide, often with great success. Where conditions are suitable, it can undoubtedly play a significant role in the development of the composting industry. As with traditional composting, vermicomposting can be used for home composting and also can be applied on a large scale at centralised sites. While home-scale vermicomposting has increased rapidly in popularity in the industrialised world since the early 1980s, there has been only meagre proliferation of municipal or agricultural-scale vermicomposting facilities. This is due to economic constraints and resistance to adapting to a new technology. However, little published technical information is available on commercial vermicomposting. According to Sharma et al. (2005) vermicomposting facilities are reported to be already in commercial operation in Japan, Canada and the U.S and it is also being efficiently practiced in the Philippines, India and China, whereas several European countries (Italy, France, Netherlands and the UK) have recently begun to use this technology (Appelhof et al. 1996). Ghosh (2004) reported that vermicomposting at a commercial scale was started in Ontario, Canada, in the 1970s and the facility is now processing about 75 tonnes of refuse per week. Commercial vermicomposting systems first appeared on the market in the United States in the early 1990s. The first mid-scale vermicomposting system was the Worm Wigwam, which was introduced in the Pacific Northwest by John Gorman-Sauvage. About the same time, Al Eggan, owner of Original Vermitechnology in Toronto, Canada, developed an automated, large-scale vermicomposting system.

Sharma et al. (2005) reported that an American earthworm company (AEC) began a farm in 1978-79 with about 500 tonnes per month capacity and Aoka Sangyo Co. Ltd., Japan has three (1000 tonnes per month) plants that process waste from the paper, pulp and food industries. Besides these, there are about 3000 other vermicomposting plants in Japan with 5 to 50 tonnes per month capacities.

It was reported by Edwards and Steele (1997) that Australia and New Zealand have a number of composting toilets of various designs using earthworms. The most sophisticated of these, the Dowmus composting toilet, has fan aeration and a compost extraction auger. Wright (2002) reported that there is a large vermicomposting plant near Brisbane, Australia, processing 20,000 tonnes per annum of sewage sludge. The waste material is generated from five treatment plants comprised of 28 processing beds, each measuring 70 m long x 3.6 m wide x 0.7 m deep. The associated mass throughput is 54.5 kg m^{-2} $week^{-1}$ and the other two plants process 6,000 tonnes per annum of pig manure.

Another technique known as "vermifiltration" consists of raising earthworms on an organic substrate, which is kept moist by a liquid containing organic matter (e.g. sewage sludge). This constitutes a biological process that favours the digestion of organic matter, while combining a simple biological indicator of environmental stability and ultimately a satisfactory purification process. Its adaptation to the treatment of wastewater from livestock buildings has been studied in the past (Sharma et al. 2005). In India, both solid waste and sewage from a neighbourhood of 500 homes were processed with vermiculture at the Indian Aluminium Co., Ltd. (White, 1996). The sewage is fed to a 200 m^2 vermifilter, designed for processing up to 100 m^3 per day and the purified water is used for irrigation.

Wright (2002) suggested that the UK's vermicomposting industry is now moving forward and large vermicomposting plants are currently in operation, such as the 3,000 m^2 facility in Sowerby Bridge, West Yorkshire and a 10,000 m^2 site in Sarn near Newtown in Mid Wales. Both of these plants process a range of biodegradable waste such as local-authority generated green-waste, paper and cardboard, combined with a range of biodegradable wastes produced from industrial and commercial sources. The Composting Association, UK, conducted a survey in 2000 that revealed that around 58% of centralised composting facilities were medium-sized, processing around 5,000 tonnes of waste per year or less. It was shown that, in comparison to municipal composting facilities, vermicomposting tends to be carried out in rural locations mainly by farmers.

For the past decade, several large-scale vermicomposting systems have been used with varying success. Given the time frame and the number of failed attempts, perhaps this industry is still in a developmental phase. This indicates the need for an ongoing assessment of factors that contribute to the success of large-scale systems and an extensive large-scale experimentation is necessary to help determine the potential of vermicomposting as a high-volume waste management technology.

2.4.8 VERMICOMPOSTING SYSTEMS

Generally, there are three main vermicomposting systems on an industrial or commercial level, namely windrows, single-batch reactors and continuous flow systems (Edwards et al. 1998). However, Sherman (2002) reported that some new techniques like wedge systems, bins, beds and other high-technology reactors have also been utilised. Vermiculture and vermicomposting are two similar but different processes. The former is the breeding of earthworms to continually increase the number of worms in order to obtain a sustainable harvest, whereas the latter is the process by which worms are used to convert organic materials (usually wastes) into a humus-like material known as vermicompost, to process the material as quickly and efficiently as possible. Studies about the methods of earthworm cultures under artificial conditions have been conducted since the early 1970s in many regions and countries of the world. Edwards and Lofty (1972) reported that there are an estimated 1800 species of earthworms worldwide. The practice of vermiculture is at least a century old but it is now being revived worldwide with diverse ecological objectives such as waste management, soil detoxification, land regeneration and sustainable agriculture.

There are several other culturing methods like pits, multi-layer boxes, earthworm beds, plastic-shed vermiculture and natural-culture in the field (Zhenjun, 2006). However, on the basis of varying climatic changes, the main vermiculture methods are windrows and pit vermiculture, which can be outdoors, whereas multi-layer box vermiculture and large-scale reactors can be indoors. Sherman (2002) suggested that the key factors for selecting different types of vermicomposting techniques are available funds, site characteristics, the availability of labour and most importantly climate, which affects the temperature and moisture conditions of the vicinity.

Vermicomposting methods can range from a worm bin in the kitchen for household scraps to large mechanised systems able to accommodate tonnes of organic materials on a continuous basis. In general, these methods can be grouped into four types discussed below.

2.4.8.1 Windrows

Vermicomposting windrows can be in the open, under cover or indoors and they require ample land or a large building (Sherman, 2000). Figure 2.2 shows an open vermicomposting windrow. A typical worm windrow ranges from 1 to 2.5 m wide and can be as long as 0.5 km (McClintock, 2004) and at the most, up to 1 m high (Sherman, 2002). They require a well-drained soil as a base or a sloped concrete pad to prevent accumulation of water and anaerobic decomposition from occurring at the bottom (Edwards, 1998). A thin layer of feedstock is added repeatedly at a thickness of 4 to 7 cm (7 to 15 cm in colder weather) Sherman (2002). Haimi and Huhta (1986) observed that worms could work a maximum thickness of 5 cm of sewage sludge. They suggested that the addition of feedstock can be continued by layering fresh material on top of the previous one, when it is converted into castings. It is recommended that the windrow should be harvested as it reaches a height of 0.5 m, to prevent thermophilic temperatures, which will drive the worms away. Sherman (2002) suggested that another key factor is the spacing of the windrows. They should be no more than 6 m apart so that worms can migrate safely and easily to the adjacent windrow. It was further added, that it is difficult to harvest the worm windrows using the labour-intensive, hand-sorting approach, rather a mechanical harvester is the best option because it is faster, although most of the worms will be in the top-most layers, where fresh feedstock is available. Another drawback is that the worms can escape from the windrow, as it has no physical barriers. However, in some circumstances the abundance of feed gives them no reason to escape. Most of the time, windrows are prepared on a concrete surface to prevent predators from killing the worms.

Figure 2.2 A photograph of vermicomposting using an open windrow method

2.4.8.2 Wedge System

The wedge system is a modified windrow approach, developed by Jim Jensen of Seattle, Washington, USA, that reduces the space requirement and simplifies harvesting. In this method, the windrow is extended by applying the feedstock in layers at a 45-degree angle against one face of the existing windrow and more wedges-windrows can be added by using the similar technique. The advantage of using this method is that there is no need for harvesting, as worms migrate laterally to the wedge-windrow, where fresh feed is applied (Sherman, 2002). Yelm Earthworm and Castings Farm, located near Yelm, Washington, USA, is one of the real-world examples of a large-scale wedge system. The 10-year-old worm farm is among the largest in North America, with 2,800 m^2 of enclosed space, in addition to production areas outdoors. About 15 tonnes of red worms are used to process a variety of feedstocks (animal manures, wood chips, leaves, spoiled hay/straw, grass clippings, yard debris, food scraps, waxed cardboard, soiled paper and corrugated cardboard (Sherman, 2002)).

2.4.8.3 Beds and Bins

Beds and bins have been used extensively throughout the vermicomposting industry to varying degrees, from home enthusiasts to part-time worm growers to medium-scale operations. They can be constructed with some wood or purchased from the market. A commercially available home vermicomposting plastic bin is shown in Figure 2.3. Regardless of the shape of the bin, the container must have holes in the sides, top and bottom for adequate aeration and drainage (Appelhof, 1997). Wright (2002) reported that providing additional holes (6 mm diameter) at the bottom of plastic containers (0.22 m^2), substantially reduced anaerobic conditions, which aided the aeration and collection of any leachate generated that might have been detrimental to the worms or might have created a foul odour.

The first home vermicomposting unit available commercially in North America was Al-Eggan's Original vermicomposter produced in Toronto, Canada. The most successful commercially sold vermicomposting rectangular unit produced by RELN Worm Factory was marketed in Australia and its circular counterpart, known as the Can-O-Worms, was marketed in New Zealand, Canada and the United States (Appelhof, 1997).

Figure 2.3 Home vermicomposting plastic bin

An advantage of beds and bins over windrows or wedge windrows is that they take less space and can be stacked vertically (see Figure 2.4). This also helps in reducing worm escape as worms are confined by the reactor walls. Furthermore, these systems do not require monitoring on a daily basis for moisture and temperature and can, therefore, be left unattended for days but the worms and the castings must be separated manually.

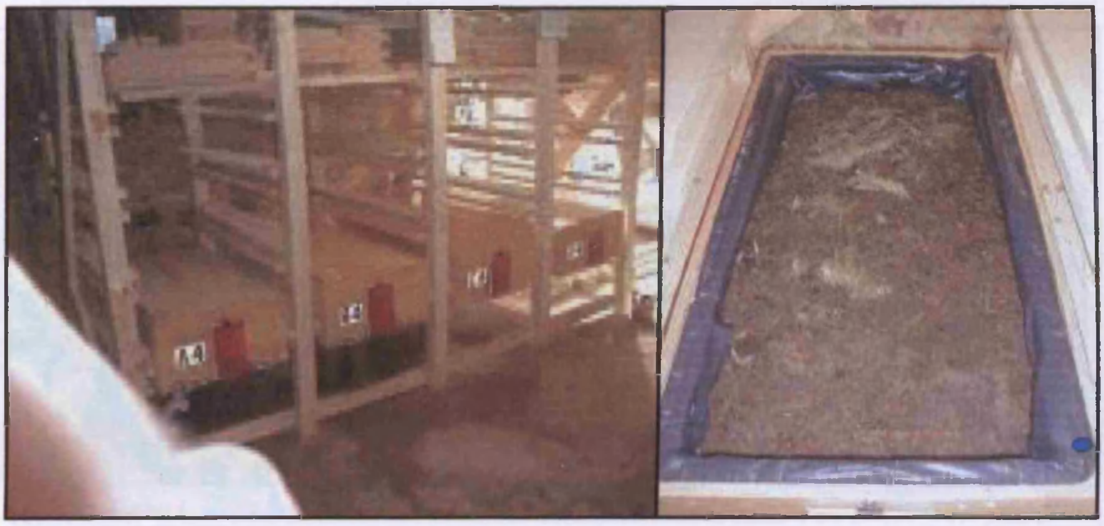


Figure 2.4 Vermicomposting stacked beds method

The outdoor large-scale beds usually require some type of cover to protect them from direct sunlight and rain. It is a labour-intensive process, because it requires the harvesting of worms and vermicompost by hand. A worm farm in North Carolina, USA (Vermicycle Organic) has beds that extend 22 cm down with temperature maintained at 13 °C, which allows worms to burrow down, if the temperature of the new feed is too hot. These beds are harvested with shovels and screened to separate worms. Similarly, ORM, based at Brecon Beacons in Wales, UK, also has an outdoor bed system made with rubber tyres and the worms are fed with moist wheat and barley in layers on a weekly basis. They utilise a rotating drum harvester to separate the worms from the casting material.

Vermiculture in plastic sheds is common in China (see Figure 2.5). Zhenjun (2006) explained that these sheds can be up to 6 m wide and 2 m high. Bed vermiculture with a heat pit is also in practice depending on the climate and is widely used during the cold seasons in Northern China, in which a heat-generating pit below the bed is excavated.

Figure 2.5 Vermicomposting under plastic sheds in China

2.4.8.4 Reactor Systems

Another type is the raised bed, often known as a 'reactor', used in the vermicomposting industry. Figure 2.6 shows automated types of vermicomposting reactor systems. These reactors can be constructed with wood or metals and have metal grid and/or mesh attached to the bottom. The mesh openings can be about 5 to 6 cm^2 (Edwards, 1998 and Sherman, 2000). Most commonly used bedding material is newspaper or peat that can be laid on top of the grating and then the feedstock can be applied. The reactors can be harvested with a bar scrapes, which runs through the last few centimeters of the bottom layer above the mesh and the casts can be collected. Moreover, these reactors can be manually operated or fully automatic and they come with temperature and moisture controls (Sherman, 2002).

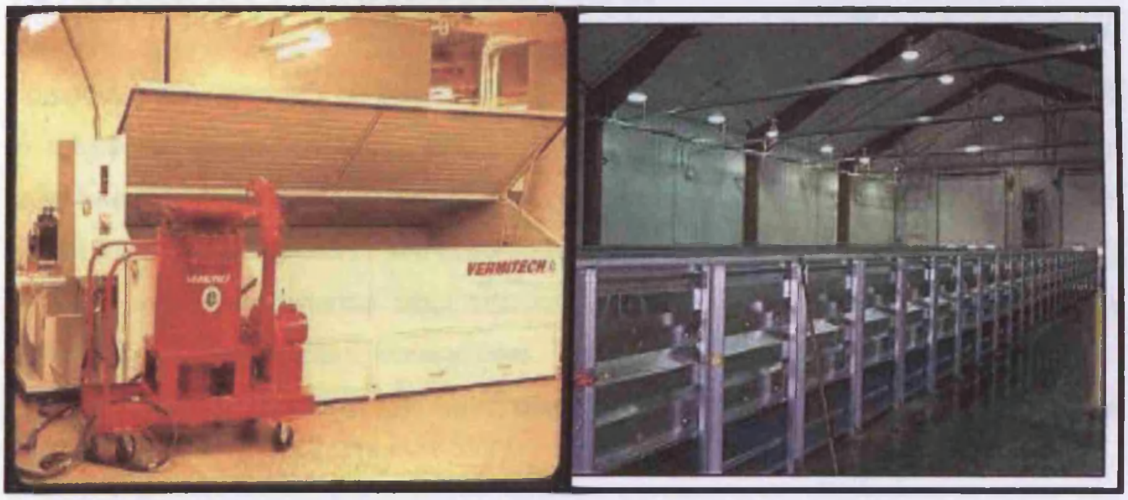


Figure 2.6 Automatic vermicomposting reactor systems

A large scale reactor system is manufactured by Biosystem Solutions, USA, which offers a Biosystem-500 modular vermicomposting reactor that can process up to 270 kg day^{-1}. Another single module (0.91 m long × 0.6 m wide × 1.2 m high), processes 9 kg day^{-1} in two drawers and is sold for around £ 950. This system has an automated irrigation control and leachate collection. Additional features, such as climate control and shredding of the feedstock, can be added at an additional cost. It requires a maximum of one hour of labour, depending on the feedstock. A system (Biosystem-500) has been installed at an elementary school in San Pablo, California, USA (Sherman, 2002).

2.5 COMPOST CHARACTERISATION

Compost quality depends on the chemical composition and proportions of materials used to create the compost (Haug, 1993) and should be among the primary goals of a composting facility. Some aspects of quality, such as product maturity and particle size, can be modified at the end of active composting through increased curing time or simple physical processing, whereas other characteristics are more difficult to remedy in the aftermath of poor process management. Furthermore, compost product quality can include aesthetic, functional and contaminant characteristics, all of which are clearly critical to product marketability.

Physical contaminants and foreign matter are the undesirable materials remaining in the final product that results from composting of waste materials. These contaminants generally refer to man-made inert particles such as glass, plastic, metal and other non-biodegradable materials (Page et al. 2005).

In composting systems, many of the separation technologies now applied to composting were originally developed to recover recyclable or combustible materials from solid wastes. While some of these technologies have been adapted for reduction of inert materials, they have rarely been optimised for reducing chemical contaminant levels (Richard, 1992). For example, the typical steps in municipal solid waste (MSW) processing systems include shredding raw material to obtain uniform particle sizes and extracting ferrous metals for recycling and recovering the organic portion, which is suitable for thermal or biological processing.

Rhyner et al. (1995) discussed that many communities have constructed or are currently constructing material recovery facilities (MRFs) to receive and sort recyclable materials. Some facilities receive source-separated recyclable materials that require minimal processing, perhaps no more than visual inspection and removal of contaminants, followed by bailing of papers and cans or filling of containers for shipping. However, other communities prefer to pick up mixed recyclable materials to save collection costs and thus heterogeneous materials are then delivered to MRF's for sorting, bailing and shipping.

Compost refining refers to separation processes, which occur after biological processing. These can include screening, air classification and/or magnetic separation and are important in preparing a visually-attractive product. Contaminant separation at this late stage has a limited effect on chemical contaminants but it can significantly reduce inert materials like plastics, glass and stones. A wide range of technologies are available and many facilities use a sequence of steps employing different processes. A composting facility designer can select among various technologies based on incoming feedstock characteristics, finished product quality specifications and the options for marketing separated by-products. Some of these technologies are discussed below.

2.5.1 SCREENING

In a composting system, screening removes large numbers of unwanted objects (plastic films, stones, metals, bottles and other refuse) from raw materials. There are many different types of screens available in the market. A report published by Entec (2004) documented various types of screens and their effectiveness. However, the most commonly used in the composting industry are trommel and star screens. For example, a trommel screen often includes a feed hopper, where material is fed into one end and the rotating action of the drum, along with the internal flights, moves the material through the slowly rotating drum. Savage et al. (2005) reported that the trommel screens rotate at relatively low speed (15 to 20 rpm), and in order to obtain a high-quality composted product, 5-6 mm opening-size screens are used, whereas, for a coarser material, opening sizes of 10 to 15 mm are best suited.

The moisture content of the material has a significant impact on the screening efficiency. Spencer (2003) suggested that regardless of the screen types, materials having moisture contents above the range of 40-45%, do not separate as cleanly as drier materials, whereas a report published by Entec (2004) stated that the screens (trommel and star) can operate over a range of moisture contents. Furthermore, star screens are principally used for classifying the final product and are not used for sorting raw feedstock. Similarly, Savage et al. (2005) suggested that star screens allow efficient treatment of material with high moisture content. It seems likely that high moisture content decreases the throughput rate and reduces the separation effectiveness. The main purpose of size segregation in a composting plant is to facilitate further separation, because, while the undersized fraction is screened, the oversized fraction is left behind and can possibly be recycled or marketed as refuse-derived fuel (RDF).

2.5.2 MANUAL SEPARATION

Technological development aside, manual sorting, which is labour-intensive and time consuming, is still an important step in the design of a solid waste management system and it continues to play an important role in collection and processing. The amount of manual sorting at a processing facility varies greatly. Some smaller facilities rely exclusively on manual sorting but at larger facilities, it might be limited to scanning the incoming materials for unacceptable items, where a mechanical separator is too expensive. However, separation of high-density polyethylene (HDPE) and polyethylene terephthalate (PET) plastics, along with paper and corrugated cardboard, are often done manually.

2.5.3 MAGNETIC SEPARATORS

Magnetic forces of attraction or repulsion can readily separate metal objects from other materials. Most commonly, it relies on the strong attraction of ferromagnetic metal objects towards a magnet. Magnetic separators have been employed for many years to extract steel cans from the waste streams at MSW processing plants, because they are efficient, reliable and relatively inexpensive. Ferromagnetic and eddy current separators are the two types of magnetic separators most commonly used.

2.5.4 SEPARATION BY INERTIA

Inertia may also be used to separate solid waste components. Inertia, which is the resistance an object has to a change in its motion, is dependent on density, that is, objects with the greatest density have the greatest inertia. Common inertial separators are the cyclone, vibrating table (stoner), ballistic separator and inclined conveyors.

2.5.5 OPTICAL/INFRARED/X-RAY SORTING

Spectroscopy techniques coupled with modem computer technology can be used to separate glass and plastic by colour and plastic resin type. For example, in optical sorting, the colour of an object, such as a bottle, is determined by passing light through it and detecting the transmitted light with one or more photo-detectors. The absorption characteristics registered by the detectors permit the instrument to determine the colour and activate air jets to remove the object from the processing line. Infrared absorption and X-ray radiation are also used for the separation of plastic bottles (Rhyner et al. 1995). These technologies identify plastics by resin type and can be coupled with visible light sensors that enable further sorting by colour.

2.6 AIR SEPARATION TECHNIQUES

Air separation is generally used towards the end of the process to remove contamination (mainly plastic) after size reduction, composting and screening. Air separation cannot reliably segregate plastic from the finished compost product with currently available technology (Savage et al. 2005). The reason is that the density and aerodynamics of the plastic and compost particles (small and dry) are too similar for practical separation. Therefore, Rynk (2001) suggested that air separation should be typically applied to the oversized fraction from screening, since this fraction contains large pieces of wood, stones and other high-density contaminants, which are simple to separate from plastics, especially plastic films due to large differences in terminal velocities.

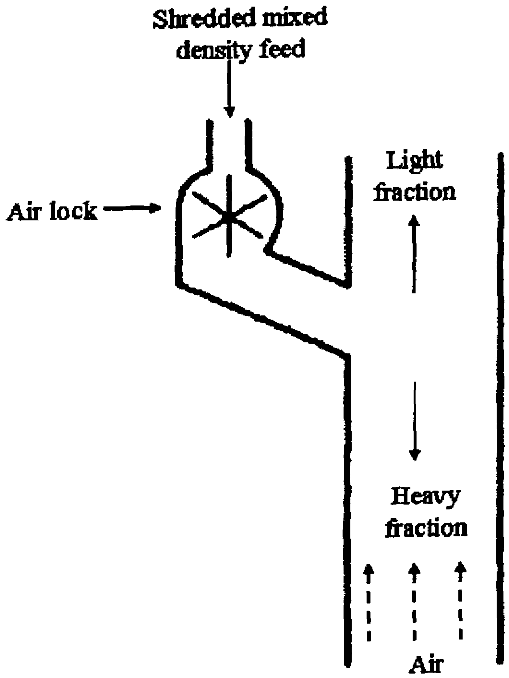
Several advantages of taking plastic out of the oversized fractions are also documented. For example, it can reduce the amount of plastic that is normally returned to the composting process and contaminates the compost. Also, as the plastic particle size decreases due to recirculation of the process, it eventually passes through the screen. Another advantage is that the clean oversized fraction can also be sold as mulch or fuel. Therefore, air separation saves the cost of sorting and landfilling the oversized fraction. However, air separation systems are mainly designed to extract plastic films (Rynk, 2001) derived from bags, packaging, plastic mulch and shrink-wrap, whereas other, heavier plastic items (bottle caps, beverage containers and utensils) tend to escape.

Rynk and Spencer (2003) found that the percentage by weight of plastic materials increases with the particle size of the compost: 1-4 mm, 4-10 mm and >10 mm < 25mm particle size contained 1.9 %, 3.5% and 6.6 % plastic films, respectively. Rynk (2001) also reported that foreign matter can be relatively high (2% to 4% of the compost's dry weight), even in well-processed composts. These percentages are very high, when compared to the new (UK) PAS 100:2005 (Table 2.1) Standard that limits contaminants to 0.5 % (m/m) in an air-dried sample, of which plastics can constitute no more than 0.25%.

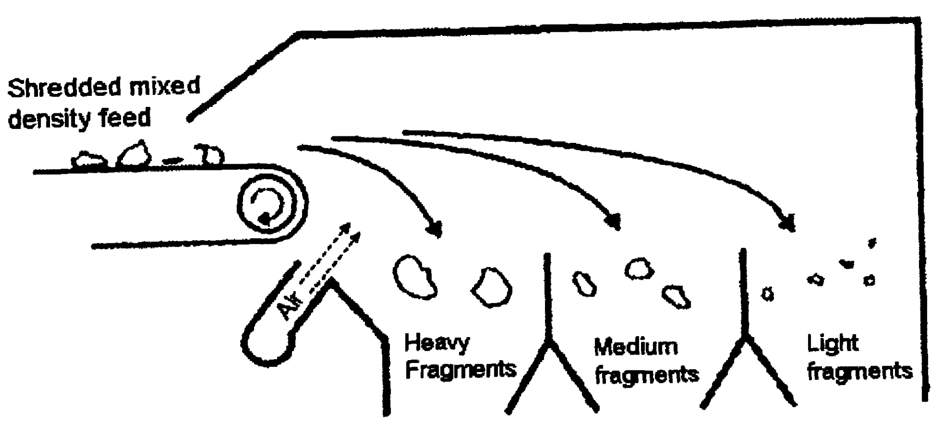
2.6.1 AIR CLASSIFICATION

Air classification is an additional separation technology used in composting facilities and is commonly used to generate a marketable RDF. This equipment is generally used in combination with trommel screens (Savage et al. 2005). Primarily, air separation uses an air current to separate materials according to their densities. The size and the shape of the particles are also very important factors. A particle that does not have an aerodynamic shape, such as light flat wood, might be carried away with the air flow, while other, rounder wood particles would drop down with other heavy materials. The terminal velocity of a particular particle is determined by its density, shape and surface roughness. When a particle falls freely through a fluid such as air, the balance between gravity and the opposing friction causes the particle to fall at a constant speed, which is the terminal velocity.

Mixed materials are fed into a chute with an upward-flowing stream of air generated by a blower (Figure 2.7a). The light materials are carried with the air, whereas the heavy materials fall down into a bin or onto a conveyor belt. The division (split) between light and heavy materials depends on the air velocity. The velocity, in turn, depends on the air flow rate and the size of the air channel. For instance, if the air velocity exceeds a particle's terminal velocity, the particle is removed by the air. Therefore, higher velocity is needed to remove heavier particles due to their large terminal velocities. Furthermore, different types of plastic, for instance polyvinyl chloride (PVC) versus polyethylene films, require different air velocities for effective separation. Moreover, a wide range of terminal velocities is required due to changes in moisture, shape and orientation. In order to achieve effective separation of the desired light fraction, the air velocity must be set at the top of the light fraction's terminal velocity range and should be below the low end of the heavier fraction's terminal velocity range. If the terminal velocities of light and heavy fractions overlap, air separation becomes difficult. In the 1970s, many experimental projects were conducted with vertical air classifiers (Rhyner et al. 1995).



a. Vertical air classifier



b. Horizontal air classifier (Air knife)

Figure 2.7 Air classification systems (copied from Waste Management and Resource Recovery (Rhyner et al. 1995)

Wind winnowing, an agricultural method developed by ancient civilisations for separating grains from chaff and to remove weevils or pests from stored grains, is an example of the horizontal air classification technique. In its simplest form, it involves throwing the mixture into the air so that the wind blows away the lighter particles, while the heavier grains fall back down for recovery. Other techniques include using a winnowing fan (a shaped basket shaken to raise the chaff) or by means of a winnowing fork or shovel on a pile of harvested grains. However, modern horizontal air classifier systems or air knife are commonly used to separate light from heavy materials. A diagram of an air knife system is shown in Figure 2.7b. The main difference between vertical and horizontal air classifier systems is that, in horizontal systems, the mixed waste enters on a conveyor belt and an inclined air jet blows the waste towards the other end with both the light and heavy fractions carried by the air in the same direction. The separation occurs when the light materials are blown farther than the heavy materials and are collected separately.

Savage et al. (2005) stated that air classification probably is the least familiar separation technology to some composting facility operators. Although, routinely used in material recovery and other industries, few composting facilities have adapted air separation machinery to use in their compost production systems. They further added that, without a doubt, air classification substantially reduces the amount of plastics in finished compost but other practices such as public awareness, source segregation, use of biodegradable bags and packaging, quality control in the tipping area, front-end sorting, proper size reduction and screening should be enforced in order to produce a finished product that contains a relatively small concentration of plastics.

2.6.2 AIR JIGGING

Jigging is a gravity separation technique used for centuries. It is based on the difference between the settling velocity among particles in a pulsating current. This technique has been extensively practiced in coal preparation, mineral processing and separation of other solid materials. However, at present there is very little information available on the use of a jigging process for the separation of waste materials.

With relevance to the medium used in the jigging process, jigging can be divided into dry and wet basis. Currently, wet jigging is used more in the mineral industries than dry jigging. The conventional jigging used in the past was employed to separate coarser to medium sized materials but the development of new jigging technology in recent years (Mukherjee et al. 2005, Dai 1999, Yang 1996 and Lyman 1992) has shown some potential to process fine materials.

When particles with different densities and sizes experience a jigging motion, each particle encounters gravity forces, fluid forces and other mechanical forces due to the collision of particles with one another and with the walls of the jig. The exact movement of particles within the jig is difficult to explain. However, by regulating the frequency and amplitude of the pulsations and net upper velocity of the current, the feed solid particles can be effectively separated by density and size in the jig machine (Dai, 1999).

A typical jig achieves a density separation by repeatedly lifting (pulsion), descending (suction) and allowing the bed of material to settle down onto a stationary screen. During the pulsion stroke, air or water moving vertically through the screen lifts the bed (see Figure 2.8a). Once the vertical velocity decreases, the material is allowed to descend and achieve a fluidised-bed condition, where each particle is capable of moving freely. When this state is achieved, the particles are allowed to settle down onto the screen (see Figure 2.8b). The majority of the separation occurs during this stage of settling, with higher-density particles descending faster than the lower-density particles. After a series of cycles (pulsion and suction) the more dense particles settles on the bottom of the bed and the lighter particles reside on the top. The successive jig strokes allows vertical movements of different density particles by their initial settling velocities (which is dependent on density than size) rather than by the particle's terminal velocity (which is dependent on relative mass). Although this process appears straightforward, it is highly dependent on synchronisation of the ascending and descending air or water movement. Mukherjee et al. (2005) studied the water movement in a conventional pressurised pulsion and gravity induced suction cycle using a laboratory jig. They suggested that in order to improve the jigging operation, identical water movement is required in both the pulsion and the suction phase.

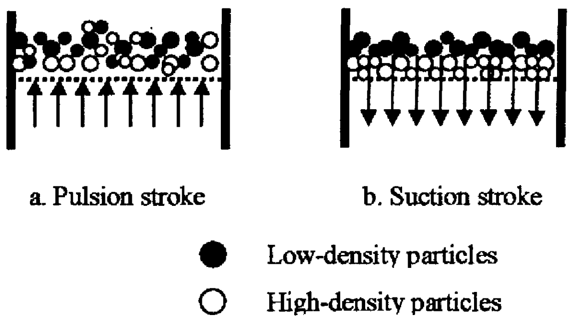


Figure 2.8 Air jigging mechanism based on density of particles
(adapted from Kawatra and Eisele 2001)

As discussed earlier, an air jig operates essentially on the same principle as a wet jig but it uses air instead of water to fluidise and pulse the bed. As the run-of-mine coal quality has decreased and the amount of fines and moisture has increased, the effectiveness of dry cleaning processes have declined. Arnold et al. (1991) documented that the use of dry concentration has not been practiced extensively, except that, in the United States, the quantity of bituminous coal cleaned using dry processes has declined from its peak of 25.4 million tonnes in 1965 to less than 4 million tonnes in 1988.

Dry jigging processes are known to be less efficient than wet methods and are generally considered suitable for only easily cleaned coals, therefore, they are most efficient on closely-sized feeds. Moreover, the gravity-dependent processes work best on coarser size fraction separations and the air jig's efficiency decreases as particle size increases, as is the case in wet separating processes. Processes for the dry-cleaning of coal are most efficient on dry feeds. Therefore, for efficient sizing and separation, many coals would need to be dried before or during the dry-cleaning process.

Dry-cleaning devices can be classified into two broad categories: gravity-dependent and non-gravity-dependent. The gravity-dependent devices are those which have been used commercially in the past: pneumatic tables, pneumatic jigs and the dry-dense-medium process. However, non-gravity-dependent devices include magnetic and electrostatic separators. Recently, dry cleaning of coal has gained interest in different industries for various reasons, the first and most important being the raising cost of water utilisation and cleaning and the second being, its capability to clean coal in arid (desert) or permafrost areas (Weitkamper and Wotruba 2004). However, to decrease respirable dust, mining operations must use a water spray on modern mining equipment.

2.6.2.1 Recent developments in air jigging

Alderman (2002) reported that there have been two relatively recent developments regarding air jigs, one for the coal industry and one for the gold industry. This includes Allmineral's (German-based, commercial-scale air jig manufacturer) air jig, which is a 1.2 × 2.4 m jig capable of processing 50 tonnes per hour of 50 mm × 0 coal. This jig employs a low-pressure, high-volume source of air to fluidise the particle bed and a high-pressure, low-volume air source to superimpose a pulsation stroke that stratifies the particle. Similar to a wet jig, the air jig utilises differential acceleration, hindered settling and consolidation trickling to achieve a stratification of higher-density and lower-density particles. This jig comes with an automatic discharge for high-density material and is designed to operate with a bed depth of up to 230 mm. De-jong and Fabrizi (2004) reported that Allmineral and Aachen Technical University in Germany has also used the "Allair" jig, to separate a mixed feed of construction and demolition waste (stones, bricks, tiles, glass, metal, wood, bitumen, textile, polystyrene, plastic, paper and dust). The feed size ranged from 5 mm to 40 mm .They claimed that this device can efficiently separate lower-density particles from higher-density particles and suggested that the "Allair" jig is a compact design with high processing capacity (50 tonnes h^{-1}) and can separate a wide range of feed materials.

Another recent development in the air jigging technology is the Rotary Air Concentrator (Alderman 2002), a machine installed in the arid region of Mexico for separating gold. This device can process feed materials less than 14 mm and can recover heavy minerals down to 80 μ. Feed screened to minus 14 mm is delivered to a central hub and distributed to the radial deck by revolving blades. Low-pressure, pulsating air is delivered through 2 mm profile wire screens, which provides the jigging action to stratify the bed of ore. Thereafter, the coarser gold particles are collected separately from the fine, gold-bearing black sands that pass through the 2 mm openings of the deck. However, so far there is no available data on the processing capacity and the efficiency of this type of device.

CHAPTER 3 EXPERIMENTAL TECHNIQUES

3.1 CARMARTHENSHIRE ENVIRONMENTAL RESOURCE TRUST (CERT) WINDROW PROJECT

Green waste compost was produced using the traditional windrow method described in Section 2.3.3.1. Mature green waste-derived compost produced at Carmarthenshire Environmental Resource Trust (CERT) Composting facility was utilised throughout the period of this study. Previous research conducted at CERT involved close monitoring of the traditional windrowing and containerised vessel systems (Notton 2005 and Hewings 2007). During these studies, apart from green waste, a range of mixed feedstocks including citrus waste, chicken litter and vegetable waste, was also examined.

3.2 THE VERMICOMPOSTING TRIAL

3.2.1 CONSTRUCTION OF VERMICOMPOSTING REACTORS

The trial was conducted by using two identical reactor beds (A and B) placed on a pair of trestles as shown in Figure 3.1. Similar feed (re-hydrated mature compost) of moisture content 60 ± 2% (m/m) was chosen for both reactors. However, for the first 4 weeks small doses of oestrogen were added to the feedstock prepared for reactor B. This was a part of a research on uptake of the hormones conducted by the School of Biosciences, Cardiff University (Swinscow-Hall et al. 2006). Wood and 18 mm thick ply sheets were used as construction materials. Each bed measured 2.4 × 1.2 × 0.43 m with a process surface area of 2.88 m^2. The base of the reactor beds was constructed by attaching a (5 mm thick) rigid wire grid (50mm square aperture) that was overlapped using a galvanised wire mesh (10 mm) in such a way that the base was left with an overall opening size of approx 6 mm. This provided sufficient aeration and drainage of any leachate generated during the trial.

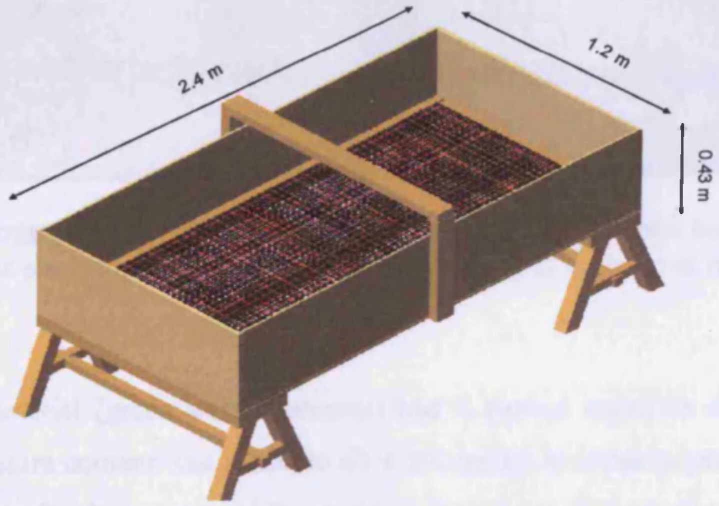


Figure 3.1 Drawing of vermicomposting reactor

A metal tray and plastic sheeting guides were placed under each reactor bed to quantify earthworm casts, dead worms and collection of any leachate generated from the base of the reactor (see Figure 3.2). In addition, fluorescent tube lights were fixed on the ceiling of the reactor cabin and also along the length at the base of each reactor. This was necessary because earthworms are very photosensitive and burrow in the presence of light, which reduces the chances of worm escape from the reactor beds.

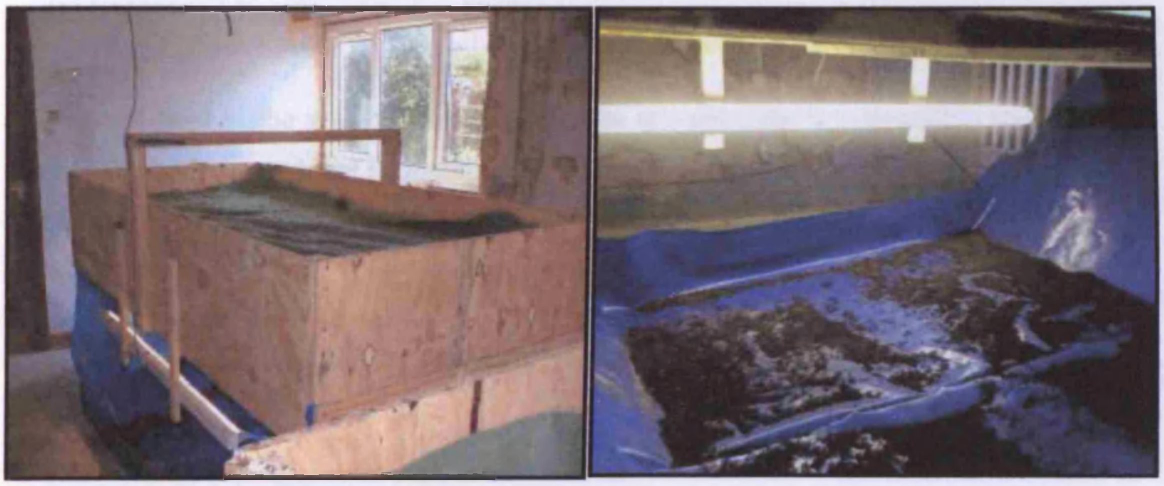


Figure 3.2 Photographs showing vermicomposting reactor (left), metal tray, plastic sheeting and fluorescent tube light fixed at the base of the reactor (right)

The dry feed material (green-waste compost) had a typical moisture content of 40% (m/m). The moisture content was raised to 60 ± 2% (m/m) in order to provide a suitable moist environment for the worms, whilst avoiding formation of slurry that could result in drowning of the worms and the development of anaerobic conditions. For comparison, Frederickson et al. (1997) and Bansal and Kapoor (2000) successfully performed vermicomposting by using lower moisture contents of 66 ± 2% and 60%, respectively (see Section 2.4.2). Hence, there is usually a need to add more moisture to the waste material before and during the vermicomposting.

3.2.2 TEMPERATURE MONITORING

The temperature was monitored using three HANNA (A141a) automatic data loggers (- 40 to 80 °C) and a hand held Checktemp 1 temperature probe (- 20 to 90 °C). The two data loggers were inserted at a depth of 40 mm in the middle of the reactor beds positioned just below the new feed material. The third data logger was used to record the ambient temperature of the reactor room. Each data logger was set to take readings at 30 minute intervals. All data were subsequently downloaded to Microsoft Excel 2002 using a HANNA 141001 infrared transmitter.

The hand held probe was calibrated as per the manufacturer's instructions and used to verify the bed and ambient temperatures.

3.2.3 MEASUREMENT OF pH, ELECTRICAL CONDUCTIVITY AND REDOX POTENTIAL

The pH and electrical conductivity (EC) measurements were made in accordance with The Composting Association, UK, Standards for Compost under the guideline of British Standard BS EN 13037:2000. A HANNA instrument Watercheck (range 0.0 to 14.0 pH with an accuracy ± 0.2 pH and range 0 to 1990 μS/cm for conductivity) was used to record pH and EC of the feedstock and earthworm casts on a weekly basis. Prior to recording each reading, the meter was calibrated, using pH buffer 7 and EC 1413 μS/cm solutions. In order to determine the pH and EC of the feedstock and casts material, a 25 g representative sample of substrate was collected from reactor A and B from at least 10 different locations at a depth within the top 50 mm layer of the reactor beds and placed in 150 ml of deionised water. After stirring the aqueous suspension for 1 minute, the meter was inserted and the pH and EC of the suspension were recorded after the readings had stabilised.

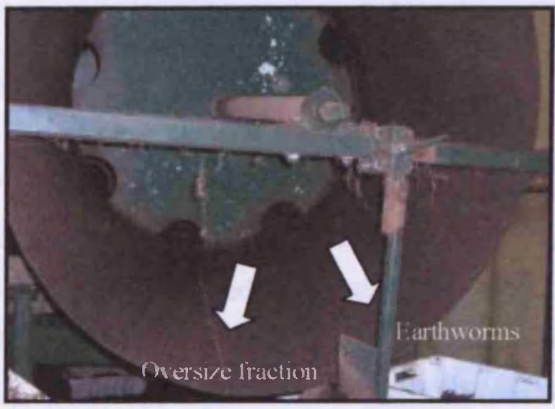
Redox potential was measured using The Composting Association, UK, Standards for Compost with British Standards BS EN 13038:2000. A Hanna oxidation-reduction potential (ORP) meter (range -999 to +999 mV with an accuracy ± 5 mV) was used to determine the redox potential of the feedstock and casts material on a weekly basis. The ORP meter combines a high-tech platinum electrode and a silver/silver chloride reference electrode. After stirring the aqueous suspension for the duration of 1 minute as reported for pH and EC, the ORP meter was inserted in the prepared suspension and the stabilised redox potential reading was recorded. This procedure was repeated on the samples collected from each reactor.

3.2.4 MEASUREMENT OF MASS

The mass of feedstock applied and the cast material produced during the harvesting were determined using a Salter electronic balance and a Salter suspended weigher model 235 with a scale interval of 0.01 kg and 0.5 kg, respectively. The initial earthworm biomass of 22 kg per reactor was also obtained using a Salter electronic balance. The earthworms comprised of only clitellate adults with no cocoons. In order to quantify the actual loss of worm mass and the amount of compost mass reduction for the first harvest, both reactors were subjected to hand sorting. However, the final harvest was carried out using a rotating drum harvester as shown in Figure 3.3. The earthworm biomass during the harvest was achieved using an analytical balance with a scale interval of 0.01 g. After hand sorting and the removal of all extraneous material, values were determined as live weight using both harvesting methods.

A. Feeding harvested materials

B. Less than 5mm vermicompost



C. Oversize fraction and earthworms collection in separate trays

D. Separated earthworms and twigs

Figure 3.3 Photographs of rotating drum harvesting

3.2.5 MOISTURE AND VOLATILE ORGANIC MATTER CONTENT

The moisture and volatile organic matter content of the feedstock and cast material were determined using The Composting Association, UK, Standards BS EN 13040:2000 and EN 13039:2000 on a weekly basis. Similar sampling procedures were introduced as reported in Section 3.2.3. A 100 g representative sample from the feedstock and casts material was accurately weighed to ± 0.001 g. The samples were then placed in porcelain dishes and air-dried at 103 ± 2 °C for 24 hours, and the dried samples were allowed to cool to room temperature before being re-weighed. The moisture content of the sample was calculated and expressed as a percentage of total mass.

In order to determine the volatile organic matter content of the feedstock and cast material, the dried samples were ground to approximately 2 mm particle size. Representative samples (5 ± 0.001g) were then placed in silica crucibles and ashed in a Carbolite furnace at 450 ° C for 5 hours. Volatile organic matter was determined as loss of mass on ignition, expressed as a percentage of the dry mass.

3.2.6 PARTICLE SIZE DISTRIBUTION

Particle size distributions on dry and wet bases were determined by placing the air-dried representative samples collected from both reactors and feed material into a set of sieves. Sieves were arranged in descending order of aperture size, 5.6, 3.35, 2.8 and 1 mm and the base pan, with the 100 g sample being evenly distributed over the 5.6 mm sieve. For dry sieve analysis, the sieves were shaken mechanically for 30 minutes (see Figure 3.4a), whereas wet sieve analysis was performed using the sieves in a vibratory cascade (see Figure 3.4b). The water was percolated along the range of sieves until the migration of the various particle sizes was completed. The quantity of material retained in each sieve was air dried and weighed and the results were expressed as percentage retained in each sieve.

a. Dry Sieving b. Wet Sieving

Figure 3.4 Particle size analyses on compost samples

3.3 CHEMICAL ANALYSES

The total nutrient and heavy metal concentrations were determined using two acid digestion techniques, while the bio-available nutrients and heavy metal concentrations were determined using water-based extraction. Details of these techniques are discussed below.

3.3.1 ACID DIGESTION

3.3.1.1 Combination of Concentrated Acids

During the vermicomposting trial, the total concentrations of elements were determined by digesting the air-dried sample using a combination of concentrated acids. A strong acid mixture including concentrated hydrogen peroxide (30% (w/v) H_2O_2), concentrated hydrochloric acid (37% (w/w) HCl) and concentrated nitric acid (70% (w/w) HNO_3) was used for this purpose. A representative mass (2 ± 0.001 g) of a dried ground sample was accurately weighed and placed in a 250 ml conical flask, then 100 ml of H_2O_2 was added to the flask and was allowed to react for two days at ambient temperature before boiling until near dryness. A stock solution of aqua regia (BS EN13650: 1999) was prepared by mixing equal volumes of HCl and HNO_3. The solution was allowed to stand for 10 minutes, 20 ml of the acid mixture (HCl : HNO_3) was added to each flask and was boiled and shaken in order to maximise dissolution of the solid. The whole contents of the flask were passed through a Whatman No. 0.22 μm filter paper and the resultant solution was diluted to 50 ml with 3% HNO_3. The liquor produced after the acid digestion was bottled and stored at 4 °C prior to further analysis.

3.3.1.2 Microwave Digestion Method

A microwave digestion technique was also used to determine the total nutrients and heavy metals concentrations. This was performed by digesting 0.1 g of air-dried composts and lettuce samples in a microwave oven (Anton Paar 3000). Briefly, a stock solution of aqua regia (BS EN13650:1999) was prepared as described in Section 3.3.1.1. Subsequently, 10 ml of the acid mixture was added to each sample and the mixture was allowed to react for 15 min. The samples were then microwaved (1400 W, 210°C at a pressure of 40 bar). After digestion, the resultant solution was adjusted to 50 ml with 3% HNO_3, filtered through a 0.22 μm filter paper and stored at 4 °C for analysis. Acid digestion of the same samples using a combination of concentrated hydrofluoric acid (HF) and concentrated hydrogen per-oxide (H_2O_2), in addition to aqua regia, was also carried out using the microwave in order to determine any variation in the results.

3.3.2 WATER-BASED EXTRACTION

All samples of composts obtained throughout the period of study were subjected to extraction of key components with distilled water. Dried compost samples of 10 ± 0.001 g were placed in Whatman Vecta Spin 20 polypropylene centrifuge tubes with the 0.2 μm pre-filter provided. 30 ml of distilled water was added to each tube. The tubes were then placed in a Stuart SSL1 orbital shaker and shaken at 200 rev min^{-1} for 1 hour. The tubes were then centrifuged (Sigma 6K15) at 4000 rev min^{-1} for 15 min. The resulting pre-filtered extract was decanted and stored in bottles at 4 °C to await analysis.

3.3.3 ANALYSIS OF ELEMENTS

The analyses of the filtrates obtained using both extraction techniques were performed by Inductively Coupled Plasma Optical Emission Spectrophotometer (Optima 2100 DV ICP-OES) see Figure 3.5. This machine allows a dual view of plasma (axial and radial) and is able to perform a multi elemental analysis simultaneously from a set of standards. The calibration standards were prepared using Fisher Scientific's 28-element custom standard (100 mg/l concentration for each element). Lower calibration standards were prepared to detect heavy metals concentrations by diluting the custom standard to 0.0, 0.01, 0.1 and 1 mg/l in a 3% nitric acid matrix. These were measured using the axial view of the plasma, which allows trace measurements because it provides a larger emission path for increased sensitivity and lower background level i.e. the lowest detection limits, while radial viewing was utilised to detect higher concentrations using calibrations such as 0.0, 1, 10 and 100 mg/l. Elements such as Ca, K, Mg, Na and P were measured using radial viewing of the plasma.

Figure 3.5 Inductively Coupled Plasma Optical Emission Spectrophotometer (Optima 2100 DV ICP-OES)

3.4 GROWTH TRIALS

3.4.1 TOMATO AND CORIANDER

3.4.1.1 COMPOST SAMPLING

Seven compost samples were collected. Five samples were taken from different composting facilities in Wales. These samples were in various stages of the curing/maturation process (as defined by the facility, Table 3.1). Two other samples of multipurpose compost were purchased from a local garden centre. Collected samples were placed in polyethylene bags and were sealed in order to minimise loss of moisture.

TABLE 3.1 Description of the compost materials used in the growth trials

Compost Source	Feedstock	Composting process	Aeration/ Mixing	Maturity/ curing period (months)	Compost association, UK Accreditation
A	Sphagnum peat	Nutrients added	NA	NA	NA
B	Green waste, woody material	Static pile on concrete pad	Mixing by turning piles	4 (max)	BSI-PAS 100
C	Green waste	Open windrow	Windrow-turning	1	None
D	Timber residues	Nutrients added	NA	NA	NA
E	Green waste	Static pile on concrete pad	Forced aeration	1	None
CERT	Green waste	Housed windrow	Windrow turned by front end loader	12	In process
Vermi-compost	Green waste	Housed indoor	Mixing by worms, feed added weekly	2	None

(names of the compost producers are not identified, NA refers to information not available)

3.4.1.2 SEED GERMINATION TEST

Germination and growth trials are convenient methods for measuring the potential plant response and information derived from such trials could aid the potential marketability of the compost. Seed germination is the first step in plant development and any adverse effects at this stage will have a direct impact on the plant's survival (Wang, 1992). Trials were divided into two sets, initially using coriander (*Coriandrum sativum* L.) and then tomato (*Lycopersicon esculentum* L. cv. 'Merit') as used in the BSI PAS-100. The composts were all used in the "as-received" form with no attempt to mix with common additives to growth media, such as sand, soil or nutrients. Plastic pots (6.5 cm diameter and 11 cm deep) were filled with compost from each source. Seeds were sown at a depth of 2 cm. Five replicate pots were used for each type of seed. For the coriander trials, ten seeds were sown in each pot, whilst for the tomato trial five tomato seeds were sown. Once the seeds had been sown, the pots were placed in a randomised design in a climate-control chamber (Sanyo-Gallenkamp, Fi-totron PG660/C/RO/HQI, Loughborough, UK) as shown in Figure 3.6. Growth trials were conducted at a constant temperature of 20 °C and relative humidity of 70% with 16 hours of photoperiod (500 μmol photons m^{-2} s^{-1} photosynthetically active radiation at canopy height), thus providing suitable environmental conditions and physical support for the germinating seeds. Watering of the growth media was carried out three times weekly with distilled water to bring the composts up to their water holding capacity. Seedlings were counted after the first and second weeks of germination and the values from each pot were recorded as a percentage.

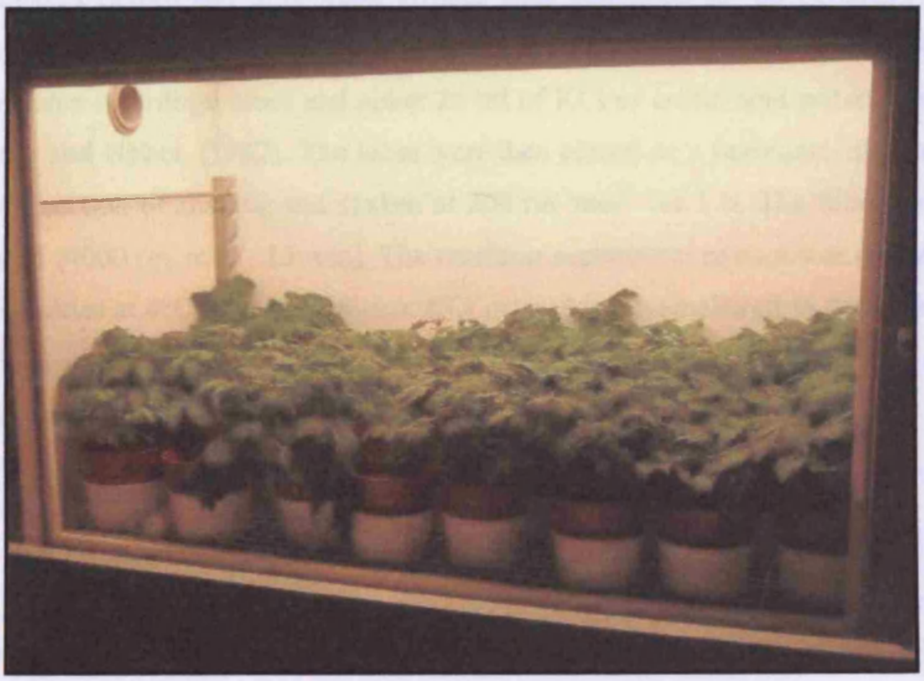


Figure 3.6 Climate control chamber used for tomato and coriander growth trials
(Test performed by author at School of Agriculture and Forest sciences, University of Wales, Bangor)

3.4.1.3 EC AND pH MEASUREMENT

Electrical conductivity (EC) and pH measurements were also discussed in Section 3.2.3. However, during growth trials, different instruments and technique were used. These measurements were performed on the original composts (as received) and on the samples taken after the coriander growth trials according to the method of Smith and Doran (1996). Compost samples were diluted with distilled water using a volume ratio of 1:1 (water : compost). Samples were then mixed and allowed to equilibrate for 1 hour. EC was measured using Jenway 4010 EC meter and pH with an Orion 410A pH meter.

3.4.1.4 COMPOST EXTRACTS

The composts before and after plant growth were subjected to the extraction of key nutrients with 1.0 M KCl and 0.5 M acetic acid. Compost samples (5 g) were placed in polypropylene centrifuge tubes and either 25 ml of KCl or acetic acid added as outlined by Keeney and Nelson (1982). The tubes were then placed on a horizontal shaker in line with the direction of shaking and shaken at 200 rev min^{-1} for 1 h. The tubes were then centrifuged (4000 rev min^{-1}, 15 min). The resulting supernatant extract was decanted and stored in bottles at 4°C to await analysis. KCl extracts were employed to determine NO_3^- and NH_4^+ concentrations in the compost, while the acetic acid extracts were used to determine Na, K, Ca and P.

3.4.1.5 NUTRIENT ANALYSIS

Ammonium (NH_4^+) and nitrate (NO_3^-) concentrations were determined in the KCl extract solution using a segmented-flow San-Plus autoanalyser (Skalar Ltd, York, UK, see Figure 3.7) according to the standard protocols provided with the instrument. This method is based on the reduction of nitrate (NO_3^-) to nitrite (NO_2^-) using a copper-cadmium reduction column with chromophoric detection of NO_2^- using N-1-

napthylethylenediamine di-hydrochloride (C_{12} H_6 Cl_{12} N_2). These chemical reactions form a reddish-purple azo dye, which is colorometrically measured at 540 nm.

Figure 3.7 Skalar San-Plus autoanalyser used to detect Ammonium and Nitrate concentration (Test performed by author at School of Agriculture and Forest sciences, University of Wales, Bangor)

Sodium, potassium and calcium in acetic acid extracts were determined with a Sherwood 410 flame photometer (Sherwood Scientific Ltd., Cambridge, UK, see Figure 3.8). Phosphorus was determined according to the spectrophotometric method of Murphy and Riley (1962).

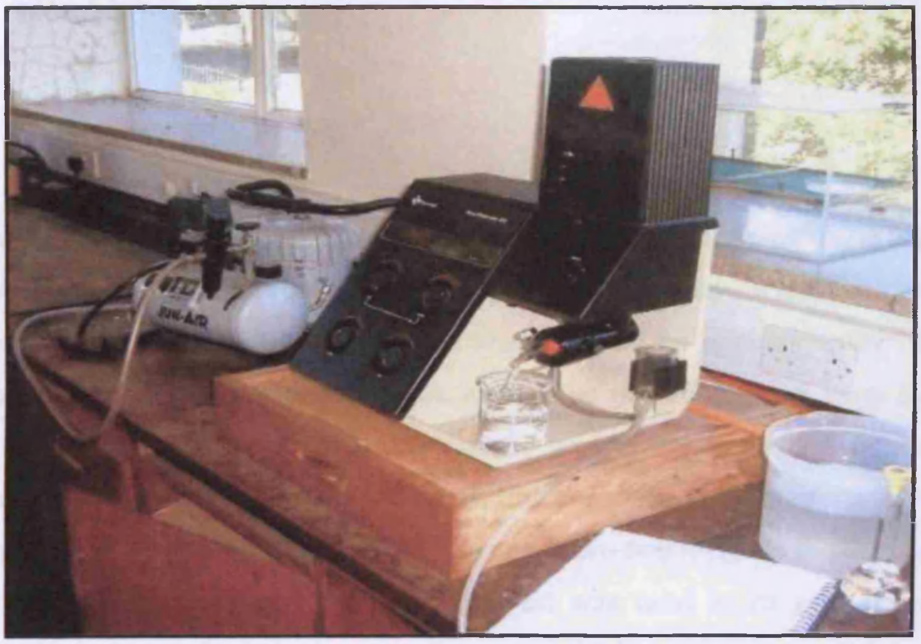


Figure 3.8 Sherwood 410 flame photometer used to detect Sodium, Potassium and Calcium concentration (Test performed by author at School of Agriculture and Forest sciences, University of Wales, Bangor)

3.4.1.6 STATISTICAL ANALYSIS

Statistical analysis (ANOVA with Tukey pairwise comparison) was undertaken with Minitab v14 (Minitab Inc, State College, PA, USA) with significant differences identified at the $P < 0.05$ level. These analyses were performed on seed germination and plant biomasses of each compost source.

3.4.2 LETTUCE

3.4.2.1 COMPOST SAMPLING

The vermicompost trial was conducted using windrow produced green-waste compost as discussed in Section 3.2. The substrate was supplied in three independent batches for the vermicomposting process. All the composts were matured for approximately 18 months prior to vermicomposting. The feed material and the resulting worm casts from each reactor harvest were subsequently utilised as the growth media for the lettuce growth trial. Representative samples of the feedstock (mature green waste compost) from each batch applied during the vermicomposting process were employed as the control media. Similarly, worm cast obtained from each harvest was used in its pure form (100% concentration). A sample from the second compost feedstock was amended with worm cast obtained from each harvest at cast concentrations of 50% (v/v) and 20% (v/v) in order to produce two blended growth media.

3.4.2.2 SEED GERMINATION

Opaque plastic pots (6.5 cm diameter and 11 cm deep, 1 litre volume) were filled with each substrate and five lettuce seeds were sown at a depth of approximately 2 cm. Three replicate pots were used for each compost media treatment. Once the seeds had been sown, the pots were transferred to a glasshouse maintained at 20 ± 2 °C and equipped with supplemental metal halide lamps (Philips power tone MHN-TD 250 W, UV block) with 16 h photoperiod and light intensity of 180 μmol photons m^{-2} s^{-1} at canopy height. Watering of the plants was carried out three times weekly to bring the composts up to their water holding capacity. Seedlings were assessed after the first week and only the single best seedling was allowed to grow with the remaining four removed from the pots.

The lettuce was then permitted to grow to full maturity with the plants being harvested 49 days after planting.

3.4.2.3 WATER HOLDING CAPACITY

Water holding capacity is the amount of water that a compost sample can absorb up to full capillary saturation. Polypropylene tubes (2.8 cm diameter and 9.8 cm deep) with a plastic net attached to the bottom were used to determine the water holding capacity of each media as shown in Figure 3.9. Representative samples from each pot were placed into the tubes with light shaking. All tubes were then weighed before being placed into a stand and transferred to a tub, which contained water up to the middle height of the tubes. Addition of water to the tubes from the top was continued until the substrate was covered by approximately 1 cm and the composts could absorb no more water. Subsequently, water was then drained for 30 min and the tubes were re-weighed before moist samples were transferred to drying containers. The samples were air dried overnight at 80 °C. The amount of moisture lost after drying is reported as a percentage of the total mass.

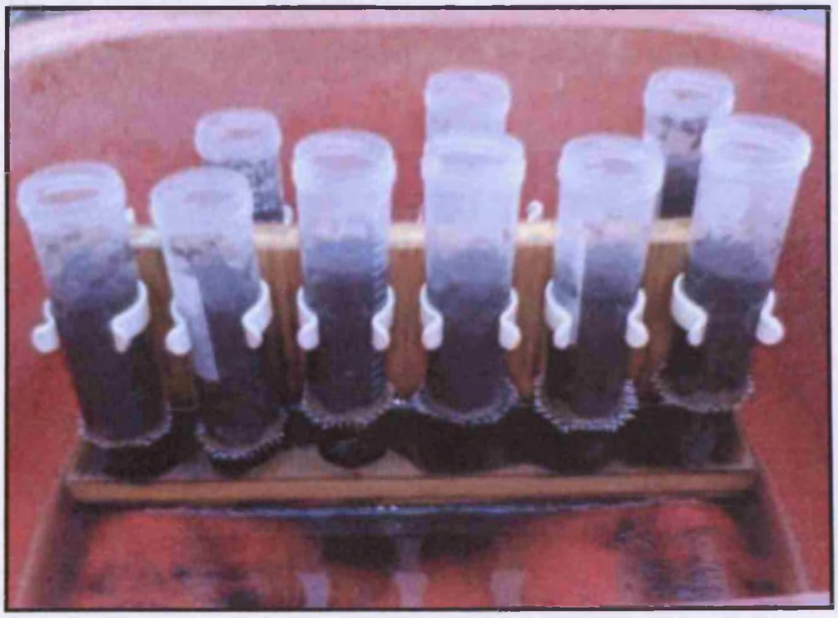


Figure 3.9 Determination of water holding capacity of growth medias used for growth trials

3.4.2.4 PLANT BIOMASS

Plant fresh weight was determined at harvest and dry weight subsequently determined after oven drying at 80 °C overnight. Dried lettuce leaves were ground to a fine powder with a Kenwood CH100 mini chopper for subsequent acid digestion.

3.4.2.5 CHLOROPHYLL CONTENT

Leaf chlorophyll content was determined using the Soil Plant Association Development, SPAD 502 meter (Minolta Corporation, Japan). The SPAD 502 has a measurement area of 0.06 cm^2 and calculates an index in "SPAD units" based on absorbance at 650 and 940 nm. The accuracy of the SPAD 502 is ± 1.0 SPAD units. The procedure for 'zeroing' the hand-held chlorophyll meter simply involved closing the measurement clamps with no material placed between them and adjusting the dial accordingly. SPAD reading for each plant represented the mean reading from 5 fully expanded leaves. The lettuce leaf was inserted at about half way from the tip and collar of the meter clamp, about the middle point between the leaf mid rib and leaf margin for each plant as shown in Figure 3.10. The chlorophyll index for each plant was the average of five readings.

Figure 3.10 Chlorophyll content measurement using Minolta SPAD 502 meter

3.4.2.6 CHEMICAL ANALYSES

The total and bio-available nutrients and heavy metal concentrations were determined on the air-dried samples of the growth media collected during lettuce growth trials. Details of the procedure are described in Section 3.3. However, total nitrogen concentrations were determined by weighing 50 mg solids (dried ground compost and lettuce) into tin capsules and then igniting at 1000 °C, NO_2 was detected by chemiluminescence using LECO 2000 CHN analyser (LECO Corp., St. Joseph, MI).

3.4.2.7 HUMIC ACID

Humic acid content was determined from the representative samples of the feedstock, vermicompost produced and two other commercially available multipurpose composts, details of which are presented in Table 3.2

Table 3.2 Description of the compost materials used for determining humic acid contents

Source	Composition
CERT feedstock	Windrowed mature green waste compost
CERT vermicompost	Mature green waste vermicompost
A	50 % in-vessel green waste compost, organic NPK (3,1,3), trace elements and humus
B	Mixture of peat and 20 % alternative ingredients/nutrients of total mix

(names of the commercial compost producers are not identified)

Humic acids were extracted using both the classical alkali/acid fractionation procedure (Valdrighi et al. 1996 and Atiyeh et al. 2002b) and the water/acid method. Compost samples from each source were dried overnight at 80 °C and subsequently ground to approximately 2 mm particle size. A 50 g sample was digested in 0.1 N aqueous KOH in polypropylene centrifuge bottles and shaken at 200 rpm in a Stuart orbital shaker for 24 h at room temperature. The undigested residue in each bottle was then separated from the solute fraction by centrifugation at 4000 rpm for 50 min using Sigma 6K centrifuge followed by vacuum filtration through a Whatman glass microfiber filter paper. The filtered supernatant was then transferred to centrifuge bottles and was acidified to pH 2.0 with 6.0 N H_2SO_4. This was then kept in a dark place for 24 h in order to obtained flocculation of the humic acids. After acidification, the humic precipitates (humates) were collected by centrifuging again at 4000 rpm for 50 min and subsequently washed with distilled water and collected on filter paper (see Figure 3.11). These humates were then frozen at –20 °C and then allowed to dry at room temperature to form a black-brown granulated humates. Each sample was weighed and the results presented as g kg^{-1} on a dry matter basis. A similar procedure was used during water/acid method, but the samples were shaken with de-ionised water instead of an alkaline solution.

Figure 3.11 Humates collected on filter paper at the end of alkali/acid fractionation method

3.4.2.8 STATISTICAL ANALYSIS

Statistical analysis (ANOVA with Tukey pairwise comparison) was undertaken with Minitab v14 (Minitab Inc, State College, PA, USA) with significant differences identified at the $P < 0.05$ level. These analyses were performed on water holding capacities, plant biomasses and chlorophyll contents of each compost source.

3.5 COMPOST CONTAMINANT CHARACTERISATION

3.5.1 INITIAL TRIAL

This initial phase involved the collection of a large compost sample from Amgen Cymru's Bryn Pica landfill site near Aberdare, South Wales. Table 3.3 describes a brief history and details of the sample. Grab samples were mixed by employing a back actor of a JCB in order to homogenised the sub pile. Sub-samples were obtained using the classical cone and quarter technique.

Table 3.3 History of collected compost sample

Compost Producer/ Facility	Bryn Pica Landfill site (Aberdare, South Wales)
Feedstock Utilised	Park waste, wood waste, green waste & kerb side collection from Rhonda Cynon Taf, County Borough Council
Date of Manufacture	December 2004 - January 2005
Shredder	Slow speed shredder / Chipper
Composting Technique	Static pile
Aeration	Mixing and turning
Pile turning	Twice after the date manufacture
Date & time of sampling	04/05/05 between 14:00 and 14:30
Screening	Sample not screened
Total size of sample	327.71 kg

A large scale representative sample (327.71 kg) was taken from a sub-pile and was well mixed as shown in Figure 3.12. This was conveyed to The Carmarthen Environmental Resource Trust (CERT) composting facility using 20 rubble bags. All bags were screened to separate different particle sizes of the compost using a Menart 1530 trommel screen fitted with a 10 mm screen. The < 10 mm fraction (commercially sold green waste-derived compost) passed through the screen and was collected on a tarpaulin sheet. This material was bagged, sealed and weighed prior to further analysis in the laboratory. Wood, contaminated wood (containing paint or varnish), stones, plastic films, rigid plastics and all other large materials were retained on the screen as "oversize" (>10 mm) and collected on the other side of the screen. This fraction of compost (oversize) was further subjected to hand sorting (>25 mm, visible physical contaminants) and manual screening (>10 mm <25 mm).


A. grab sampling B. sub-piling formation


C. mixing sub-pile D. re-mixing of sub-pile

Figure 3.12 Sample collection and mixing for compost quality assessment

The <10 mm compost fraction was subjected to further dry sieve analysis using BS EN13040:2000 to obtain smaller size ranges. Sieves were arranged in descending order of aperture size (5.6, 2.8, 1 mm and the base pan) with the 100 g sample being evenly distributed over the 5.6 mm sieve. A similar method was reported in Section 3.2.6.

To identify physical contaminants, a traditional sink and float method was also used. This method is normally used in the mineral industry to separate smaller fractions. The preliminary analysis on the quantity of sink (stone, glass and metal) and float (plastic films, wood and contaminated wood) was performed on the particle fractions >10 mm <25 mm and >1 mm <5.6 mm of the compost (%m/m). Media of varying specific gravity were prepared in order to quantify the sink and float fractions in the selected compost particle size.

Liquids having specific gravity of 0.80, 1.0, 1.2 and 1.4 were used as a float medium. These liquids were prepared by mixing tetrachloroethylene (C_2Cl_4) with common diesel fuel oil in order to obtain desired specific gravities, which were measured using hydrometers. Materials including plastic film, wood and contaminated wood were collected on the surface as the float fraction (buoyant), while stones, glass and metals were determined from the sink fraction.

3.6 AIR SEPARATION TRIALS

3.6.1 AIR CLASSIFICATION

The results obtain from the initial trial as described in Section 3.5.1 revealed different types and quantities of various physical contaminants. The data obtained were used to determine the type, amount and proportion of each contaminant in order to prepare a representative mixture (standard feed). For this reason, various physical contaminants were prepared, which were added to mature compost produced at the Carmarthenshire Environmental Resource Trust (CERT) composting facility that had been screened to less than 10 mm. The standardised feed comprised of 5 kg (<10 mm, particle size) CERT compost and a total of 2 kg of the standardised contaminants. This complex mix was tested in laboratory based air separation trials.

3.6.1.1 Characteristics of Contaminants

Table 3.4 highlights the characteristics of the contaminants in the standardised feed. The characteristics of these undesirable materials are of fundamental importance. They could be present in various forms and quantities, depending upon the level of contamination in the feed material undergoing the composting process. The quantity of physical contaminants also depends on the type of collection performed e.g. kerb side collection has historically a higher proportion of contaminants than Civic Amenity site green waste.

Table 3.4 Characteristics of the prepared physical contaminants

Contaminants	Type	Thickness (mm) *	Sizes (mm) (All in square shape)
Film plastics	A	0.01	25, 50 and 100
	B	0.02	25, 50 and 100
	C	0.03	25, 50 and 100
	D	0.05	25, 50 and 100
	E	0.06	25, 50 and 100
Rigid plastics	A	2	+ 10 – 15, + 15 – 25 and + 25
	B	3	+ 10 – 15, + 15 – 25 and + 25
	C	4	+ 10 – 15, + 15 – 25 and + 25
Non-ferrous metals	Aluminium	0.55	+ 10 – 15, + 15 – 25 and + 25
	Copper	0.45	+ 10 – 15, + 15 – 25 and + 25
Ferrous metals	Steel	0.80	+ 10 – 15, + 15 – 25 and + 25
	Painted steel	0.70	+ 10 – 15, + 15 – 25 and + 25

* Thickness measurements: TESA Swiss digital vernier calliper (IP 65)

3.6.1.1.1 Plastic films

Five different types of plastic films (e.g. bin liners, black refuse bags and rubble bags) with thickness ranging from 10 μm to 60 μm cut into squares of 25 mm, 50 mm and 100 mm were used as light plastic materials, as shown in Figure 3.13. Plastic films of different thicknesses were selected in order to examine if they had any impact on removal efficiency.

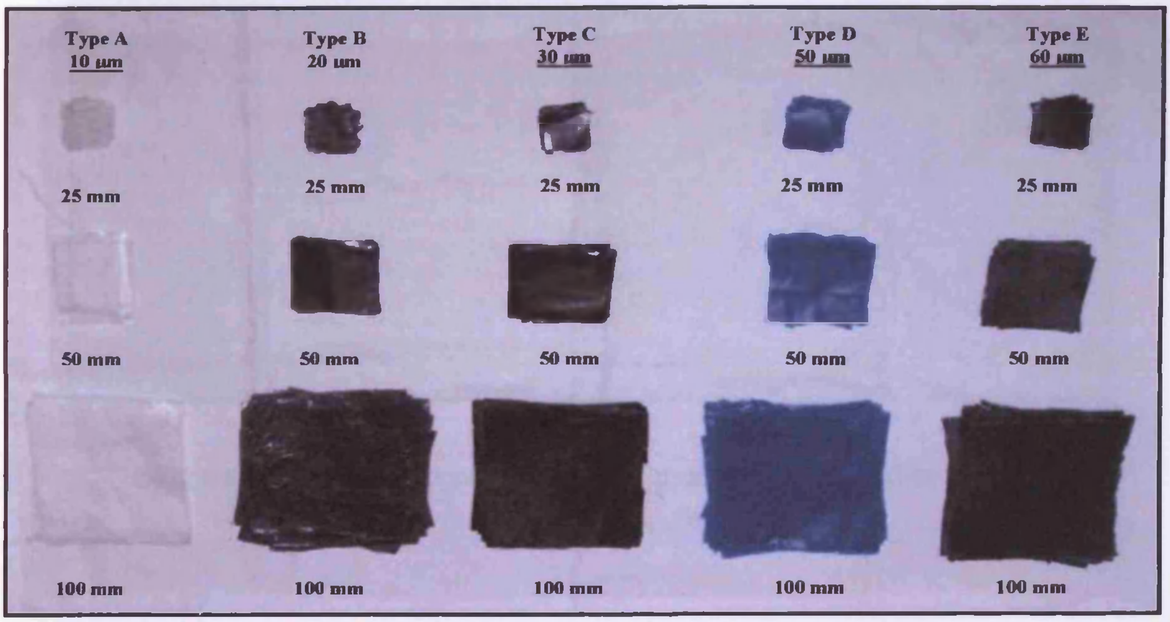


Figure 3.13 Five different types of plastic films used in standardised mix

3.6.1.1.2 Rigid plastics

Rigid plastic sheets of nominal thickness 2 mm, 3 mm and 4 mm, were cut into square shapes of sizes + 10 mm – 15 mm , + 15 mm – 25 mm and + 25 mm as shown in Figure 3.14.

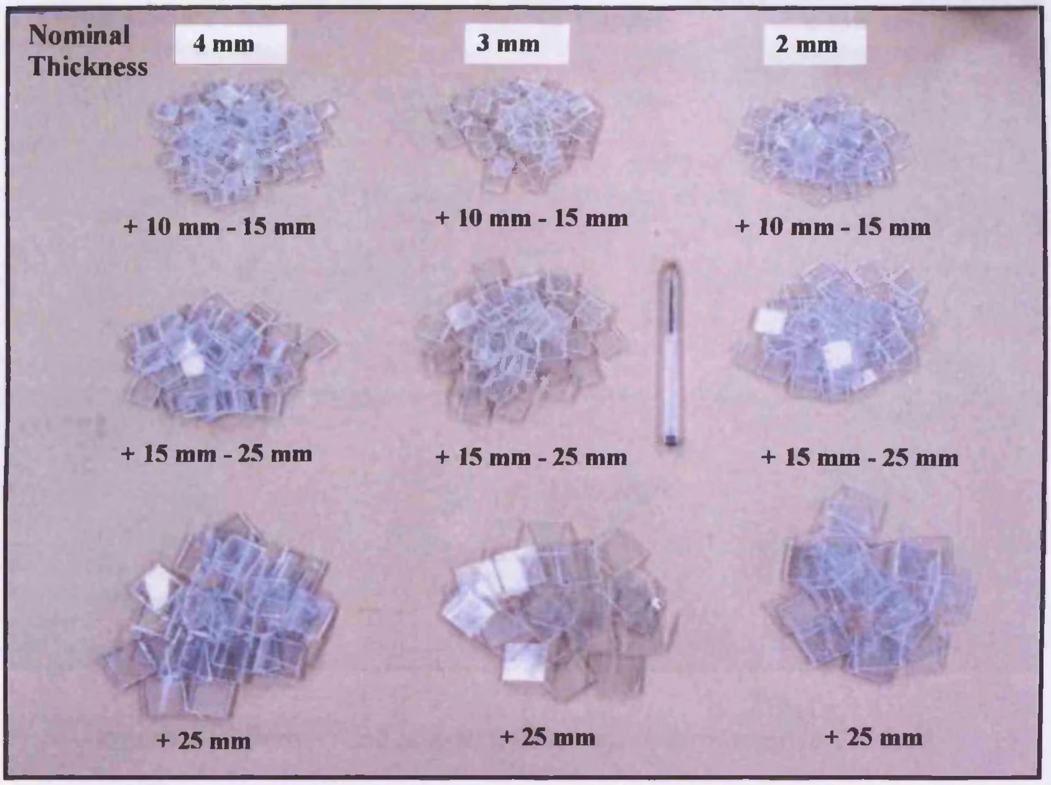


Figure 3.14 Three types of rigid plastics used in the standardised mix

3.6.1.1.3 Metals

Both ferrous and non-ferrous metals (painted steel, steel, copper and aluminium sheets) were cut into square shapes of known mass and thickness and were also incorporated in the standard mix (see Figure 3.15).

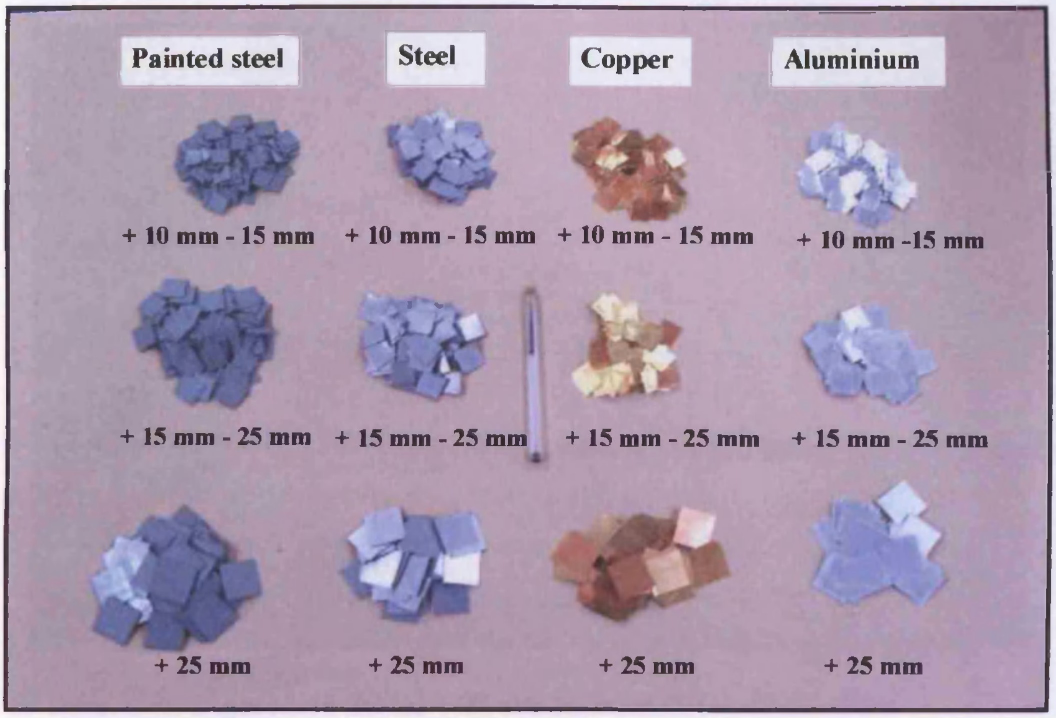


Figure 3.15 Ferrous and non-ferrous metals incorporated to the feed

3.6.1.1.4 Stones

Various sizes of stone aggregates i.e. 6 mm, 14 mm and 25 mm were added to the compost (see Figure 3.16).

Figure 3.16 Stones + 25 mm included in the standardised contaminants mix

3.6.1.2 LABORATORY TRIALS

An air classification test rig was designed and fabricated to test the removal efficiency of different contaminant materials at different air flow rates, as shown in Figure 3.17. It is a system to remove plastics and other light materials according to their density. During the laboratory trial, two types of classifiers were used (Type 1 and Type 2) with a Perspex tube (240 mm diameter) and a PVC pipe (147 mm diameter). Both classifiers were connected to an extraction system, which utilises an upward flow of air generated by a 5.50 kW fan (Donaldson Torit DCE, Model no. UMA 153). The classifiers were placed on a metal mesh stand, to allow the upward flow of air through the base. The air flow through the classifiers was varied using air flow regulators.

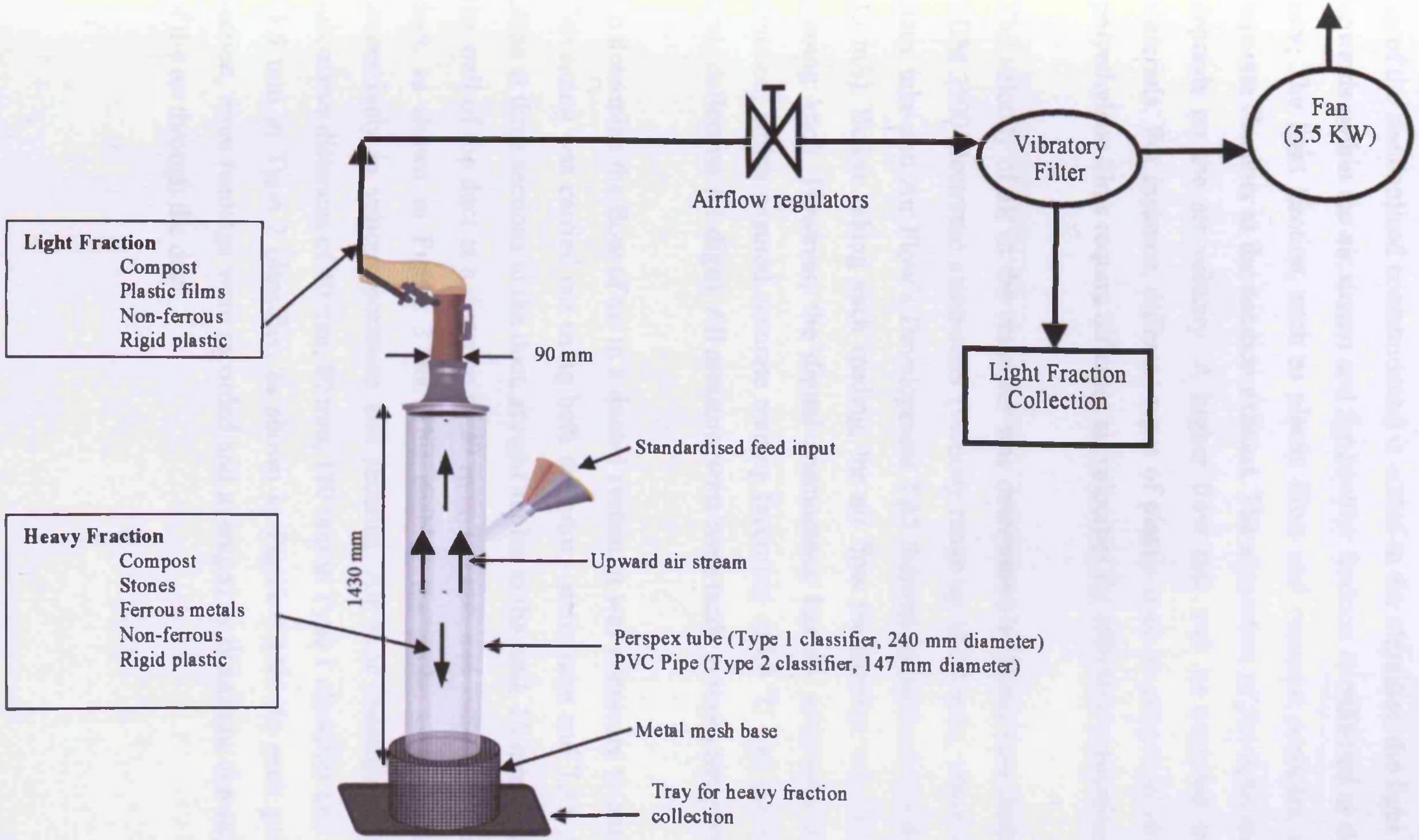
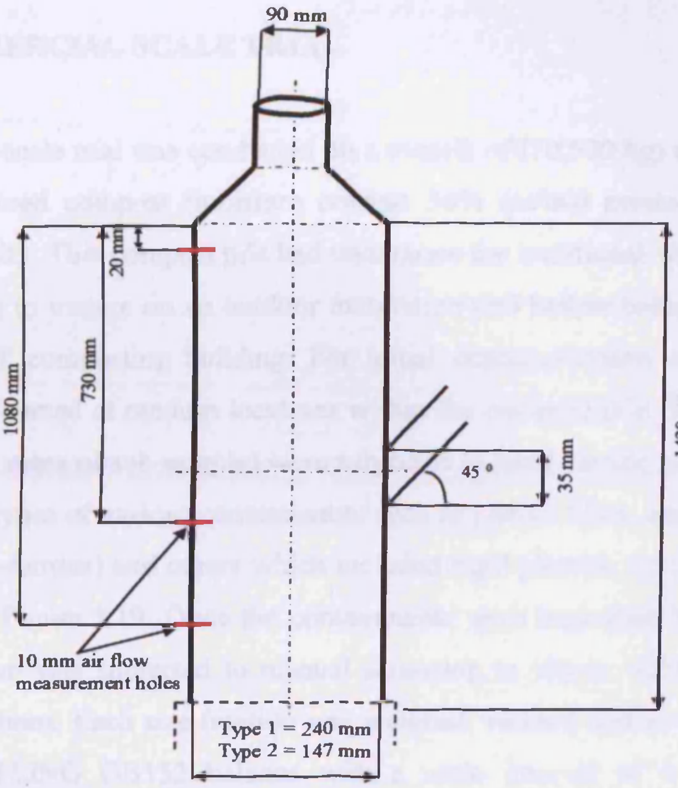


Figure 3.17 Schematic diagram of air classification system

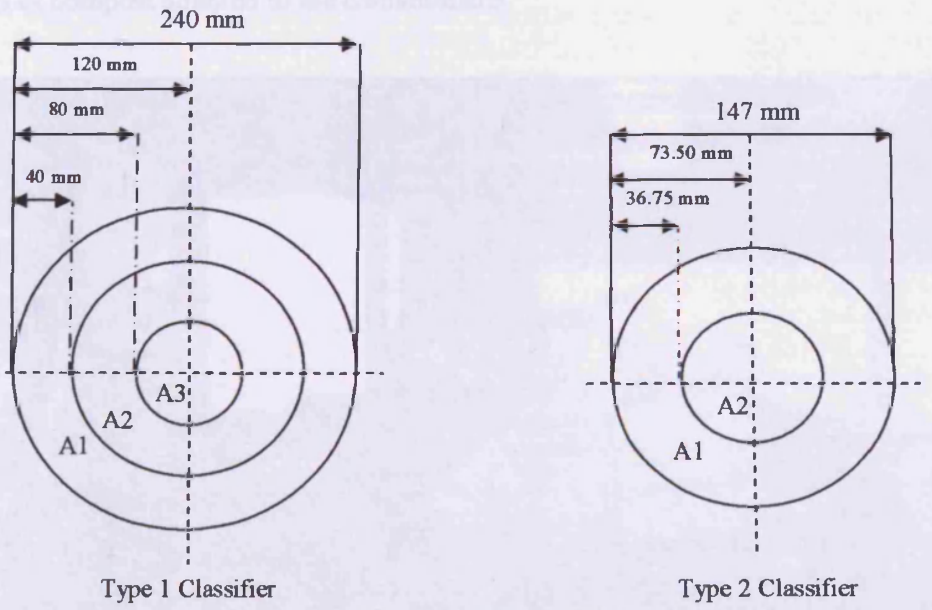
When the standardised feed (5 kg <10 mm, particle size CERT compost and a total of 2 kg of the standardised contaminants) is added to the classifier, the light fraction is carried upwards within the air stream and the heavier fraction is collected at the base in a metal tray. The light fraction, such as plastic films and compost particles, are collected in a separate chamber at the aeration exhaust. The separation of the light and heavy fractions depends on the air velocity. A higher flow rate will be required to remove heavier materials. For instance, different types of plastic such as polyvinyl chloride (PVC) and polyethylene films require different air velocities for effective separation.

The velocity of air in the classifier was determined by using two different instruments, EDM 2500 electronic manometer (velocity range up to 28 m/s), when attached to Pitot - static tube and Air Flow's Development TA5 thermal anemometer (velocity range up to 30 m/s). Before taking each reading, the air flow manometer was calibrated using the zeroing knob. However, the digital anemometer has an automatic electronic zeroing function, which ensured accurate reading (accuracy at 20 °C and 1013 mbar ± 2% full scale deflection ± 1 digit). All measurements were made at room temperature (20 ± 1 °C).

To determine the flow of air in a ducted system, it was necessary to carry out a traverse. Traversing was carried out using both the pitot - static tube and TA5 Anemometer in a plane at three sections in the duct, at right angles to the wall. 10 mm holes were drilled in the wall of the duct at a distance of 20 mm, 730 mm and 1080 mm from the top of the duct, as shown in Figure 3.18a. This enabled the probe to be inserted and moved successively in various positions and sections. Air flow measurements were made at successive distances of 40 mm, 80 mm, 120 mm in Type 1 classifier and at 36.75 mm and 73.5 mm in Type 2 classifier, as shown in Figure 3.18b. At each point of a specific section, three readings were recorded and averaged to determine the superficial velocity of the air through the duct.



a. Front view



b. Traversed points

Figure 3.18 Dimensions of the air separation test rig and traverse points

3.6.1.3 COMMERCIAL SCALE TRIAL

The commercial-scale trial was conducted on a sample of (10,500 kg) mature unscreened green waste-derived compost (moisture content 56% (m/m)) produced at the CERT composting facility. This compost pile had undergone the traditional windrowing process and was allowed to mature on an outdoor maturation pad before being mixed and piled inside the CERT composting building. For initial characterisation, representative sub samples were collected at random locations within the compost pile. These sub samples (297.93 kg, total mass of sub sample) were subjected to hand sorting in order to quantify the amount and types of various contaminants such as plastic films, stones, glass, metals (ferrous and non-ferrous) and others which included rigid plastics, textiles and rubber as demonstrated in Figure 3.19. Once the contaminants were separated from the compost, each waste stream was subjected to manual screening to obtain >25mm and <25 mm particle size fractions. Each size fraction was weighed, washed and re-weighed using an electronic OERTLING OB152 balance with a scale interval of 0.01 g. This was performed in order to determine the mass of the actual contaminant (as received) and the mass of compost adhered to the contaminants.

Figure 3.19 Hand sorting of contaminants from 297.93 kg of sub sample

The total contaminants in the 10,500 kg sample of the unscreened compost from the CERT facility were calculated from the data obtained by hand sorting of sub samples. After characterising the sub samples, both the contaminants and cleaned compost were re-added to the compost pile (10,500 kg) for further tests using commercial scale machines.

The CERT composting facility has a "Terra Select T4" trommel screen and "Komptech Hurrikan" windsifter (see Figure 3.20 and 3.21) to manufacture different size fractions of compost (end products) and to remove contaminants from the oversize fraction respectively. The results obtained from the characterisation of the sub-sample of unscreened compost were used to measure the efficiency of these machines in removing contaminants from the >25 mm fraction.

The mature unscreened compost pile (10,500 kg, moisture content 58 % (m/m)) was passed through the 25 mm square mesh trommel to obtain compost greater than 25 mm "oversize fraction" and <25 mm "undersize fraction" as shown in Figure 3.20. The trommel screen comes with an elevated conveyor belt at the far end of the screen that feeds the over size fraction (>25 mm particle size) to the "Komptech Hurrikan" windsifter inlet (see Figure 3.21).

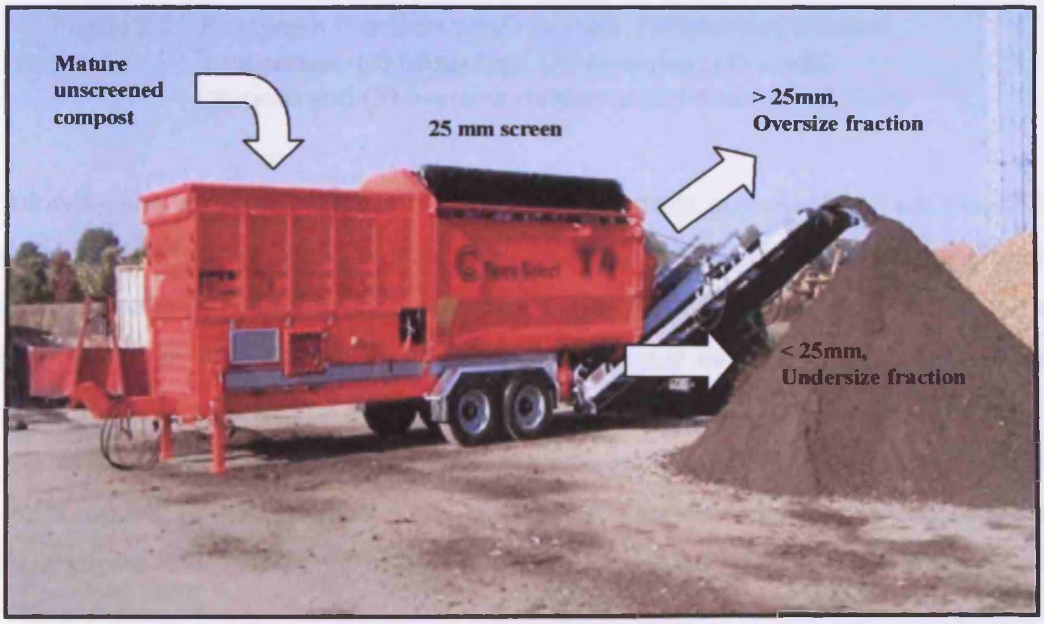


Figure 3.20 Terra Select T4 screen used during commercial scale trial

The "Komtech Hurrikan" had 4 outputs, which include light fractions, metals, stones and oversize residue. Light materials mainly plastic films and small compost particles are captured in a trailer with a net on top. Metals are directed to one area via a magnetic roller on the elevator and a chute. Large stones are removed via an adjustable angle of a smooth elevator that causes heavy and round objects to travel down to a further chute. The compost oversize residue is stockpiled behind the machine, after passing over the smooth elevator as shown in Figure 3.21.

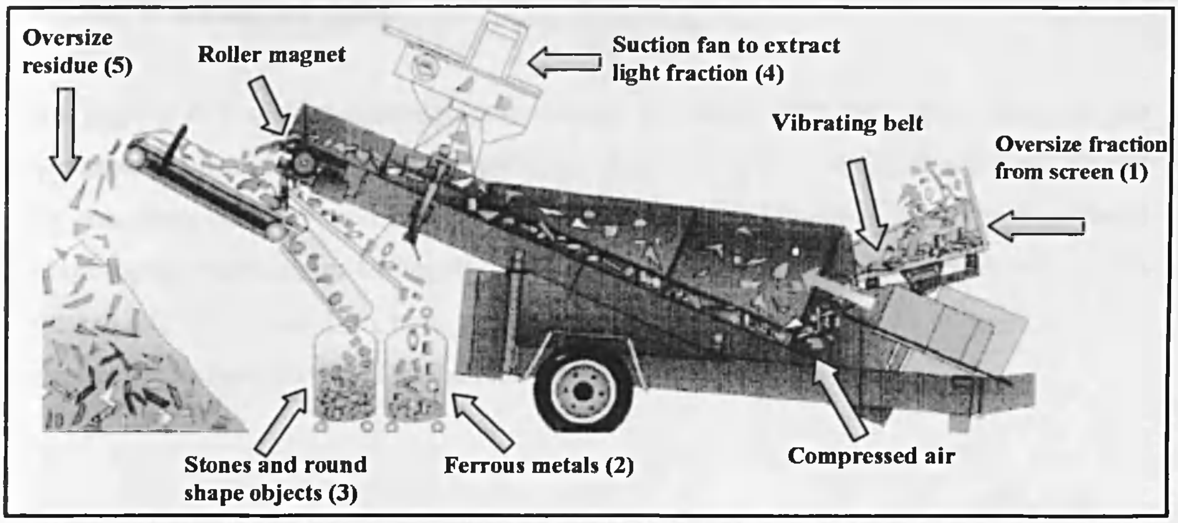


Figure 3.21 Komptech Hurrikan waste streams, (1) oversize fraction from screen, (2) Metal trap, (3) de-stoner, (4) Light fractions and (5) oversize residue (copied from Rynk, R 2001)

Following the machine separation of >25 mm particle size fraction, additional hand sorting was performed on the materials collected in the metal trap, de-stoner and oversize residue in order to determine the type and quantity of contaminants removed by the wind sifter. However, light fractions, which mainly consisted of plastic films, were excluded for further examination. The mass of compost (>25 mm particle size) in each output and mass of light fraction were determined using a Salter suspender weigher model 235 with a scale interval of 0.5 kg, whereas the mass of hand sorted contaminants within the other waste stream was determined using an electronic OERTLING OB152 balance with a scale interval of 0.01 g. A sub-sample of light fraction (plastic films) and all other hand-sorted contaminants were washed and re-weighed in order to determine the actual mass of the contaminants.

3.6.2 THE AIR JIG TRIAL

3.6.2.1 Working and Setup

Air jigging is a gravity concentration process in which light and dense fractions are separated from each other by the application of vertical pulses of air. A small air jig test rig has been designed and fabricated at the School of Chemical and Environmental Engineering, Nottingham University, as shown in Figure 3.22. The air jig is set-up in a rectangular box about 1 m high with a cross sectional area of 0.03 m^2 and a screen attached to its base on which the bed material is supported.

Figure 3.22 A photograph of air jig test rig (Test performed by author at School of Chemical and Environmental Engineering, Nottingham University)

The air jig works by applying compressed air generated by a fan in short pulses at a constant velocity (39 m/s) to the base of the column containing a compost-stone sample. These pulses are generated by employing two pneumatic butterfly valves (1 and 2) as shown in Figure 3.23. The intermittent flow of air (1.2 m^3/s) through the individual valve occurs alternatively i.e. by opening and closing of each valve. This action was achieved by using computer controlled actuators, which regulate the upward flow of compressed air through the column.

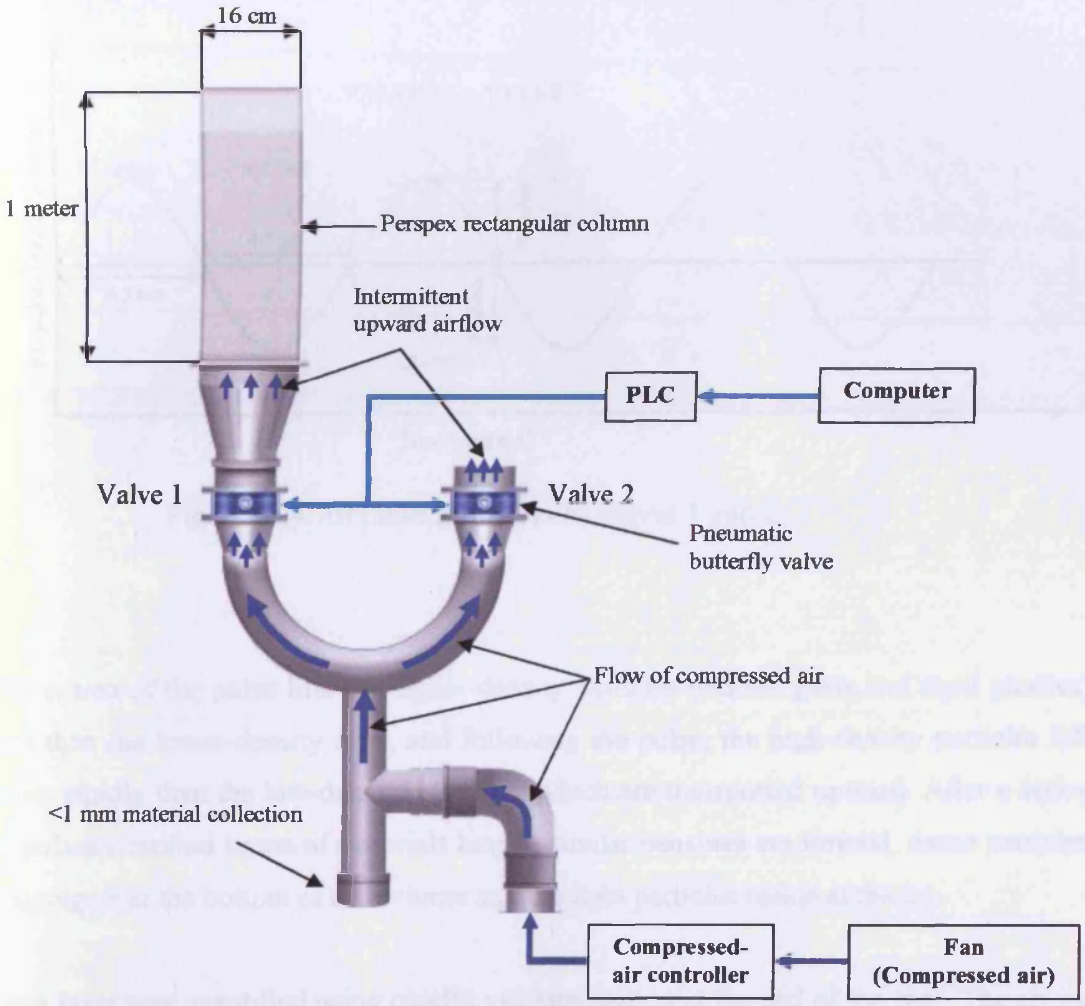


Figure 3.23 Schematic diagram of an air jig setup

The air jig operated for a period of 114 seconds. For the current trial, the actuators were set at an interval of 0.5 seconds for both opening and closing of each valve (see Figure 3.24) and a 39 m/s superficial velocity of air was attained, in order to achieve the effective separation of materials. However, the test rig is designed to change both the air flow and actuation of valves depending on the material used.

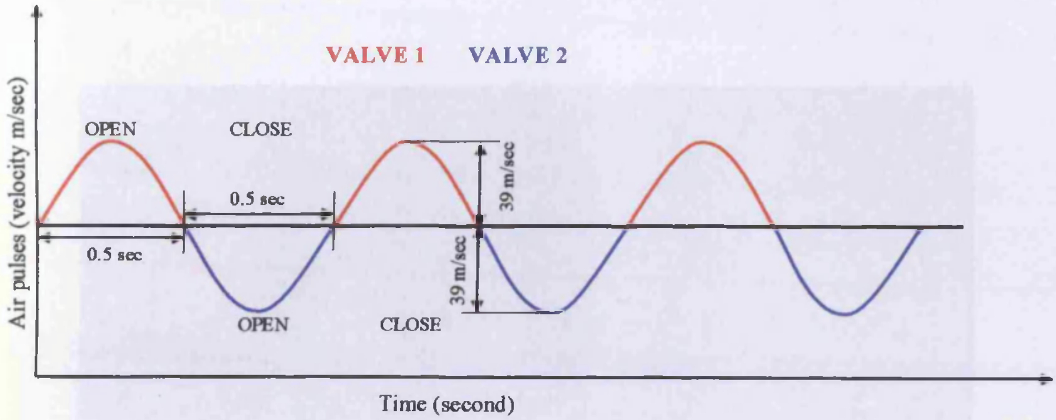


Figure 3.24 Air pulse formation by valves 1 and 2

The action of the pulse lifts the higher-density particles (stones, glass and rigid plastics) less than the lower-density ones, and following the pulse, the high-density particles fall more rapidly than the low-density particles, which are transported upward. After a series of pulses stratified layers of materials having similar densities are formed, dense particles congregate at the bottom of the column and the light particles reside at the top.

Each layer was quantified using careful vacuum suction at the end of the trial. The air jig also utilises a digital camera to monitor the separation efficiency and pictures are captured every two seconds.

3.6.2.2 Sample Preparation

A sample of coloured stones was mixed with a sample of <10 mm CERT mature green-waste compost (moisture content 37%). The base of the air jig had a 1 mm mesh, because of this the compost sample was screened to remove the <1 mm particles. The mixture contained 75% by mass of stones and 25% of compost, as shown in Figure 3.25a. The coloured stones ranged from 2 mm to 10 mm, as shown in Figure 3.25b.

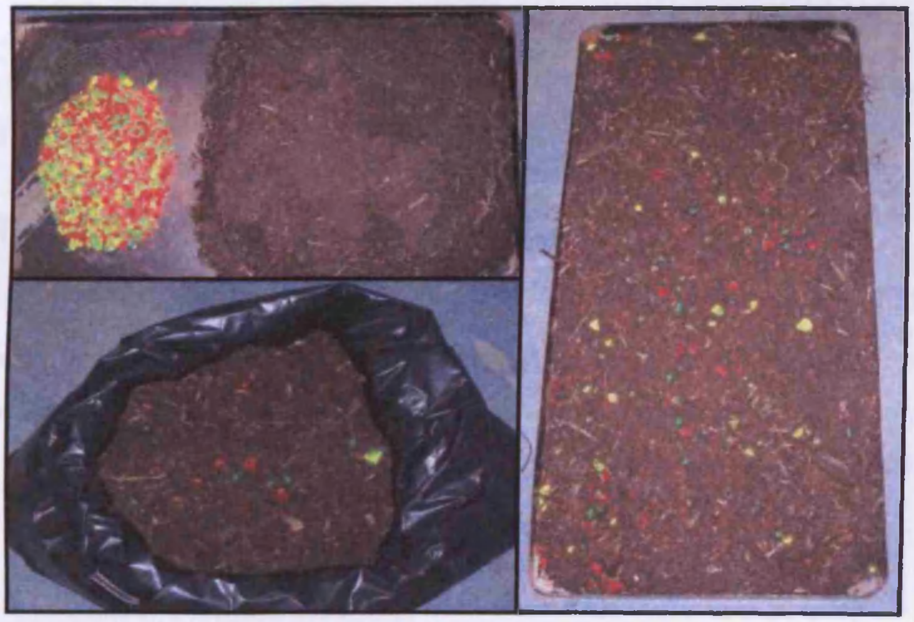


Figure 3.25a Compost and stones used as feed to the laboratory air jig

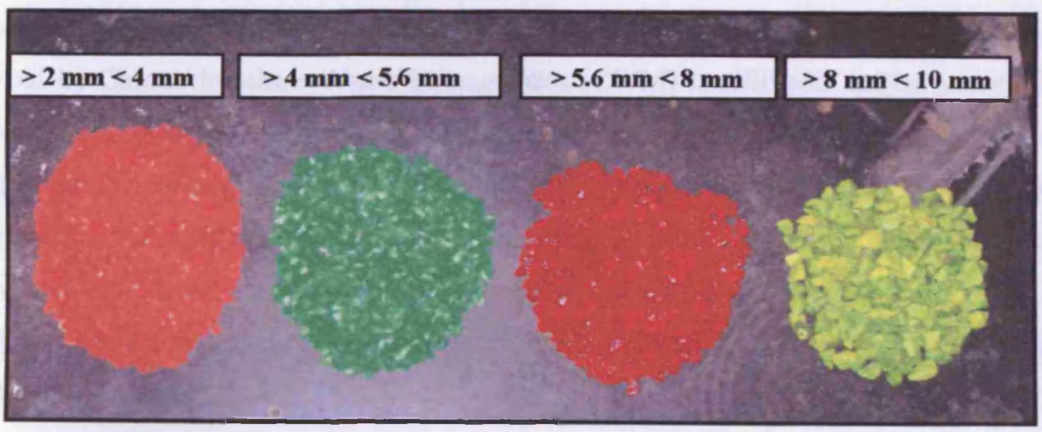


Figure 3.25b Size range of the coloured stones added to compost

CHAPTER 4 VERMICOMPOSTING TRIAL

4.1 PREAMBLE

This chapter presents an in depth investigation into vermicomposting to examine if value could be added to the existing finished screened green-waste compost at the CERT facility. A vermicomposting trial was executed using commercially produced mature (<10 mm, particle size) green waste-derived compost as the feed material.

4.2 THE VERMICOMPOSTING TRIAL

The vermicomposting trial was established in June 2005 at Ty Hen farm house, a site owned by Carmarthenshire Waste Management (CWM) landfill site at Nantycaws near Carmarthen, West Wales. It was decided that the study should be carried out undercover to protect the earthworms from any detrimental climatic effects. It was found that key parameters for controlling the vermicomposting process, such as temperature, pH, electrical conductivity and redox potential, remained within the recommended range for efficient vermicomposting. The parameters monitored throughout the trial are discussed in the sub sections below:

4.2.1 TEMPERATURE MONITORING

Figures 4.1 and 4.2 illustrate temperature data obtained using the automatic data loggers, which were recorded continuously within the reactor beds A and B throughout the trial. This was also used to compare with the data-logged ambient temperature for the same time period. Figure 4.1 shows the temperature recorded within the reactor beds A and B from June 6th to July 5th 2005, however, for the first four weeks the ambient temperature was not recorded and therefore during the initial stages temperatures were not compared. It can be seen in Figure 4.1 that the temperatures within both reactors are almost identical with minimum and maximum temperatures of 14 and 23 °C respectively.

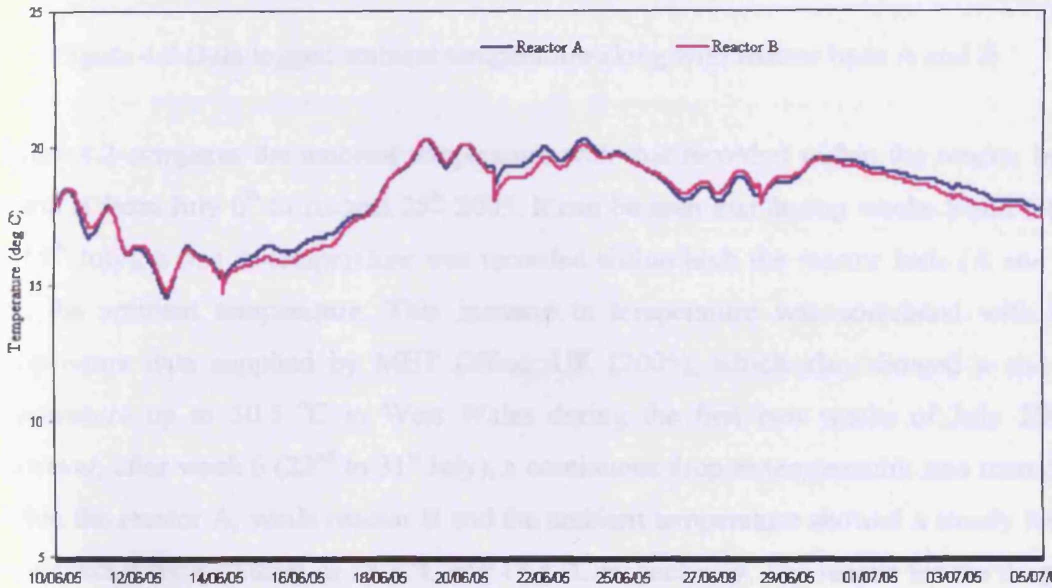


Figure 4.1 Temperature recorded within reactor beds A and B

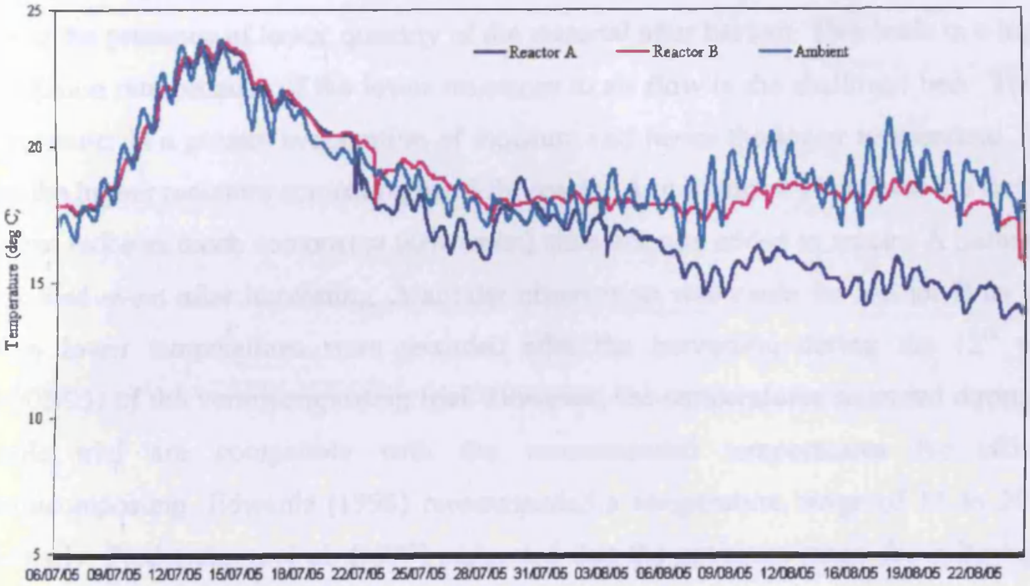


Figure 4.2 Data logged ambient temperature along with reactor beds A and B

Figure 4.2 compares the ambient temperature with that recorded within the reactor beds A and B from July 6th to August 25th 2005. It can be seen that during weeks 5 and 6 (6th to 15th July), a rise in temperature was recorded within both the reactor beds (A and B) and the ambient temperature. This increase in temperature was correlated with the temperature data supplied by MET Office, UK (2005), which also showed a rise in temperature up to 30.5 °C in West Wales during the first two weeks of July 2005. However, after week 6 (22nd to 31st July), a continuous drop in temperature was recorded within the reactor A, while reactor B and the ambient temperature showed a steady trend with average temperatures of 18.1 °C and 18.5 °C respectively. The reason for the drop in temperature observed for reactor A was directly linked to the harvesting, which was performed during the 6th week (21/07/05) of the trial. For the purpose of harvesting, the entire contents of reactor A were hand sorted (see Section 4.2.3.2). After the worms had been separated from the cast material, they were transferred back to the reactor with the fresh/feed bedding (173 kg) and the temperature data logger was again inserted at a depth of 40 mm in the middle of the reactor bed positioned just below the new feed material.

Reactor B was left undisturbed and contained 842.4 kg of cast material. It is thought that the lower temperature observed within the reactor bed A when compared to reactor B was due to the presence of lower quantity of the material after harvest. This leads to a higher ventilation rate because of the lower resistance to air flow in the shallower bed. This in turn results in a greater evaporation of moisture and hence the lower temperature. Note that the higher moisture content reported for reactor A in Figure 4.11 reflects the fact that almost twice as much compost at 60% (m/m) moisture was added to reactor A during the first feed event after harvesting. A similar observation was made for reactor B as well, when lower temperatures were recorded after the harvesting during the 12th week (24/08/05) of the vermicomposting trial. However, the temperatures recorded during the whole trial are compatible with the recommended temperatures for efficient vermicomposting. Edwards (1998) recommended a temperature range of 15 to 20 °C. Similarly, Frederickson et al. (1997) suggested that the optimum range for culturing *D. Veneta* is considered to be around 15 to 25 °C. In a later study, Frederickson and Howell (2003) also demonstrated that maintaining a moderate temperature, 13.7 ± 0.8 ° C, significantly increases worm reproduction rates. Somewhat similar results were obtained by Fayolle et al. (1997), who showed that 10, 15, 20 and 25 °C temperatures were suitable for growth and cocoon production of *D. veneta* and suggested that, at 10 °C, this specie has a very long life cycle. They further explained that with an increase in temperature from 10-15 °C to 20-25 °C, development time was reduced considerably. Appelhof (1997) demonstrated that vermicomposting using *E. fetida* showed best results within the temperature range of 15-25 °C. It was further added that they can also work at temperature as low as 10 °C, but freezing temperatures and above 30 °C are lethal for them. This was further supported by Tognetti et al. (2005), who also reported that temperatures above 30 °C can eradicate the worms.

Figure 4.3 Variation of pH in feedstock and casts

As with the pH, the values of EC for the substrate were also consistently higher than those for the cast materials throughout the trial and ranged between 1115 µS/cm to 1415 µS/cm (see Figure 4.4). These values are high when compared to commercially available compost (720 µS/cm, see Table 5.1), however they are consistent with the value (1410 µS/cm) obtained by Short et al. (1999) from vermicomposting of waste paper sludge. It is speculated that the high values obtained might be a result of the high concentrations of water soluble K, Na and Ca present in both feed and casts, see Table 5.5. Atiyeh et al. (2002b) suggested that the EC of the vermicompost depends on the raw materials used for vermicomposting and is related to their ion concentration

It is clear from Figure 4.4 that during the first two weeks of the trial, lower values of EC were observed for the cast materials when compared to that of the feed. As the trial continued no significant change in the values of EC were observed. This might have been due to the fact that earthworms remained active only during the initial stages of the trial and as the trial progressed a decline in the growth and reproduction of the earthworms was observed (see Figures 4.8 and 4.9).

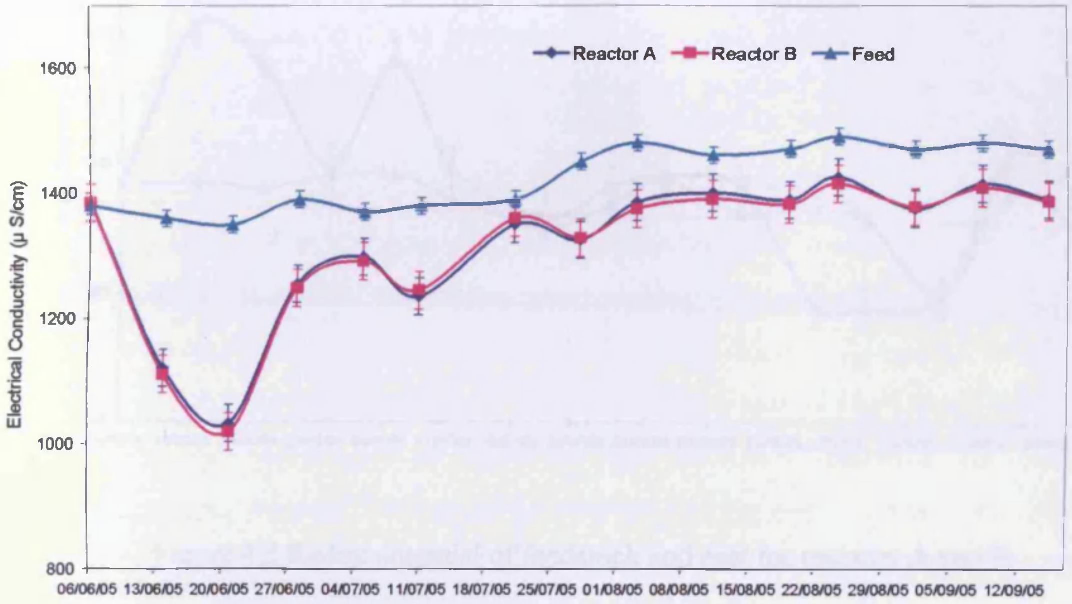


Figure 4.4 Electrical conductivity of feed and cast materials

Redox potential is an indicator of whether the reactor remained anaerobic (negative RP values) or aerobic (positive RP values). Figure 4.5 shows the redox potential for the feed and the cast materials. It can be seen that the redox potential values remained positive throughout the trial period and ranged between 82 to 195 mV (relative to silver/silver chloride reference electrode, see Section 3.2.3). The trend of positive RP values shows that both reactors remained aerobic throughout the trial period. The two initial peaks 195 mV, 180 mV and 192 mV, 175 mV for reactor A and B, respectively, coincide with the period of maximum activity of earthworms during the initial stages of the trial, which was not sustained towards the end of the vermicomposting trial (see Figures 4.8 and 4.9).

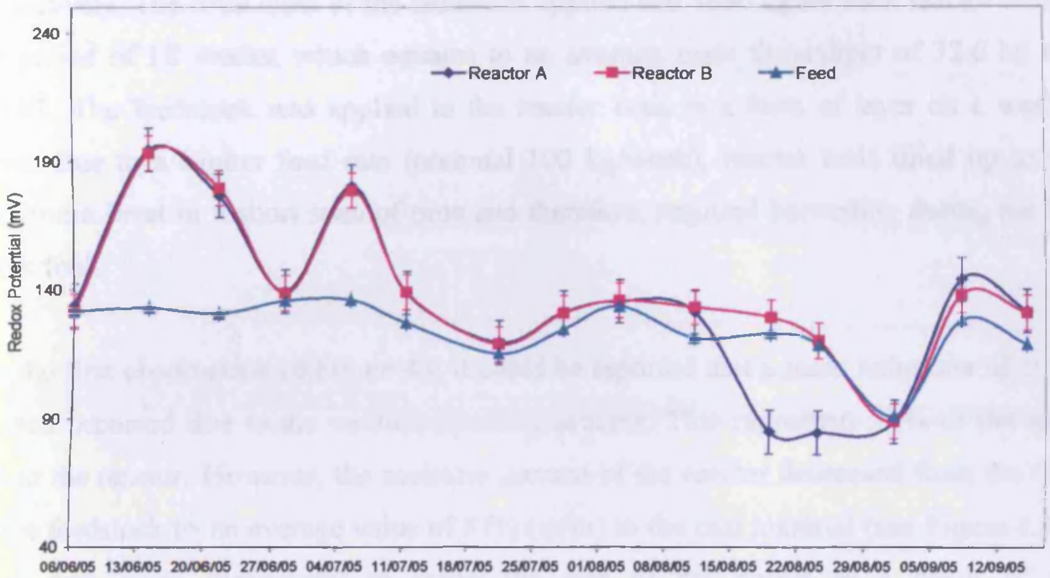


Figure 4.5 Redox potential of feedstock and cast for reactors A and B

4.2.3 MASS DATA

4.2.3.1 Mass Reduction

The cumulative mass of the feedstock (constant moisture content, 60 ± 2 %, see Section 3.2.1) applied to reactors A and B on a weekly basis is presented in Figures 4.6 and 4.7 respectively. Research conducted by Wright (2002) found that by using fresh biodegradable material (fruits and vegetables) and newspaper as a feedstock, an average mass throughput of 5.2 kg m^{-2} $week^{-1}$ was achieved, while Short et al. (1999) obtained 4 kg m^{-2} $week^{-1}$ by utilising waste paper sludge. Therefore, during the current trial a higher feed rate was chosen, knowing that mature green waste compost contained much lower levels of readily digestible substrate. No clear indication of the correct feedrate was available so a nominal 100 kg/week was chosen.

Reactors A and B received initial bedding/feedstock material of 172 kg and 165 kg respectively. The total mass of the feedstock applied was 1690 kg for each reactor during the period of 18 weeks, which equates to an average mass throughput of 32.6 kg m^{-2} $week^{-1}$. The feedstock was applied to the reactor beds in a form of layer on a weekly basis. Due to a higher feed rate (nominal 100 kg/week), reactor beds filled up to the maximum level in a short span of time and therefore, required harvesting during the 18-week trial.

On the first observation of Figure 4.6 it could be reported that a mass reduction of 195.8 kg had occurred due to the vermicomposting process. This represents 27% of the mass fed to the reactor. However, the moisture content of the reactor decreased from the 60% in the feedstock to an average value of 57% (m/m) in the cast material (see Figure 4.11). It is then more meaningful to report the loss of dry solids as a result of the vermicomposting process. This was 22% during the first six weeks of operation of reactor A. Similarly, the overall loss of dry solids for the 18 week period was 18%, showing that rate of loss must have decreased during the latter period of the trial.

Looking at reactor B (see Figure 4.7), the mass losses on the basis of dry solid reduction were 20% and 14% again showing a large deterioration in rate of metabolism of substrate by the worms in the latter period. The drop in mass reduction observed within both reactors was mainly due to the decline in earthworm biomass (see Figures 4.8 and 4.9) recorded during the same time period.

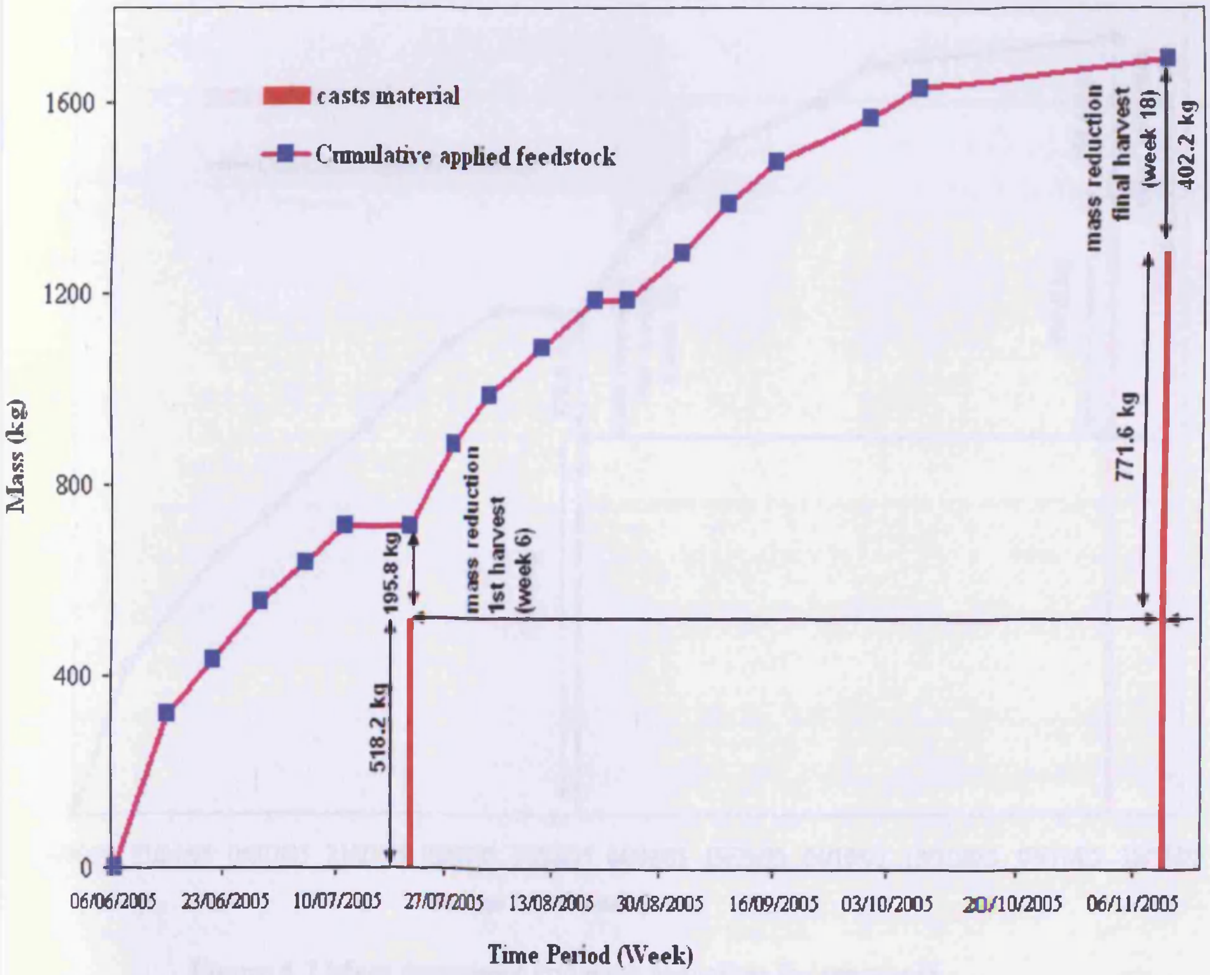


Figure 4.6 Mass throughput and mass reduction for reactor A

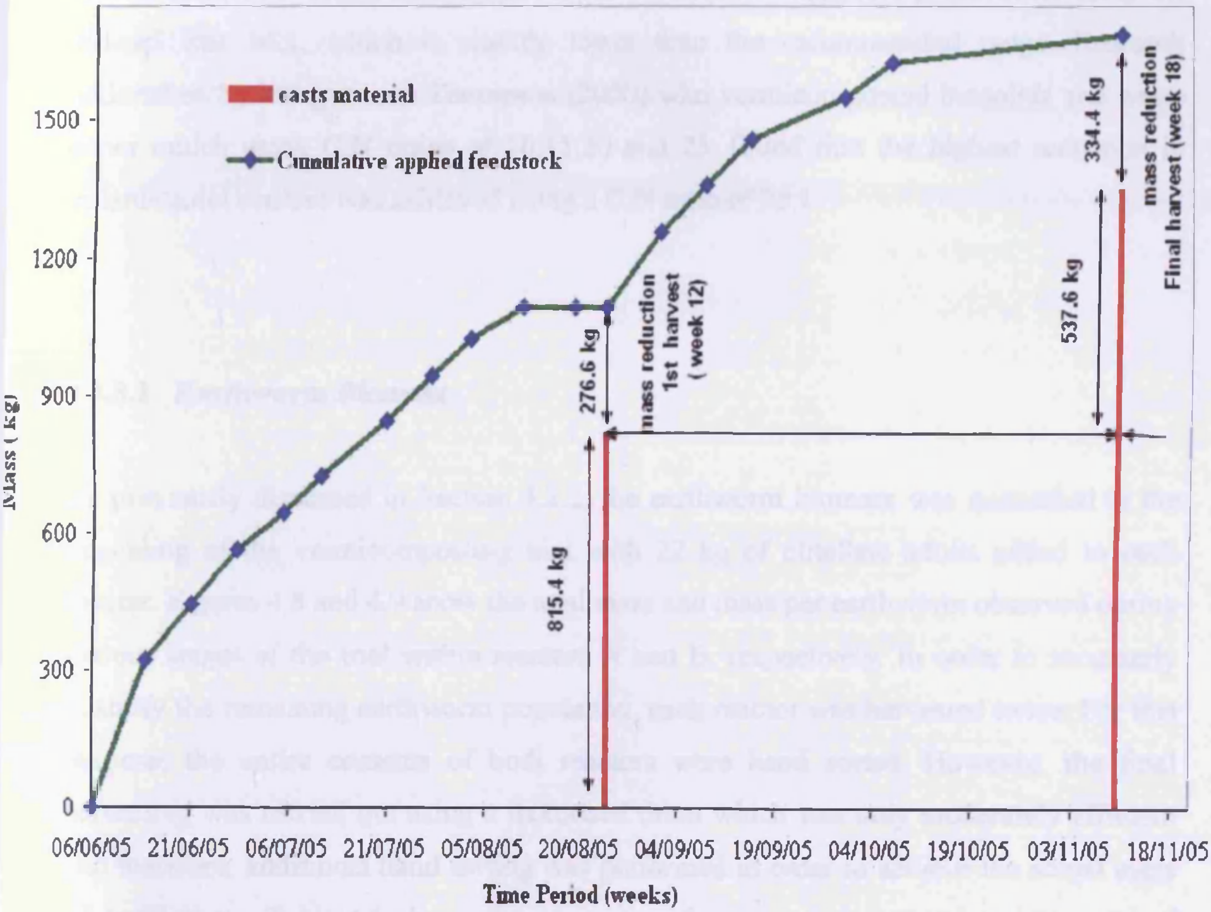


Figure 4.7 Mass throughput and mass reduction for reactor B

It is important to note that the mass reduction achieved is low when compared to other published data. Wright (2002) reported a maximum mass reduction of 86% during vermicomposting of fresh biodegradable material (fruits and vegetables) and newspaper. However, a lower mass reduction of 49% was obtained when mixtures of composted biodegradable matter, newspaper and green-waste were utilised as feed materials. This shows as expected that the type of feedstock is crucial in controlling the vermicomposting process. The Composting Association, UK (2004) recommends that earthworms will process more waste and reproduce quickly when fed with fresh, finely shredded organic materials containing a carbon to nitrogen (C:N) ratio of the order of 15:1 to 35:1. The carbon to nitrogen ratio of the feedstock (mature green-waste compost) utilised was 14:1, which is slightly lower than the recommended range. Research undertaken by Ndegwa and Thompson (2000) who vermicomposted biosolids and waste paper mulch using C:N ratios of 10,15,20 and 25, found that the highest reduction in volatile solid content was achieved using a C:N ratio of 25:1.

4.2.3.2 Earthworm Biomass

As previously discussed in Section 3.2.2, the earthworm biomass was quantified at the beginning of the vermicomposting trial with 22 kg of clitellate adults added to each reactor. Figures 4.8 and 4.9 show the total mass and mass per earthworm observed during various stages of the trial within reactors A and B, respectively. In order to accurately quantify the remaining earthworm population, each reactor was harvested twice. For this purpose, the entire contents of both reactors were hand sorted. However, the final harvesting was carried out using a motorised drum which was only moderately efficient and therefore, additional hand sorting was performed in order to achieve the actual mass of earthworms. Table 4.1 shows the mass of earthworms, cast material and biomass of worm per kg of the compost observed during the first harvest of reactor A and B. Reactor A was harvested by hand sorting the top (100 mm) and bottom layer (150 mm), while reactor B was harvested in two equal halves along the length of the reactor (each measuring 1.2 m, see Figure 3.1). It can be seen in Table 4.1 that reactor A contained 7.96 kg and 8.53 kg of earthworms in the top and bottom layers respectively, while, reactor B contained equal mass (6.4 kg) of earthworms in both halves. The mass of cast materials in the top and bottom layers of Reactor A was 180.4 kg and 337.8 kg respectively. The higher mass of cast materials observed in the bottom layer was due to compaction of the cast material, as fresh feed was applied in the form of a layer on the pervious one on a weekly basis. During the harvesting of reactor A, it was also observed that the material in the bottom layer was more moist than the top layer, which is also responsible for a higher mass observed in the bottom layer when compared to the top layer. For reactor A, the worm biomass in the top and bottom layer was 44.13 g/kg and 25.26 g/kg respectively, while reactor B comprised of 15.44 g/kg and 15.89 g/kg of worm biomass per kg of compost in the 2 halves.

A number of researchers (Appelhof 1997, Edwards 1998 and Sherman 2002) suggested that worms will be concentrated mostly in the top layers, where fresh feedstock is present. It can be seen in Table 4.1 that the figures obtained from harvesting of reactor A also indicate that earthworm biomass concentration was higher in the top layer, where the fresh feed was added.

Table 4.1 The mass of earthworms, cast materials and worm biomass per kg of compost observed during first harvest of reactor A and B

Mass	Reactor A (week 6)		Reactor B (week 12)	
	Top layer (100 mm)	Bottom layer (150 mm)	First half	Second half
Cast materials (kg)	180.4	337.8	414.85	400.55
Earthworms (kg)	7.96	8.53	6.4	6.4
Earthworm biomass per kg of compost (g/kg)	44.13	25.26	15.44	15.89

Results presented in Figure 4.8 show a worm mass reduction from 22 kg of total earthworm biomass to 16.5 kg and 5.4 kg within reactor A at the end of the 6th and 18th week respectively. Similarly, for reactor B there was a worm mass reduction to 12.8 kg during the first harvest and only 2.2 kg worms were present at the final harvest as shown in Figure 4.9. This is consistent with the results obtained by Wright (2002) who showed that while using composted biodegradables, newspaper and green waste, 82% reduction in earthworm biomass was observed when compared to the initial inoculation. Frederickson et al. (1997) also found that using pre-composted green waste had a deleterious effect on worm growth and population.

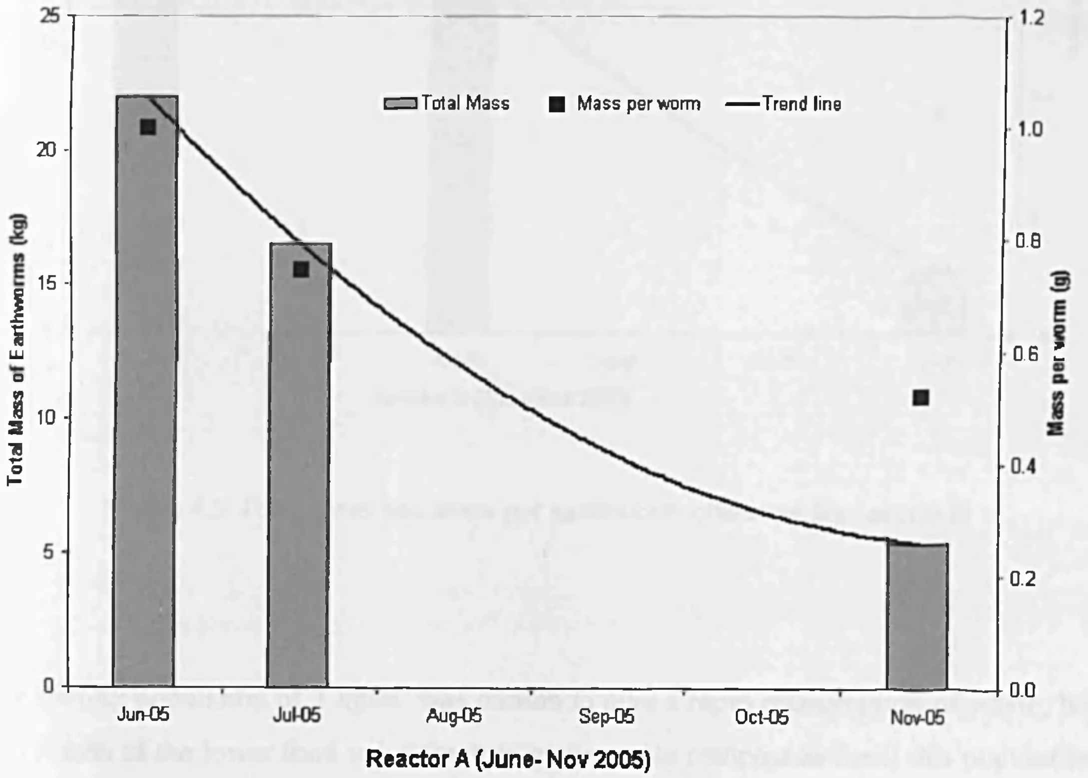


Figure 4.8 Total mass and mass per earthworm observed for reactor A

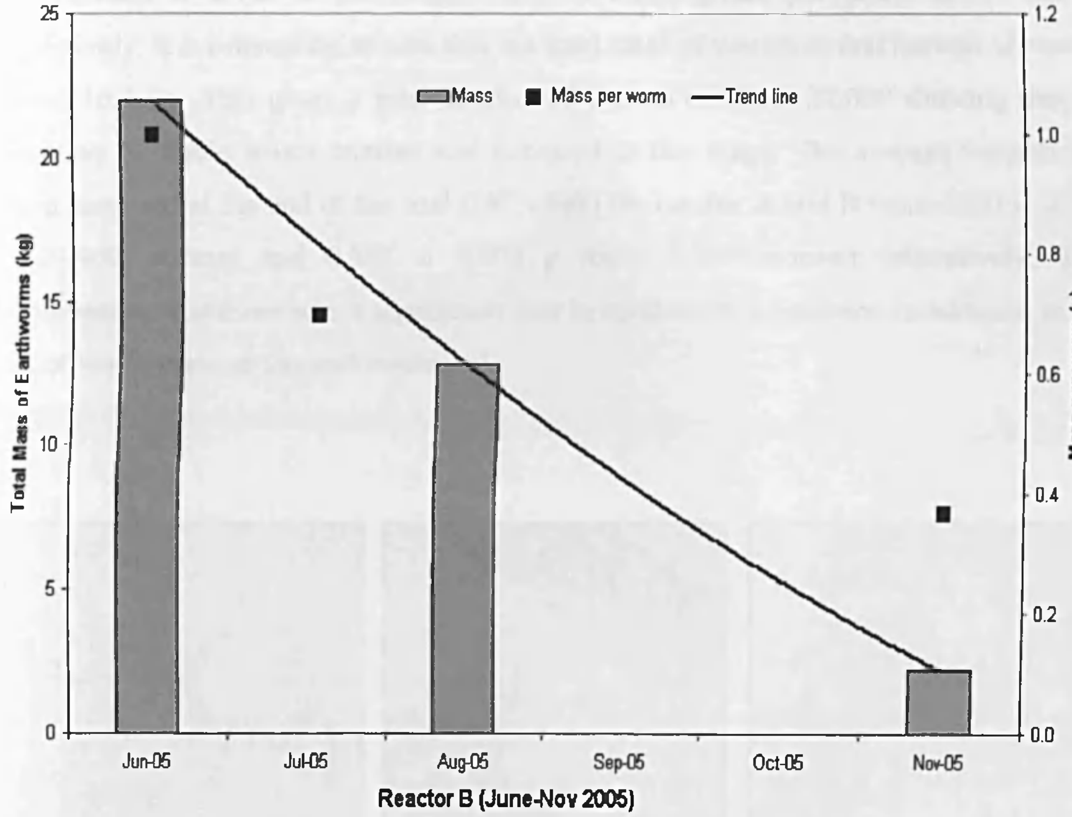


Figure 4.9 Total mass and mass per earthworm observed for reactor B

The starting population of 7 kg/m^2 was chosen to give a rapid consumption of waste, but as a results of the lower food value (mature green-waste compost as feed) this population could not be sustained. At the end of the trial, the average stock density was about 1.3 kg/m^2 and the value was still decreasing especially in reactor B.

Figures 4.8 and 4.9 show the mass per earthworm observed within reactor A and B. During the trial, regular visual inspection revealed a rapid decline of earthworm population. Figure 4.10 shows photographs of the earthworms during various stages of the trial. Initially, average weight of the earthworms was approximately 1 ± 0.002 (mean

± standard error) gram per worm (22,000 worms) whereas, after a period of 6 weeks it was reduced to 0.747 ± 0.003 and 0.695 ± 0.002 grams per worm for A and B respectively. It is interesting to note that the total mass of worms at first harvest of reactor A was 16.5 kg. This gives a total number of worms of about 22,000 showing that no reduction in viable worm number had occurred at this stage. The average weights per worm recorded at the end of the trial (18th week) for reactor A and B were 0.521 ± 0.003 g (10,400 worms) and 0.367 ± 0.002 g (only 3,000 worms) respectively. This demonstrates that there was a significant loss in earthworm population in addition to the loss of worm mass as the trial continued.

Initial inoculation End of 6th week 18th week. End of trial

Figure 4.10 Earthworms during various stages of the trial. The photographs are representative of at least 100 live earthworms.

4.2.4 MOISTURE AND VOLATILE SOLIDS CONTENT

The moisture content for the feedstock and casts materials within reactor A and B on a weekly basis is shown in Figure 4.11. The mass of the feed material applied to each reactor including the quantity of water varied on a weekly basis. A calculated amount of water was added to the dry compost (40 %, m/m) to bring the feed material to a desired moisture content of 60 ± 2% (m/m). This was necessary since earthworms breathe through their skins, which must be moist for the exchange of air and excretion of waste to take place. It was found on visual observation that adding too much water to the dry compost formed a slurry. Appelhof (1997) also suggested that too much moisture present as stagnant water in the reactor can reduce the available oxygen and cause worms to drown.

During the lettuce growth trial, it was found that the water holding capacity of the feedstock was 63% (see Section 5.3.2, Figure 5.7). Hence, the moisture content of 60 ± 2% for vermicomposting was a suitable option. It can be seen in Figure 4.11 that the moisture content of the cast material is consistently lower than that of the feedstock and ranged from 55% to 58% m/m. The decrease in moisture content of cast material observed during the 5th and 6th week coincides with the increase in temperature shown in Figure 4.2. Figure 4.11 also shows that after the 6th week the moisture content of cast material within reactor A remained consistently higher than reactor B until 12th week. This might have been due to the lower temperatures recorded within the reactor A when compared to reactor B (for details see Section 4.2.1). Edwards (1998) and Phillips (1998) determined that the optimum moisture content for the growth of *E. fetida* was 80 to 90%, with limits of 60 to 90% observed, while *D. veneta* were able to withstand a wide range of moisture contents. Furthermore, Edwards (1995 and 1998), Neuhauser et al. (1988) and Kaushik and Garg (2003) found that in order to achieve optimum conditions for vermicomposting, moisture content should be maintained within the range of 70-90% (w/w). However, studies conducted by Frederickson et al. (1997), Bansal and Kapoor (2000) successfully performed vermicomposting by using lower moisture contents of 66 ± 2% and 60% respectively. It can be seen that average moisture content of the feedstock and cast materials was 60% and 57% (m/m) respectively. In light of the recommended moisture content for the maximum growth of *D. veneta*, lower moisture contents observed within the reactor beds (A and B) might be a contributory factor in low earthworm biomass observed in Figures 4.8 and 4.9.

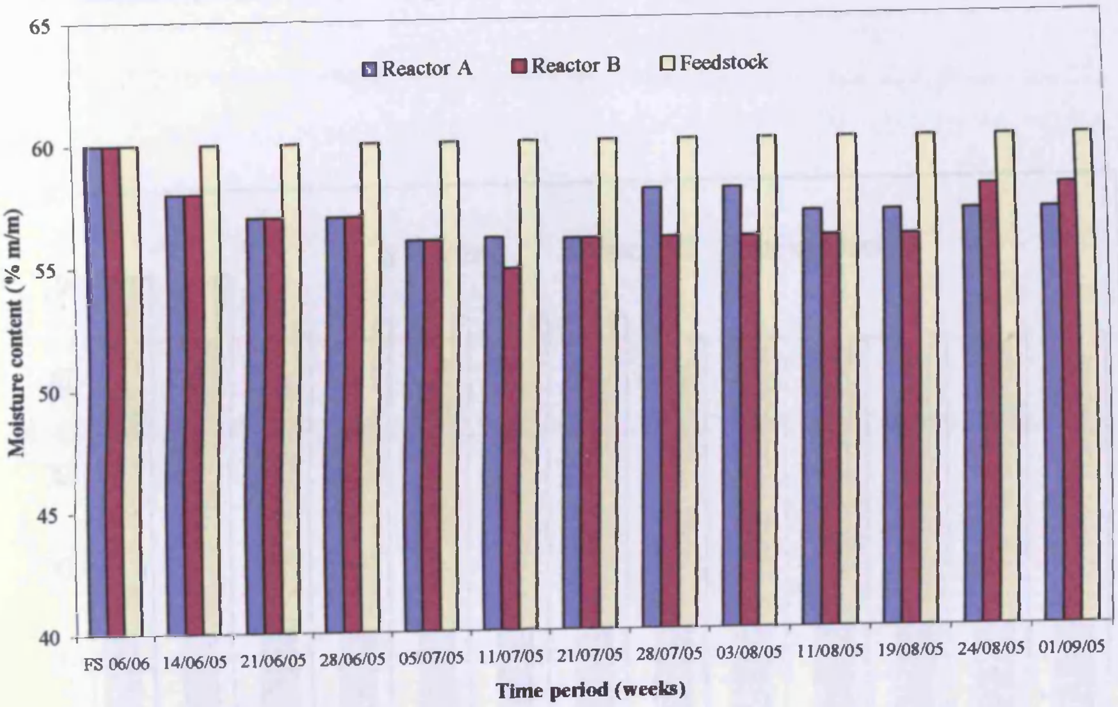


Figure 4.11 Moisture content within the feed and vermicompost for both reactors

The percentage volatile organic matter content for the substrate and casts materials within reactor A and B on a weekly basis is shown in Figure 4.12. The feedstocks applied were taken from three different batches of the mature compost, which had a volatile solid content of 51% (week 1 and 2), 46% (week 3 to 7) and 43% (week 8 to 18) (m/m) respectively.

Figure 4.12 shows that during the first 8 weeks, there was a considerable reduction in the volatile solids. The greatest reduction in volatile organic matter content was observed in reactor B during the 4[th] week, when the volatile solid content was reduced from 46% to 35% (m/m). There was no obvious reduction in volatile solids towards the end of the trial period. This was caused by the fact that earthworms remained active only during the initial stages of the trial and as the trial continued a decline in earthworm growth and reproduction was observed (see Figures 4.8 and 4.9).

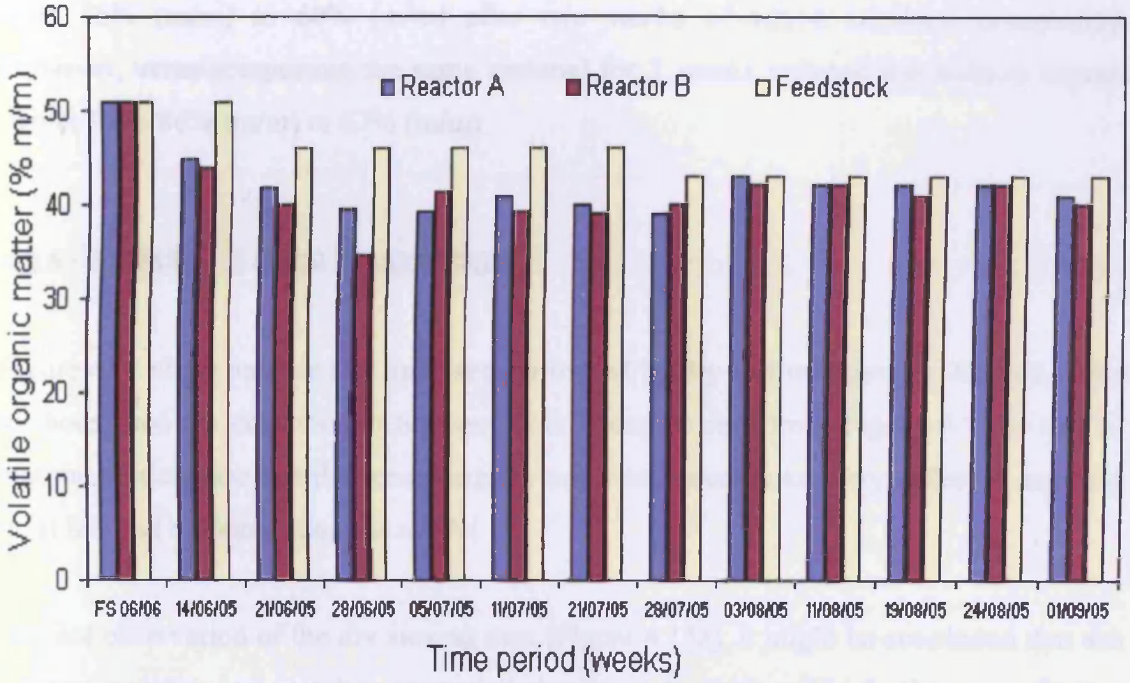


Figure 4.12 Volatile solids within the feed and vermicompost for both reactors

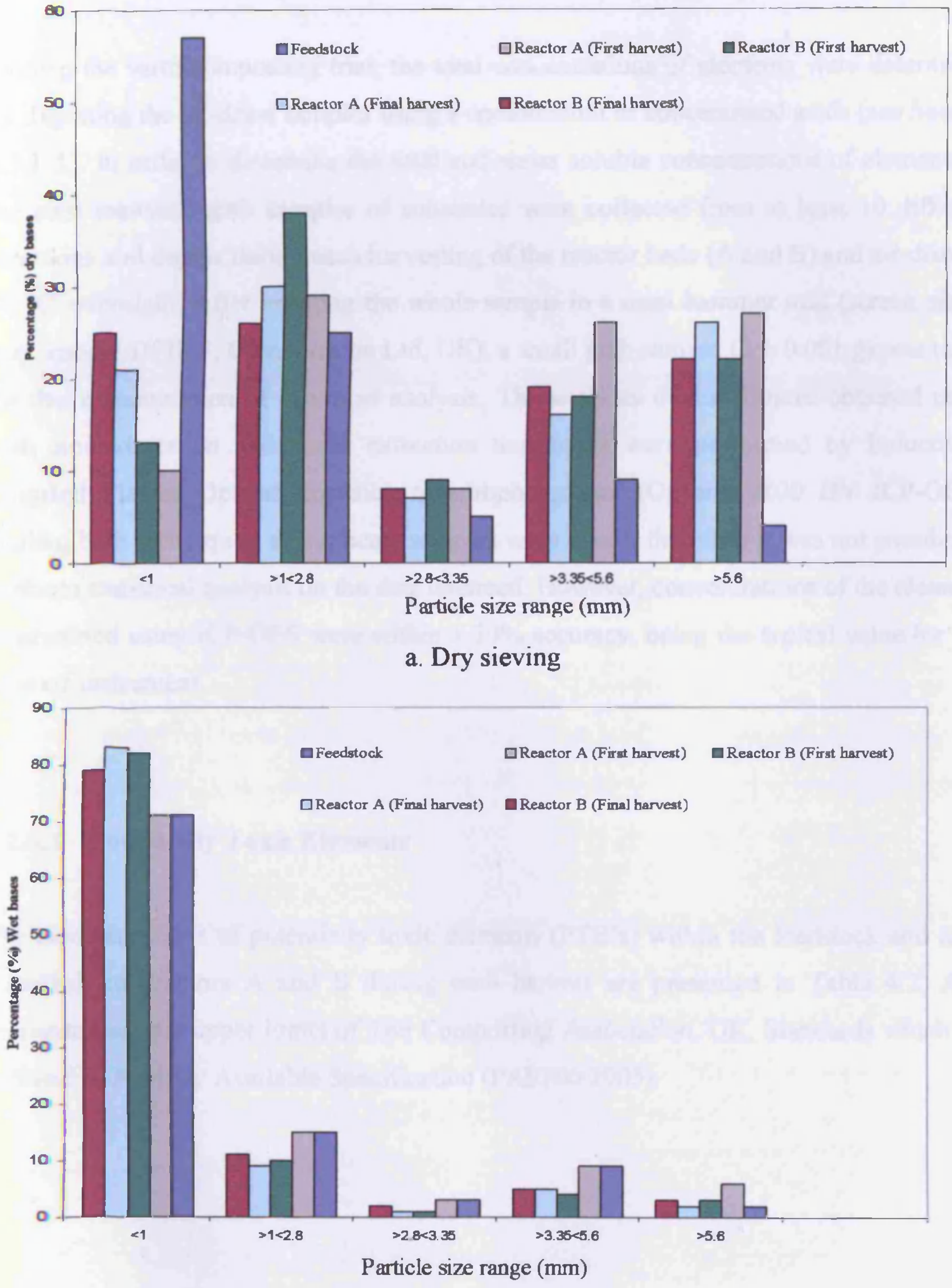
Epstein (1997) reported that the volatile solid represents the total carbon content of the material. In other words, the faster the organic matter decomposition, the greater is the production of CO_2, which directly reduces the volatile solid content. Measuring the reduction in the volatile organic matter content of a material is often used as an indication of stabilisation of waste. Frederickson et al. (1997) vermicomposted freshly shredded green waste (200 g) using 4 or 8 *E. andrei* earthworms in 0.5 litre pots for a period of 8 weeks and found that volatile organic matter content of fresh green waste was 62% (m/m). In the same study, combining vermicomposting with windrow composting to process green waste, a lower volatile organic matter content (33%) was observed for the cast material after vermicomposting compared to the windrowed compost (37%) for the same time period (8 weeks). They also suggested that combining the windrow composting and vermicomposting is an effective method of stabilising fresh green waste.

Norbu (2002) studied windrow composting and vermicomposting of vegetable market waste on a pilot scale. It was found that the volatile solid content of the waste reduced from 86% (m/m) to 60% (m/m) after two weeks of active windrow composting. However, vermicomposting the same material for 3 weeks reduced the volatile organic matter from 86% (m/m) to 67% (m/m).

4.2.5 PARTICLE SIZE ANALYSIS

Figure 4.13 show particle size analyses performed by dry and wet sieving. Details of the methods used are described in Section 3.2.6. It can be seen from Figure 4.13 (a and b) that the particle size distributions using dry and wet screening are very different and care must be used in interpreting the results.

On first observation of the dry sieving data (Figure 4.13a), it might be concluded that the vermicomposting process has consumed the fine (<1 mm) material. However, Figure 4.13b shows that the fine content has remained roughly the same in the casts compared to the feed material. A better explanation therefore is that the worms excrete material (cast) where the fines are aggregated together into clumps that survive the conditions in the dry sieves. It is well known that the worm excrete polysaccharides that are 'sticky' and are capable of the aggregation. During the more intense conditions in the wet sieving method, these aggregates are split into their individual components. Marinissen et al. (1996) also found that polysaccharides are responsible for enhanced aggregate stability and reported that after washing, the polysaccharides content of casts was reduced from 80% to 45%.



a. Dry sieving

b. Wet sieving

Figure 4.13 Particle size analyses of feed and vermicomposts

4.2.6 CHEMICAL ANALYSES OF COMPOSTS

During the vermicomposting trial, the total concentrations of elements were determined by digesting the air-dried samples using a combination of concentrated acids (see Section 3.3.1.1). In order to determine the total and water soluble concentrations of elements of the cast material, grab samples of substrates were collected from at least 10 different locations and depths during each harvesting of the reactor beds (A and B) and air-dried at 80 °C overnight. After grinding the whole sample in a mini hammer mill (screen size 2 mm, model DFH48, Glen Creston Ltd, UK), a small grab sample (2 ± 0.001 g) was taken for the determination of chemical analysis. The analyses of the filtrates obtained using both acid digestion and water extraction techniques were performed by Inductively Coupled Plasma Optical Emission Spectrophotometer (Optima 2100 DV ICP-OES). During both techniques, no replicate samples were tested, therefore it was not possible to perform statistical analysis on the data obtained. However, concentrations of the elements determined using ICP-OES were within ± 10% accuracy, being the typical value for this type of instrument.

4.2.6.1 Potentially Toxic Elements

The concentrations of potentially toxic elements (PTE's) within the feedstock and casts material for reactors A and B during each harvest are presented in Table 4.2. Also presented are the upper limits of The Composting Association, UK, Standards which are defined as Publicly Available Specification (PAS100:2005).

Table 4.2 Concentrations of potentially toxic elements at various stages of the trial

Element	Feedstock (mg/kg)	Vermicompost (mg/kg)				PAS100 (mg/kg)
		First harvest		Final harvest		
		Reactor A (week 6)	Reactor B (week 12)	Reactor A (week 18)	Reactor B (week 18)	
Zn	260.8	399.0	268.3	217.5	387.8	≤400
Cd	1.0	0.8	0.8	0.5	0.5	≤1.5
Cr	55.5	42.5	59.5	58.3	54.8	≤100
Ni	23.8	15.8	22.8	20.8	23.3	≤50
Cu	60.8	48.3	59.8	50.8	53.0	≤200

It can be seen in Table 4.2 that the concentration of total heavy metals ranged within the limit levels of the compost and quality standards, PAS100:2005 (see Table 2.1), except for Zn, where the highest concentrations were observed in the samples taken during the first (399.0 mg/kg) and the final harvest (387.8 mg/kg) within the reactors A and B respectively, whereas, the feed showed a lower concentration (260.8 mg/kg).

On evaluating the overall results for the total toxic elements, it is apparent that there is no significant increase in the concentration of total heavy metal after the vermicomposting process. If the mass of the product had been significantly lowered compared to that of the feed, an increase in the concentration of PTE's would have been expected. The data in the table do not show this trend, rather a scattering of values reflects unavoidable errors in sampling and analysis.

At present, there is little knowledge about the increase in concentrations of elements associated with the mass reduction during vermicomposting process. Wright (2002) vermicomposted fresh biodegradable, newspaper and green-waste and achieved a mass reduction of 62%. It was reported that the feed consisted 51 mg/kg of Zn, while casts contained 49 mg/kg. During the same study, a lower mass reduction (49%) was observed, while vermicomposting composted biodegradable, newspaper and green waste. It was found that the cast contained significantly higher quantity (49 mg/kg) of Zn, when compared to 5 mg/kg in the feed. It is interesting to note that there is no correlation between the observed mass reductions and the change in the concentrations of Zn. It is thought that this might be the result of a combination of analytical errors and sampling associated with the heterogeneous nature of the materials used during vermicomposting process. Another research study conducted by Elvira et al. (1998) determined that the casts produced from vermicomposting of mixed feedstock of waste paper sludge and cattle manure consisted 108 mg/kg of Zn, while the feedstock comprised of 110 mg/kg. While, using dairy sludge in addition to paper sludge and manure, the concentration of Zn in feedstock and casts was 123 mg/kg and 165 mg/kg, respectively. However, no analytical data were provided on the mass reduction to support the change in Zn concentration after the vermicomposting process.

The concentrations of water-soluble PTE's associated within the respective feedstock and vermicompost samples are presented in Table 4.3. The first observation is that the concentrations are very low compared to the total values presented in Table 4.2, with very little dissolution of the various metals. Focusing on the feedstock for illustration, in order of ascending solubilities, Cr is the least soluble (0.02% of the available metal) followed by Ni (0.2%), Zn (0.33%) and Cd at a relatively high value of 20% of the available metal. A similar trend is obtained for the remaining columns of data.

The water solubility of Zn in the cast obtained from the first harvest of reactor A is significantly higher than the solubility of the metal in the other casts. This might be merely an anomalous result but a similar result, was obtained when the pure vermicompost was examined during the lettuce growth trial (see Section 5.3.6.1, Table 5.7).

Table 4.3 The quantity of bio-available potentially toxic elements at various stages of the trial

Element	Feedstock (mg/kg)	Vermicompost (mg/kg)			
		First harvest		Final harvest	
		Reactor A (week 6)	Reactor B (week 12)	Reactor A (week 18)	Reactor B (week 18)
Zn	0.86	2.06	0.84	0.82	0.92
Cd	0.02	0.02	0.02	0.02	0.02
Cr	0.01	<0.01	0.01	0.01	0.01
Ni	0.05	0.03	0.05	0.05	0.04
Pb	0.02	0.02	0.03	0.02	0.02

4.2.6.2 Nutrients

The concentrations of total and water-soluble nutrients determined for the various samples are shown in Tables 4.4 and 4.5 respectively. Again, as with the PTE's there is no significant difference between the total nutrient content of the casts compared to the feed. The values obtained for the concentration of each element are higher than the average UK composts values.

It is clear from Table 4.4 that the expected increase in the concentrations of the total nutrients associated with the average mass reduction (16%) observed during the vermicomposting process were not observed. As stated in Section 4.2.6.1, a combination of unavoidable analytical errors and sampling associated with such heterogeneous materials might be the reason for no significant increase in the concentrations of the total nutrients in the cast material. In contrast to this, various researchers have claimed an increase in the nutrient content and suggested that this was due to an accelerated mineralisation of organic matter (rapid breakdown of carbon compounds and production of CO_2) after vermicomposting (Atiyeh et al. 2002c and Kaushik and Garg 2003, Loh et al. 2005). However, McClintock (2004) suggested that it is likely that the nutrient content in worm cast produced varies according to the feedstock utilised. It was further added that the nutrient content of the vermicompost is often lower than that of the feed material.

Table 4.4 Total nutrient content within the feedstock and vermicompost during each harvest

Element	Feedstock (mg/kg)	Vermicompost (mg/kg)				Average UK* compost (mg/kg)
		First harvest		Final harvest		
		Reactor A (week 6)	Reactor B (week 12)	Reactor A (week 18)	Reactor B (week 18)	
P	4,055	3,448	4,263	3,733	3,483	2,131
K	10,155	8,565	10,400	9,340	9,403	8,264
Ca	35,525	42,975	32,750	40,050	39,775	20,194
Na	1,667	1,494	1,687	1,556	1,719	592
Mg	3,053	2,970	3,043	3,043	2,900	2,870

* The average nutrient content for UK compost, The Composting Association and ReMaDe project, Enviros Consulting Ltd The Waste & Resource Action programme (WRAP), 2004.

Turning to the water soluble nutrients (Table 4.5) it is again apparent that there is little difference between the casts and the feedstock, with a very slight decrease in availability in the casts compared to the feed. The lowest water soluble was P with similar concentrations in both the feedstock and average casts (20 mg/kg). However, Ndegwa et al. (2000) vermicomposted biosolids and reported an increase of 25% in the concentration of P in the final product. However, no analytical data were provided on the mass reduction to support this (25%) increase in P concentration after the vermicomposting process. Edwards and Burrows (1998) reported that while vermicomposts contained greater concentrations of all elements, a lower concentration of magnesium is often found.

Table 4.5 Plant available nutrients within the feedstock and vermicompost during each harvest

Element	Feedstock (mg/kg)	Vermicompost (mg/kg)			
		First harvest		Final harvest	
		Reactor A (week 6)	Reactor B (week 12)	Reactor A (week 18)	Reactor B (week 18)
P	20	18	21	20	20
K	4,667	4,143	3,897	4,239	4,242
Ca	448	473	334	410	440
Na	617	587	506	553	563
Mg	114	118	81	102	108

4.2.7 CONCLUSIONS

The study on the vermicomposting using mature green waste-derived compost focused on several key characteristics of the process, from which the following conclusions have been drawn.

- An average mass reduction of 16% was achieved as the original compost was converted to vermicompost with an average mass throughput of 32.6 kg m^{-2} $week^{1}$ used over the entire trial period.

- Utilising mature green waste-derived compost as feed for the vermicomposting had a deleterious effect on the earthworm biomass and the population was not sustained.

- There was a significant reduction in the volatile solid content during the initial stages of the vermicomposting process and no obvious reduction in volatile solids was observed towards the end of the trial period.

- Within experimental error, there was no observed increase in the total metal or nutrients concentrations in line with the overall compost mass reduction. The concentration of bio-available metal and nutrient in the casts showed negligible change when compared to that of the feedstock, apart from Zn observed for reactor A, which showed an increased concentration during the initial stages of the vermicomposting trial.

CHAPTER 5 GROWTH TRIALS

5.1 PREAMBLE

This chapter presents results on the replicated growth trials on coriander and tomato using two commercially available multipurpose composts and five waste-derived composts. This was followed by another set of growth trials undertaken with lettuce, using product of the vermicomposting trial (pure worm casts), green waste compost and mixtures of the two to determine the extent of growth enhancement gained through the vermicomposting process. The mixtures comprised of 50/50 (v/v) and 20/80 (v/v) of worm casts and green waste feedstock.

5.2 TOMATO AND CORIANDER

Growth trials on tomato and coriander were conducted using two commercially available multipurpose composts and five waste-derived composts including a vermicompost (for details of the compost sources, see Section 3.4.1.1). This work was performed with the objective of demonstrating that waste-derived products could perform in a similar manner to the classical growth media.

5.2.1 General Observations

Representative examples of the tomato and coriander plants at the time of harvest are presented in Figures 5.1 and 5.2 respectively. Based on visual observation, it was clear that significant differences in plant morphology were apparent in the coriander and tomato plants grown in the different composts (for details of the compost sources see Table 3.1). These differences were manifest from the time of seedling establishment right through to harvest and generally increased over time. It was clear from visual observation that waste derived composts B, C and E showed poor plant growth. Obvious differences included those of plant height, size and colour of leaves and overall health of the plants.

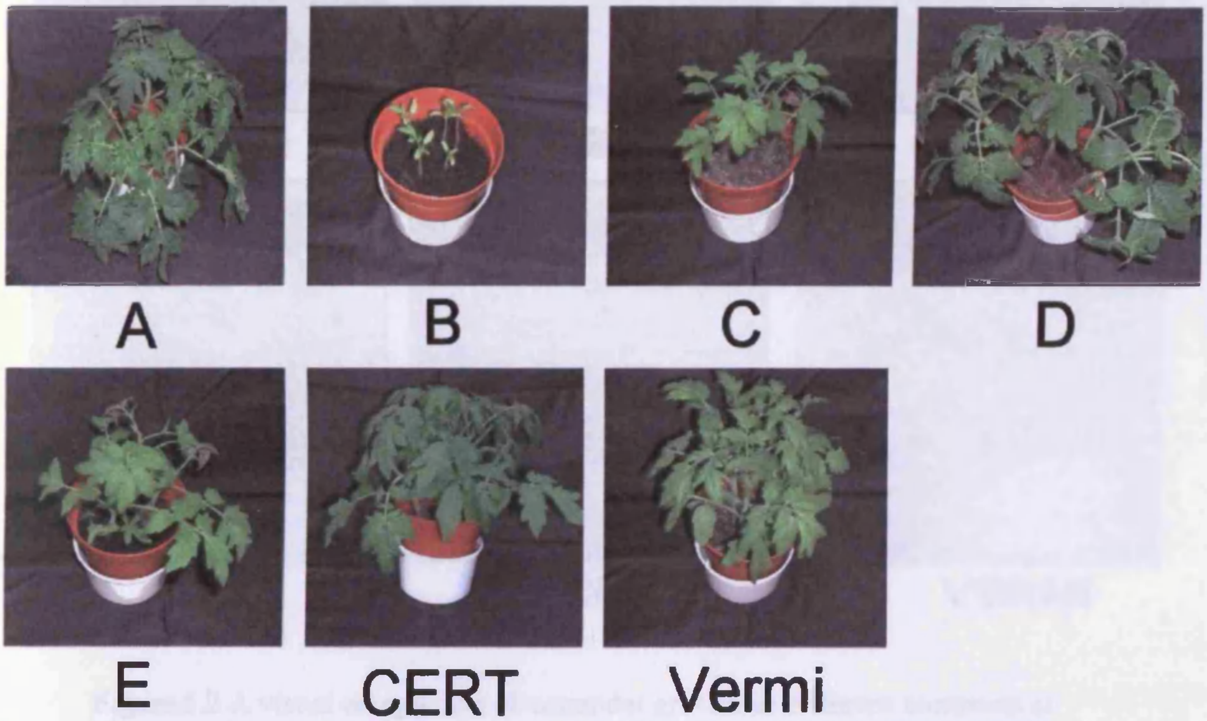


Figure 5.1 A visual comparison of tomato growth in different composts at harvest. The photographs are representative of at least 5 replicate plants.

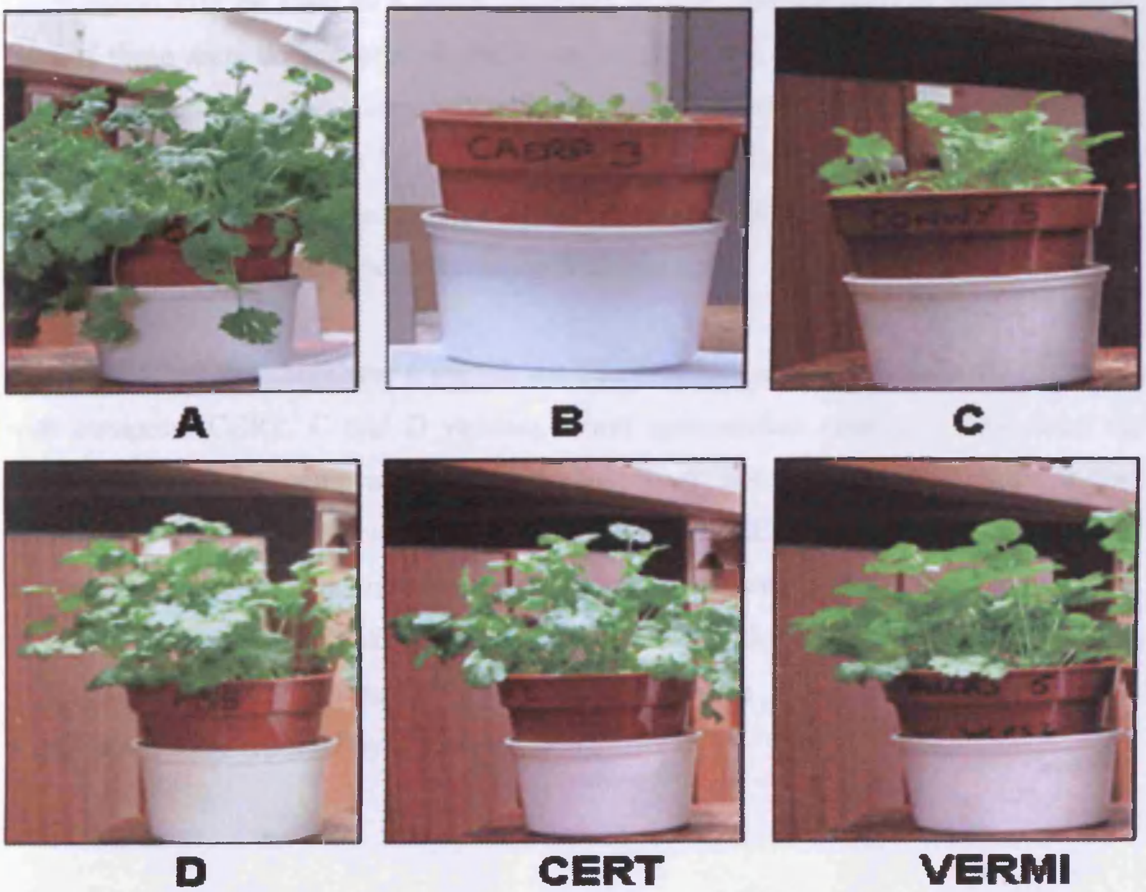


Figure 5.2 A visual comparison of coriander growth in different composts at harvest. The photographs are representative of at least 5 replicate plants. Compost E was not utilised during coriander growth

5.2.2 Seed Germination

Germination may be used as a quick indicator of phytotoxicity within growing media, even if these tests do not provide information about the intensity of the toxic effect (Wang and Keturi, 1990). Germination rates for coriander and tomato seeds after one week are presented in Figure 5.3. The values presented in Figure 5.3 are in comparison to the commercial compost A, with significant differences tested at $P < 0.05$ level. Columns with NS represent no significant difference to compost A.

Results showed that there was a significant decrease in germination rates for coriander with composts CERT, C and D yielding lower germination rates (55-75%) than the commercial compost (compost A) during the first week. For the same time period, higher germination rates (90-95%) were recorded for composts CERT, C, D and vermicompost during the tomato growth trial, composts B and E showed a lower germination rate (75%). However, the tomato is known to be more tolerant of adverse conditions, suggesting that the germination rates may vary with the plant species. Similar observations were reported by Wu et al. (2000).

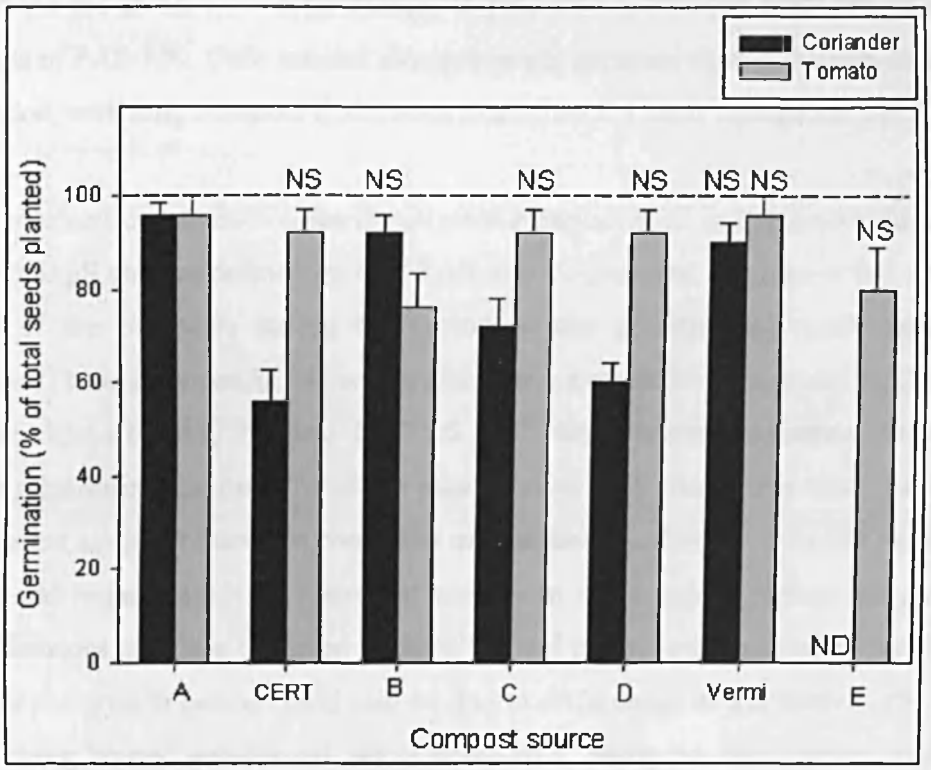


Figure 5.3 Germination rates of coriander and tomato plants in a range of commercial and waste-derived composts for 7 days (values represent means ± standard error (n = 5) ND indicates not determined)

5.2.3 EC and pH Measurement

Results of the measurements of electrical conductivity (EC) and pH of the raw materials and on the materials remaining in the pots after the coriander growth trials are presented in Table 5.1. EC and pH measurements were also discussed earlier in Section 4.2.2, however, during the coriander growth trials, different instruments and techniques were used (for details see Section 3.4.1.3). These measurements were not performed during the tomato growth trials.

For all of the waste-derived composts the original pH levels (average pH 7.7) were higher than those of the two commercially available composts, A and D (5.5 and 5.3). However, none of the pH levels were high enough to present any obvious problems as defined by the limits of PAS-100. Only limited changes in pH occurred during the one month growth trial period, with only compost C showing more than 0.3 units change i.e. pH 7.2 to 7.9.

Values of electrical conductivities for original compost B, C and D lie comfortably in the range <500 μS cm^{-1} as defined by BSI PAS-100. Significant changes in EC occurred for several of the composts during the period of the growth trial, with most showing increases. These increases in EC were particularly notable for composts C, D and CERT with the values of 811, 973 and 1217 μS cm^{-1} respectively, suggesting an increase of soluble salts during the time for which plant growth took place. It is also speculated that this increase simply reflects the continued mineralisation of organic matter i.e. production of CO_2 and organic acids by microbial activity in the compost during the growth trial. The differences in values observed for both EC and pH in various compost sources before and after the growth period could also be due to differences in the method (for example, CERT being housed windrowed, while compost C being an open windrowed) used to manufacture the compost, feedstock utilised and the time allowed for maturity/curing of composts (for details see Table 3.1).

Table 5.1 pH and electrical conductivity measurements of the commercial and waste derived composts before and after the coriander growth trials.

Compost Source	pH		EC (μS cm^{-1})	
	Original	After	Original	After
A	5.5	5.2	720	226
B	8	8.2	282	364
C	7.2	7.9	360	811
D	5.3	5.5	368	973
CERT	7.9	7.6	646	1217
Vermi	7.6	7.5	710	689

(values represent the mean of 5 independent measurements)

5.2.4 Plant Biomass

The fresh and dry weights of coriander and tomato seedlings grown on various compost sources are presented in Figures 5.4 and 5.5. Columns with different letters (a, b, c, d, and e for both fresh weight and dry weight) are significantly different from each other at $P < 0.05$ while those with the same letters are not significantly different. It can be seen in Figure 5.4 that the highest values of coriander fresh (28 g) and dry weights (3 g) were recorded for the commercial compost (compost A), while the lowest values were observed for composts B and C. It is thought that this poor plant growth was due to low levels of nitrogen in these composts (see Table 5.2). This was further supported by the 'colour' of the leaves, where the coriander plants grown in compost B and C showed a yellowish tint within the leaf structure, suggesting nitrogen deficiency.

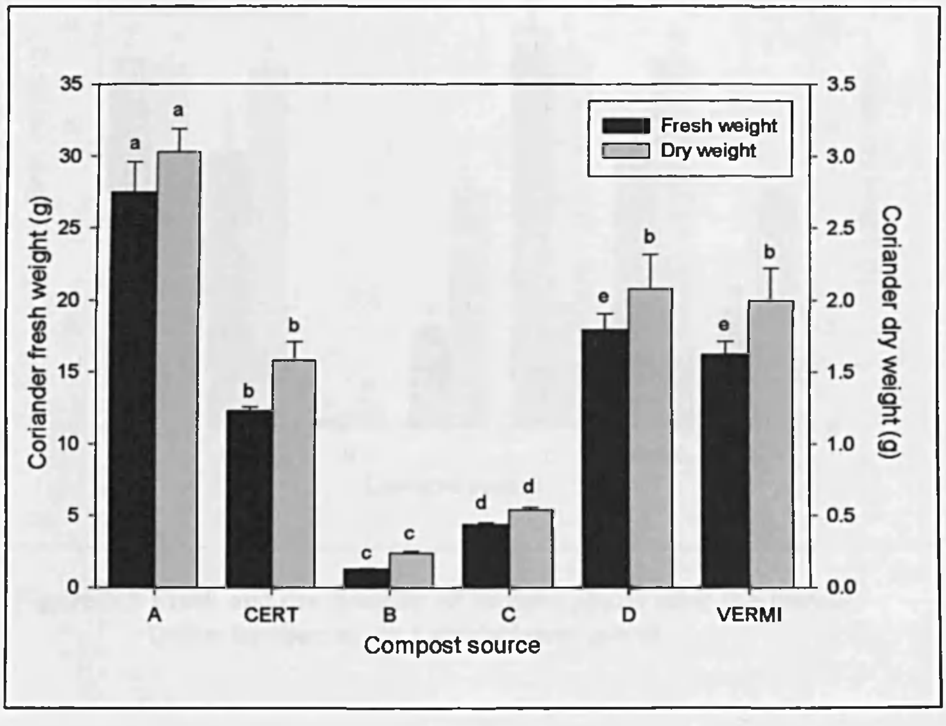


Figure 5.4 Fresh and dry weights of coriander plants after the harvest
(values represent means ± standard error (n = 5)

It can be seen in Figure 5.5 that there are no significant differences between fresh and dry weights of tomato seedlings grown on the two commercial composts (A and D). Similarly, no significant differences were observed in the values of fresh and dry weights obtained for CERT and vermicompost. It is believed that the better plant growth observed for the commercial composts (A and D), waste-derived compost CERT and vermicompost could be due to higher levels of plant available nitrogen (see Table 5.2). As with the coriander, it is again apparent from Figure 5.5 that the tomato plants grown on compost B also showed poor results. It is speculated that this could be due to the lower concentrations of the soluble nitrogen and the shorter time (4 months) allowed for maturity/curing of compost B (for details see Table 3.1).

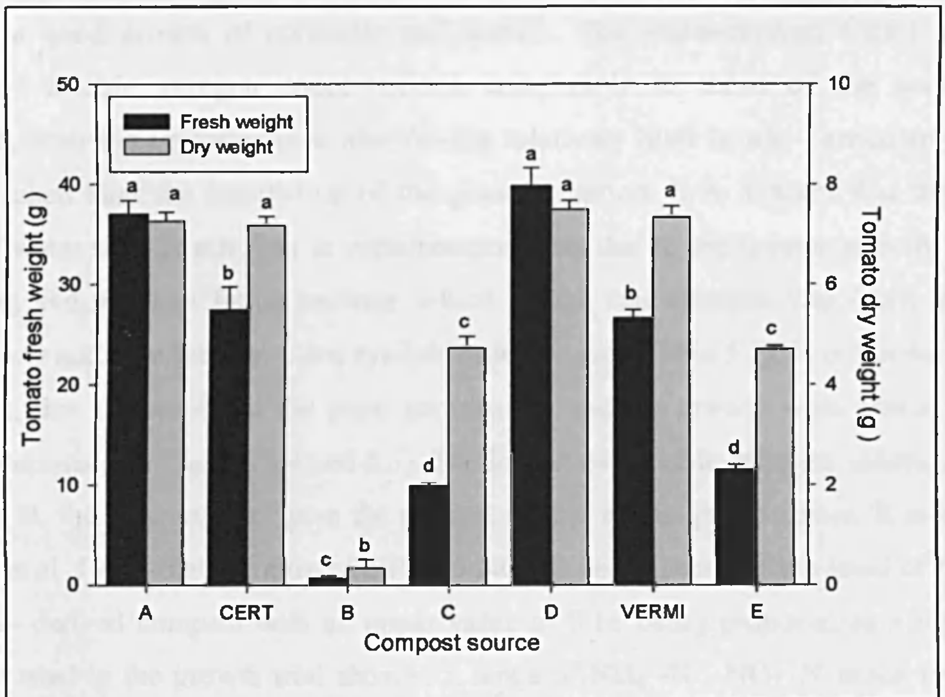


Figure 5.5 Fresh and dry weights of tomato plants after the harvest
(values represent means ± standard error (n = 5))

5.2.5 Chemical Analyses of the Composts

Concentrations of the chemical species determined in the various extract solutions were converted to the corresponding concentrations of those species expressed as mass per unit mass of the relevant solid samples. The values for NH_4^+, NO_3^- and the ratios of NH_4^+ to NO_3^- are presented in Table 5.2. Nitrogen in these forms is readily available for take-up by plants, however, the relative balance between these two inorganic forms is critical in regulating the growth of many plants (Marschner, 1995). As N is often growth limiting in many media, it is expected that the results of the growth trial would correlate with the nitrogen levels in Table 5.2. As expected, the nitrogen values obtained for the commercial composts A and D were amongst the highest and these composts also showed a good growth of coriander and tomato. The waste-derived CERT compost possessed soluble nitrogen concentrations comparable to those of the commercial products, with the vermicompost also having relatively high levels, particularly in the sample taken after the completion of the growing period. It is thought that the higher level of water soluble nitrogen in vermicompost was due to the greater activity of both nitrifying and nitrogen fixing bacteria, which means that nitrogen was fixed from the atmosphere and converted to plant available nitrates (see Table 5.2). It is not surprising, therefore, that the results of the plant germination and the growth were reasonable for these composts (see Figures 5.4 and 5.5). The lowest extractable nitrogen values were for compost B, the material that gave the poorest results in the growth trials. It is reported (Bernal et al. 1998) that the ratio of NH_4^+ to NO_3^- is an indicator of the level of maturity in waste- derived compost with an upper value of 0.16 being proposed as a limit. The compost used in the growth trial showed a range of NH_4^+-N : NO_3^--N ratios from 3 to 0.03, but there is no clear indication that low values correlate with enhanced plant growth characteristics. Indeed, the commercially available compost A gave the best growth performance whilst giving a ratio of between 1 and 2. Therefore, it is thought that unidentified biological factors are responsible for the differences in growth behaviour.

Table 5.2 Ammonium-N and nitrate-N concentration and the NH_4^+-N : NO_3^--N ratio for composts involved in growth trials.

Compost source	NH_4^+ (mg N kg $^{-1}$)		NO_3^- (mg N kg $^{-1}$)		NH_4^+-N : NO_3^--N ratio	
	Original	After	Original	After	Original	After
A	112 ± 7	68 ± 15	55 ± 4	73 ± 21	2	0.93
B	1 ± 0	3 ± 0	1 ± 0	1 ± 0	1	3
C	0.5 ± 0	5 ± 1	3 ± 1	9 ± 3	1.6	0.5
D	4 ± 1	21 ± 2	127 ± 8	110 ± 15	0.03	0.19
E	ND	7 ± 1	ND	23 ± 12	ND	0.3
CERT	81 ± 4	4 ± 0	141 ± 2	125 ± 20	0.5	0.03
Vermi	3 ± 0	18 ± 8	28 ± 4	91 ± 19	0.10	0.19

(Values represent mean ± standard error of the mean (n = 5) ND indicates not determined)

The availability of plant nutrients in the compost (K, P, Ca and Na) before and after the tomato trials was assessed and the results are presented in Table 5.3. Generally, the concentrations of nutrients within the waste derived composts were similar to those of the commercially available peat-based compost (Compost A). The results presented in Table 5.3 suggest that the availability of macronutrients in the waste derived composts is probably not a significant factor limiting plant growth, as the concentrations measured before and after plant growth were similar or showed a small level of depletion. It is speculated that the levels present in the compost are more than sufficient to meet the needs of the plants tested. Therefore, it seems likely that some other factors may be responsible for limiting growth in the waste-derived composts in comparison to the commercially available peat-based compost. These might include the absence of suitable microbial symbionts for the plant (e.g. mycorrhizas) or absence/suppression of other key members of the soil microbial community. Groups of soil microorganisms that live in very intimate contact with roots are the arbuscular mycorrhizal (AM) fungi. These fungi are known to assist the plant in uptake of nutrients and to improve plant growth (Douds et al. 2005). Visual observation of some of the composts indicated significant abundance of mesofaunal (e.g. mites) and fungal activity. The impacts of these on plant growth can be variable depending upon the nature of the environment and their negative impact on plant growth cannot be discounted. In addition, the presence of organic phytotoxins remaining from the composting process may still be present at sufficiently high concentrations to inhibit growth and germination (e.g. volatile fatty acids). Although the composts possessed significantly different water holding capacities and moisture release characteristics, due to the well managed watering regime this can be discounted as a significant growth limiting factor.

Table 5.3 Plant available nutrients in the composts before and after the tomato growth trial.

Compost Source	Phosphorus mg kg^{-1}		Calcium mg kg^{-1}		Potassium mg kg^{-1}		Sodium mg kg^{-1}	
	Original	After	Original	After	Original	After	Original	After
A	96 ± 2	60 ± 2	409 ± 11	635 ± 40	523 ± 19	316 ± 18	185 ± 3	203 ± 10
B	26 ± 2	20 ± 2	2690 ± 137	2332 ± 81	1074 ± 22	1083 ± 30	277 ± 3	319 ± 14
C	5 ± 2	5 ± 2	5285 ± 241	5577 ± 280	508 ± 10	659 ± 11	365 ± 6	490 ± 14
D	31 ± 2	25 ± 2	429 ± 3	661 ± 66	717 ± 3	693 ± 45	275 ± 6	329 ± 17
E	117 ± 2	91 ± 2	1747 ± 12	1688 ± 59	1428 ± 24	1452 ± 79	343 ± 7	352 ± 28
CERT	69 ± 2	64 ± 2	1816 ± 164	2544 ± 168	1265 ± 20	1449 ± 60	348 ± 9	452 ± 36
Vermi	143 ± 2	122 ± 2	3078 ± 168	2412 ± 110	997 ± 2	1300 ± 28	315 ± 7	421 ± 9

(Values represent mean ± standard error of the mean (n = 5))

5.2.6 Conclusions

The preliminary study of the ability of waste-derived composts to support plant germination and growth showed that:

- In general, the plants grown on waste-derived compost did not appear as vigorous as those where commercial media were used.
- Commercially available composts performed better than waste-derived compost and where performance has been unsatisfactory it has been possible to attribute the poor behaviour to low levels of plant nutrient, specifically nitrogen.
- Plant growth varied from one waste-derived compost to another and has been attributed to other unidentified biological factors than the availability of nutrients such as phosphorus and potassium.

5.3 LETTUCE

Replicated plant growth trials were undertaken with lettuce using pure worm cast (vermicompost), green waste-derived compost (FS) and mixtures of the two to determine the extent of growth enhancement gained through the vermicomposting process. The mixtures comprised of 50/50 (v/v) and 20/80 (v/v) of worm casts and green waste feedstock. Details of the compost sampling were discussed in Section 3.4.2.1. The main objective of this study was to evaluate if the product obtained from vermicomposting of mature green waste compost could enhance plant growth either in use on its own or blended with green waste compost.

5.3.1 General Observations

Representative examples of the lettuce plants at the time of harvest are presented in Figure 5.6. Based on general observations, it is clear that there were no significant differences in the plant morphology in the lettuce plants grown in the feedstock and green-waste compost amended with 50% and 20% (v/v) vermicompost. However, obvious differences were observed in the plants grown in pure (100%) vermicompost throughout the trial period. These differences included plant height, size and colour of leaves, plant biomass and overall health of plants. Some of these differences are discussed in detail in subsequent sections. It is evident from the visual observation that pure vermicompost showed poor plant growth when compared to the other compost treatments. This was demonstrated by the number and surface area of the leaves. This was further supported by the 'colour' of the leaves, where the lettuce grown in pure vermicompost showed a yellowish tint within the leaf structure, suggesting nitrogen deficiency.

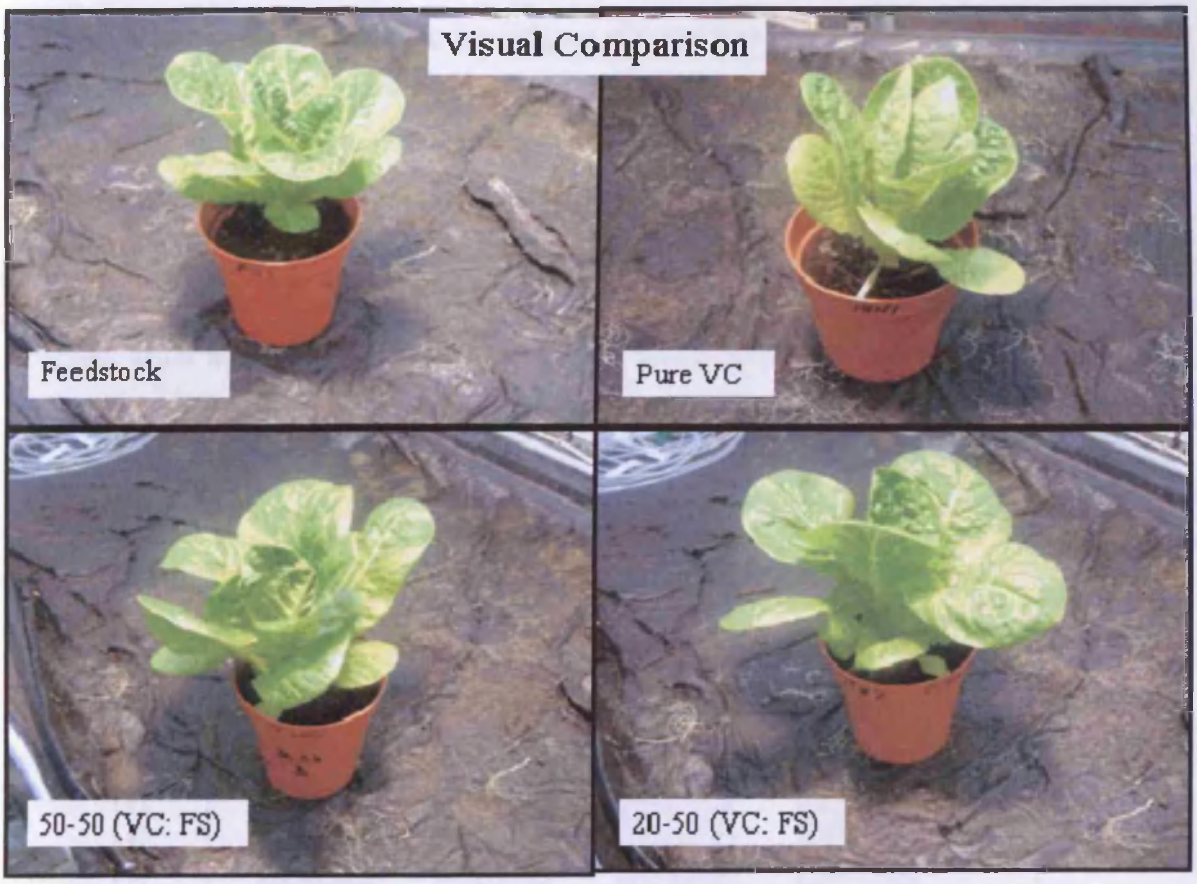


Figure 5.6 A visual comparison of lettuce growth in the different compost treatments at harvest. The photographs are representative of at least three replicate plants.

5.3.2 Water Holding Capacity

This parameter was measured to investigate if water holding capacity could be enhanced by vermicomposting of mature green waste compost. Water holding capacities for each compost treatment are presented in Figure 5.7. Columns with different letters (a and b) are significantly different from each other at $P < 0.05$, while those with the same letters are not significantly different. It can be seen in Figure 5.7 that there is a maximum increase of 4% (m/m) after the vermicomposting process. The pure worm casts had the highest water holding capacity of 67% (m/m), while 50-50 (v/v) and 20-80 (v/v) blends of worm cast and green waste compost had 65% and 66% respectively.

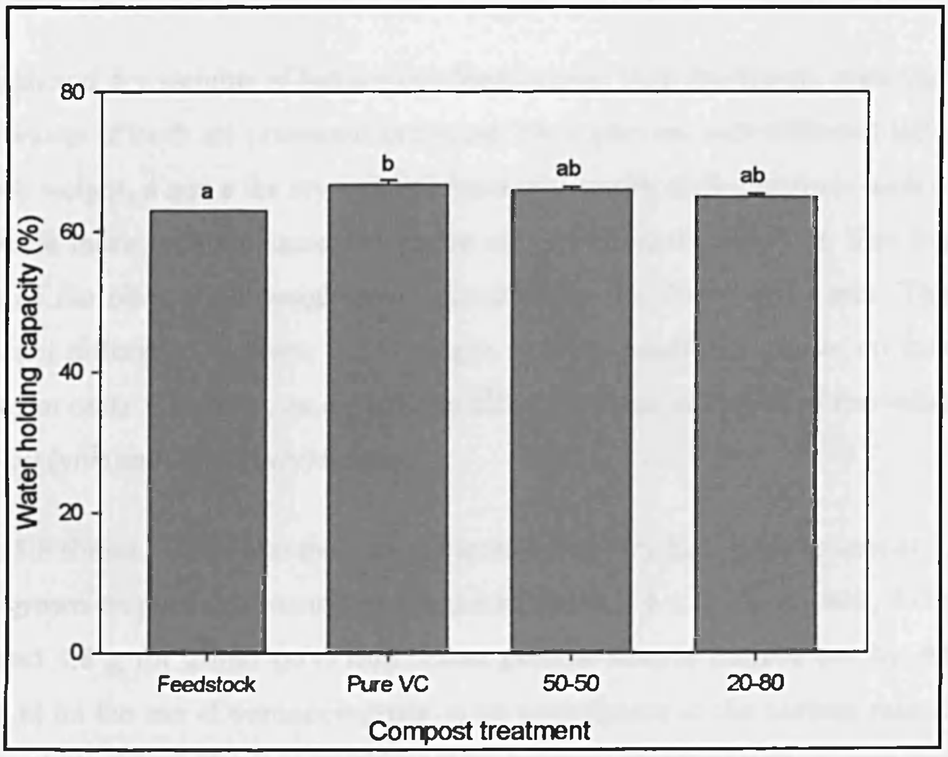


Figure 5.7 Water holding capacity for each compost treatment used for lettuce growth.

It is clear from Figure 5.7 that there is no significant increase in water holding capacity of the two mixtures when compared to that of the feedstock. A study conducted by Roberts et al. (2007) used five different mixtures in the ratios: 0:100%, 40:60%, 60:40%, 80:20%, 100:0% (v/ v) of vermicompost : peat-based growing medium respectively. They found no significant differences in either moisture holding capacity or air filled porosity of the growth media. In contrast to this, Hashemimajd et al. (2004) reported that mixing of vermicompost to potting (soil and sand) would increase water holding capacity of the media. Atiyeh et al. (2001) also claimed that by increasing the rate of pig manure worm cast in container media from 5% to 50%, the water holding capacity of peat-based substrate increased by 3%.

5.3.3 Plant Biomass

The fresh and dry weights of lettuce seedlings grown with feedstock, pure vermicompost and mixtures of both are presented in Figure 5.8. Columns with different letters (a and b for fresh weight, d and e for dry weight) are significantly different from each other at $P < 0.05$ while those with the same letters are not significantly different. The highest value (70 g) of the plant fresh weight was recorded for the 20-80 (v/v) mix. There was no significant difference between fresh weight of plant seedlings grown on feedstock and pure worm casts. Similarly, no significant difference was observed in the values obtained for 50-50 (v/v) and 20-80 (v/v) mixes.

Figure 5.8 shows clearly that the mass of lettuce on a dry basis was lowest at 3.2 g for the plants grown on pure vermicompost compared to the 3.6 g for feedstock, 4.6 g for 50-50 (v/v) and 4.8 g for 20-80 (v/v) mix. Plant growth studies carried out by Atiyeh et al. (2000a,b) on the use of vermicomposts as an amendment to the potting mix showed that even a relatively small concentration could enhance plant growth. It was found that by using only 10% (v/v) of pig manure vermicompost in the container mix, the dry weight of the French marigold, tomato seedlings and tomato fruit increased significantly (31%) over those of the plants grown in the control media. It was also reported that pure vermicompost had a negative effect on the overall plant growth as compared to the plants grown in the control. This retardation in plant growth and productivity was due to high a salt concentration in the pig manure vermicompost (11,760 μ S/cm) or poor porosity and poor aeration of the medium (Atiyeh et al. 2000a). However, in the present study, significantly lower values of electrical conductivity were observed for pure worm casts (between 1115 and 1415 μ S/cm, see Section 4.2.2) and still plant grown in pure vermicompost showed poor results. It is thought that electrical conductivity and physical differences alone cannot account for the poor performance of plant grown in 100% vermicompost. Therefore, it is hypothesised that unidentified biological factors associated with the vermicompost are responsible for the observed differences.

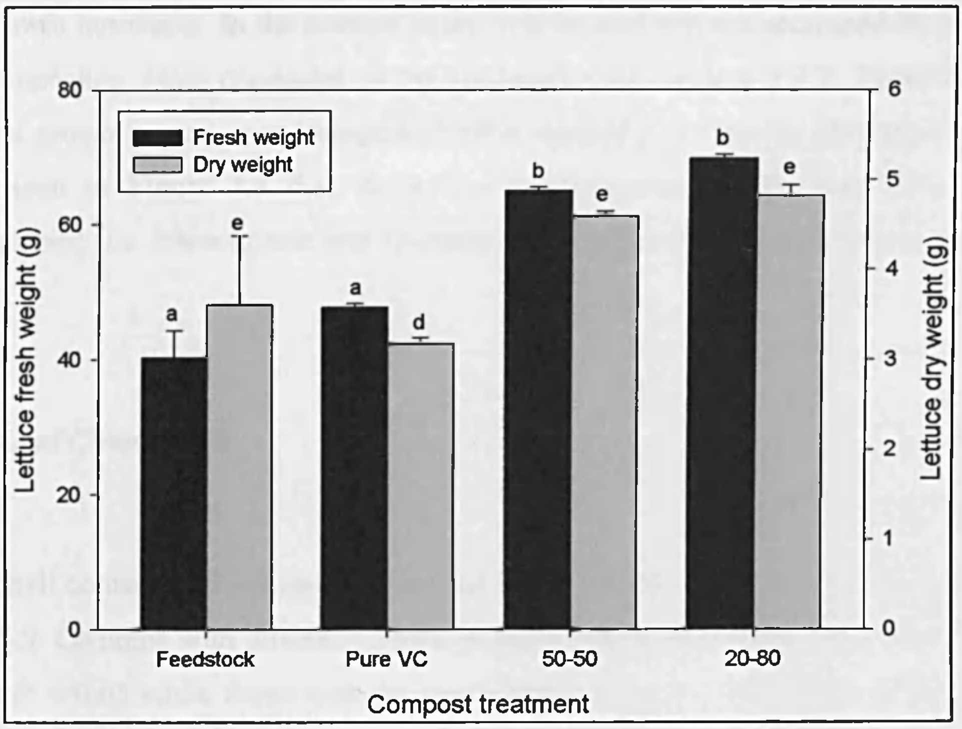


Figure 5.8 Fresh and dry weights of lettuce plants after the harvest

Research conducted by Kale (1993) and Subler et al. (1998) claimed that the presence of plant growth regulators (e.g. hormones) and/or symbiotic microbes (e.g. mycorrhizas) in the worm cast could be responsible for the improvement in plant growth after vermicomposting process. Recent studies by Atiyeh et al. (2002b) and Arancon et al. (2004b) showed that the plant growth enhancement was not related to the mineral nutrient changes that occurred during the vermicomposting process, but is due to the worm cast's humic acid content. However, Edwards et al. (2006) found that the growth hormones that had been adsorbed on humic acid during vermicomposting could be responsible for enhanced plant growth and disease suppression properties. A number of researchers isolated indole acetic acid (Canellas et al. 2002 and Arancon et al. 2003) and cytokinins and auxins (Krishnamoorthy and Vajranabhaiah 1986) from the humic fraction of vermicompost and reported that an accelerated plant growth was due to the presence of plant growth hormones. In the present study, humic acid content increased by 12% after vermicomposting when compared to the feedstock (see Section 5.3.7, Table 5.10) and still plant grown in pure vermicompost (100%) showed poor results. However, it can be clearly seen in Figure 5.8 that using low concentrations (50% and 20%, v/v) of vermicompost (i.e. lower humic acid content) in a potting media showed the highest plant biomass.

5.3.4 Leaf Chlorophyll

Chlorophyll contents (SPAD units) of lettuce leaves for compost treatments are shown in Figure 5.9. Columns with different letters (a and b) are significantly different from each other at $P < 0.05$ while those with the same letters are not significantly different. Leaf chlorophyll content is a key indicator of plant health and helps in identifying the amount of nitrogen uptake by the plant. It is evident from Figure 5.9 that by using pure vermicompost the plant growth yielded the lowest chlorophyll content (28 SPAD unit), whereas no significant difference was observed for the feedstock and the two mixtures (50-50 v/v and 20-80 v/v). Atiyeh et al. (2000a) observed similar differences during marigold seedlings growth. They reported a higher chlorophyll content in plants grown in media with 10 or 20 % pig manure vermicompost or with 10% vermicomposted food waste than plant grown in control media. In contrast to this, a study conducted on the same plant specie by Subler et al. (1998) observed that the differences between the vermicompost and compost treatments in leaf chlorophyll concentration occurred only after one week of its germination and suggested that these differences diminished as the plants grew. Galli et al. (1992) observed an increase of 30 % in protein synthesis in lettuce seedlings following the application of vermicompost and showed that no differences were recorded in the presence of compost. They also suggested that an increase in soil productivity, which cannot be explained by mineral nutrients alone, is often recorded when composted organic wastes are supplied to croplands.

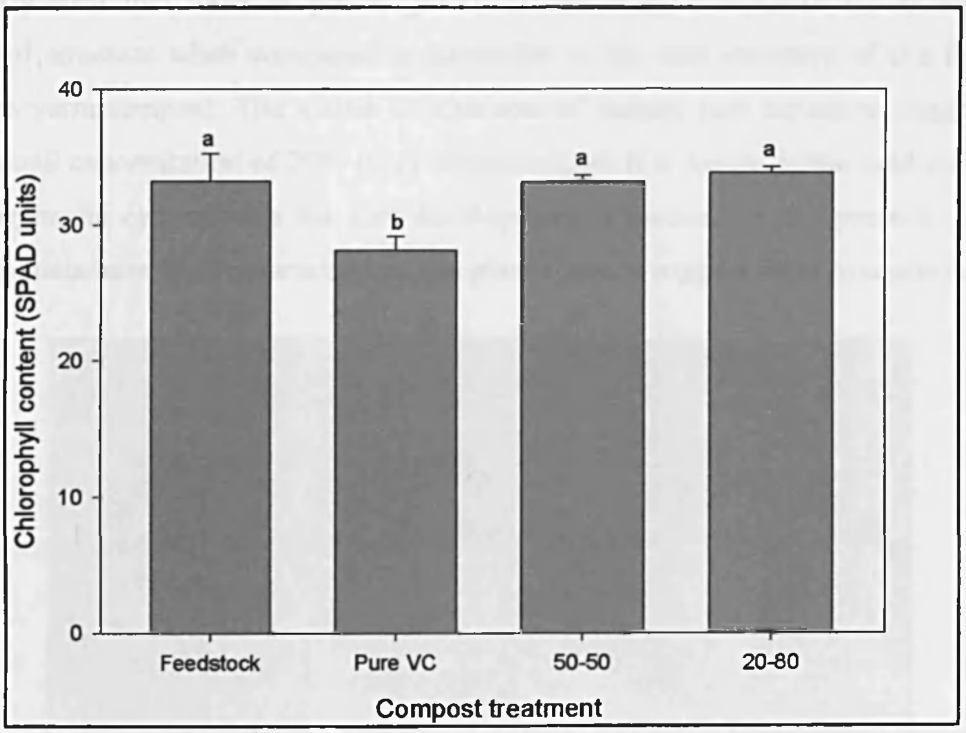


Figure 5.9 Chlorophyll content for each compost treatment

5.3.5 Plant Root

Figure 5.10 illustrates the contents of three pots after they were carefully emptied onto the laboratory bench. Canellas et al. (2002) utilised vermicomposted cattle manure to grow maize plants and found that the plant growth hormones within the humic substances derived from vermicompost are responsible for the enhanced root growth. Some of the researchers (Kale et al. 1987, Subler et al. 1998 and Cavender et al. 2003) found that the use of vermicompost enhances the growth of symbiotic microbes (e.g. mycorrhizas), stimulates root growth and increases the plant's ability to uptake added inorganic nutrients. In the present study, humic acid content increased by 12% after vermicomposting when compared to the feedstock (see Section 5.3.7, Table 5.10). It can be clearly seen that roots of plants grown in the 20-80 (v/v) mix exhibited a well developed structure when compared in particular to the root structure of the feedstock and pure vermicompost. The visual comparison of lettuce root structure suggests that only a small concentration of 20% (v/v) vermicompost (i.e. lower humic acid content) in a potting media can enhance the root development. However, in the present study, no analytical data have been determined on the plant roots to support this observation.

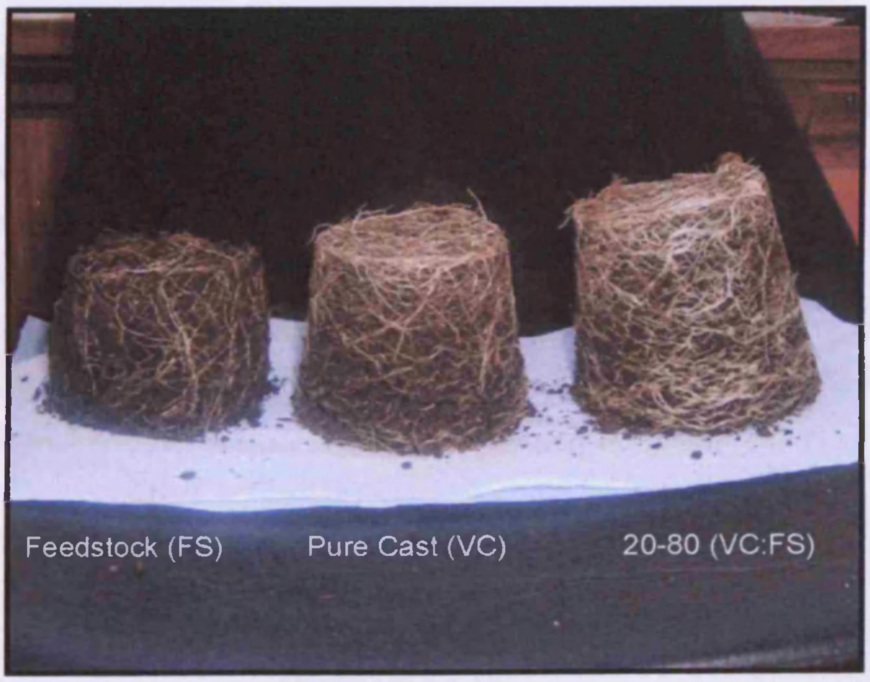


Figure 5.10 A visual comparison of lettuce root structure in different compost treatments at harvest. The photographs are representative of at least three replicate plants

5.3.6 Chemical Analyses

Chemical analyses were also discussed earlier in Section 4.2.6, however, a microwave digestion technique was used to determine the total nutrients and heavy metals concentrations during the lettuce growth trial (see Section 3.3.1.2). This was performed by digesting 0.1 g of air-dried composts and lettuce samples in a microwave oven (Anton Paar 3000).

5.3.6.1 Composts analyses

Tables 5.4 and 5.5 present the nutrient contents in the growth substrates as total and plant available, respectively. These must be considered alongside the mass reduction of approximately 16% that occurred as the original compost was converted to vermicompost (see Section 4.2.3.1). It would be expected that the concentration would increase, if the mass of the material had been reduced significantly, after the vermicomposting process. This concentration increase was not observed and it is thought that this might have occurred due to a combination of analytical errors and sampling associated with such heterogeneous materials.

It can be seen in Table 5.4 that the concentration of total nutrient is higher within the feedstock compared to the pure vermicompost, 50-50 (VC:FS) and 20-80 (VC:FS) mixtures, except for Ca which is almost similar in each of the substrates. Turning to the water soluble nutrients (Table 5.5), it is again apparent that the availability of nutrient is higher in the feedstock compared to pure vermicompost and the two mixtures. The lowest concentrations of available P occurred in the 20-80 (VC:FS) mixture and it is interesting to note that this is related to the highest plant biomass and leaf chlorophyll, as shown in Figures 5.8 and 5.9.

Table 5.4 Total nutrient content within the feedstock, pure vermicompost, 50-50 and 20-80 (v/v) mixtures

Compost Treatment	N	P	K	Ca	Mg	Na
Feedstock (FS)	16.83 ± 0.53	3.6 ± 0.01	11.4 ± 0.17	37.4 ± 2.20	4 .0 ± 0.06	1.5 ± 0.07
Pure cast (VC)	15.30 ± 0.36	3.1 ± 0.08	9.7 ± 0.21	36.6 ± 0.88	3.9 ± 0.16	1.3 ± 0.03
50-50 (VC:FS)	15.74 ± 0.60	3.4 ± 0.20	10.3 ± 0.43	37.1 ± 3.30	3.9 ± 0.22	1.3 ± 0.06
20-80 (VC:FS)	16.46 ± 0.65	2.8 ± 0.12	9.8 ± 0.40	36.5 ± 3.92	3.8 ± 0.23	1.4 ± 0.07

Values represented in the table are mean ± standard error of the mean (n = 3))
All values are in g/kg (dry basis)

Table 5.5 Plant available nutrient within the feedstock, pure vermicompost, 50-50 and 20-80 (v/v) mixtures.

Compost Treatment	Ca	K	Mg	Na	P
Feedstock (FS)	728 ± 115	7,359 ± 326	170 ± 26	1,143 ± 74	66 ± 4
Pure cast (VC)	677 ± 53	5,634 ± 177	158 ± 15	968 ± 34	56 ± 4
50-50 (VC:FS)	528 ± 93	6,150 ± 521	132 ± 22	1,035 ± 95	48 ± 4
20-80 (VC:FS)	283 ± 16	5,157 ± 152	75 ± 5	833 ± 28	28 ± 1

Values represent mean ± standard error of the mean (n = 3))
All values are in mg/kg (dry basis)

Tables 5.6 and 5.7 show the total and bio-available concentrations of the feedstock, pure vermicompost and mixtures of the two. It can be observed from Table 5.6 that Zn is present in the highest concentration for all media. However, that concentration remains below the limit set by the Composting Association, UK Standards (PAS 100) as shown in Table 5.6. Once again, as with the total nutrients, there is not the expected conservation of mass associated with the vermicompost and the mixing processes. This was due to the experimental errors also mentioned above. Bansal and Kapoor (2000) mixed sugarcane trash with cattle dung and vermicomposted using *E. fetida* in a 90 days experiment. They reported a significant increase (16%) in total Zn and observed no change in the total P and K contents in the final product.

Table 5.6 Concentrations of total potentially toxic elements in the growth media

Compost Treatment	Cr	Cu	Ni	Pb	Zn
Feedstock (FS)	93 ± 23	110 ± 06	38 ± 04	134 ± 05	238 ± 17
Pure cast (VC)	66 ± 09	96 ± 05	35 ± 01	129 ± 08	296 ± 12
50-50 (VC:FS)	58 ± 08	85 ± 01	34 ± 02	128 ± 03	289 ± 29
20-80 (VC:FS)	58 ± 09	82 ± 04	33 ± 01	134 ± 07	261 ± 17
PAS100 *	<100	<200	<50	<150	<400

Values represent mean ± standard error of the mean ($n = 3$))
All values are in mg/kg (dry basis)
* Publicly Available Specification BSI-PAS 100:2005 for composted material. The Composting Association, Standard, UK

It is clear from Table 5.7 that for all the potentially toxic elements, the availability (i.e. water solubility) is very low. The most soluble is Zn, with only about 0.5% of the total being available. Somewhat similar results were also observed during the vermicomposting trial (see Table 4.3). For the Zn alone there is some evidence of increased availability in the vermicompost compared to the feed compost. For example, the feedstock contained 0.827 mg/kg of soluble Zn when compared to 3.360 mg/kg observed for pure vermicompost.

Table 5.7 Concentration of bio-available potentially toxic elements in the growth media

Compost Treatment	Cr	Cu	Ni	Pb	Zn
Feedstock (FS)	ND	0.294 ± 0.037	0.048 ± 0.005	0.035 ± 0.010	0.827 ± 0.053
Pure cast (VC)	ND	0.236 ± 0.028	0.042 ± 0.002	0.043 ± 0.006	3.360 ± 0.910
50-50 (VC:FS)	ND	0.160 ± 0.030	0.032 ± 0.010	0.040 ± 0.000	1.278 ± 0.430
20-80 (VC:FS)	ND	0.131 ± 0.006	0.010 ± 0.000	0.030 ± 0.000	0.872 ± 0.036

Values represent mean ± standard error of the mean (n = 3))
All values are in mg/kg (dry basis)
ND indicates not detected

5.3.6.2 Plant analyses

The concentrations of total nutrients and heavy metals in the lettuce are presented in Tables 5.8 and 5.9, respectively. For all but N and Zn, the concentration in plants grown in the various media are similar. The lettuce grown in pure vermicompost exhibited low values of N compared to the other composts, as shown in Table 5.8. For example, when compared to the feedstock the pure vermicompost N content was about 25 % lower i.e. 22.3 g/kg compared to 29.5 g/kg. These results correlate with the leaf chlorophyll contents, which showed that by using pure vermicompost, the plant growth yielded the lowest chlorophyll content i.e. lower nitrogen uptake by plant (see Figure 5.9). Zn is more plant available in the vermicompost compared to other growth media (see Table 5.7) and the composition of lettuce leaves as shown in Table 5.9 reflects these observations, with significantly more of the metal appearing in the plants grown using the vermicompost. Valerio et al. (2007) reported that a higher level of Zn in growth media has a negative effect (phytotoxicity) on plant growth. Therefore, in the present study, higher concentration of Zn could also be the reason for poor plant growth using pure vermicompost.

Table 5.8 Concentration of total nutrient content in the lettuce plants

Compost Treatment	N	P	K	Ca	Mg	Na
Feedstock (FS)	29.5 ± 4.44	3.6 ± 0.40	68.7 ± 3.20	5.8 ± 0.17	1.8 ± 0.082	4.7 ± 0.19
Pure cast (VC)	22.3 ± 1.90	4.4 ± 0.20	77.4 ± 2.54	6.9 ± 0.08	1.9 ± 0.070	4.5 ± 0.19
50-50 (VC:FS)	24.0 ± 1.30	4.3 ± 0.08	79.8 ± 0.80	7.1 ± 0.22	2.0 ± 0.058	4.7 ± 0.15
20-80 (VC:FS)	25.0 ± 0.69	4.4 ± 0.12	80.01 ±1.11	6.2 ± 0.18	1.9 ± 0.034	4.8 ± 0.17

Values represent mean ± standard error of the mean (*n* = 3))
All values are in mg/kg (dry basis)

Table 5.9 Concentration of total potentially toxic elements in the lettuce plants

Compost Treatment	Cr	Cu	Ni	Pb	Zn
Feedstock (FS)	ND	37 ± 1	ND	41 ± O	112 ± 9
Pure cast (VC)	ND	39 ± 4	ND	39 ± 1	160 ± 10
50-50 (VC:FS)	ND	35 ± 0	ND	43 ± 1	132 ± 17
20-80 (VC:FS)	ND	34 ± 1	ND	42 ± 1	113 ± 7

Values represent mean ± standard error of the mean (*n* = 3))
All values are in mg/kg (dry basis)
ND indicates not detected

5.3.7 Humic Acid

Recent research on the plant growth improvements due to application of worm casts by Atiyeh et al. (2002b) and Arancon et al. (2004b) has attributed the enhancements to a range of parameters such as humic acid content and growth hormones that had been adsorbed on humic acids during vermicomposting (Edwards et al. 2006). Therefore, in the present study, the humic acid content was extracted from representative samples of the feedstock, product of vermicomposting (pure vermicompost) and two other commercially available multipurpose composts. Details of compost sources are presented in Table 3.2.

The amount of humic acid within the feedstock, vermicompost produced and the two commercially available multipurpose composts is shown in Table 5.10. Two methods (alkali-acid and water-acid) were used to determine the humic acid content in the composts (see Section 3.4.2.7). It can be seen in Table 5.10 that after vermicomposting, an increase by 12% in humic acid content was observed. Sharma et al. (2005) reported that humic substances can occur naturally in mature animal manure, sewage sludge or paper mill sludge, but their amount and rate of decomposition increases dramatically by vermicomposting. However, it is interesting to see that the two commercially available composts (A and B), which are also considered favourable for enhanced plant growth showed the highest (64.4 g/kg) and the lowest (10.2 g/kg) humic acid content. Turning to the water soluble humic acid, it can be seen in Table 5.10 that no significant difference exists between the feedstock and the vermicompost with 0.9 g/kg and 0.86 g/kg respectively, while the commercially available nutrient-added composts showed the highest and the lowest water soluble humic acid. Therefore, it is speculated that the enhanced plant growth associated with the use of worm casts might not be due to humic acid content only, but could also be due to the presence of plant growth hormones and suitable microbial symbionts (e.g. mycorrhizas) or the absence/suppression of other key members of the soil microbial community for the plants in vermicompost.

Table 5.10 Humic acid content within the feedstock, pure vermicompost and two other commercially available composts

Source	Humic acid (g/kg)	
	Alkali-Acid Method	Water-Acid Method
CERT Feedstock	38.8 ± 0.4	0.9
CERT Vermicompost	51.2 ± 1.2	0.86
A *	64.4 ± 0.6	4.58
B *	10.2 ± 0.6	0.2

Values represented in Alkali-Acid column are standard error of the mean ($n = 4$).
All values are in g/kg (dry basis)).
* Names of the commercial compost producers are not identified.

5.3.8 Acid Digestion Using Combination of Acids

Acid digestion using aqua regia was performed in accordance with PAS-100:2005 standards throughout the study and the results are presented in Tables 5.4 and 5.6. However, another test using a combination of concentrated H_2O_2 and concentrated HF, in addition to aqua regia was also carried out to determine the total nutrients and heavy metals concentrations. These analyses were performed to determine if there were any variations in the results by using this combination of acids. This was performed by digesting 0.1 g of air-dried representative samples of the feedstock and pure vermicomposts samples in a microwave oven (Anton Paar 3000). The concentrations of total nutrient and potentially toxic elements in the feedstock and vermicomposts are shown in Tables 5.11, 5.12, 5.13 and 5.14. The expectation would be that the more complex reagent suite would extract more of the analytes of interest.

Results showed that there was no significant variation in the concentrations of elements determined by the different solvents except for Na, P and Ni, where using aqua regia + H_2O_2, aqua regia + HF and a combination of aqua regia + H_2O_2 + HF on the same samples showed a significant change in the concentrations. It is satisfying that the data in Table 5.11 show good agreement with those in Tables 5.4 and 5.6.

Table 5.11 Concentration of total nutrient and potentially toxic elements in the feedstock and pure vermicompost using Aqua Regia only.

Compost Treatment	Ca	K	Mg	Na	P	Cu	Cr	Zn	Ni	Pb
Feedstock	29,450	12,053	3,767	1,633	2,959	86	69	320	22	104
Pure VC	37,560	8,898	3,505	1,262	2,858	80	53	ND	22	99

All values are in mg/kg
ND indicates not detected

It can be seen in Table 5.12 that by using aqua regia + concentrated H_2O_2, feedstock and pure vermicompost resulted in slightly higher concentrations of Na, P and Cu. However, a lower concentration of Ca in pure vermicompost was observed, when compared to that of using aqua regia alone (see Table 5.11).

Table 5.12 Concentration of total nutrient and potentially toxic elements in the feedstock and pure vermicompost using Aqua Regia and Concentrated H_2O_2

Compost Treatment	Ca	K	Mg	Na	P	Cu	Cr	Zn	Ni	Pb
Feedstock	37,260	13,775	4,141	2,566	5,380	125	79	309	26	112
Pure VC	34,470	11,408	3,957	2,482	4,674	121	50	320	21	116

All values are in mg/kg

It is clear from Table 5.13 that by treating the samples of both feedstock and pure vermicompost with aqua regia + concentrated HF, a significant increase in the concentration of Na, but a lower concentration of Ni was observed.

Table 5.13 Concentration of total nutrient and potentially toxic elements in the feedstock and pure vermicompost using Aqua Regia and Concentrated HF.

Compost Treatment	Ca	K	Mg	Na	P	Cu	Cr	Zn	Ni	Pb
Feedstock	32,970	14,370	4,484	7,933	3,407	109	78	391	5.5	137
Pure VC	40,253	14,098	4,010	7,855	3,004	92	50	ND	4.25	122

All values are in mg/kg
ND indicates not detected

Table 5.14 Concentration of total nutrient and potentially toxic elements in the feedstock and pure vermicompost using Aqua Regia, Concentrated H_2O_2 and Concentrated HF.

Compost Treatment	Ca	K	Mg	Na	P	Cu	Cr	Zn	Ni	Pb
Feedstock	31,405	13,673	4,065	6,730	4,252	83	77	287	6.25	114
Pure VC	41,580	11,670	3,943	6,246	4,245	82	58	301	3.25	117

All values are in mg/kg

Results presented in Table 5.14 suggest that by using a more complex reagent suite (aqua regia + H_2O_2 + HF) significantly higher levels of P and Na and a lower level of Ni were observed. It is thought that this lower level of Ni could be due to the formation of NiF_2.

5.3.9 Conclusions

The study to evaluate if the product obtained from vermicomposting of mature green waste compost could enhance plant growth either on its own or blended with green waste compost showed that:

- The highest fresh and dry weights of lettuce plants were observed for 20-80 (VC:FS) (v/v) mix and that the use of pure vermicompost showed lowest plant dry weight.

- The lettuce grown in pure vermicompost exhibited the lowest values of leaf chlorophyll and depressed N content compared to the plants grown with the other treatments.

- The lowest water soluble nutrients occurred for 20-80 mix (v/v) and correlated with the highest plant biomass and leaf chlorophyll.

- The concentrations of all heavy metals were well within the upper limits defined by the Composting Association, UK PAS 100:2005 standards.

- Only zinc showed increased plant availability after the vermicomposting process.

CHAPTER 6

COMPOST CONTAMINANT CHARACTERISATION

6.1 PREAMBLE

Compost contaminant characterisation studies were conducted on unscreened mature compost samples to identify the physical contaminants followed by laboratory and commercial scale air separation trials.

6.2 COMPOST CONTAMINANT CHARACTERISATION

The amount of contaminants in a composted product can have a number of impacts on the end use. There is a maximum limit on the contaminants in the BSI PAS 100:2005 standards for composts (see Table 2.1), and it is likely that as the production and the use of composted organic waste increases over time, the market place for products that do not meet these standards will decline. If the final product is not of satisfactory quality, it is likely to have a negative value due to the cost of either disposal or use in a market place where the producer has to cover the cost of delivery and spreading.

The initial phase of the characterisation study involved the collection and analysis of a compost sample from Amgen Cymru's Bryn Pica landfill site near Aberdare, South Wales. This compost was specifically selected since the feedstock utilised to manufacture Bryn Pica compost included Rhonda Cynon Taf, South Wales park waste, wood waste, green-waste and kerbside collection. Therefore, it was thought that it would contain higher levels of various types of physical contaminants. The results obtained from the initial trial were used to determine the type, amount and proportion of each contaminant in order to prepare a representative mixture (standardised feed). The standardised feed was added to screened (<10 mm particle size) mature compost produced at CERT composting facility, located in West Wales. This compost and contaminants mixture was used in laboratory based air separation trials.

The second phase of the study involved characterising CERT's unscreened composted product. Following characterisation, this product was used to examine and analyse the efficiency of commercially available separation machines. A laboratory air jig was also examined to determine the suitability of this type of technology to separate high-density contaminants from <10 mm screened mature green waste compost.

6.2.1 INITIAL TRIAL

As previously described in Section 3.5.1, the unscreened composted product (327.71 kg) obtained from Bryn Pica landfill site was characterised during the initial phase of study to establish the guidelines for further analyses on CERT compost and to compare the quantity of various types of physical contaminants in composts. This section describes the results obtained during this initial characterisation. Figure 6.1 shows the size distribution by mass of Bryn Pica compost sample (as-received) in the form of a pie chart. The chart indicates that 57% (186.40 kg) of the sample was less than 10 mm, 21% (68.40 kg) was between 10 mm and 25 mm and the over size fraction i.e. greater than 25 mm was 22% (72.91 kg) of the total collected sample. Materials with size less than 10 mm (undersize) and >10 mm <25 mm particle size were dried at low temperature, typically at 40 °C overnight, and the moisture contents (% m/m) determined were 42% and 38%, respectively.

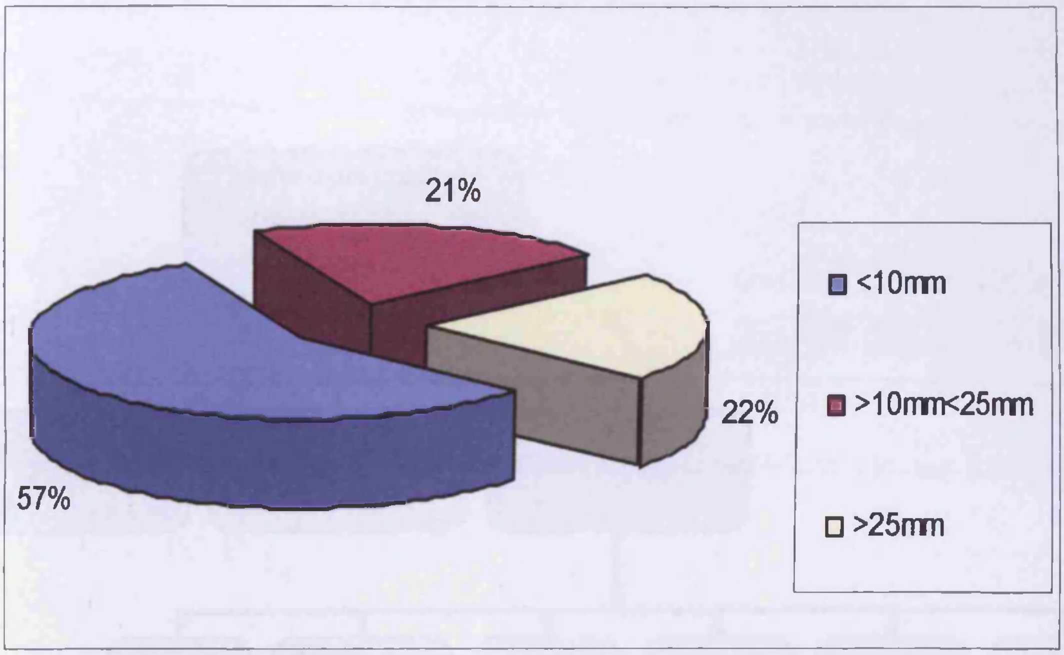


Figure 6.1 Screen analysis of the Bryn Pica compost sample on as-received bases

Results for hand sorting of the visible contaminants in the >25 mm are shown in Figure 6.2, 67% (48.5 kg) of this fraction was clean wood and 6% (4.7 kg) was contaminated wood (paint or varnished wood), thus wood accounted for 73% (53.2 kg) of the total. The next largest fraction was stones at 19% (13.8 kg), followed by 4.5% (3.25 kg) of plastic films and 3.4% (2.48 kg) of others. Other materials comprised about 1% (0.95 kg) rigid plastic, 2% (1.29 kg) paper products, 0.34% (0.25 kg) textile, 0.11% (0.08 kg) glass and 0.1% (0.1 kg) of metal. It was interesting to correlate these results with the type of feedstock utilised i.e. Rhonda Cynon Taf, South Wales kerbside collection and park waste. Therefore, presence of 1% >25 mm plastic films and 16% wood in the total sample (327.1 kg) tested, is not surprising. Photographs of the physical contaminants of the hand sorted >25 mm sample are shown in Figure 6.3.

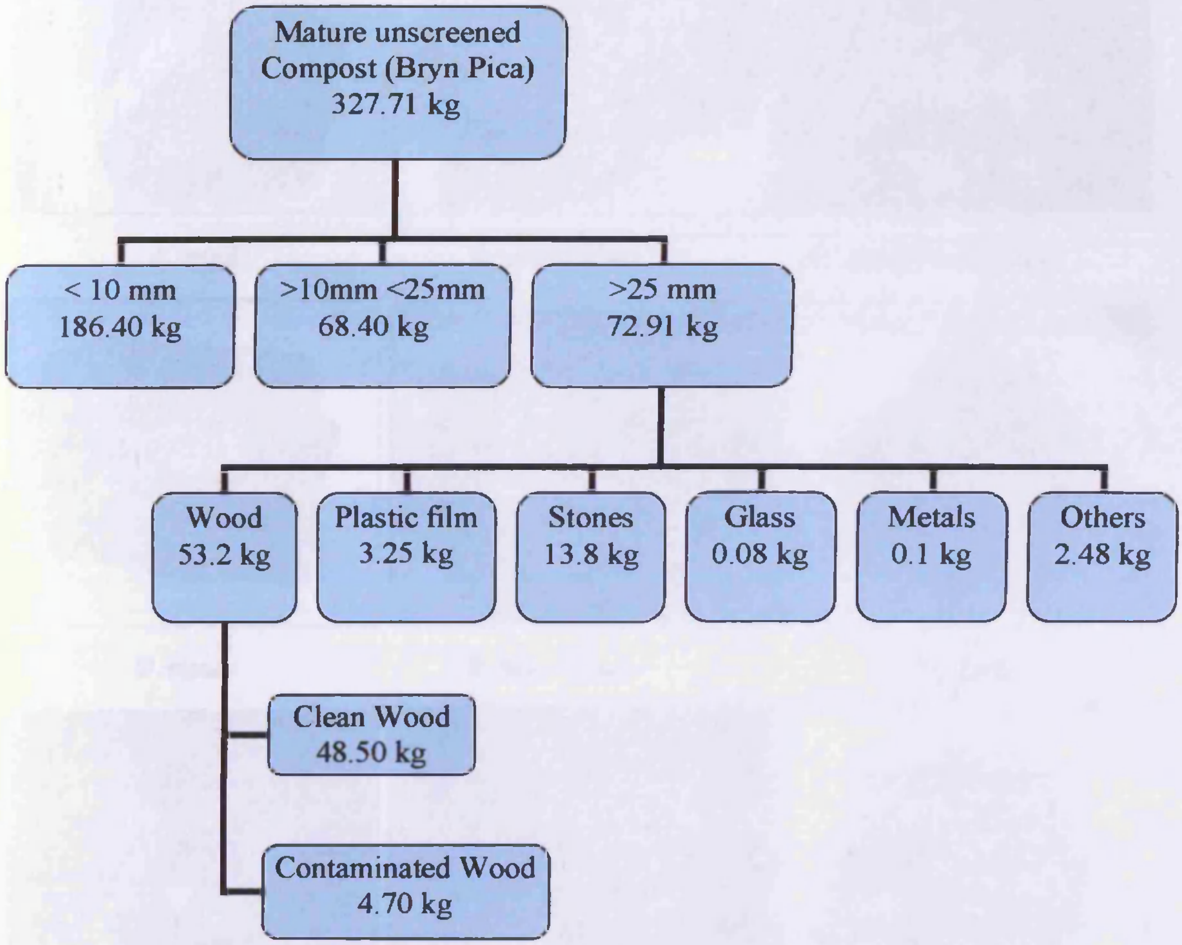


Figure 6.2 Characterisation of Bryn Pica compost sample (as-received) after screening and hand sorted >25 mm physical contaminants

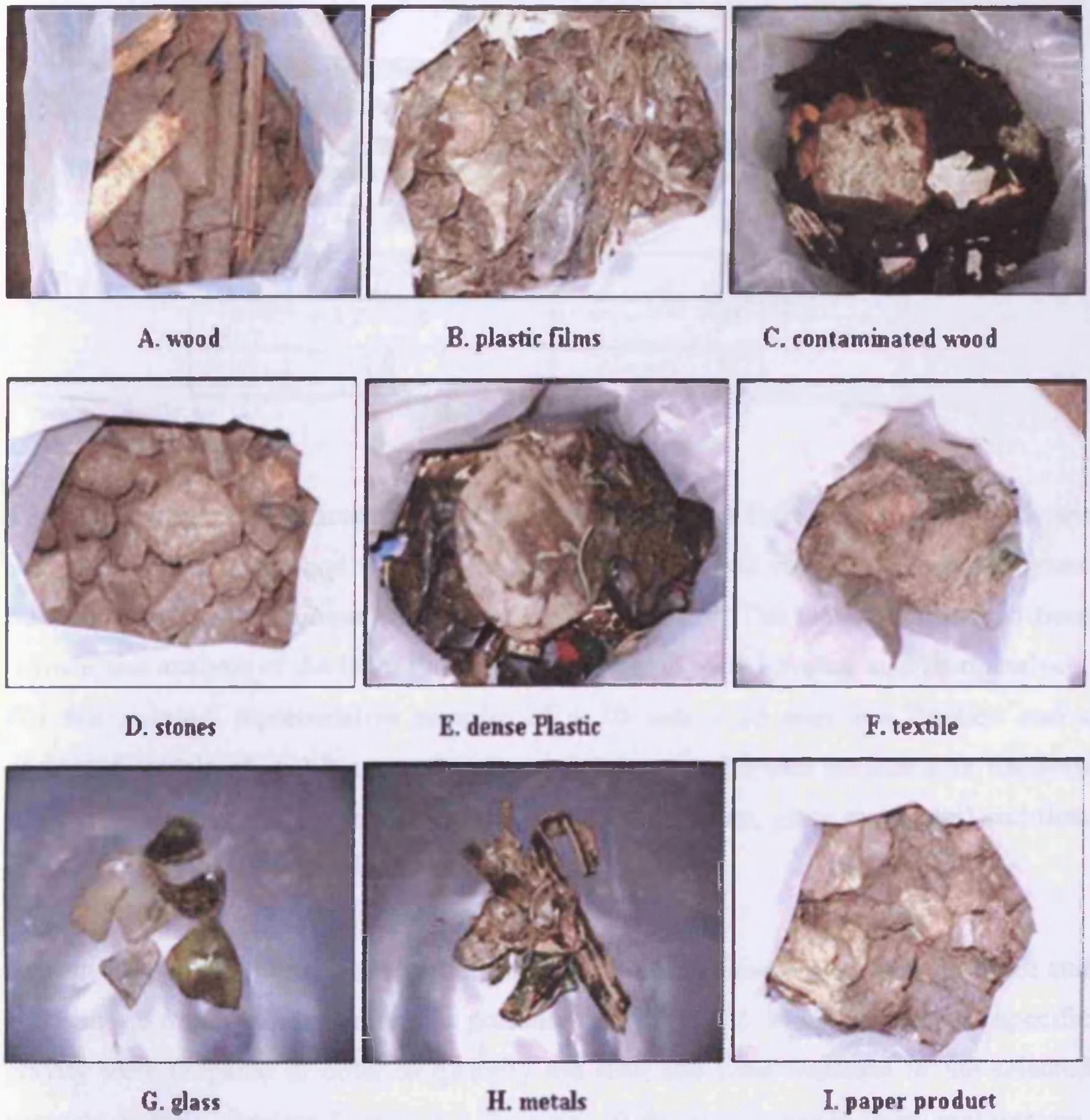


Figure 6.3 Physical contaminants found in >25 mm size fraction of the Byrn Pica sample

The particle size analysis on a dry basis of the <10 mm fraction of the Bryn Pica compost sample is shown in Table 6.1.

Table 6.1 Size distribution (dry sieving) of <10 mm fraction of the Bryn Pica compost sample

Size distribution (mm)	Weight fraction (%, m/m)
+ 5.6	15
+ 2.8 – 5.6	31
+ 1.0 – 2.8	37
– 1.0	17

To identify physical contaminants, the traditional sink and float method was used (see Section 3.5.1). This method is normally used in the mineral industry to separate sized fractions into separate components on the basis of density. The materials obtained from particle size analysis of the Bryn Pica compost were subjected to sink and float analysis. For this purpose, representative samples of + 10 mm – 25 mm size fraction and a combined sample of + 2.8 mm – 5.6 mm and + 1mm – 2.8 mm particle size fractions were utilised in order to determine the quantity of sink (stone, glass and metal) and float (plastics, wood and contaminated wood).

The analysis on the quantity of sink and float for the particle size + 10 mm – 25 mm and + 1 mm – 5.6 mm of the compost is presented in Table 6.2. Media of varying specific gravity were prepared in order to quantify the sink and float fractions in the selected compost particle size (see Section 3.5.1). It was difficult to quantify each contaminant, therefore it was assumed that wood and plastic films falls in float range. Similarly stone, metal and glass were collected as a sink fraction. The percentage weight of materials floated (wood, plastic film etc) in + 10 mm – 25 mm size fraction, when immersed in specific gravity 0.8, 0.8-1.0, 1.0-1.2 and 1.2-1.4 liquids were 24%, 13%, 7% and 1% respectively. Similarly material floated in the particle size range of + 1 mm – 5.6 mm were 4%, 6%, 21% and 1% for the same specific gravity range. The total quantity of material observed as sink fraction (stones, glass and metal) in all four specific gravity liquids were 55 % for + 10 mm – 25 mm size and 68% for + 1 mm – 5.6 mm size fractions.

Table 6.2 Preliminary Sink and Float analysis of compost sample

Particle Size Range	Float (%, m/m)				Sink (%, m/m)
	SG 0.8	SG 0.8 - 1.0	SG 1.0 - 1.2	SG 1.2 - 1.4	
+ 10 mm - 25 mm	24	13	7	1	55
+ 1 mm - 5.6 mm	4	6	21	1	68

6.2.1.1 Conclusions

The characterisation study on Bryn Pica compost showed that:

- The significant quantity of + 25 mm wood material (16%) and plastic films (1%) observed during the screening analysis was due to feedstocks utilised i.e. park waste and the kerbside collection, to manufacture the compost.

- The quantity of materials found as sink fraction were 55% and 68%, while 45% and 32% materials were determined as float fraction for the particle size ranges of + 10 mm – 25 mm and + 1mm – 5.6 mm, respectively. However, it was difficult to quantify each contaminant (stones, metals, glass, wood, and plastic film) by using the sink and float technique.

6.2.2 LABORATORY SEPARATION BY AIR CLASSIFICATION

The laboratory trial was undertaken using an air separation test rig to ascertain the removal of elements of the standardised mix of contaminants. The design and setup of the test rig was described in Section 3.6.1.2. The feed used in the air separation test rig was made up of 5 kg (<10 mm, particle size) CERT compost and a total of 2 kg of the standardised contaminants, characteristics of which are described in Section 3.6.1.1. The moisture content of the compost utilised during the laboratory trial was within the range of 36-38%.

Figure 6.4 shows the proportion of compost and different contaminants removed in the air stream at varying velocities in the air separation test rig. As described in Section 3.6.1.2, the air velocities were determined using a Pitot-static tube and Air Flow's Development TA-5 thermal anemometer. It was found that the velocities determined using both the instruments were within ± 10%, therefore air velocities used during the laboratory trial were an average of readings taken by both the instruments (see Appendix A).

It can be seen in Figure 6.4 that at air velocities from 1.70 m/s to 4.24 m/s plastic film and compost were the only materials removed in the air stream. At the lowest velocity (1.70 m/s), 73% of the plastic film and 22% of the compost were removed. This removal rate increased to 87% of plastic film and 45% of compost at 2.67 m/s, 100% of the plastic film and 73% of compost at 4.24 m/s and at the maximum velocity of 5.90 m/s, 83% of the compost was removed. At a velocity of 4.74 m/s, 28% of 2 mm thick rigid plastics (square shape) were removed, as were 58% of 0.55 mm thick square shapes of aluminium. These proportions increased to 91% for the 2 mm thick rigid plastic and 93% for the 0.5 mm thick aluminium when the air velocity was 5.90 m/s. whereas, rigid plastic of 3 mm and 4 mm thickness, stones, ferrous metals were not removed in the air stream at any of the tested air flow rates.

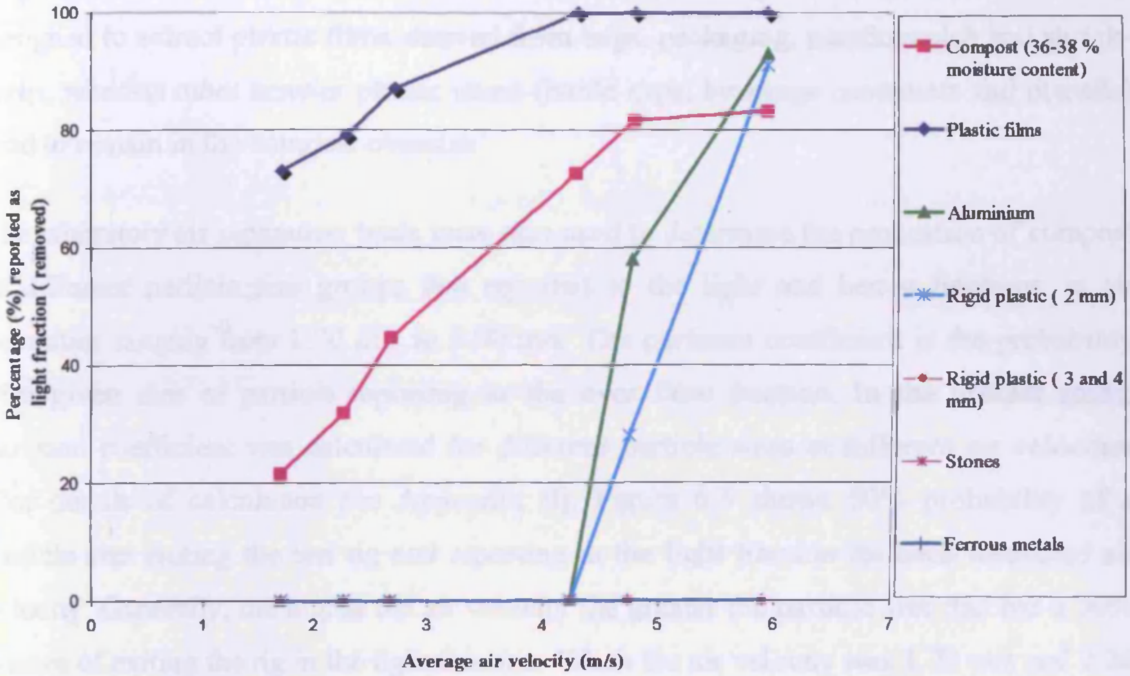


Figure 6.4 Proportion of compost and different contaminants removed in the air stream at varying velocities in the air separation test rig

The results presented in Figure 6.4 demonstrated that by using a simple air separation system a large proportion of the <10 mm screened compost was also removed in the air stream at velocities that removed 100% of the plastic film contaminants. It is likely that the moisture content of 36-38% may have influenced the proportion of compost removed in the air stream. Savage et al. (2005) reported that at present there is no air separation technology available in the market that can reliably separate plastic films from finished compost product. The reason for this is that the density and aerodynamics of the plastic and compost particles (small and dry) are too similar for practical separation. This is why most of the air separation machines on the market are designed to remove light contaminants from the oversize fraction rather than the product fraction, as a large portion of the compost fines would be removed along with the light contaminants. Rynk (2001) suggested that air separation should be typically applied to the oversize fraction from screening since it contains large pieces of wood, stones and other high-density contaminants, which are simpler to separate from plastics especially plastic films (due to large difference in terminal velocities). However, air separation systems are mainly designed to extract plastic films derived from bags, packaging, plastic mulch and shrink-wrap, whereas other heavier plastic items (bottle caps, beverage containers and utensils) tend to remain in the compost oversize.

The laboratory air separation trials were also used to determine the proportion of compost of different particle size groups that reported to the light and heavy fractions, at air velocities ranging from 1.70 m/s to 5.90 m/s. The partition coefficient is the probability of a given size of particle reporting to the over flow fraction. In the present study, partition coefficient was calculated for different particle sizes at different air velocities (For details of calculation see Appendix B). Figure 6.5 shows 50% probability of a particle size exiting the test rig and reporting to the light fraction for each measured air velocity. Generally, the higher the air velocity the greater the particle size that has a 50% chance of exiting the rig in the light fraction. When the air velocity was 1.70 m/s and 2.26 m/s, the particle size with a 50% chance of exiting in the light fraction was 1.10 mm and 1.23 mm respectively, while at air velocities 2.67 m/s, the particle size reduced to 1.12 mm. This would have occurred due to a slightly higher moisture content (36-38%) of the compost sample, which caused the smaller particle size (1.12 mm) of the compost to report to the lighter fraction. It can be seen in Table 6.3, when air velocity was increased to 4.24, 4.74 and 5.90 m/s, the particle size increased to 1.40, 1.50 and 1.82 mm respectively.

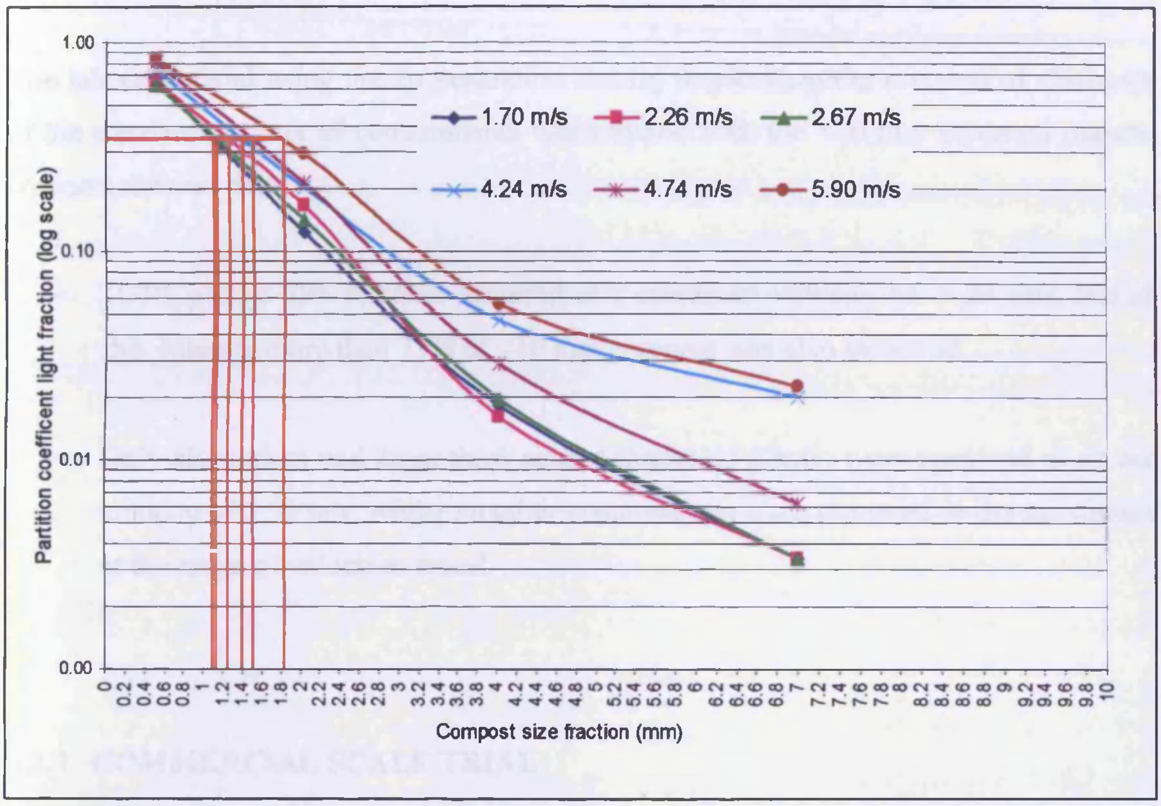


Figure 6.5 Probability of a particle size exiting the test rig in the light fraction, the particle size that has a 0.5 probability of exiting in the light fraction is shown for each measured air velocity (Y-axis is on logarithmic scale)

Table 6.3 Compost particle size with a 50% chance of exiting the test rig in the light fraction, at a range of different air velocities

Air Velocity (m/s)	1.70	2.26	2.67	4.24	4.74	5.90
Particle size (mm)	1.10	1.23	1.12	1.40	1.50	1.82

6.2.2.1 Conclusions

The laboratory trial using the air separation test rig to ascertain the removal of elements of the standardised mix of contaminants when mixed with the <10 mm screened mature compost showed that:

- 100% plastic film removal occurred at a minimum velocity of 4.24 m/s, but at this velocity more than 73% of <10 mm compost was also removed.
- Only aluminium and 2mm thick square shapes of plastic were removed at an air velocity of 5.90 m/s, whilst no other contaminants were removed in the air stream at the range of velocities tested.

6.2.3 COMMERCIAL SCALE TRIAL

As discussed previously, in Section 3.6.1.3, the CERT composting facility has a "Terra Select T4" trommel screen and "Komptech Hurrikan" windsifter (see Figures 3.20 and 3.21), to manufacture different grades of compost and to remove contaminants from the oversize fraction, respectively. The Komptech Hurrikan has been specifically designed to remove light material (plastic film), ferrous metals and large stones from compost oversize. A sample of unscreened compost was characterised and results obtained were used to determine the efficiency of these machines in removing contaminants from the >25 mm fraction.

6.2.3.1 Initial Characterisation

A sample of unscreened composted product weighing 10,500 kg was mixed and piled inside the CERT building. Representative sub-samples (total of 297.93 kg) were obtained using the classical cone and quartering technique for initial characterisation by hand sorting as described in Section 3.4.1.3. The 297.93 kg of sample contained 291.6 kg of biodegradables and 6.33 kg of total contaminants, being 97.8 % and 2.1 % of the total sample, respectively. Of the contaminants, 3.02 kg (48%) were light materials, 2.46 kg (39%) were stone and glass, 0.31 kg (5 %) were metals and those materials classified as others, weighed 0.54 kg (9 %), as detailed in Figure 6.6.

After washing, the light fraction had reduced to 1.95 kg, indicating that 1.07 kg (35%) of the unwashed light fraction was compost that had adhered to the light contaminants. Of the washed light components, 1.44 kg (74%) was >25 mm, and 0.51 kg (26%) passed through the 25 mm sieve. The stone and glass fraction contained only 0.19 kg (8%) of adhered compost. Of the remaining stones and glass, 2.15 kg (95%) was <25 mm and 0.12 kg (5%) was >25 mm. Of the 0.31 kg of metal contaminants, 0.04 kg (13%) was compost and of the remaining cleaned fraction amounting to 0.28 kg, 0.25 kg (89%) was >25 mm and 0.03 kg was <25 mm. The 'others' sample was made up of 0.1 kg (19%) adhered compost and of the cleaned sample 0.31 kg (70%) was >25 mm. Photographs of contaminants are presented in Figure 6.7.

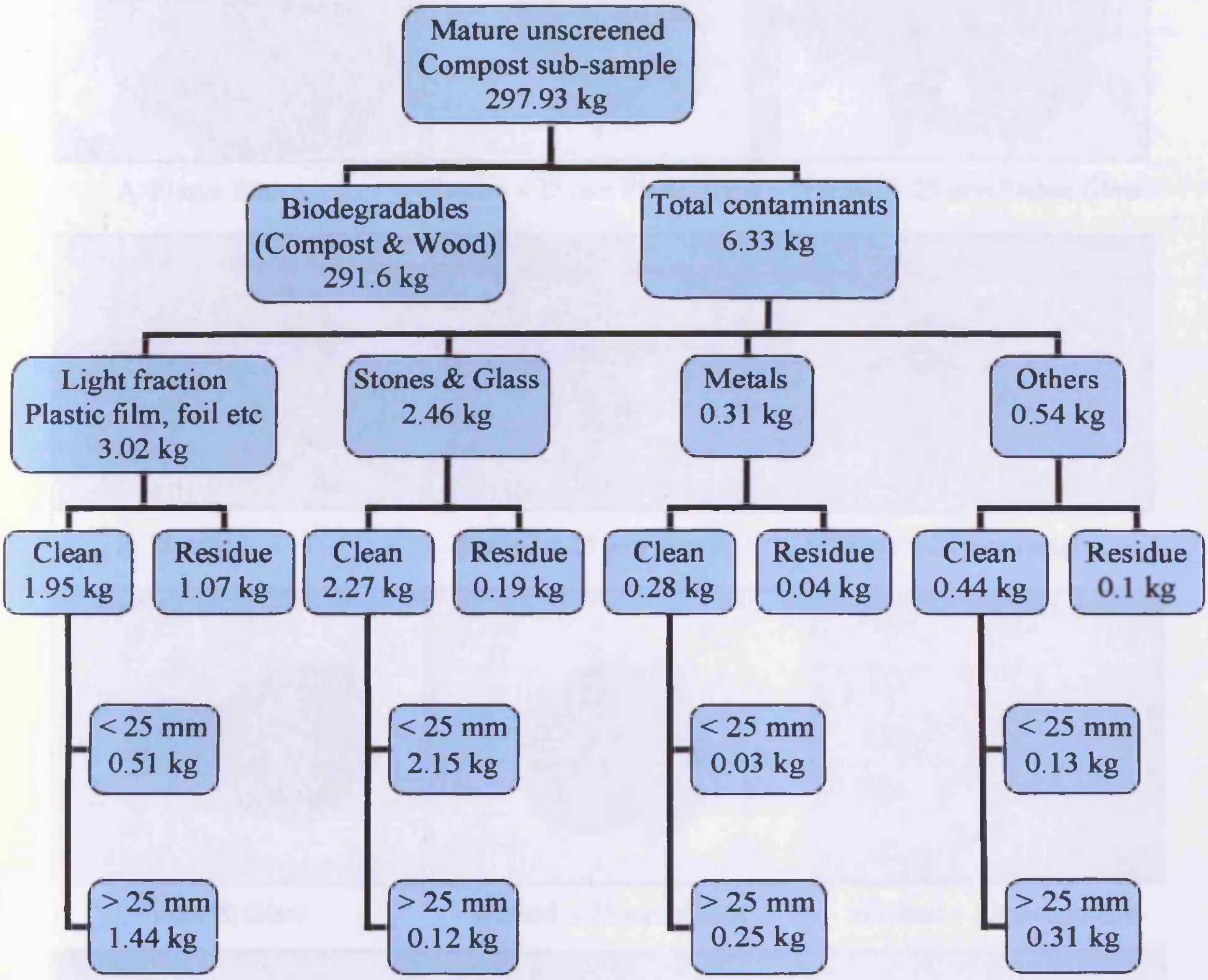


Figure 6.6 Characterisation of the hand sorted sub sample of unscreened CERT compost

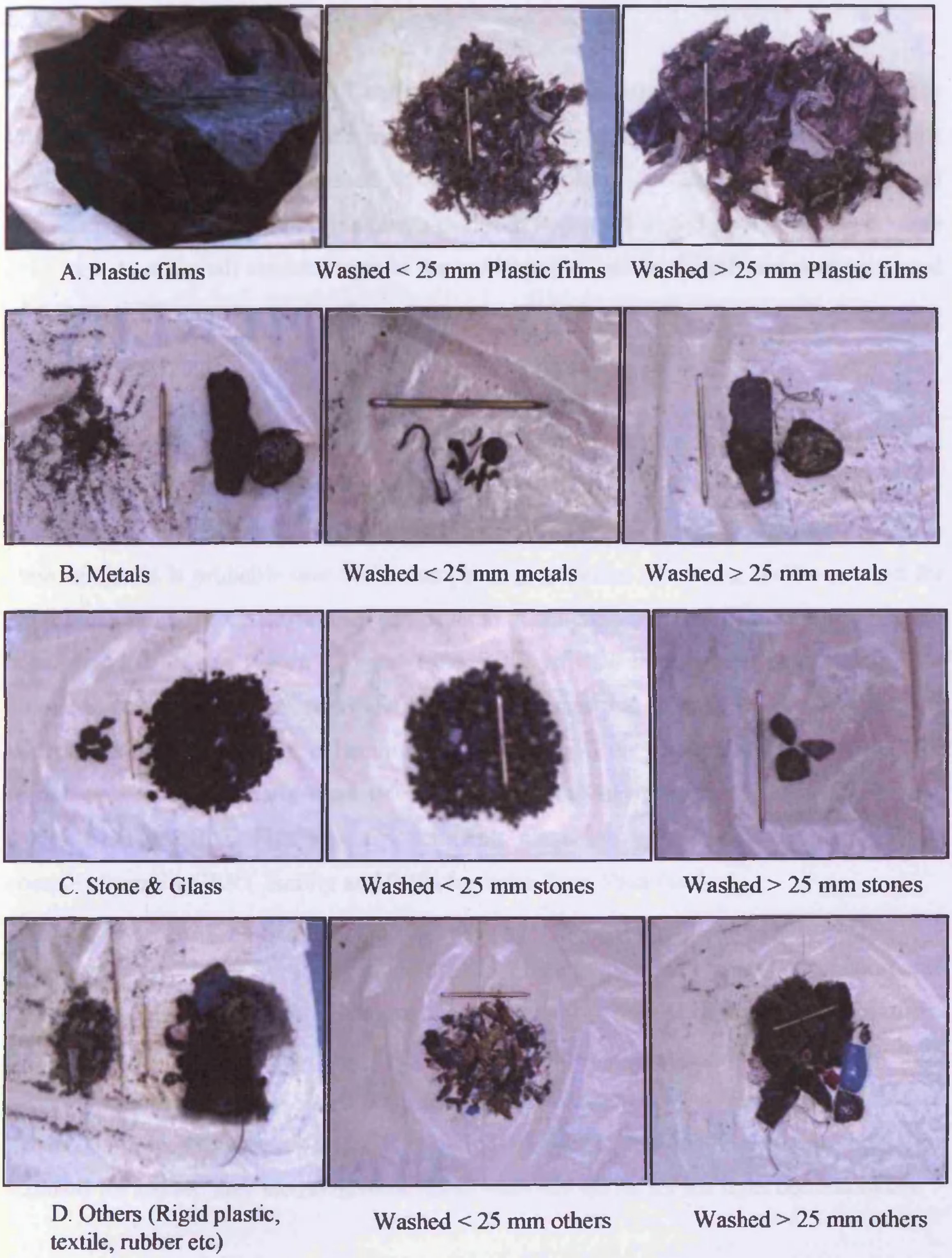


Figure 6.7 Photographs of light, metal, stone and other contaminants before and after washing, and the proportion less than and greater than 25 mm

6.2.3.2 Comparison with Compost from Bryn Pica

Bryn pica compost and the CERT compost were different from each other, mainly due to the feedstock utilised, equipments and the methods employed to manufacture the two (for details see Table 3.3). As discussed previously in Section 6.2.1, approximately one-third of a tonne of compost sample from Bryn pica that was hand sorted contained 6% coarser (>25 mm, as-received) contaminants of the total sample and the CERT compost consisted of 0.9 % (>25 mm, as-received) contaminants of the material examined (see Section 6.2.3.1).

The greater mass of contaminants found in compost from the Bryn Pica facility was mainly due to the greater mass of stones at 4.2% (see Figure 6.2), when compared to the 0.04% found in the compost from the CERT facility (see Figure 6.6). The difference in mass of stones is probably due to the composting operation occurring on the ground for Bryn Pica, while the CERT facility composts on a concrete surface. Light materials were 0.48% for CERT (see Figure 6.6) and 1.0% for Bryn Pica facility (see Figure 6.2). The greater mass of plastic films observed for Bryn Pica was due to the type of collection i.e. kerb side collection whereas, collection was mainly via Civic Amenity sites for the CERT composting facility. Metals were 0.08% for the compost from the CERT facility and 0.03% from the Bryn Pica site. Contaminants classified as others were 0.1% of the compost from the CERT facility and 0.4% from the Bryn Pica facility.

Stones are arguably the least visible and are more acceptable in compost, when compared to the other contaminants classification, though there is still a maximum allowance of 8% for stones >4 mm in the BSI PAS 100:2005 for composts. The limit for light contaminants in the BSI PAS 100:2005 standard is < 0.25% m/m of air dried sample (see Table 2.1). These results indicate that although composts from both sites would pass the standard for stones, they would have failed to meet the limits set for light contaminants.

6.2.3.3 Efficiency of Contaminants Removal Using a "Terra Select" Trommel Fitted with a 25 mm Screen and a "Komptech Hurrikan" Wind Sifter

The level of contaminants in the organic waste delivered to composting facilities is dependent upon a number of factors. The contaminants level in green waste that originated from civic amenity sites is dependent upon the operators at the site, whilst that coming from kerbside collections, from either households or commercial properties, is dependent upon how vigorous the collected waste is inspected and that the waste acceptance requirements are enforced. Even the best managed collections cannot remove all contaminants.

Figure 3.20 shows the Terra Select T4 trommel screen used during the commercial scale trial. Footage of the commercial scale trial is also available as Video 1 (see Appendix C). The 10,500 kg sample of unscreened compost was fed into the screen over a period of approximately 30 minutes and the compost had a moisture content of 56% (m/m). It is interesting to note that Spencer (2003) suggested that, regardless of the screen type, materials having moisture contents above the range of 40-45% do not separate as cleanly as drier materials. In the present study, the moisture content (56%, m/m) of compost sample did not appear to have any negative effect on the separation efficiency (see Section 6.2.3.6, Table 6.6). A report published by Entec (2004) documented that the screens (trommel and star) can operate over a range of moisture contents. However, high moisture content decreases the throughput rate and reduces the separation effectiveness.

It was shown in Figure 3.20 that 8684 kg of (83%) of the compost passed through the 25 mm screen (undersize) and, therefore, was not processed by the air separator, leaving 1816 kg (17%) that was >25 mm (over size) and was delivered to the separator via the trommel screen's oversize conveyor belt. Of the >25 mm material fed into the separator, 1548.6 kg was in the compost oversize, 46.8 kg reported to the light fraction, 42.8 kg in the stone trap and 178 kg in the metal trap. Each of these fractions was hand sorted to separate the material that was designed to be in each fraction, from that material that was not designed to be captured. Each sub fraction was then weighed and the light, stone and metal fractions were washed and weighed to determine the mass of adhered compost.

The 1548.6 kg oversize sample following hand sorting was split into 1520 kg of compost (being 98% of the total) and 28.55 kg (2%) of contaminants. The contaminants (as-received) were further split into light, stone, metal and others and were then washed to remove adhered compost. The mass of each fraction is shown in Figure 6.8.

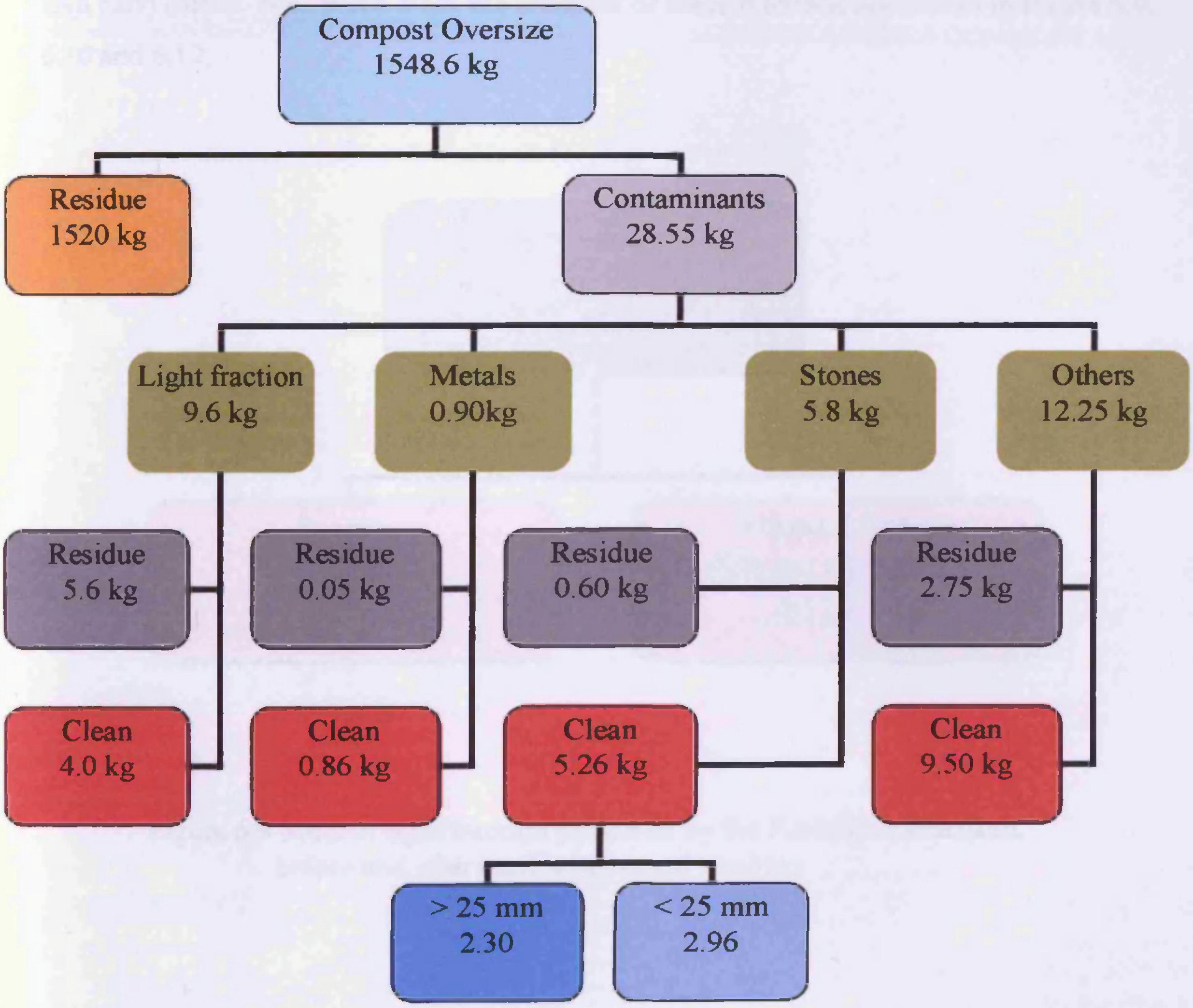


Figure 6.8 Contaminants found in the oversize fraction after passing through the "Komptech Hurrikan" air separator, before and after washing

After washing, the light fraction had reduced to 4.0 kg, indicating that 5.6 kg (58%) of the unwashed light fraction was compost that had adhered to the light contaminants. Of the 0.90 kg of metal contaminants, 0.05 kg (5%) was compost and the cleaned fraction amounting to 0.86 kg (95%). The stone and glass fraction contained only 0.60 kg (10%) of adhered compost. Of the remaining cleaned stream, 2.96 kg (56%) was <25 mm and 2.30 kg (44%) was >25 mm. The 'others' sample was made up of 2.75 kg (22%) adhered compost and the cleaned sample was 9.50 kg (78%).

The material in the light, stone and metal trap separated by the "Komptech Hurrikan" was also hand sorted. The results from the analyses of these fractions are shown in Figure 6.9, 6.10 and 6.12.

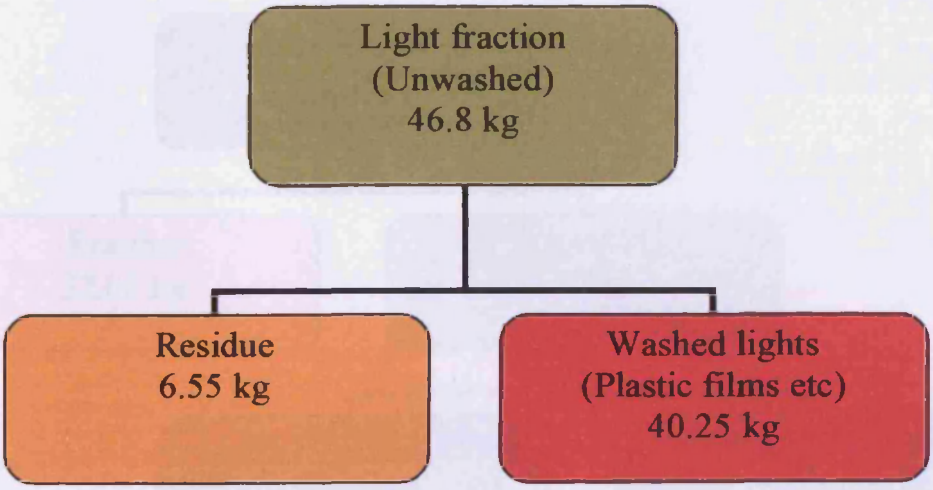


Figure 6.9 Mass of light fraction separated by the Komptech Hurrikan, before and after hand sorting and washing

Figure 6.9 shows the mass of light fraction in over size material separated by the "Komptech Hurrikan". It can be seen that 46.8 kg of the light fraction was separated by the "Komptech Hurrikan" from the oversize fraction, of which 40.25 kg (86%) was clean, while, 6.55 kg (14%) was compost adhered to the light fraction.

Figure 6.10 shows that 42.80 kg of material was collected in the stone trap. After hand sorting, it comprised of 37.60 kg (88%) of residue (mainly >25 mm wood) and 5.20 kg (12%) of stones. After washing, the stone fraction was reduced to 4.94 kg, comprising 2.69 kg (54%) of >25 mm and 2.25 kg (45.5%) of <25 mm stones (see Figure 6.11), whereas 0.26 kg (5%) of compost was adhered to unwashed stones.

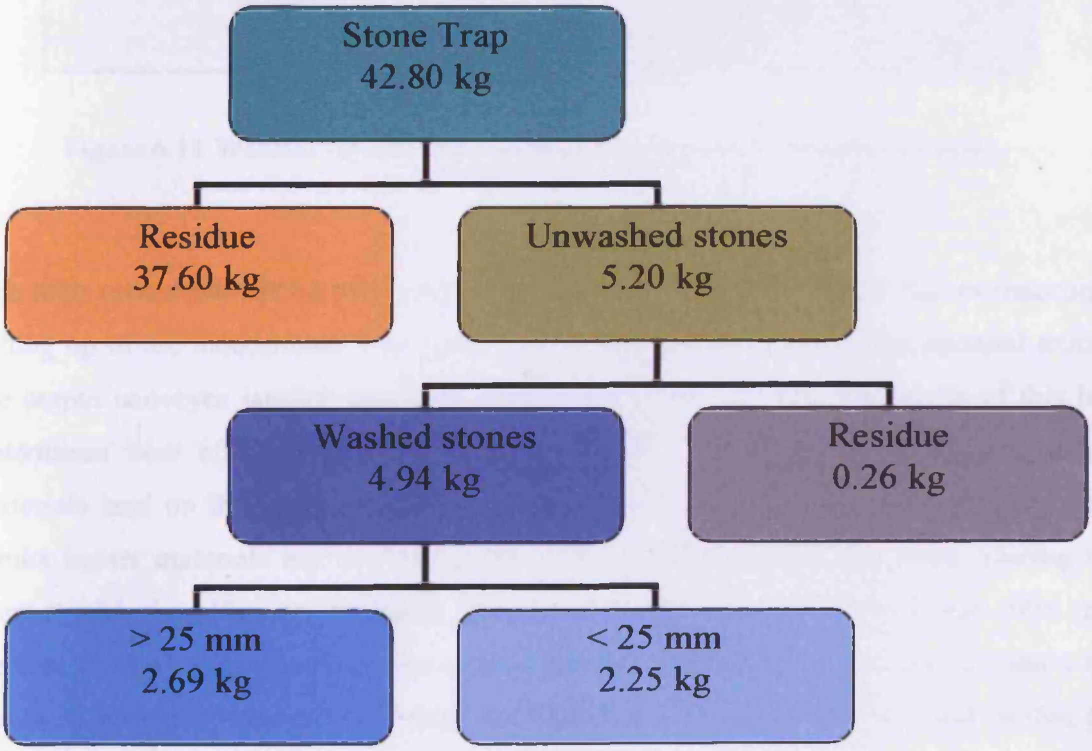


Figure 6.10 Mass of stone fraction separated by the Komptech Hurrikan, before and after hand sorting and washing

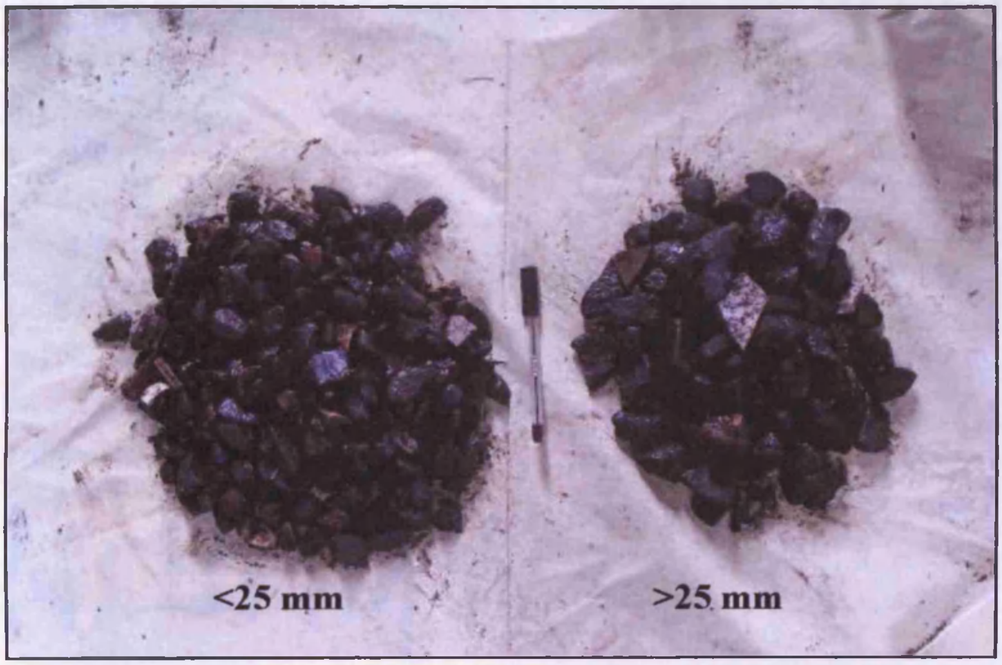


Figure 6.11 Washed stones collected in the stone trap (<25 and >25 mm)

The high proportion (88%) of residue in the stone trap is likely to be due to inaccurate setting up of the mechanism. The stone trap mechanism operates by the material exiting the output conveyor landing on a fast moving smooth conveyor. The angle of this belt determines how effective it is in removing stones. When dense or large spherical materials land on this conveyor, they fall back down the conveyor into the stone trap, whilst lighter materials are carried up the conveyor to the discharge point. During the current trial, the efficiency of stone removal from the oversize fraction was 48% (see Section 6.2.3.6). The machine was new to the facility and, therefore, the operators did not have the experience to know what the optimum angle was, so it is possible that the stone trap could operate more efficiently.

Figure 6.12 shows quantity of metal fraction separated by the "Komptech Hurrikan". It can bee seen that 178 kg of material was collected in the metal trap. After hand sorting, 174.4 kg (98%) of residue and 3.6 kg (2%) of metal were found. Of this 3.4 kg (94%) was clean metal (see Figure 6.13), while 0.2 kg (5.5%) of compost was adhered to the metal fraction.

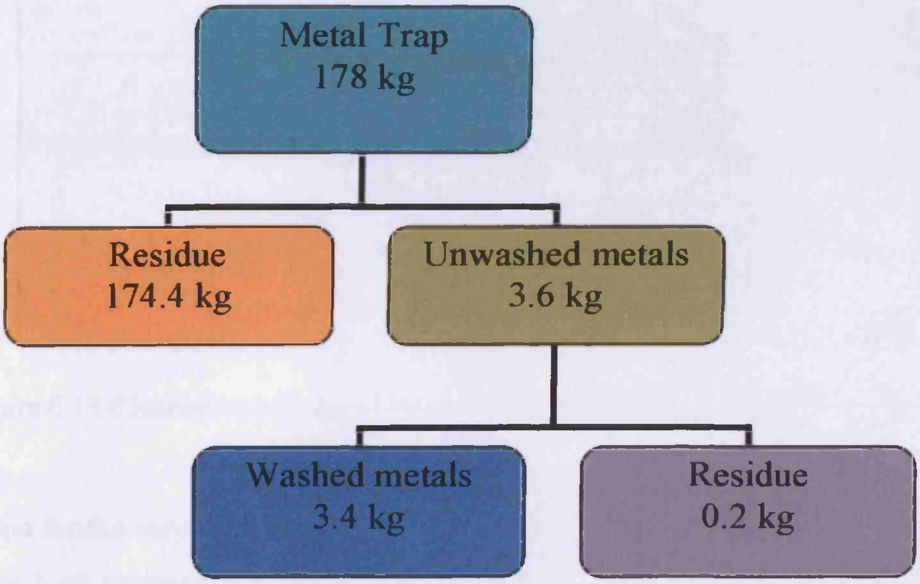


Figure 6.12 Mass of metal fraction separated by the Komptech Hurrikan, before and after hand sorting and washing

Figure 6.13 Cleaned metals found in the metal trap of "Komptech Hurrikan"

The reason for the very high proportion of residue (98%) in the metals trap was partially due to the high moisture content of the compost being screened and the heavy rainfall during screening (see Video 1, Appendix C). The metal trap operates on the output conveyor, the top roller of which is magnetised. Ferrous metals stay on the conveyor belt as it turns around the top roller, whilst non-ferrous materials are thrown off the end. The ferrous metals then fall from the conveyor belt into the metal trap as it moves away from the top roller. During the current trial, the efficiency of metal removal from the oversize fraction was 80% (see Section 6.2.3.6). The very wet conditions resulted in some compost adhering to the conveyor belt and then dropping into the metal trap. The operators stated that when the machine had been used in dryer conditions, this situation had been much better.

6.2.3.4 Calculation of Total Contaminants in CERT Compost

The total contaminants in a 10,500 kg sample of the unscreened compost from the CERT facility were calculated from hand sorting a 297.30 kg sub sample. The contaminants found in this sub sample are described in Section 6.2.3.1. The mass of contaminants in the total sample were calculated from the mass found in the sub sample and are shown in Table 6.4.

Table 6.4 Predicted total, <25 mm and >25 mm contaminants in a 10,500 kg sample of unscreened compost at the CERT facility, calculated from the characteristics of a 297.3 kg sub-sample

Contaminant	Total (kg)	<25 mm (kg)	>25 mm (kg)
Light fraction	68.86 (40%)	18.11 (18%)	50.75 (68%)
Stones	79.92 (46%)	76.00 (76%)	3.92 (5%)
Metals	9.8 (5%)	0.88 (1%)	8.92 (12%)
Others	15.5 (9%)	4.72 (5%)	10.78 (15%)
Total	174.08	99.71	74.37

6.2.3.5 Predicted Contaminants Compared To Actual

The 297.3 kg sub sample that was hand sorted suggested that the 10,500 kg sample would contain a total of 74.37 kg of clean contaminants in the >25 mm size fraction (see Table 6.4). A total of 68.15 kg of contaminants was found in the >25 mm compost oversize, as demonstrated in Figures 6.8, 6.9, 6.10 and 6.12. The mass of contaminants found in the >25 mm oversize fraction (1816 kg) was 91.6% of that predicted by the initial characterisation test. The difference between the predicted and found mass of each contaminants category is shown in Table 6.5.

Table 6.5 Comparison of predicated and actual lights, stones, metals and other contaminants in the >25 mm fraction

	Light	Stone	Metal	Other
Predicated (kg)	50.75 (74%)	3.92 (5%)	8.92 (91%)	10.78 (70%)
Actual (kg)	44.25 (65%)	10.20 (15%)	4.26 (6%)	9.5 (14%)
Difference (kg)	- 6.50	+ 6.28	+ 4.66	- 1.28
Found as a proportion of predicted	0.87	2.6	0.48	0.88

The light and other contaminants found when compared to predicted, were both slightly less at 0.87 and 0.88 respectively. The mass of stones found was 2.6 times greater than predicted at 10.20 kg, this difference was partially due to a significant portion of stones found in >25 mm fraction being <25 mm (5.21 kg). If these <25 mm stones are removed from the actual mass of stones found in the >25 mm fraction, then the stones >25 mm (4.99 kg) found as a proportion of predicted, changes to 1.3. The <25 mm stones that were found in the >25 mm fraction was mainly due to the compost adhered to the smaller stones, making the whole particle size >25 mm and ensuring it did not pass through the screen. The metals found in the >25 mm fraction was only 0.48 of that predicted at 4.26 kg, this is likely to be partially caused by a large proportion of the mass of >25 mm metals in the hand sorted sub sample being due to one large item (see Figure 6.7B).

The predicted total contaminants <25 mm suggested that approximately 100 kg of contaminants remained in the 25 mm screened compost (see Table 6.4), which is the fraction that would be sold as a product. The majority of this mass was stones, which were predicted to be 76 kg or 76% of the total contaminants in this fraction. The <25 mm fraction was predicted to contain 18.11 kg of light contaminants, 4.72 kg of contaminants categorised as "others" and metals at just 0.88 kg.

The allowance for physical contaminants (non-stones fragment) >2 mm in the BSI PAS 100:2005 standards is < 0.5% m/m of the air dried sample, of which no more than 50% can be plastic (See Table 2.1). The <25 mm compost in this test had a theoretical total mass of these types of contaminants of 23.71 kg or 0.27% of the total undersize fraction (8684 kg), approximately half of the allowed limit. The light materials were 0.21% of the total, which is within the allowable limit of 0.25%. Stones >4 mm have a separate maximum allowance of 8% of the total (in grades other than mulch, see Table 2.1). Stones in this sample weighed 76 kg or 0.88% of the total, well within the maximum allowance. The whole of the 10,500 kg sample would have failed the allowance for plastic prior to screening, as the predicted plastic was 0.65% of the total (see Table 6.4), but it would have passed the allowance for stones and other contaminants.

6.2.3.6 Efficiency of Screening and Separation Technology

When the 10,500 kg sample was passed through the trommel screen with a 25 mm mesh, 83% passed through the screen, leaving 17% as oversize that was passed through the "Komptech Hurrikan". Screening to <25 mm resulted in changes to the contamination rate. These changes are detailed in Table 6.6.

Table 6.6 Predicted contamination rate in the unscreened CERT compost, and in the two fractions resulting from screening the compost to 25mm

CERT Compost	Light	Stones	Metal	Others
Unscreened	0.65%	0.76%	0.09%	0.15%
<25mm	0.21%	0.87%	0.01%	0.05%
>25mm	2.8%	0.22%	0.49%	0.59%

It can be seen in Table 6.6 that the light, metal and 'other' contaminants were reduced in the <25 mm sample when compared to the unscreened compost, from 0.65% to 0.21% for light, from 0.09% to 0.01% for metals and from 0.15% to 0.05% for 'others'. The proportion of stones increased from 0.76% to 0.87%. Therefore, simply screening to 25 mm resulted in 83% of the unscreened compost changing from one that would fail the physical contaminants allowance of the BSI PAS 100:2005 standard, to one that would pass.

The proportion of light, metal and other contaminants in the >25 mm sample was increased in comparison to the unscreened sample. Light contaminants increased from 0.65% to 2.8%, metals from 0.09% to 0.49% and other from 0.15% to 0.59%, whilst, the proportion of stones was reduced from 0.76%, to 0.22%.

The 17% of compost that was >25 mm was passed through the "Komptech Hurrikan" so that contaminants (especially plastic film) could be reduced. Reduction of contaminants in this oversize fraction is required, as this fraction is usually re-shredded and passed through the compost process again. If the contaminants are not removed, there would be an increase in contamination rate over time, which is likely to result in the <25 mm fraction not meeting the physical contaminants requirement by BSI PAS 100:2005.

The oversize fraction from the trommel screen fed into the "Komptech Hurrikan" weighed 1816.15 kg. The majority of this exited the machine in the oversize fraction, amounting to 1548.6 kg or 85% of the total. Following hand sorting of this fraction, it was shown that 19.56 kg (1.3%) was contamination (as received) as shown in Figure 4.38. This contamination was made up of light materials (0.26%), metals (0.06%) stones (0.34%) and others (0.61%). The total mass of each contaminant entering the "Komptech Hurrikan" was found from the hand sorting of each fraction exiting the separator, as shown in Figures 6.8, 6.9, 6.10 and 6.12. The total mass of each contaminant category entering the separator, minus the mass found in each separated fraction describes the efficiency of the machine in removing the contaminants from the oversize fraction.

Figure 6.14 Total contaminants (foreground), <25 mm fraction (right) and >25 mm fraction (left).

As shown in Figure 6.8 and 6.9, the mass of light contaminants entering the machine (clean) was 40.25 kg and 4 kg remained in the oversize, giving a removal efficiency of 91%. The efficiency of metal removal from the oversize fraction was 80%, and for stone 48%. The contaminants in the 'others' category remained in the oversize fraction.

Compost material was also separated into light, metal and stone fractions. The addition of compost to the separated contaminants will increase the cost of disposal of these materials, or may affect the suitability of these contaminants for recycling. In this case, 14% of the separated light fraction was compost, 88% of material in the stone trap was compost and 98.1% of the material in the metal trap was compost.

6.2.3.7 Conclusions

During the commercial scale trial, it was demonstrated that the removal of contaminants from the composted product was effectively undertaken by particle size separation. Results showed that:

- Screening to <25 mm resulted in compost meeting the physical contaminants requirements of the BSI PAS100:2005.

- The oversize fraction (>25 mm) amounted to 17% of the total, which was made up of 2.4% light, 0.27% of stones (>25 mm), 0.23% of metal and 0.52% of other contaminants. The remaining 96.5% of the oversize was made up of (composted) organic matter, which was mainly wood.

- The <25 mm compost had a theoretical total mass of light, metals and 'other' contaminants of 23.71 kg or 0.27% of the total (8684 kg), approximately half of the allowed limit. The light materials were 0.21% of the total, which is within the allowable limit of 0.25%. Stones <25 mm were 0.88%, well below the limit required by the BSI PAS100: 2005 standard.

- 91% of the light fraction, 80% of the metals and 48% of the stones were removed from the compost oversize by the "Komptech Hurrikan". The oversize after passing through the wind sifter was more than 98% (composted) wood.

- There is no evident technology that would be capable of removing 'others' (textiles, rubber, rigid plastic etc) from the compost oversize, so it may continue to be a problematic contamination type.

6.2.4 THE AIR JIG TRIAL

6.2.4.1 Introduction

The separation technology discussed in Sections 6.2.2 and 6.2.3 proved to be less suitable for removing high density contaminants such as stones, glass and rigid plastic from the <25 mm fraction, as a large proportion of the fine compost particles can also be removed by the technology used to remove the light contaminants.

If stones >4 mm make up more than 8% of the compost product, it will result in a failure to comply with the physical contaminants requirement of the BSI PAS 100:2005 standard (see Table 2.1). Stones in composted product are not visually obtrusive, but the occurrence of the glass particles can be a visual and safety concern to the users of the composted products. The quantity of glass that can be found in composts produced from non-source segregated feedstocks can be a barrier to its uses. Therefore, technology that can remove small dense contaminants from composted product would be a valuable addition to the organic waste recycling industry.

6.2.4.2 Results

As discussed previously in Section 3.4.2, a laboratory air jig was utilised to separate dense contaminants from the compost (see Figure 3.22). The scope of this initial test was to determine if an air jig would operate effectively on a composted material. For this reason, results were not quantified. However, the jigging cycle was monitored using a digital camera, which was able to capture pictures every two seconds. Footage of the air jig trial is also available as Video 2 (see Appendix C). A sample of coloured stones (2 mm to 10 mm, particle size) was mixed with a sample of <10 mm screened CERT compost with a moisture content of 37% (see Section 3.6.2.2, Figure 3.25a).

The air jig was operated for 114 seconds with a series of air pluses at 0.5 second intervals at high velocity (39 m/s) to the base of a column containing the compost sample. Figure 6.15 shows the progress of the jigging separation after every 6 seconds until the desired separation was achieved (114 sec). It is clear from the photographs that the dense particles can be effectively separated from the less dense compost in a short span of time. However, it is likely that the moisture content of 37% may have influenced the separation of compost from high-density materials. Clearly, further work is required to test the viability of this technology in the composting industry.

In a large-scale system, the materials would be separated while travelling along a stationary or vibrating bed. The materials having different densities are then separated by a weir type system that allows the dense particles to fall below the weir, whilst the light materials move over the weir and are deposited separately. This technology has been extensively practiced in coal preparation, mineral processing and separation of other solid materials. At present, there is little knowledge about the use of the jigging process for separation of waste materials. De-jong and Fabrizi (2004) reported that Allmineral (German-based, commercial-scale air jig manufacturer) and Aachen Technical University in Germany designed and utilised “Allair” jig to separate a mixed feed of construction and demolition waste (stones, bricks, tiles, glass, metal, wood, bitumen, textile, polystyrene, plastic, paper and dust). The feed size ranged from 5 mm to 40 mm. They claimed that this device can efficiently separate lower-density particles from higher-density particles and suggested that the “Allair” jig is a compact design with high processing capacity (50 tonnes h^{-1}) and can separate a wide range of feed materials.

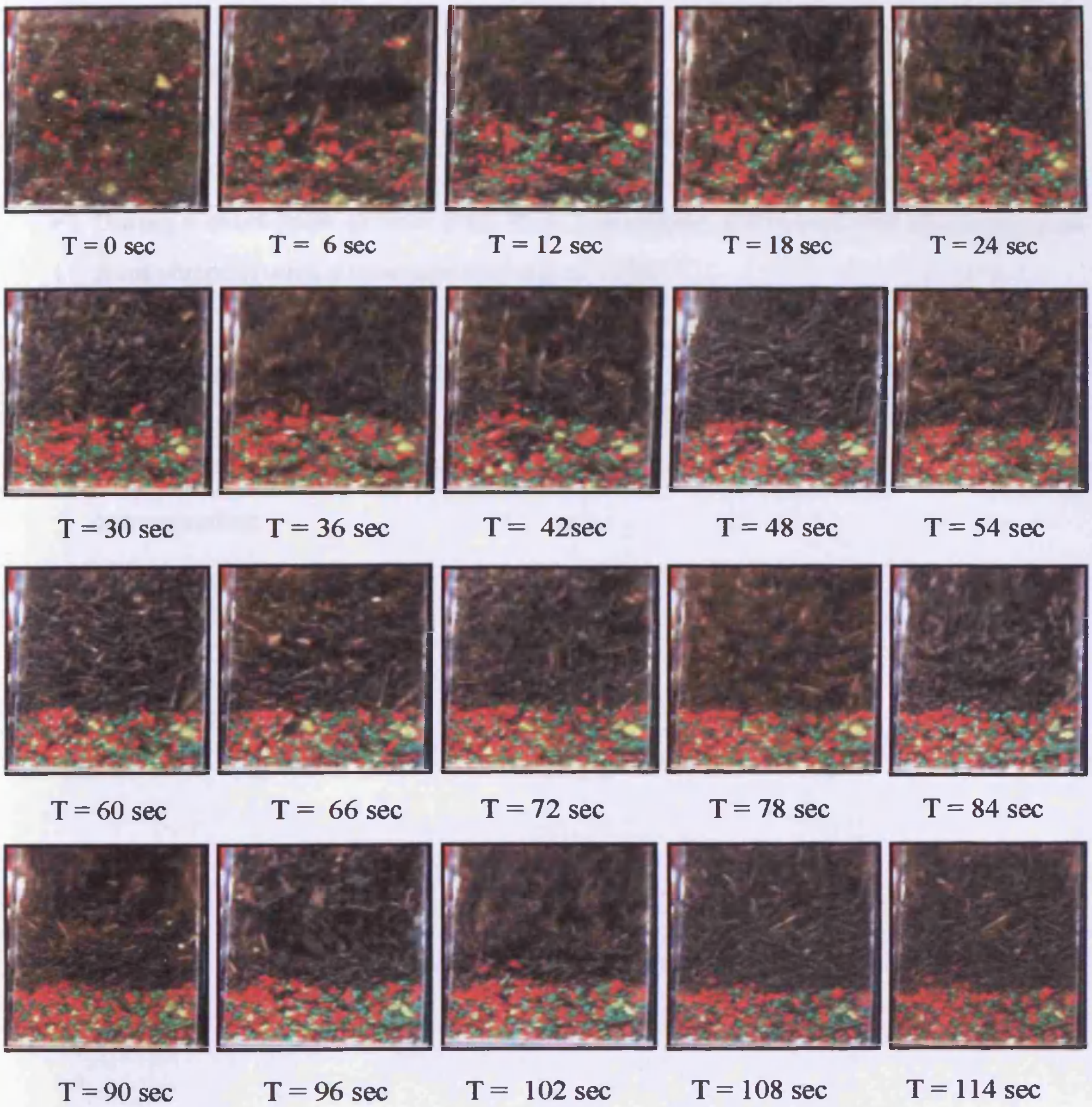


Figure 6.15 Compost and stone mix in the test rig, Photographs of jigging cycle after every 6 second

6.2.4.3 Conclusions

- The air jig proved to be an efficient method for the separation of high-density contaminants such as stones, glass and rigid plastic from less dense compost.

- During a short span of time (less than 2 minutes), dense particles were separated from compost with a moisture content of 37%.

- It is possible that with further examination the air jig method may prove a suitable solution for the removal of smaller particles of stones, glass and other high-density contaminants from composted products with acceptable levels of contamination.

CHAPTER 7 CONCLUSION AND RECOMMENDATIONS

7.1 THE VERMICOMPOSTING TRIAL

A vermicomposting trial was conducted for a period of 18 weeks by utilising re-hydrated (60%, m/m moisture content) mature green-waste compost as a feedstock. This was performed to investigate the extent to which vermicomposting and the traditional windrow composting of green waste might be combined in order to enhance the value of the final product. It was found that key parameters for controlling the vermicomposting process, such as temperature, pH, electrical conductivity and redox potential, remained within the recommended range for efficient vermicomposting. An average mass throughput of 32.6 kg m^{-2} $week^{-1}$ was used over the entire trial period. A minimum average compost mass reduction of 16% was observed and the overall earthworm biomass was reduced from an initial average value of 7 kg/m^2 to 1.3 kg/m^2, suggesting that the earthworm population was not sustained by utilising mature green waste as a feedstock. In addition to this, results obtained showed that there was a significant reduction in the volatile solid content only during the initial stages of the vermicomposting process and no obvious reduction in volatile solids was observed towards the end of the trial. Chemical analyses were also performed on representative samples of the feedstock and cast materials, and these showed that there was no significant increase in the concentrations of the total and bio-available heavy metals or nutrients after the vermicomposting process, with exception of Zn. However, the concentrations of all heavy metals were within the maximum limits defined by the Composting Association, UK PAS 100:2005 standard.

7.2 GROWTH TRIALS

7.2.1 CORIANDER AND TOMATO

Replicated growth trials on coriander and tomato were conducted using two commercially available multipurpose composts and five waste-derived composts. This work was performed with the objective of demonstrating that waste-derived products could perform in a similar manner to the classical growth media. It was found that the commercially available peat-based composts (composts A and D) showed higher seed germination rates and plant biomass than those grown on waste-derived composts. There were significant differences in plant height, size and colour of the leaves and overall health of the plants grown in various waste-derived composts. Retarded plant growth was observed for waste-derived composts B and C, when compared to CERT compost and vermicompost. Results showed that this poor plant growth was attributed to nitrogen deficiency in composts B and C or unidentified biological factors other than the availability of nutrients such as phosphorus and potassium.

7.2.2 LETTUCE

Replicated plant growth trials were undertaken with lettuce using pure worm cast (product of vermicomposting trial), green waste-derived compost and mixtures of the two i.e. 50/50 (v/v) and 20/80 (v/v) of worm casts and green waste feedstock. Results showed that plant biomass production was optimal with a 20/80 (v/v) compost blend, whilst pure worm cast and green waste compost yielded poor plant growth. Leaf chlorophyll content indicated that pure worm cast inhibited plant growth and depressed N content, whereas plants grown with the other treatments contained a similar amount of chlorophyll. It was found that pure vermicompost contained more humic acid (12%) than the feedstock, but both showed almost similar plant growth. In general, the vermicomposting process did not result in an increased availability of nutrients or potentially toxic elements, the only exception being Zn.

7.3 COMPOST CONTAMINANT CHARACTERISATION

7.3.1 INITIAL TRIAL

The initial phase of the characterisation study involved the collection and screening analysis of one-third of a tonne compost sample from Amgen Cymru's Bryn Pica landfill site near Aberdare, South Wales, which was manufactured by utilising Rhonda Cynon Taf, South Wales park waste, green-waste and kerbside collection. It was found that the compost sample contained 1% of plastic films in the hand sorted coarser (>25 mm particle size) fraction, which was correlated to kerbside collection.

7.3.2 LABORATORY SEPARATION BY AIR CLASSIFICATION

Based on the data obtained from the initial trial, laboratory air classification was undertaken to ascertain the removal of elements of the standardised mix of contaminants from <10 mm CERT compost. It was found that at the minimum average air velocity of 4.24 m/s, 100% of plastic films were removed. However, due to low moisture content (36-38%), a major portion (73%) of <10 mm compost was also removed in the air stream.

7.3.3 COMMERCIAL SCALE TRIAL

The second phase of the characterisation study involved examining CERT's unscreened composted product (10.50 tonnes). Following characterisation, this product was used to examine and analyse the efficiency of commercially available separation machines. For initial characterisation, approximately one quarter of a tonne sub-sample was hand sorted to remove 4 categories of contaminants (lights, metals stones and others), which were sieved to separate into less than and greater than 25 mm fractions. These fractions were weighed, washed and weighed again to determine the mass of actual contaminants (as-received) and the mass of compost adhered to the contaminants. It was found that the total washed contaminants were 4.94 kg (1.66%) of the sub-sample, of which 1.44 kg were lights, 0.25 kg were metals and 0.31 kg were others in the >25 mm size fraction, while 2.15 kg were <25mm stones.

When comparing the Bryn Pica compost with the CERT compost, it was found that both were different from each other. Results showed that approximately one-third of a tonne compost sample from Bryn Pica that was hand sorted contained 6% coarser (>25 mm, as-received) contaminants of the total sample and the CERT compost consisted of 0.9 % (>25 mm, as-received) contaminants of the material examined.

A sample of unscreened compost (10.5 tonne, 56% moisture content) was fed into a 'Terra Select T4' screen over a period of approximately 30 min. Of the total compost, 83% passed through the 25 mm screen, leaving 17% that was greater than 25 mm and was delivered to a 'Komptech Hurrikan' air separator via a trommel screen oversize conveyor belt. It was found that following screening, the <25 mm fraction would meet the physical contaminant limits of the BSI PAS-100:2005 standard. Results showed that 91% of the light materials, 80% of the metals and 48% of the stones were removed from the compost oversize by the 'Komptech Hurrikan'. None of the other contaminants were removed from the compost oversize by 'Komptech Hurrikan' as it was not designed to remove these types of materials.

7.3.4 THE AIR JIG TRIAL

A laboratory air jig was utilised to separate dense contaminants such as stones, glass and rigid plastics from <10 mm CERT compost. The objective of this trial was to determine, if an air jig would operate effectively on the composted material. It was found that in less than 2 minutes, various sizes of stones were separated from the compost and stone mix sample. The results indicated that the air jigging method could be a suitable solution for the removal of smaller particles of stones, glass and other high-density contaminants from composted products with acceptable levels of contamination.

7.4 RECOMMENDATIONS

Based on the findings of the study conducted on the quality enhancement of mature green waste compost, the following recommendations for further research are proposed:

- The vermicomposting trial using mature green waste compost as a feedstock showed minimum compost mass reduction and a significant decline in reproduction and growth of earthworms over a period of 18 weeks. Therefore, it could be said that there was no real added value after vermicomposting of mature green waste compost. However, if the trial were continued using the same feedstock, fresh worms would have to be restocked on a regular basis, which would incur an additional cost apart from the handling and labour costs.

- Further investigation is required to identify the exact mechanism responsible for enhanced plant growth associated with the use of vermicompost as an amendment to the growth media/green waste compost.

- A large quantity of dry (37%, m/m moisture content) <10 mm compost was removed in the upward air stream during the laboratory air separation trial, therefore additional investigations should be undertaken using varying moisture content of the compost to determine its effect on the separation efficiency.

- Further investigation of the air jig method should be undertaken using a large-scale system for the removal of stones, glass and other high-density contaminants from composted products.

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APPENDIX A

Calculations of average air velocities used during the laboratory based air separation trial.

Table A-1 Calculation of average air velocity using Type 1 classifier with air flowing through all (4) regulators.

Distance from top (mm)	Distance (mm) 40	80	120	Velocity V1 (m/s)	Velocity V2 (m/s)	Velocity V3 (m/s)	Area A2 (m^2)	Area A2 (m^2)	Area A3 (m^2)	A1V1 (m^3/s)	A2V2 (m^3/s)	A3V3 (m^3/s)	Mean Superficial velocity, U1 (m/s)	Average of air velocity. Ui (m/s)
Pitot Tube														
20	2.6	3.2	3.8	1.30	2.90	3.80	25.13	15..08	5.03	32.67	43.73	19.11	2.11	
730	0.4	1.2	3.6	0.20	0.80	3.60	25.13	15..08	5.03	5.03	12.06	18.11	0.78	
1080	1.8	2.6	3.0	0.90	2.20	3.00	25.13	15.08	5.03	22.62	33.18	15.09	1.57	
TA5 Thermal Anemometer														1.70
20	2.03	4.55	4.80	1.02	3.29	4.80	25.13	15..08	5.03	25.51	49.61	24.14	2.19	
730	1.80	2.57	2.92	0.90	2.19	2.92	25.13	15..08	5.03	22.62	32.95	14.69	1.55	
1080	2.47	3.15	3.22	1.24	2.81	3.22	25.13	15.08	5.03	31.04	42.37	16.20	1.98	

Table A-2 Calculation of average air velocity using Type 1 classifier with air flowing through 2 regulators.

Distance from top (mm)	Distance (mm) 40	80	120	Velocity V1 (m/s)	Velocity V2 (m/s)	Velocity V3 (m/s)	Area A2 (m^2)	Area A2 (m^2)	Area A3 (m^2)	A1V1 (m^3/s)	A2V2 (m^3/s)	A3V3 (m^3/s)	Mean Superficial velocity, U1 (m/s)	Average of air velocity. U (m/s)
Pitot Tube														
20	2.5	3.7	4.2	1.25	3.10	4.20	25.13	15..08	5.03	31.41	46.75	21.13	2.19	
730	2.6	3.4	3.6	1.30	3.00	3.60	25.13	15..08	5.03	32.67	45.24	18.11	2.12	
1080	3.3	3.6	4.0	1.65	3.45	4.00	25.13	15.08	5.03	41.46	52.03	20.12	2.51	
TA5 Thermal Anemometer														2.26
20	2.42	5.34	5.87	1.21	3.88	5.87	25.13	15.08	5.03	30.41	58.51	29.53	2.62	
730	2.13	2.94	3.51	1.07	2.54	3.51	25.13	15..08	5.03	26.76	38.23	17.66	1.83	
1080	2.65	3.83	4.03	1.33	3.24	4.03	25.13	15.08	5.03	33.30	48.86	20.27	2.26	

Table A-3 Calculation of average air velocity using Type 1 classifier with all (4) air flow regulators closed.

Pitot Tube														Average of air velocities. Ui (m/s)
Distance from top (mm)	Distance (mm)			Velocity V1 (m/s)	Velocity V2 (m/s)	Velocity V3 (m/s)	Area A2 (m^2)	Area A2 (m^2)	Area A3 (m^2)	A1V1 (m^3/s)	A2V2 (m^3/s)	A3V3 (m^3/s)	Mean Superficial velocity, U (m/s)	
	40	80	120											
20	3.2	4.4	5.2	1.60	3.80	5.20	25.13	15.08	5.03	40.21	57.30	26.16	2.73	2.67
730	2.9	3.7	4.2	1.45	3.30	4.20	25.13	15..08	5.03	36.44	49.76	21.13	2.37	
1080	3.4	4.2	4.1	1.70	3.80	4.10	25.13	15.08	5.03	42.72	57.30	20.62	2.67	
TA5 Thermal Anemometer														
20	3.55	6.22	6.62	1.78	4.89	6.62	25.13	15.08	5.03	44.61	73.67	33.30	3.35	
730	2.45	3.62	3.90	1.23	3.04	3.90	25.13	15..08	5.03	30.78	45.77	19.62	2.13	
1080	3.31	4.47	4.74	1.66	3.89	4.74	25.13	15.08	5.03	41.59	58.66	23.84	2.74	

Table A-4 Calculation of average air velocity using Type 2 classifier with air flowing through all (4) regulators

Pitot Tube										
Distance from top (mm)	Distance (mm)		Velocity V1 (m/s)	Velocity V2 (m/s)	Area A2 (m^2)	Area A2 (m^2)	A1V1 (m^3/s)	A2V2 (m^3/s)	Mean Superficial velocity, U1 (m/s)	Average of air velocities. Ui (m/s)
	36.75	73.50								
20	7.00	7.50	3.50	7.50	12.73	4.24	44.56	31.80	4.50	4.24
730	5.50	7.00	2.75	7.00	12.73	4.24	35.01	29.68	3.81	
1080	6.50	8.00	3.25	8.00	12.73	4.24	41.37	33.92	4.44	
TA5 Thermal Anemometer										
20	6.55	7.56	3.28	7.56	12.73	4.24	41.69	32.05	4.35	
730	6.12	6.99	3.06	6.99	12.73	4.24	55.82	42.19	4.04	
1080	6.41	7.70	3.20	7.70	12.73	4.24	40.80	32.65	4.33	

Table A-5 Calculation of average air velocity using Type 2 classifier with air flowing through 2 regulators.

Pitot Tube										
Distance from top (mm)	Distance (mm)		Velocity V1 (m/s)	Velocity V2 (m/s)	Area A2 (m^2)	Area A2 (m^2)	A1V1 (m^3/s)	A2V2 (m^3/s)	Mean Superficial velocity, U1 (m/s)	Average of air velocities. Ui (m/s)
	36.75	73.50								
20	7.50	9.00	3.75	9.00	12.73	4.24	47.74	38.16	5.06	4.74
730	6.50	7.50	3.25	7.50	12.73	4.24	41.37	31.80	4.31	
1080	6.70	9.50	3.35	9.50	12.73	4.24	42.65	40.28	4.89	
TA5 Thermal Anemometer										
20	7.45	8.57	3.73	8.57	12.73	4.24	47.42	36.34	4.94	
730	6.38	8.03	3.19	8.03	12.73	4.24	40.61	34.05	4.40	
1080	7.12	8.88	3.56	8.88	12.73	4.24	45.32	37.65	4.89	

Table A-6 Calculation of average air velocity using Type 2 classifier with all (4) air flow regulators closed.

Distance from top (mm)	Distance (mm) 36.75	Distance (mm) 73.50	Velocity V1 (m/s)	Velocity V2 (m/s)	Area A2 (m^2)	Area A2 (m^2)	A1V1 (m^3/s)	A2V2 (m^3/s)	Mean Superficial velocity, U1 (m/s)	Average of air velocities. Ui (m/s)
Pitot Tube										
20	9.30	9.50	4.65	9.50	12.73	4.24	59.19	40.28	5.86	5.90
730	9.10	9.30	4.55	9.30	12.73	4.24	57.92	39.43	5.74	
1080	9.40	11.00	4.70	11.00	12.73	4.24	59.83	46.64	6.27	
TA5 Thermal Anemometer										
20	9.10	9.07	4.55	9.07	12.73	4.24	57.92	38.46	5.68	
730	8.77	9.95	4.40	9.95	12.73	4.24	55.82	42.19	5.78	
1080	9.52	10.75	4.76	10.75	12.73	4.24	60.59	45.58	6.26	

APPENDIX B

Calculations of partition coefficient for different particle sizes of compost at different air velocities used during laboratory based air separation trial.

Table B-1 Calculation of partition coefficient for different particle sizes of compost at an average velocity of 1.70 m/s

Average Air Velocity = 1.70 m/s								
Compost Size Fraction (K, mm)	Light Fraction (A)	Heavy Fraction (B)	Total Material F = A+B	K*A	K*B	F1 = K*A + K*B	Partition Coefficient = K*A/F1	Partition Coefficient = K*B/F1
9	0.00	4.23	4.23	0.00	531.71	531.71	0.00	1.00
7	0.00	4.31	4.31	0.00	541.77	541.77	0.00	1.00
4	0.35	19.00	19.35	44.43	2388.30	2432.73	0.02	0.98
2	5.63	40.27	45.90	714.67	5061.94	5776.61	0.12	0.88
0.5	120.96	57.89	178.85	15354.66	7276.77	22631.44	0.68	0.32
Total	126.94	125.70	252.64	16113.76	15800.49	31914.25	0.82	4.18

Table B-2 Calculation of partition coefficient for different particle sizes of compost at an average velocity of 2.26 m/s

Average Air Velocity = 2.26 m/s								
Compost Size Fraction (K, mm)	Light Fraction (A)	Heavy Fraction (B)	Total Material F = A+B	K*A	K*B	F1 = K*A + K*B	Partition Coefficient = K*A/F1	Partition Coefficient = K*B/F1
9	0.00	7.87	7.87	0.00	1239.10	1239.10	0.00	1.00
7	0.05	12.09	12.14	6.50	1903.60	1910.10	0.00	1.00
4	0.63	31.50	32.13	81.60	4959.70	5041.30	0.02	0.98
2	13.36	55.29	68.65	1731.30	8705.40	10436.70	0.17	0.83
0.5	115.55	50.70	166.25	14974.1	7982.70	22956.80	0.65	0.35
Total	129.59	157.45	287.04	16793.60	25790.50	41584.10	0.84	4.16

Table B-3 Calculation of partition coefficient for different particle sizes of compost at an average velocity of 2.67 m/s

Average Air Velocity = 2.67 m/s								
Compost Size Fraction (K, mm)	Light Fraction (A)	Heavy Fraction (B)	Total Material F = A+B	K*A	K*B	Fl = K*A + K*B	Partition Coefficient = K*A/Fl	Partition Coefficient = K*B/Fl
9	0.00	2.23	2.23	0.00	324.60	324.60	0.00	1.00
7	0.00	10.02	10.02	0.00	1458.30	1458.30	0.00	1.00
4	0.84	32.31	33.15	94.50	4702.40	4796.90	0.02	0.98
2	14.10	56.42	70.52	15374.90	8211.40	9586.30	0.14	0.86
0.5	97.51	44.56	142.07	10965.00	6485.30	17450.30	0.63	0.37
Total	112.45	145.54	257.99	12434.30	21181.90	22616.20	0.79	4.21

Table B-4 Calculation of partition coefficient for different particle sizes of compost at an average velocity of 4.24 m/s

Average Air Velocity = 4.24 m/s								
Compost Size Fraction (K, mm)	Light Fraction (A)	Heavy Fraction (B)	Total Material F = A+B	K*A	K*B	Fl = K*A + K*B	Partition Coefficient = K*A/Fl	Partition Coefficient = K*B/Fl
9	0.00	3.33	3.33	0.00	529.00	529.00	0.00	1.00
7	0.31	11.07	11.38	35.85	1758.58	1794.43	0.02	0.98
4	3.12	46.36	49.48	360.86	7364.75	7725.61	0.05	0.95
2	27.12	77.00	104.12	3136.70	12232.22	15368.92	0.20	0.80
0.5	85.11	21.10	106.21	9843.82	3351.95	13195.77	0.75	0.25
Total	115.66	158.86	274.52	13377.24	25236.50	38613.74	1.02	3.98

Table B-5 Calculation of partition coefficient for different particle sizes of compost at an average velocity of 2.67 m/s

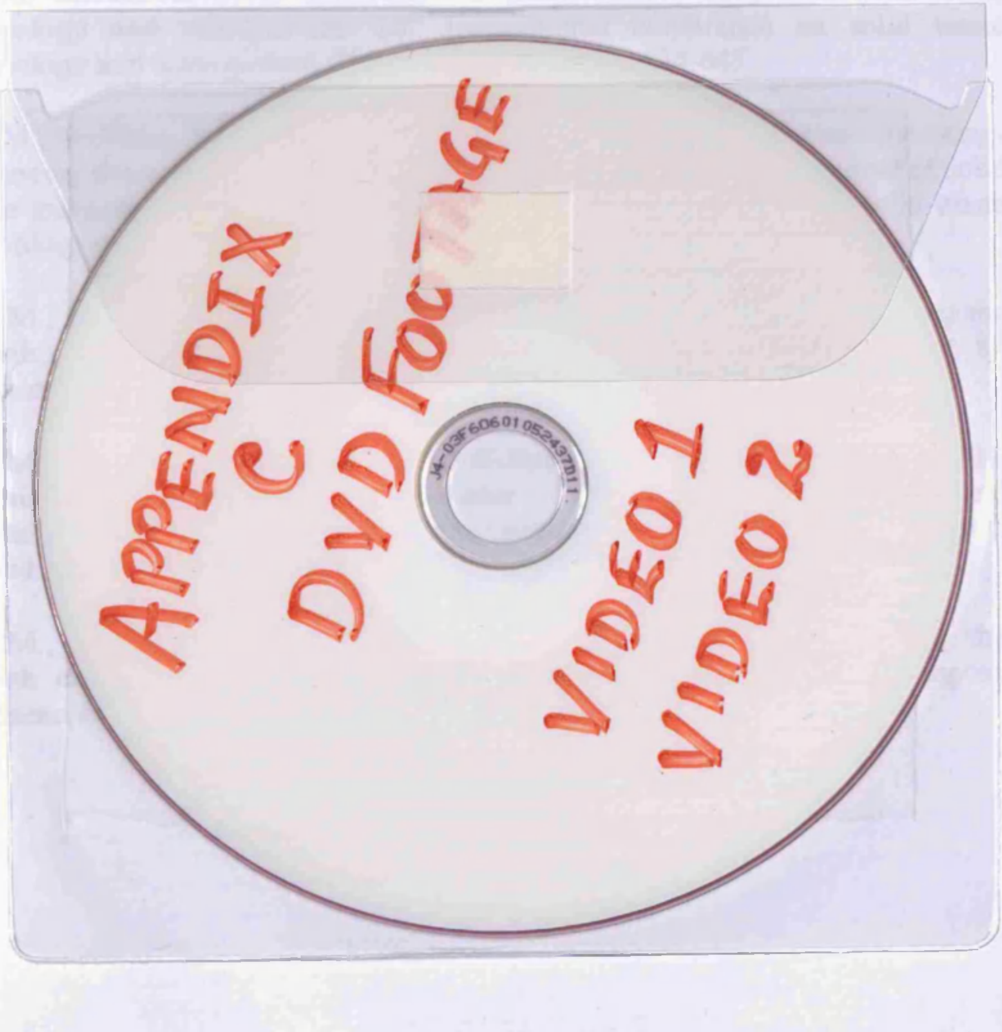
Average Air Velocity = 4.74 m/s								
Compost Size Fraction (K, mm)	Light Fraction (A)	Heavy Fraction (B)	Total Material F = A+B	K*A	K*B	Fl = K*A + K*B	Partition Coefficient = K*A/Fl	Partition Coefficient = K*B/Fl
9	0.00	13.77	13.77	0.00	3038.76	3038.76	0.00	1.00
7	0.50	41.20	41.70	56.27	9092.02	9148.29	0.01	0.99
4	6.07	103.63	109.70	683.12	22869.07	23225.19	0.03	0.97
2	28.63	53.02	81.65	3222.02	11700.45	14922.47	0.22	0.78
0.5	77.34	9.06	86.40	8703.84	1999.36	10703.20	0.81	0.19
Total	112.54	220.68	333.22	12665.25	48699.66	61364.91	1.06	3.94

Table B-6 Calculation of partition coefficient for different particle sizes of compost at an average velocity of 2.67 m/s

Average Air Velocity = 5.90 m/s								
Compost Size Fraction (K, mm)	Light Fraction (A)	Heavy Fraction (B)	Total Material F=A+B	K*A	K*B	F1=K*A+K*B	Partition Coefficient =K*A/F1	Partition Coefficient =K*B/F1
9	0.00	25.80	25.80	0.00	5613.56	5613.56	0.00	1.00
7	1.57	41.65	43.22	208.61	9062.21	9270.81	0.02	0.98
4	8.54	88.14	96.68	1134.71	19177.50	20312.21	0.06	0.94
2	35.28	52.03	87.31	4687.65	11320.69	16008.34	0.29	0.71
0.5	87.48	9.96	97.44	11623.47	2167.10	13790.56	0.84	0.16
Total	132.87	217.58	350.45	17654.44	47341.06	64995.49	1.21	3.79

APPENDIX C

DVD footage of the commercial-scale air separation and laboratory based air jigging trials (Video 1 and 2).



APPENDIX D

LIST OF PUBLICATIONS:

- Ali, M., Griffiths, A.J., Williams, K.P., and Jones, D.L., 2005. Comparison of growth characteristics for waste-derived composts. The Journal of solid waste technology and management. 20th International conference on solid waste technology and management, Philadelphia, USA. Pp. 634-643.
- Ali, M., Griffiths, A.J., Williams, K.P., and Jones, D.L., 2006. Vermicomposting-Enhancing the quality of compost derived from green waste?. The Journal of solid waste technology and management. 21st International conference on solid waste technology and management, Philadelphia, USA. Pp. 667-680.
- Ali, M., Griffiths, A.J., Williams, K.P., and Jones, D.L., 2006. Evaluating the growth characteristics of lettuce in vermicompost and green waste compost. 8th International Symposium on Earthworm Ecology, Krakow, Poland.
- Ali, M., Wright, L.M., Griffiths, A.J., Williams, K.P., and Morgan, A.J., 2006. Vermicomposting of biodegradable wastes - Effects of varying feedstocks and process conditions. 8th International Symposium on Earthworm Ecology, Krakow, Poland.
- Ali, M., Griffiths, A.J., Williams, K.P., and Jones, D.L., 2007. Evaluating the growth characteristics of lettuce in vermicompost and green waste compost. European Journal of Soil Biology Vol. 43. Pp. S316-320.