SITA Environmental Trust

Composting of Mechanically Segregated Fractions of Municipal Solid Waste – A Review

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SITA Environmental Trust

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Executive Summary

Over recent years there has been a resurgence of interest in composting of Municipal Solid Waste (MSW). A large amount of source segregated wastes are now composted across Europe, and the compost is used routinely by many users from domestic users to commercial users.

Source segregation leaves behind residual organic materials. Composting combined with mechanical separation processes may provide a means of recovering lower grade composts and other recyclates both from the residual wastes, and from general waste collections, where for economic, social or other reasons composting of source segregated materials is not carried out. This combination of mechanical and biological treatments has come to be known as "MBT", and this technique is seeing an increasing number of applications across Europe.

However, while "MBT" is "new", mixed waste composting is not, and a large amount of information has been collected about the performance of composting, sampling and separation systems for mixed waste composting. Sita Environmental Trust have been supporting a project which aims to collate the large body of existing information about composting mechanically separated fractions of MSW including sampling and sample preparation issues; and then to present this information in a form that is easily accessible to the UK waste management industry, environmental consultants and researchers.

The volume of material is enormous, and only a faction of it can be referenced in a conventional review. Hence this review operates in conjunction with an on-line bibliography at (www.compostinfo.info), which currently provides access to a bibliography of 1,600 references linked to mixed waste composting. The review is intended to provide a general grounding in the subject and to sign post readers to sources of further information. The review is not intended as a "design and build manual" nor does it provide definitive guidance on legal, regulatory, policy or health and safety issues. Among many findings, the review identified the following key points:

Composting - past and present: past and recent UK and European composting experience shows a cycle of interest and then disinterest in composting of MSW. At present, while it is generally agreed that composts made from source segregated materials are likely to make higher quality composts, there is increasing interest in composting mechanically segregated MSW feedstocks as part of an "MBT" process. MBT, or mechanical biological treatment, allows a range of secondary materials to be recovered, including compost, albeit of a lower grade.

Feedstocks and composition: the physical, chemical and biological characteristics of mechanically segregated MSW are highly variable. Contamination of the compostable fraction by trace elements and "inerts" – i.e. non-compostables - appears to be an intractable problem, with residual inerts and elevated trace element contents remaining in the refined compost. The "best" composts made from mechanically segregated MSW are similar in trace element content to the poorest composts produced from source segregated materials.

Sampling and analysis: MSW is a highly heterogeneous and variable material. Specialist approaches are needed for its sampling, sample preparation and analysis.

Biology of composting: the key biological effects are decomposition including a period of decomposition at elevated (Thermophilic) temperatures. The compost is sanitised by a correctly optimised composting process. The dominant process variables are aeration, temperature and moisture, and it can be difficult to sufficiently aerate the composting mass to control temperatures and so maximise processing rates, without over-drying it.

Pre-processing methods: a wide variety of technologies for compost feedstock preparation (separation technologies such as, hand picking, size separation, density based separation, use of electric or magnetic fields) have been developed over the past 50 years or more. Size reduction plays an important role in pre-processing before composting, with size reduction by screening *without* shredding largely preferred.

Composting techniques: the principal techniques used in MSW composting are turned windrow approaches, open aerated systems, and contained systems (vertical and horizontal reactors and agitated systems). In the past rotating drum reactors followed by aerated piles or turned windrows was the dominant composting approach. Each approach has advantages and disadvantages. However, rotary compost reactors are rarely used for long enough to do more than mix and condition the feedstock, and initiate the thermophilic stage of composting. Operating problems appear to be most frequently reported for vertical continuous or silo type reactors.

Refining and packaging: refining uses similar separations to pre-processes, residual content of inerts may remain a problem. This may be masked by fine milling or pelleting.

Health and safety, emissions and emissions control: the principal emissions and health and safety issues are leachate, odour and volatile organic compounds, dust, bioaerosols and other health risks, vermin / birds / insects and fire risks. These can all be effectively controlled in a well managed and planned composting operation.

Product quality and environmental impacts: The dominant benefit of composts arises from their organic matter content, although they do contain useful amounts of plant nutrients and may have a significant liming effect. Concerns about contents of trace elements and inerts have limited the use of composts made from mechanically segregated fractions of MSW in the past. An emerging concern is exists with elevated levels of toxic organic compounds reported where tests have been carried out, although the significance of these is still being debated.

End-uses: composts produced from mechanically segregated fractions of MSW are likely to incur some form of ongoing regulation; possibilities might include soil improvement and soil forming for restoration, daily cover in landfill management, as a pre-treatment prior to landfill and perhaps as a pre-treatment for energy recovery.

Operational and Strategic Issues: MSW composting could play a role in sustainable waste management. However, regulations standards and guidelines for compost exclude products made from mechanically segregated fractions of MSW from “premium grade” markets in the UK. The possible lower grade uses for compost, mentioned above, are currently subject to regulatory uncertainty. This regulatory uncertainty is perhaps the most critical issue affecting the implementation of MBT systems in the UK, and the provision of clear benchmarks and guidance should be undertaken as a matter of some urgency by the regulators and policy departments concerned.

Contents

1. Introduction

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Source segregation leaves behind residual organic materials. Composting combined with mechanical separation processes may provide a means of recovering lower grade composts and other recyclates both from the residual wastes, and from general waste collections, where for economic, social or other reasons composting of source segregated materials is not carried out. This combination of mechanical and biological treatments has come to be known as "MBT", and this technique is seeing an increasing number of applications across Europe.

However, while "MBT" is "new", mixed waste composting is not, and a large amount of information has been collected about the performance of composting, sampling and separation systems for mixed waste composting. It appears that not all of this information is being exploited by MBT developers, who may therefore be at risk of repeating research that has already been done, or perhaps even repeating mistakes from the past, or not carrying out adequate sampling and analysis.

SITA Environmental Trust have been supporting a project which aims to collate the large body of existing, and apparently forgotten, information about composting mechanically separated fractions of MSW including sampling and sample preparation issues; and then to present this information in a form that is easily accessible to the UK waste management industry, environmental consultants and researchers.

1.1 Aims

The aim of this review is to collate the large body of existing, and apparently forgotten, information about composting mechanically separated fractions of municipal solid waste (MSW) including sampling and sample preparation issues; and then to present this information in a form that is easily accessible to the UK waste management industry, environmental consultants and researchers.

The volume of material is enormous, and only a fraction of it can be referenced in a conventional review. Hence this review operates in conjunction with an on-line bibliography at (www.compostinfo.info), which currently provides access to a bibliography of around 1,600 references linked to mixed waste composting. The review is intended to provide a general grounding in the subject and to sign post readers to sources of further information. The review is not intended as a "design and build manual" nor does it provide definitive guidance on legal, regulatory, policy or health and safety issues.

The review covers the following topics.

- **Composting: past and present**: past and recent UK and European composting experience

- **Feedstocks and composition**: the physical, chemical and biological characteristics of mechanically segregated MSW used for composting

- **Sampling and analysis**: Methods for quantifying and assessing the performance of mechanical separation, composting and refining systems, in particular sample collection, assessment and preparation. I.e. sampling and sample handling, designing the sampling scheme, sample collection, sub-sampling, sample preparation, preservation and transport, interlaboratory comparisons, health and safety issues, physical methods, chemical methods and biological methods.

- **Biology of composting**: the terms used, a process description and review of process optimisation.

- **Pre-processing methods**: technologies used for compost feedstock preparation (separation technologies such as, hand picking, size separation, density based separation, use of electric or magnetic fields; size reduction approaches; process integration; other conditioning approaches; and materials handling issues).

- **Composting techniques**: turned windrow approaches, open aerated systems, and contained systems

- **Refining and packaging**: separation processes used in refining, fine milling and pelleting, mixing and bagging, other techniques

- **Health and safety, emissions and emissions control**: considering in particular: leachate, odour and volatile organic compounds, dust, bioaerosols and other health risks, vermin / birds / insects and fire risks

- **Product quality and environmental impacts**: The quality of the composts produced by from mechanically segregated fractions of MSW, including: major chemical properties, trace elements, organic pollutants, inerts, microbial and pathogen issues, maturity and stability

- **End-uses**: for composts produced by from mechanically segregated fractions MSW considering: landfill applications, land restoration, soil improvement, mulches, growing media, and composting as a pre-treatment for landfill

- **Operational and Strategic Issues**: the role MSW composting can play in sustainable development, regulations standards and guidelines for compost products and the composting process, and compost marketing.

This review has been compiled to provide generic guidance only. r^3 environmental technology limited, AEA Technology PLC and the SITA Environmental Trust accept no responsibility whatsoever for any loss or prosecution resulting from acting on the information contained herein. Adherence to any recommendations or information does not necessarily imply endorsement by r^3 environmental technology limited, AEA Technology PLC and the SITA Environmental Trust; neither does it necessarily ensure compliance with the respective regulatory requirements. It is strongly suggested that specialist advice be sought where appropriate.

1.2 Context

Composting as a waste management technique for MSW is growing in importance. However, it is not clear that the lessons and knowledge of the past are informing some current projects and future project proposals. By far the most frequent application of composting to MSW, over the past ten years, has been for the treatment of separately collected wastes - mainly from civic amenity sites. This constitutes, by volume, the bulk of MSW material composted in the UK.

Recently a number of projects in the UK have focused on composting mechanically separated fractions of mixed MSW, and some of these have run into difficulties about the acceptability of their products, both to regulators and those managing Recycling Credits. It also appears that the WRAP /BSI guidance on compost standards is not appropriate for compost production from mechanically segregated MSW; for example it provides little guidance on the principles of sampling, sample assessment and sample preparation (for analyses) of heterogeneous MSW streams.

A large number of mixed waste composting projects (MBT) projects are “in the pipeline” and may be commissioned in the next few years. There are a number of drivers for this. These are, in no strict order of priority:

- *The advent of the Landfill Directive*: composting separately collected wastes may reduce waste to landfill by, say, 20%, but it may not deal with the vast majority of biodegradable wastes in MSW - can composting offer a wider opportunity?
- *The "organic crunch"*: not only is there going to be a large volume of biodegradable MSW looking for a home, but also controls on sewage sludge, agricultural wastes and industrial wastes (for example the ending of sea disposal and stricter controls on re-use in agriculture) mean that there will be even larger volumes of biodegradable wastes potentially looking for beneficial re-use.
- *Dereliction*: An increasing desire to restore land, in particular restoring large areas of land for softer end-uses, and the potential combination of compost re-use with non-food production such as biomass.

These developments have lead to the discovery of a number of new and exciting, and often unique, composting approaches based on mixed waste separation, which nonetheless bear an uncanny resemblance to techniques that have been used in the past and were often well understood.

A large amount of information exists about compost feedstock preparation, product refining, use of mixed MSW fractions and appropriate sampling, sample handling and sample preparation. Much of this experience came from the UK, for example from:

- the work of Warren Spring Laboratory (WSL), subsequently AEA Technologies for the National Household Waste Analysis Programme and past mixed MSW composting work for the Department of the Environment, and
- others such as Leeds University, Luton University, MEL, Sheffield University, Enviros Aspinwalls (now part of Enviros), HLC Henley Burrowes.

This experience appears not to be widely available, as consultancy and other reports can lack due consideration of the difficulties of MSW analyses. Indeed the value of some of the reporting carried out is open to question. This is, probably, in part because organisations from many sectors have entered the MSW composting arena over the 1990s. Those without previous MSW background may have found it difficult to either review existing literature or to access what is largely an unpublished state of the art on MSW sampling and analysis. Making this information more widely available would enhance the technical state of the art as practised in composting in the UK.

The intentions of the project proposed here are that:

- future composting initiatives benefit from the existing platform of knowledge being made widely and easily accessible,
- these future initiatives advance this state of the art rather than repeating it,
- the wider consulting community has easy access to the state of the art for MSW sampling and analysis and refining and handling of MSW process streams.
- so (1) if mixed waste composting truly does have the potential to generate a beneficial re-use in particular areas, its chances of reaching this potential are maximised and (2) there is "technology transfer" to those carrying out composting of separately collected feedstocks.

1.3 Approach

The work carried out comprised

- Task 1: Inventory of existing document holdings
- Task 2: Identification and collection of further documents
- Task 3: Preparation of an annotated bibliography
- Task 4: Preparation of a review report
- Task 5: Publication, dissemination and promotion
- Task 6: Project Management and Progress Reports

1.4 Project Team

This work has being carried out by:
r3 environmental technology limited – www.r3environmental.com
AEA Technology PLC – www.aeat.co.uk.

The project team was lead by Paul Bardos (r3) and Pat Wheeler (AEA Technology). The review author is Paul Bardos (r3).

WSL in Stevenage was instrumental in MSW recycling and composting research until 1993, after which time its work passed on to AEA Technology. Paul Bardos (r3) and Pat Wheeler (AEA) were both involved with this composting work and carried it on in their subsequent organisations.

2. Composting: Past and Present

Municipal Solid Waste (MSW) poses a difficult and complex problem for society. Some of the difficulties arise because the MSW stream is quantitatively large and qualitatively heterogeneous, reflecting the myriad consumer products manufactured in modern industrial society. Inconveniently, MSW is largely generated in densely populated areas where its management is most constrained. Thus the problem cuts across a very wide range of human activities and interests. At the same time, MSW represents a uniquely familiar environmental problem, in that everyone contributes to it palpably in the course of daily living. (Finstein 1992)

The application of composting to municipal solid wastes in mechanised treatment plants has been recorded in the technical literature going back 50 years of more. The recorded use of "refuse derived fuel" (RDF) is even older (Alter 1984). The earliest recorded use of municipal solid waste in its discarded form as a fuel to generate steam during the last quarter of the nineteenth century, apparently in England. The technology was quickly adopted in the United States, Germany and Japan. In New York City, in the 1890's solid waste was handpicked to remove useful materials and the residue became another form of RDF which was burned to generate electricity. Jeris and Regan (1973) describe composting plants of the 1920s and 1930s. In 1961 Brunt described the *Engineering and Economics of Composting Plant*, reviewing plants in Scotland against "old fashioned" processes in the USA, Italy and Denmark. Interestingly this paper has one of the first mentions of 60 degrees C as a minimum composting temperature. Gothard (1959) describes a composting plant in Jersey and suggests process temperatures should be greater than 65^{o}C to ensure sanitisation of materials. Harrison (1965) describes the composting plant in Leatherhead. Hoortenstein and Rothwell (1973) review the use of composted municipal refuse as a "soil amendment" going back to 1944. de Haan 1981 and Obeng *et al.* 1987 briefly review the use of composting by the Netherlands, another country with a long history of applying composting to waste. The composting plant at Wijster was opened in 1929, and by the end of 1960 fifteen composting plants were operating in the Netherlands, some at very large scales (Teensma 1961) and a number of composting plants operated in the USA through the 1960s (US EPA 1971). Indeed the first issues of the journal "Compost Science" date back to 1961. The year the authors of this critical review were born.

By 1971 composting in the UK had declined to 0.3% of the annual *MSW* arising. Composting plants existed at Worthing and Chesterfield. A *Working Party on Refuse Disposal* report to the Department of the Environment (1971) described the state of the art in composting in some detail, and much of what it says about composts (then produced from mechanically segregated and ground refuse) might seem very familiar to today's experts. The compost was seen as a soil conditioner rather than a fertiliser, given its contamination with "undesirable" inorganic materials. The Working Party concluded that *it is evident that to date municipal compost has had little or no attraction in agriculture or horticulture in Britain, nor do we think its attraction to be much greater as a humus or soil conditioner in private garden*s. In these circumstances there seemed to be no justification for installing composting plants on the basis of an expected sale of compost unless governmental subsidies were made available for the agricultural use of compost. Composting a fill material for landfill was seen as having few advantages over using pulverised refuse. Net composting production costs, allowing for sale of compost, were estimated at £3 per tonne, which is probably higher in real terms than net processing costs today (typical gate fees £15 to £25 per tonne, depending on throughput).

The research into composting by Biddlestone *et al.* at the University of Birmingham stimulated renewed interest in composting (e.g. Gray *et al.* 1973). Their work investigated and documented the key composting process control parameters: aeration and temperature and to a lesser extent pH, referring back as far as the work of Waksman in the 1930s (e.g. Waksman and Cordon 1939). Gray *et al.* 1973 listed composting plants around the world. Three composting process approaches were identified in the UK: *DANO, NUSOIL,* and *RENOVA.*, all based on mechanically segregated fractions of *MSW*. Operating plants in the

UK were located at: Blyth (2 tonnes per day throughput), Chesterfield (40-50 tpd), Cowdenbeath (*DANO* 10-13 tpd), Locherbie (*DANO* 30 tpd), Dum. Kirkconnel (10 tpd), Jersey (vertical compost reactor - up to 80 tpd), Leatherhead (*DANO* 45 tpd), Leicester (*DANO* 70 tpd), Newark, Paisley (80 tpd), Radcliff (*DANO* 20-25 tpd), Wetherby (up to 66 tpd), Worthing (up to 45 tpd). However, Gray *et al.* also listed a number of composting plants which were closed down between 1971 and 1973, located at: Bristol, Cheadle and Gatley, Edinburgh, Kilmarnock, Manchester, Middlesbrough, Twickenham. A plant at Caister was the only facility built after 1971 (Gray and Biddlestone 1980). Biddlestone and Gray reported retrospectively on their work in 1980. While there was clearly concern about the content of trace elements in the composts made from *MSW*, acute toxicity in crop plants was rarely observed and boron appeared to be the chief culprit. Stead and Irwin (1980) described a composting facility near Chichester.

The most well known of the composting plants in the UK was the DANO plant at Leicester (Wanlip) which produced a composted product called “Lescost”. This even merited an item on the children’s TV show *Blue Peter*, which mentioned that the compost could be used in parks, but was not suitable for growing food. Ultimately the Lescost plant shut down (Hughes 1977). The Wanslip plant was originally built in 1966, damaged by fire in 1968 and recommissioned in 1969. The plant operated till the mid-1970s and shut down because it could not find markets for its composts. Hughes (1977) reports that the compost stockpile was sold on quite easily, although Clark (1973) reports that the compost quality was poor and could not easily be sold while the plant was operating. The plant (and others) is listed in the case studies section of this review. Wanlip was the last major composting plant processing mechanically segregated *MSW* for some time in the UK.

In the late 1970s through to the late 1980s a large programme of work was carried out by the Department of the Environment, and subsequently ETSU, to investigate recent advances in refuse processing technology for producing refuse derived fuel (e.g. Barton and Poll 1983). This centred on two new plants, one built at Byker based on what was seen as a more established approach based on the processing of shredded refuse, and one built at Doncaster based on a more technically risky approach of trommel screening refuse before processing to RDF. The trommel screening approach was found to be more reliable and produce a better quality fuel. The Doncaster and Byker plants implemented much of what is regarded today as “MBT” technology, but even they were based on earlier technologies improved over time.

Research at Warren Spring Laboratory considered both composting (Ege and New 1988) and anaerobic digestion (Le Roux 1979) as possible recycling routes for the organic rich rejects from the RDF process. These were seen as a potential opportunity for organic matter recycling (Bardos *et al.* 1991, Poll 1994). It became clear that trommel screening rather than shredding as the “front end” for *MSW* processing also resulted in better quality composts. However by the early 1990s the work at Warren Spring had concluded that even with advanced separation and refining techniques the quality of compost produced from mechanically segregated composts was fundamentally limited by the nature of the feedstock, with particular concerns over inerts and heavy metal contamination levels, matching similar findings across Europe (Favioni 2002). Quality of composts from source segregated materials was found to be much better (Newport *et al.* 1993) in line with findings from many other investigations, (e.g. Richard 1991). However, review work indicated that the heavy metal contamination levels in some composts produced from source segregated materials was no better than that of the better composts from mechanically segregated feedstocks (Wheeler and Bardos 1992).

In the early 1990s research work was proposed to the Department of Trade and Industry and the then Department of the Environment to develop a programme for developing composting approaches for source segregated wastes, particularly from civic amenity sites, which in preliminary studies had shown great promise for producing a step change in compost quality. However, this work was not carried out as funding was ended.

Since then interest in composts derived from source segregated materials has been unstoppable (Border 1999, DETR 2000, Gale and Walker 1997, The Composting Association 2003), although some interest in composting from mechanically separated wastes continued.

A composting plant. based on mechanically segregated *MSW* was built at Castle Bromwich and then shut down in the early 1990s. Composting plant. based on mechanically segregated *MSW* was proposed at Reading in Berkshire, but could not be financed. Very recently composts produced from mechanically segregated wastes have been applied to land in Greater Manchester and in Norfolk. In both cases the poor quality of the compost has lead to major controversy. Composting plants based on mechanically segregated *MSW* have recently been commissioned in Neath, Wales and in Aberdeenshire (Pringle and MacDonald 1999, Pringle and Svoboda 2002). The Neath Plant also produces “green waste composts” from separately collected materials. It is still developing ideas for end-uses for the mechanically segregated waste compost, but anticipates no revenue from them. The Aberdeen compost is intended for landfill restoration. (Note: - the feasibility of converting mixed-MSW composting plants to source segregated feedstocks is discussed by Kranert and Horst 1990.)

The Neath plant is perhaps in the vanguard of the so-called “mechanical biological treatment” plants which seek to apply mechanical segregation and biological processing to mixed refuse, ideally residual waste left after source segregated materials have been removed (Crowe *et al.* 2002), an approach known in the Warren Spring days as “Integrated waste management”. A large number of MBT plants have been proposed in the UK, and they are seen by many, including Greenpeace, as an alternative to thermal conversion of residual wastes left after source segregation of materials including compostables (Greenpeace 2001). The actual scale of MBT processing in the UK appears, as yet to be relatively small, with 85,000 tonnes reportedly processed in 2001 (The Composting Association 2003). However, major uncertainties remain about how the compost (or digestate) products of MBT will be used. Currently envisaged applications are:

- Applications perceived as less sensitive by producers, such as restoration (Godley *et al.* 2002)
- Simply as a landfill pre-treatment (Bockreis and Steonberg 2004)
- As a feedstock for energy from waste conversion (Efstathios. and Stentiford 2004)

So the circle of composting continues to turn in the UK and elsewhere (each country seems to be making similar voyages of discovery and rediscovery, e.g. Ernst 1989, European Commission 1997).

The purpose of this review is that the “cycles” of the past can be recycled to inform the present cycle of interest in composting and mechanical segregation, which is most commonly expressed as “MBT”. The aim is for decision-makers and developers to have the opportunity to benefit from lessons learned in the past.

In 2003 the House of Commons Environment, Food and Rural Affairs Committee found that "Biodegradable (organic) waste is important because it represents a high proportion of household waste and because when disposed of in landfill it produces the greenhouse gas methane. Conversely, when managed well, biodegradable waste can be used to make valuable high quality compost, which in turn can reduce our reliance on peat-based composts and can be used as a soil improver."

3. Feedstocks and composition

MSW is one of many feedstocks that have been or are composted. In fact the dominant compostable wastes are agricultural wastes (Bardos *et al.* 1991).

Composts have been produced from unprocessed MSW and from MSW that has been processed in some way to increase its relative content of biodegradable material, and/or render the refuse more quickly degradable (typically by wetting and/or size reduction). When these materials are used as the input source for a composting process they are often referred to as "feedstocks".

The aims of applying composting to MSW encompass one or more of the following: producing a "product" that can be put to some kind of use, reducing the mass of MSW, improving the qualities of the MSW for subsequent disposal or processing – for example as a pre-treatment for landfill.

The principal effects of the composting process are biodegradation, drying, increasing bulk density and physical attrition. The waste components that are most changed are those that are biodegradable. Composting is of relatively short duration – weeks to months depending on the processing route, hence rapidly biodegradable materials are those most affected. More slowly biodegradable components may persist through the composting process, and even as the compost is matured. This persistence can be a particular problem for various types of "biodegradable" plastic (Colyer 2004), but also for paper, card and wood – including woody components of garden waste, and notoriously for MSW composts: cigarette ends (filters).

The possible effects that composting has on non-biodegradable components such as glass or many plastics is that of physical attrition, drying and the removal of adhering organic matter. These components are often referred to as "inerts" since they are not affected by biodegradation. Mechanical pre-processing and compost refining processes (discussed elsewhere in this review) seek to remove these inert components as concentrates, to leave a more organic rich "compost" product. Inert components are detrimental to compost quality either as visible contaminating components, or as sources of potentially toxic substances in compost, or both. They may also pose physical risks to grazing animals, or to people using MSW compost simply by virtue of being sharp.

Hence the quality of any compost produced from MSW is constrained by the proportion of so called "inerts" in the feedstock, and the effectiveness of processes to remove them before and after composting. The "inert components" are not necessarily chemically inert, for example metal ions may leach from batteries.

In many cases MSW fractions are one component of a compost feedstock, and other compostable materials may be added, most commonly sewage sludge. In the UK, sewage effluent, from both domestic and industrial premises, is treated at wastewater treatment plants. There are three standard stages of treatment:

- Primary sludge is the settled solids from wastewater entering the treatment works
- Secondary sludge is the solids arising from biological treatment (untreated sludge has an approximate dry solid content of 2-7%).
- Tertiary sludge is formed when the remaining solids are precipitated out to produce a clear effluent for discharge.

The composition of MSW feedstocks can be considered in three ways, its physical characteristics, its biological characteristics and its chemical characteristics. The composition of MSW is very variable. Some of this variation is related to seasonal trends, the approach to waste collection, and the locales waste is collected from. However, even within a given locale and time of year composition is variable. This makes extrapolations of conclusions from one area to another highly problematic. Regional comparisons are further complicated by differences in analytical approach, and a standardised methodology for solid waste analysis could enable greater comparability and accuracy of waste data within the European Union (Dobson 2003).

MSW can contain hazardous components, and its degradation can cause hazards. Health and safety issues for composting plants are outlined in the Critical Review Section, *Health and Safety, Emissions and Emissions Control*. However, this is not a comprehensive treatise on the subject and plant managers should seek professional advise on risk assessment and compliance with health and safety regulations.

3.1 Physical characteristics

There are four basic ways in which the composting of MSW may be approached:

- composting whole mixed MSW;
- composting a mechanically concentrated organic fraction;
- composting separately collected materials (e.g. via collections from Civic Amenity sites or kerbside collection of wastes segregated by householders);
- encouraging composting by individual waste producers (e.g. home composting).

This review focuses on composting from mixed MSW collections.

Composts are not made from whole MSW streams in the UK because of the relatively small content of compostable material, and because some MSW materials are better suited for other forms of recovery (for example metals, paper and plastic). Suggestions for the composition of the organic fraction from an ‘average’ householder range from 21% to 35% for food and garden waste, and the content of paper and card is estimated as 35% - % by mass (CIWM 2002).

Estimates from the Warren Spring Laboratory (Bardos *et al.* 1991, Newport 1990, Newport *et al.* 1993) suggest the proportion of compostable materials in UK MSW is 35% by mass. The overall biodegradable content of MSW in Wales has been estimated as 61% - “organics” 36% and paper and card 25% (Welsh Assembly Government 2003).

Often, surveys of waste composition are reported for "bin waste" only, i.e. from refuse collection vehicles. However, MSW includes CA site waste, fly-tipped, street sweepings etc. so the use of these terms must be specific. These different sources would also be affected differently by the implementation of source segregation schemes.

The Warren Spring estimate is based on the content of materials falling into three categories during analyses of (bin-waste) refuse by hand sorting. The physical classification of the components of MSW is typically on the basis of size distributions and categories (Poll 1988) - see Critical Review Section, *Sampling and Analysis – Physical* The three categories are:

- *putrescibles* - plant, kitchen and garden wastes;
- *miscellaneous combustibles* - disposable nappies, sanitary towels, leather goods, wood;
- *fines* - materials less than 10 mm in size that are too fine to sort by hand (such as household dust or soil).

These materials may contain or entrain a proportion of non-compostable material and, furthermore, may incorporate non-compostable categories such as glass, paper and plastics. For example, woody wastes, plastics and some fibres used in disposable nappies and sanitary towels persist through composting. Paper and card are not included as (a) these tend to be diverted for recycling or energy recovery, and (b) paper is only slowly degraded during composting (Bardos and Lopez-Real 1989).

Experience in the UK and overseas strongly indicates that composting of whole refuse is unlikely to produce a usable product - - see Critical Review Section, *Composting Past and Present*, although unsorted MSW has been composted in the past (e.g. Atchley and Clark 1979, de Haan 1981). Mechanical segregation processes can concentrate the compostables present in refuse as well as producing other fractions suitable for energy recovery, metals recycling etc. This integrated approach to MSW management has re-emerged in recent years as "Mechanical Biological Treatment". The separation employed at these plants can be divided into two main strategies: those where all the incoming refuse is shredded prior to sorting, and those where the first sorting stage is screening with a rotary trommel screen.

The separated undersize stream, from the trommel screening, is the compost process feedstock, and typically includes fines; putrescibles; broken glass and ceramics etc; small pieces of wood, plastic, paper and card; metallic items including batteries (New and Papworth 1988, Wheeler 1990 and 1993).

Composts produced from the compostable-rich fractions liberated by these two strategies differ in their ease of refinement and their composition. Compost products derived from screening pulverised refuse tend to be richer in fine particles of paper, plastic and glass than composts produced from the screening of unpulverised refuse. As a result, composts produced from pulverised refuse fractions are harder to refine than composts produced from unpulverised refuse screenings (Wheeler 1990). The overall organic content of pulverised refuse fractions may also be higher, because of the increased paper content. Despite the potential liberation of metal contaminants during pulverisation, the technical literature indicates that composts produced from pulverised refuse fractions tend to have lower heavy metal contents than composts produced from unpulverised refuse fractions (Wheeler and Bardos 1992). The reduction in metal concentration may be due to the dilution effect of the higher content of paper and shredded inerts in the compost, or may be a feature of the composition of different household waste inputs.

Further pre-treatment processes may be applied before composting, in particular density based separations (such as ballistic separation) and also separation of metallic components (e.g. magnetic or using eddy current systems). Pre-processing techniques are discussed in more detail in the Critical Review Section, *Pre-processing Methods*.

Many commentators believe that *Mechanical-Biological (MBT)* treatments are best operated in parallel with schemes separating materials at source, for example garden and kitchen wastes, "dry recyclables" (paper, plastic, metals), glass, and schemes encouraging waste re-use at source (for example home composting). The rationale for this combined approach is that the quality of products recovered from separately collected materials tends to be higher. However, separation at source will dent but not eliminate the municipal waste stream, and a significant amount of "residual" or "grey" waste will remain (Gould and Meckert 1994). MBT is seen as a means of recovering, perhaps lower grade, materials from this residual MSW and/or energy, and in reducing the content of biodegradable materials eventually being landfilled. (Chertow 1989, Damiecki and Kettern 1993, Greenpeace 2000 & 2001, Jager *et al.* 1998, Koller and Thran 1997, Lechner *et al.* 2004).

For compost production, mechanically segregated MSW, has constraints in terms of its levels of contamination by "inerts" (i.e. non-biodegradable components) and trace elements (see Critical Review Section, *Feedstocks and composition - Chemical characteristics*. The Critical Review Sections: *Pre-processing Methods* and *Refining* discuss the approaches that have been employed to limit the impact of these inerts in compost product. Ultimately there is an inverse relationship between product yield and product quality – the greater the removal of inerts, the lower the compost yield, as organic material entrained with the inerts is removed (New and Papworth 1988). The usefulness of composts produced from mechanically segregated composts is being hotly debated, with positions ranging from their not having much use at all (Hammer 1992), to a range of possible "lower grade" uses (Godley *et al.* 2002). Compost uses are discussed in more detail in the Critical Review Section, *End-Uses*.

It should not be assumed that materials separated at source will be free of contamination. Plastic, glass and rubble can be significant contaminants in composts produced from "green wastes" (Wragg 2004), and wide ranging contamination may occur in separately collected kitchen wastes. Dealing with this inerts contamination may require similar pre-processing and refining techniques to those used for mechanically segregated MSW streams.

3.2 Chemical characteristics

The key chemical properties of MSW fractions as a compost feedstock are:

- its content of potentially useful substances such as the major plant nutrients (NPK) and other plant nutrients such as magnesium, and calcium (also important for their potential "liming" effect
- its content of potentially harmful substances such as toxic organics and trace elements.

Source segregated materials are now generally seen as being of "higher quality" for compost production than mechanically segregated feedstocks. See the Critical Review Section, *Composting Past and Present*.

Content of trace elements has been a particularly contentious issue. A review of literature available in the early 1990s concluded that composts produced from mechanically segregated

MSW tended to have higher contents of most trace elements than composts produced from materials separated at source. However, the "best" composts produced from mechanically segregated MSW have lower levels of trace elements than the "worst" composts produced from materials separated at source (Wheeler and Bardos 1992).

There is a high degree of contentiousness (a) about how far some trace elements should be seen as "trace nutrients" versus potential soil pollutants, and (b) whether compost quality should be appraised on the basis of "total" as opposed to "bio-available" levels of trace elements (European Commission 2002, Petruzzelli and Pezzarossa 2002). This is discussed further in the sections on "product quality and environmental impacts" and "end-uses".

The sources of heavy metals in composts are many, for example from metallic components in refuse; household dust; wine bottle tops; compounds added to plastics, paints and inks; cosmetics and medicines; and household pesticides (Culboard *et al.* 1988, Eder 1986, Hagenmaier and Krauss 1982, Krauss 1985, Rousseaux *et al.* 1989 Rugg *et al.* 1992, van Roosmalen *et al.* 1987). The trace elements in mechanically segregated MSW fractions appear to be an intractable problem. Contamination levels tend to show a net increase over composting, in part as dry matter is lost to biodegradation (Anid 1986, Hernando *et al.* 1989, van Roosmalen *et al.* 1987) and indeed trace elements appear to be concentrated by common refining techniques (Bardos 1989). Perhaps this concentration is the result of components of low metal content such as glass fragments.

It has been observed that trace elements tend to be concentrated in the finer fractions (Petruzzelli *et al.* 1989, van Roosmalen *et al.* 1987), removal of this fine fraction prior to composting may not eliminate a sufficient amount of trace elements to make a "step change" in compost quality, and also greatly reduces compost yield. A particular problem appears to be that finely divided materials high in trace elements stick to putrescible materials, for example dust coating wet materials, and metal items such as copper staples penetrating larger putrescible or other organic materials (Krauss *et al.* 1987). There may be alternative pre-processing and refining strategies that might, at least in part, produce composts from mixed MSW with lower levels of trace elements (see the Critical Review Sections: *Pre-processing methods - Process Integration* and *Refining*). There is also some evidence that the toxic elements in finished composts may be less leachable than those in raw materials, but conflicting reports also exist – see the Critical Review Section, *Product Quality and Environmental Impacts - Trace Elements*. It has also been reported that adding sewage sludge can lead to elevated trace element contents in MSW-derived composts (Hagenmaier and Krauss 1982).

Some operators combine (or used to combine) green waste from source segregated sources with mechanically segregated MSW before composting (e.g. Catto 1999). One possible reason for doing this might be to reduce the content of trace elements and inerts in the compost, compared with that which would have resulted from composting of mechanically segregated MSW alone. Ultimately the "dilution" achieved may still be insufficient to make a step change in compost quality, and a potential "quality" product stream from composting the green waste alone is lost.

An emerging concern has been over the significance of toxic organic substances in composts derived from source segregated or mechanically segregated MSW feedstocks. These arise from a variety of sources, including plastics, coatings on papers, pesticides, soot (PAHs), various household chemicals, ash and products of incomplete combustion (de Haan 1981, Hagenmaier *et al.* 1986, Harms and Sauerbeck 1983, Malloy *et al.* 1992). Some information on contents of toxic organics in MSW feedstocks is also available for analyses carried out to assess incinerator performance (e.g. Tosine *et al.* 1985, Wenborn *et al.* 1999). Some toxic organics, for example many PAHs will degrade in time in composts, or are sorbed into humic materials (Hagenmaier *et al.* 1986, Harms and Sauerbeck 1983). At present toxic organic compounds are not seen as a major problem for sewage sludge or MSW composts (European Commission 2002, Smith 2000). However, available information is limited, and analyses are difficult and expensive. Several Member States have suggested limit values for some organic compounds (for example PAHs) in forthcoming revisions of the EC sewage sludge Directive. These limitations would severely curtail the use of sewage sludge in agriculture (Smith 2001), and, given the EC policy linkage between biowastes and sewage sludge, would also limit compost use in agriculture. However, no final decisions have yet been taken (European Commission 2001, 2002 & 2003).

Composts produced from mechanically segregated MSW tend to be relatively low in nitrogen (1% total N), but high in potassium content. Compositional information is discussed further in the *Critical Review Section*, *Product Quality and Environmental Impacts*.

3.3 Biological characteristics

The components of MSW vary in their biodegradability (Bardos and Lopez Real 1989; CIWM 2002) for example - and only as a “rule of thumb”:

- rapidly degradable (putrescible) materials such as food scraps
- slowly degradable organic materials such as egg board, tissue paper, leaves
- gradually degradable organic materials such as wood and paper
- nondegradable materials such as glass, metals and the main classes of thermoplastics: polythene, polypropylene, polystyrene and polyvinyl chloride (Evans 1974).

Biodegradability is an intrinsic property of the material. It is linked to the ease with which materials can be subjected to enzymic attack, and the range of enzymes (and hence organisms) able to react effectively with the material as a substrate. The most biodegradable materials are typically those which yield energy to micro-organisms or nutrition, or in the case of anaerobic systems can supply oxygen / act as terminal electron acceptors (as oxygen does in aerobic respiration). In some cases substrates may be degraded co-incidentally because they can substitute for a common substrate, for example chloro-ethane is oxidised by the same enzyme that oxidises methane. These rapidly degradable materials fuel the rapid temperature increases characteristic of the thermophilic stage of composting (discussed later in this review), and can be used by a wide range of organisms.

More slowly degradable materials are typically carbon rich and nitrogen poor, and the carbon is in a less readily usable form, for example as cellulose rather than starches. Relatively fewer organisms degrade these materials, and the rate of degradation is slower.

Gradually degradable organics include wood, card and paper. Paper and card, although cellulose rich, are rendered only gradually biodegradable both by their physical nature and because the cellulose is somewhat denatured by the paper/card production process, reducing the ease of enzyme attachment. Wood tends to be degraded by specialist fungi which employ the production of oxygen and hydroxyl radicals and non-specific lignase enzymes. This fungal degradation system can also degrade a number of organic pollutants such as pentachlorophenol and PAHs. There is an extensive technical literature on the degradation of cellulose and lignin (Alfani and Cantarella 1987, Tuomela *et al.* 2000).

Biodegradation may be impeded also if materials are rendered unavailable or inaccessible to microbial attack, for example in disposable nappies (Line 1998) or the cardboard in a packaging laminate would be rendered in accessible by plastic and foil coatings. Physical attrition may abrade these coatings, and render the card accessible to biodegradation. However, the films themselves will remain as an "inert" contaminant in the compost (Encarnacion-Rodriguez *et al.* 1995).

Many items disposed of to the waste stream contain a mixture of materials of differing degradability like disposable nappies (Line 1998). Some of these materials, for example the absorbent gel in the nappy, may be dispersed by the composting process, but not necessarily fully degraded (Stegmann *et al.* 1993). It is a contentious issue whether or not such dispersed materials should be considered composted. This argument is particularly contentious for some classes of so-called "degradable" plastics, where the end result is that the polymer is broken down to such an extent that it is no longer visible, but is still present. This is particularly pertinent given the current interest in the use of "degradable" plastic bags for waste collection (Cole and Leonas 1991). There are two difficulties, the first is that the degradation of the material may be slow so that remnants remain visible as a contaminant in a compost product at point of use (Colyer 2004). The second, is whether it is appropriate to release a material containing undegraded polymer back into the environment, even if it is fragmented, in a compost product (Klemchuk 1990, Satkovsky 2002). There is some evidence that finely divided polythene is slowly biodegradable (Lee *et al.* 1991).

Inorganic compounds may also be attacked by micro-organisms, either to liberate energy to drive their metabolic activity (for example the oxidation of sulphur) or indirectly through the release of ligands and/or acids. Under anaerobic conditions biological processes may mobilise inorganic contaminants. Arsenic and some heavy metals may be converted into volatile and highly toxic methylated forms by microbial activity (Atlas and Bartha 1987).

MSW fractions also contain micro-organisms, both those that might promote composting, and those that are potential pathogens. Typically, MSW fractions will compost spontaneously, and so need no biological inoculation. Pathogen issues are considered in the Critical Review Sections: *Biology of Composting - Process Optimisation, Health and Safety, Emissions and Emissions Control - Bioaerosols & Other Health Risks*, and *Product Quality and Environmental Impacts - Microbial and Pathogen Issues*.

4. Sampling and analysis

The characteristics of samples collected from a lot are used to make estimates of the characteristics of that lot. Thus, samples are used to infer properties about the lot in order to make correct decisions concerning that lot. Therefore, for sampling to be meaningful, it is imperative that a sample is as representative as possible of the lot, and more generally, each subsample must be as representative as possible of the parent sample from which it is derived. Subsampling errors propagate down the chain from the largest primary sample to the smallest laboratory analytical subsample. If a collection of samples does not represent the *population from which they are drawn, then the statistical analyses of the generated data may lead to misinformed conclusions and perhaps costly decisions.*

It is quite a "lot" to ask of the tiny (on the order of a few grams, and often much lower) laboratory analytical subsample to be representative of each of the larger and larger (parent) samples in the chain from which it was derived, up to the entire lot (which could be many tons). Therefore, it is imperative that each subsample is as representative as possible of the parent sample from which it is derived. Any subsampling error is only going to propagate down the chain from the largest sample to the smallest laboratory analytical subsample.

The primary reason that samples are being taken is to make some determination about the lot (e.g., a contaminated site). The study goals and objectives determine the acceptable statistical characteristics for the study. If a decision depends on the analytical results, then the first issue is to determine what type of measurements are needed and how accurate and precise they should be. These goals are referred to as Data Quality Objectives -DQOs (extracts from US EPA 2003).

MSW is a complex material stream. It is particulate, and contains particles which vary substantially in terms of:

- size
- shape
- density
- hardness
- stiffness / flexibility
- surface properties
- composition.

A lot of particles are almost two-dimensional in nature, for example papers, while others may wrap themselves around other particles, for example textiles. Some particles may be composites of different materials – for example packaging. Often particles of different kinds are contained in several layers of bags.

This complexity is also true for processed fractions of MSW, including mechanically segregated fractions, composts and refined compost product (Barton 1983, Barton and Wheeler 1988). The potential range of variability may, of course, be reduced by processing, but perhaps not to the degree that one might expect. For example, after trommel screening at 50 mm, the undersize should be mostly below 50 mm in size and the oversize mostly greater than 50 mm in size. However, it is quite possible for the undersize fraction to contain materials larger than 50 mm in one dimension and the oversize materials smaller than 50 mm, depending on how the material fell onto the screen. The oversize may still contain smaller particles entrained or contained in or on larger particles. The undersize may contain larger particles which were deformed and forced through the trommel screen. Particles may also break and fall through trommel or flat bed screens, often this is intentional in waste processing, however where screening is used in sample appraisal it is a potential source of error.

There is a link between "information" required by a user and sampling and analysis. The nature of this linkage is often overlooked, but it is critical to determining the approach to sampling and analysis that should be undertaken. The critical factors relate to the type of information needed and the "quality" of information necessary, which in turn are determined by what the information will be used for. These linkages are well explored in other environmental business sectors, for example contaminated land management (Crumbling *et al.* 2001), but do not appear to be widely considered in the appraisal of waste composting.

Most commonly information from sampling and analysis is used in the composting sector
- as part of a quality monitoring process (including compliance with guidelines and regulations)
- for the evaluation of safety, health and environment (SHE) impacts
- for predictions about likely process performance, especially at the planning and commissioning stages
- for predictions of likely quality and SHE impacts.

Sampling and analysis information may also have a range of uses in research activities beyond the day to day operations of a composting facility.

Most practioners understand that this information is subject to errors, but not all understand the range of potential sources of error and relative importance of these errors to information for decision-making. A very basic distinction is between systematic errors and random errors. A systematic error is one which is a function of the sampling or analysis approach, for example digestion of a compost sample with *aqua regia* will not liberate all trace elements into solution, hence estimates of "total metals" for example will always be *systematically* under-estimated. Random errors are unpredictable errors that are a fundamental property of what is being measured – its intrinsic variability. Statistical techniques can be used to compare measurements to determine the probability that they are different given known random error. Often the techniques employed assume that random errors follow the *Normal* distribution. However, this is not always true, for example distributions may be *skewed* away from Normal, for example, skewed distributions are often observed for "heavy metals" in organic materials. An EC project (HORIZONTAL) has been investigating the distribution of trace elements and micro-organic pollutants in soils, sewage sludges and composts (including from MSW), and has collated and reviewed the various guidelines available for the sampling and analysis of these materials (Lambkin *et al.* 2004).

Errors can arise at various stages of the sampling and analysis process:
- during sample collection
- during sample preparation, preservation and storage
- during subsampling
- during analysis.

Understanding the significance of errors can be compounded by a statistically inadequate sampling regime, that prevents an adequate understanding of the variability of the measurement being made.

It is also important to understand the cost of the information being collected versus its utility to the decision maker. A common mistake is to invest a lot of money in few measurements with high analytical precision, when the intrinsic variability of the material being sampled renders a limited set of data points useless or even misleading in cases of compliance with regulatory or guideline standards. In these circumstances it may be better to make many analyses at, say, 20% precision, rather than few at 1% precision. Increasing use is being made of sensors and field based measuring techniques as a means of collecting a large volume of indicative data (e.g. see the EC Project SENSPOL:
http://www.cranfield.ac.uk/biotech/senspol/).

Sampling is discussed in a little more detail in a subsection of this Critical Review Section. The other subsections deal with biological, chemical and physical techniques, beginning with physical techniques. For MSW fractions and products it is usually advisable for physical pre-treatment to take place before measurement of chemical parameters, for fraction of size greater than 10 mm, for composts as well as feedstocks (Brunner and Earnst 1986, Wheeler 1993)

4.1 Sampling and Sample Handling

4.1.1 Designing the sampling scheme

The statistical theory underpinning sampling of streams in waste management processing is developed from the work of Gy for the mining and metallurgical processing industries (Gy 1970, 1976, Morvan 1988, US EPA 2003). This work has been used to determine sampling rates and approaches for MSW fractions and products (Barton 1983, Poll 1988). While standardised approaches do not yet exist for MSW fractions and products, methods used at Warren Spring Laboratory for assessing the performance of refuse derived fuel plant and subsequently in the Environment Agency's National Household Waste Analysis Programme (NHWAP) and by the EC-SWA-Tool project, offer approaches with useful "track record" or previous use (Barton 1983, 1984; Barton and Poll 1983; Barton and Wheeler 1988; Barton *et al.* 1988, Dobson *et al.* 2003, Environment Agency 1996; Johnson *et al.* 1993, Martin *et al.* 1995, Welsh Assembly Government 2003). Methods have also been elaborated by the United States Environmental Protection Agency (USEPA 1973 and 1989). In 2004 Defra published comprehensive guidance for waste composition analysis for local authorities (Defra 2004).

Guidance is available from the Defra 2004 guidance mentioned above for MSW composition analysis. British Standards Institution have published standards for the sampling of soil improvers and growing media (BS EN 12579:2000), which is based on the work of the European Centre for Normalisation (CEN, http://www.cenorm.be) Technical Committee 223. Sampling. Guidance is also given the WRAP/BSI PAS 100 guidance "Specification for Compost" (2002, http://www.wrap.org) and in the British Standard for Topsoil (BS EN 3882: 1994). A wider review of available methodologies has been compiled by the EC Horizontal Project (Lambkin *et al* 2004.), and detailed recommendations made. British Standards are available from: http://www.bsonline.techindex.co.uk. A comprehensive review of MSW sampling, particularly from a management point of view, has been written by Lewin *et al.* (2004).

CEN TC 292, on *Characterization of Waste* is carrying out standards development work in progress on waste stream sampling. (Web link: http://www.cenorm.be/CENORM/BusinessDomains/TechnicalCommitteesWorkshops/CENTechnicalCommittees/CENTechnicalCommittees.asp?param=6273&title=CEN%2FTC+292).

Sampling design is a complex subject. Compliance of sampling design with a standard does just that, i.e. complies with the standard. It does not offer any particular guarantee that sampling is statistically or technically rigorous. If in doubt, professional help should be sought.

Sample recording is an important part of designing the overall sampling strategy. Samples need to be described in such a way that provenance of analytical data is always clear (taking into account sample origin and date, sample handling and analytical methods). It is also important that information can be readily stored and recalled from storage in some kind of data management system.

4.1.2 Sample Collection

Sample collection for compost feedstocks and products is likely to be either from stockpiles, or from process streams. Sample collection may also be necessary for soils to receive, or which have received, composts, and for the assessment of process emissions, such as leachate, dusts, bioaerosols, odour, volatile organic compounds and also the assessment of nuisance problems such as flies and vermin.

Process sampling is where samples are taken from the material as it enters or exits a processing step, for example from across a conveyor belt or the outputs of a screen. Process sampling offers major advantages over stockpile sampling for compost and feedstock appraisal (Barton 1983, Barton and Wheeler 1988, Poll 1988). The advantages are:

1) Samples can be collected from incremental process samples, which allows the whole of the process stream to be assessed, compared with stock piles where bias may be possible, for example related to the proximity to surface, and because of the differential settlement of materials in stockpiles
2) Samples can be more easily logged and recorded
3) Quality control issues can be more easily specified and executed
4) Process performance can be more clearly assessed, for example undersize and oversize from a screening process.

To avoid bias, it is important in process sampling that the whole stream is collected, for example material carried at the edges of conveyor belts does not spill over.

Methods for stockpile sampling are offered in the British Standard for the sampling of soil improvers and growing media (BS EN 12579:2000). Sampling guidance is also given the WRAP/BSI PAS 100 guidance “Specification for Compost” (2002, http://www.wrap.org) and in the British Standard for Topsoil (BS EN 3882: 1994). A wider review of available methodologies has been compiled by the EC Horizontal Project (Lambkin *et al.* 2004). British Standards area available from: http://www.bsonline.techindex.co.uk.

Methods for sample collection for soils are described in BS 3882:1994. However, more extensive guidance is available from techniques developed for site investigation (see http://www.eugris.org).

Methods for microbial, leachate, odour, dusts, vermin, flies, volatile organic compounds and bio-aerosols appraisal are reviewed in Alvarez *et al.* 1972, Burge and Millner 1980, Federal Environment Agency – Austria 1998, Gotaas 1956, Gilbert *et al.* 1999, Kim *et al.* 1995, Ulen 1997, Warde-Jones 1996, Wheeler *et al.* 2001. Further information is available in this Critical Review in the sections on: *Sampling and analysis - Biological methods*, *Health and Safety, Emissions and Emissions Control*, and *Product quality and environmental impacts - Microbial and pathogen issues*. Further links to method references and data are provided by the Defra *Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes* (Defra 2004).

4.1.3 Sub-sampling, Sample Preparation, Preservation and Transport

A series of processes take place between sample collection and analysis:

- aggregation of samples
- sub-sampling prior to on site analyses / dispatch
- sample packaging and preservation
- transportation
- off site sub-sampling and analyses
- dispatch of samples for specialised analyses.

Incremental process samples (or samples from different stockpile locations) are typically bulked before onward treatment. These then need to be thoroughly mixed, to prevent a bias towards any particular individual component sample, although guidance on what constitutes thorough mixing is usually not specified. For dealing with MSW fractions, guidance is available from Poll 1988, Defra 2004, Dobson *et al.* 2003, Environment Agency 1996, Welsh Assembly Government 2003 and SEPA 2004.

Where particle sizes are likely to be greater than 10 mm it is advisable to screen the aggregated sample before subsampling takes place. This screening may form part of an on site size and category analysis procedure (see Critical Review Section, *Sampling and Analysis – Physical*). The samples being screened may be several 10s of kilograms, the size of the sample being screened depends on its particle size. Samples should be screened at declining screen sizes, typically: 10, 20, 40, 80 and 160 mm. It is important that the split of the sample mass across the size ranges is recorded. Sub-samples of the screened fractions, usually taken by coning and quartering, can then be taken for:

- moisture content determination
- organic matter estimation by ashing (followed by glass content assessment for <10 mm fraction)
- category analysis by handsorting
- air drying (at low temperatures) prior to sample preparation for chemical analyses (mass loss on drying must be recorded). Chemical analyses (and several physical measurements) for the whole sample can be estimated by combining the results reported for each fraction, in proportion to the proportion of mass each screened faction represents of the total sample. This screening step is very important to prevent sample bias towards particle size (Poll 1988).

A few measurements may take place on unscreened samples, including assessments for bulk density and pH. The Animal By-Product regulations and standards such as BSI/WRAP PAS 100 require microbiological assessments. It would seem best to apply these to samples which have not been screened, because (a) the screening process may change the biological properties of the material, (b) the screening process will carry over cross-contamination. Some guidance on taking samples for microbiological purposes is provided by BSI/WRAP PAS 100 and the Animal By-Products Regulations 2003 (SI 2003/1482).

In some situations it may be possible for a number of these operations to be carried out at the waste facility where samples are being collected from. However, it may be necessary to carry many of these operations out off site. It is generally advisable to carry out all of the stages described thus far within 24 hours, unless refrigeration of the bulk samples is possible. The samples are biologically active, and may degrade substantially otherwise. Bulk samples are generally stored in heavy duty polythene bags.

For MSW fractions and products size reduction is a necessary step prior to chemical analyses of air dried samples. This size reduction tends to proceed in several steps, a bulk size reduction in a knife mill, hammermill or similar unit down to 2 mm size, followed by further sub-sampling, followed by milling to a fine powder. This size reduction process is a potential source of major errors and biases. Significant issues for the first step of size reduction down to 2 mm include the following:

- some materials such as stones may be manually removed – which leads to a bias in the analytical data – the removal of items such as button cells prior to milling is a complicated issue. The milling of the button cell would cause a massive toxic element spike in the sample, and possibly cross-contaminate future samples (Brunner and Earnst 1986). On the other hand the button cell is a part of the metal load of the compost.
- the mill is typically steel, hardened with another metal such as nickel or manganese – ensure that the hardening agents are not elements to be analysed in the samples being milled
- the mill is a source of sample cross-contamination if it is not cleaned after each operation, for example by running a sand “blank”.

These knife and hammermills typically manage throughputs of up to several 10s of kilograms per hour, adequate to mill or grind an entire of air-dried sub-sample.

The way that further sub-samples are taken can be a major source of bias or error in subsequent data. Where it is at all possible mechanical sample splitting using a spinning riffle (also known as a “sectorial” splitter) is advisable (Morvan 1988, US EPA 2003). Spinning rifles with a capacity of several kilograms are available, down to small units for use in analytical laboratories. Gerlach *et al.* (2002) evaluated five soil sample splitting methods (riffle splitting, paper cone riffle splitting, fractional shovelling, coning and quartering, and grab sampling) with synthetic samples. Individually prepared samples consisting of layers of sand, sodium chloride and magnetite were left layered until splitting to simulate stratification from transport or density effects. Method performance rankings were in qualitative agreement with expectations from Gy sampling theory. Riffle splitting performed the best, with approximate 99% confidence levels of less than 2%, followed by paper cone riffle splitting. Coning and quartering and fractional shovelling were associated with significantly higher variability and also took much longer to perform. Common grab sampling was the poorest performer, with approximate 99% confidence levels of 100%-150% and biases of 15%-20%. Gerlach found that, for these synthetic samples, sampling accuracy was at least two orders of magnitude worse than the accuracy of the analytical method. The synthetic samples he tested seem rather homogeneous compared with composts and mixed waste fractions, even after they have been hammermilled down to < 2 mm.

Very often it is the <2 mm fraction which would be sent for chemical analysis, and again very often this is off site. Milling of the <2 mm fraction often takes place in TEMA mills, or similar equipment. Where the mills are made of steel, it is important to know what the iron is alloyed with. For example using a mill with a steel hardened with nickel will render subsequent analytical data for nickel meaningless (unless of course the amount of nickel abraded by the milling process can be exactly known). It is also important to specify how sub-samples of both the <2 mm for further milling, and sub-samples of the subsequent powder for analysis are taken. Grab samples will introduce a lot more error than using a spinning riffle or similar mechanical device. Requirements for sample dispatch and packaging are written into the standard methods for chemical techniques, and should be specified by the analytical service provider.

Problems of sample preparation are far greater where analysis is for organic compounds (Langenkamp and Luca 2001, US EPA 1989). These may be destroyed by heat or lost due to volatilisation during conventional sample drying and milling processes. Sample collection, preservation and transportation requires special measures, particularly where volatile, semi-volatile of biodegradable organic components are to be assessed.

British Standard BS EN 13040:2000 provides guidance on "Soil improvers and growing media. Sample preparation for chemical and physical tests, determination of dry matter content, moisture content and laboratory compacted bulk density". British Standards are available from: http://www.bsonline.techindex.co.uk.

The US EPA has published an excellent, and easily accessible, guidance on obtaining representative laboratory analytical subsamples from particulate laboratory samples (US EPA 2003).

4.1.4 Interlaboratory Comparisons

Sampling and sample handling (recording preparation, preservation, transport) can be the weak link in the sampling and analysis information gathering process for chemical analytical data. However, while analytical variability within a single laboratory tends to be low, inter-laboratory comparisons indicate that there can be substantial variation in between the chemical analytical results laboratories report back for a single reference sample, perhaps by a factor of ten (or more) in some comparisons (Bourque *et al.* 1999, Holmes *et al.* 1998, Kreft and Bidlingmaier 1996). Little is known about how data reported for physical and biological properties might vary between laboratories. For physical composition data, the lack of standard methodologies can make any comparisons between data from different sources rather unreliable (Bampatsis and Dobson 2004, Fischer and Crowe 2000).

4.1.5 Health and Safety Issues

Sample collection and processing are potentially hazardous operations. A few examples of hazards (by no means an exhaustive list) include: being struck by vehicles or machinery; being trapped in machinery, being struck by flying objects, noise and dust. Sample collection and processing operations should therefore only take place with the advice of recognised health and safety officers, both for the site where work is being carried out, and for the employer of the operatives, and must be compliance with appropriate health and safety law and regulations.

SEPA (2004) state in their guidance: *Suitable and sufficient risk assessments of all associated work activities should be carried out by [organisations], in accordance with their own protocols and procedures, prior to conducting any MSW analysis. From these, safe systems of work must be drawn up, to include details of the correct waste handling methods, personal protective equipment requirements and appropriate hygiene procedures. Staff working on the analysis must be made aware of both documents. All staff carrying out MSW analysis must be trained and competent to carry out their appointed tasks safely.*

4.2 Physical Methods

Physical analyses of composts and compost feedstocks may be carried out for a variety of purposes:

- to determine quantities, size and category composition, moisture contents of feedstock and compost components, which are also a precursor for further analyses because of the complexity of the materials being assessed
- to determine bulk densities, materials handling properties
- as part of product quality and product performance (e.g. as a soil improver or growing medium), assessment the most common assessments include air volume, water volume, shrinkage value and total pore space, these may be assessed to fulfil compliance needs for guidelines and standards;
- prediction / monitoring of performance

The physical classification of the components of MSW is typically on the basis of size distributions and categories (see Critical Review Section, *Sampling and Analysis – Physical*). Categories used by the Warren Spring Laboratory and subsequently by AEA technology PLC include: “putrescibles”, “paper and card”, “glass”, “ferrous metals”, “non-ferrous metals”, “textiles”, “miscellaneous combustibles”, “miscellaneous non-combustibles”, “wood”, “dense plastic”, “film plastic” (see Table A). Classifications are made by sorting by hand. Materials tend to be sorted into size ranges before classification to prevent a bias towards larger items in the hand-sorting. Sizing is usually on a logarithmically decreasing scale e.g., screening at 160, 80, 40, 20 and 10 mm. Typically materials below 10 mm in size are regarded as too small to hand-sort and are referred to as “fines” (Poll 1988). These were developed under the Environment Agency’s National Household Waste Analysis Programme (e.g. Environment Agency 1996, Parfitt 1997), in Wales (Welsh Assembly Government 2003) and in 2004 the Scottish Environmental Protection Agency released a slightly revised set of categories (SEPA 2004). Approaches may be varied when assessing feedstocks collected from civic amenity sites, as opposed to households (Poll *et al.* 1990). In 2004 Defra published comprehensive guidance for local authorities on waste composition analysis (Defra 2004).

Table A Waste Composition Categories Suggested by Defra 2004

Primary	Secondary
Paper	Newspapers
	Magazines
	Other Recyclable Paper
	Paper Packaging
	Non-recyclable Paper
Card	Liquid Cartons
	Board Packaging
	Card Packaging
	Other Card
Dense Plastic	Plastic Bottles
	Other Dense Plastic Packaging
	Other Dense Plastic

Plastic Film	Other Plastic Film
	Packaging Plastic Film
Textiles	Textiles
	Shoes
Glass	Glass Bottles
	Glass Jars
	Other Glass
Miscellaneous Combustibles	Treated Wood
	Untreated Wood
	Furniture
	Disposable Nappies
	Other Miscellaneous Combustibles
	Carpet and Underlay
Miscellaneous Non-combustibles	Construction and Demolition
	Other Miscellaneous Non-combustibles
Ferrous Metal	Ferrous Food
	Ferrous Beverage Cans
	Other Ferrous Metal
Non-ferrous Metal	Non-ferrous Food
	Non-ferrous Beverage Cans
	Other Non-Ferrous Metal
WEEE (waste electrical and electronic equipment)	White Goods
	Large Electronic Goods
	TV's and Monitors
	Other WEEE
Hazardous	Household Batteries
	Car Batteries
	Engine Oil
	Other Potentially Hazardous
	Identifiable Clinical Waste
Organic Non-catering	Garden Waste
	Soil
	Other Organic
Organic Catering	Home Compostable Kitchen Waste
	Non-home Compostable Kitchen Waste
Fines	Fines

These are not the only classification approaches. Overall principles of sizing and classification into categories are widely accepted (e.g. Martin *et al.* 1995), however, the nature of the sizing and the categorisation varies. Efforts are underway in an EC funded project, SWA-Tool, to produce a standardised approach in Europe (Bampatsis and Dobson 2004, Dobson *et al.* 2003), who suggest a set of "primary" category classes: organic (biowaste); wood, paper and cardboard, plastics, glass, textiles, metals, hazardous household waste, complex (composite) products, inert, other and fines (<10 mm fraction). Further differentiation is possible via a series of subclasses. The EC funded AWAST project (EC Project 2004) is also developing standard approaches for the appraisal of MSW composition. However, their suggestions are different to those of SWA-Tool. The cross-referencing of even general waste arising statistics at a European level is unreliable, owing to the differing range of waste types considered as "household" or "municipal" waste in different countries (Fischer and Crowe 2000). Guidance on information capture for essential waste statistics and local management reporting in the UK is available from http://www.wastedataflow.org/, which also serves as an overarching web-based data management system, and from Defra via: http://lasupport.defra.gov.uk/Default.aspx?Menu=Menu&Module=Article&ArticleID=103. At this web link can be found a beta testing version of the *Materials Captures Toolkit*. This includes the following functions (among many more decision-support modules):

- Module 1 – Waste Arising; analysing and projecting waste arisings
- Module 2 – Current Services; entering baseline data on current schemes
- Module 3 – Waste Composition; analysing the composition of different waste streams.

While category analysis is not usually carried out on fractions below 10 mm, it is often important to make an assessment of glass content, as this is a visible compost contaminant. This assessment can be carried out by identifying the glass content in a sample that has been weighed and then ashed (New and Papworth 1988). Other methods of determination of the inerts fraction in compost based on density and other separations have been tested (e.g. Morvan 1992). However, these are not in common use in the UK.

As well as category and size analyses, a range of other physical parameters are important in compost processing, and may have a bearing on the design of the composting system, such as: temperature (in particular), hydrological characteristics (moisture content, water holding capacity and water permeability), bulk density, particle size distribution, porosity and air flow resistance, mechanical, thermal and electrical properties. Agnew and Leonard (2003) give a series of typical values for a number of physical parameters, including particle size distribution, porosity, mechanical and electrical properties, along with empirical formulae for bulk density particle density, free air space and specific heat capacity. Some methods are also given by Poll (1988). Again there are no generally accepted "standard" international methods.

Information about size and category distributions is used to assess the likely compostability of the waste stream in question, the likely "quality of any composted product, what other materials may be recovered from it, and to inform the design of pre-processing and refining steps.

A series of models have been developed by various authors to enable outline predictions to be made of the possible performance of different waste collection and processing methods - screening, shredding and sorting methods (e.g. Billecoq 1981, EC Project 2004, Poll 1989, Wheeler *et al.* 1989, Wheeler 1992). Information on size and category analysis has also been used to try and predict likely levels of contamination of composts with heavy metals, following observations that "fines" tend to carry the largest "load" of trace elements (van Roosmalen *et al.* 1987). Size and category data has also been linked with information about the economic circumstances of areas where materials are collected from (Barton and Poll 1983), and this kind of analysis appears as early as 1969 (Galier and Partridge 1969). This kind of linkage could be used to "target" materials from different locales in urban areas for particular waste recycling interventions.

These models, ultimately, are only as good as the information collected. Combining the use of process models with generic data is not the best way of making reliable predictions of likely compost process performance. The collection of local waste size and category analyses is always to be recommended.

The availability of standard protocols for physical measurements is higher for composted products. However, it must be borne in mind that these protocols do not take into account the likely range of particle sizes in composted fractions of MSW. As a "rule of thumb" it may advisable to limit their use to products that have been screened 10 mm or less. For product streams with larger particle sizes, it may be advisable for these measurements to be made on sized fractions (as suggested in the Critical Review Section, *Sampling and analysis – Sampling*).

Guidance is available from the British Standards Institution, based on the work of the European Centre for Normalisation (CEN, http://www.cenorm.be) Technical Committee 223. Available standards are:

- BS EN 12580:2000 - Soil improvers and growing media. Determination of a quantity
- BS EN 13040:2000 - Soil improvers and growing media. Sample preparation for chemical and physical tests, determination of dry matter content, moisture content and laboratory compacted bulk density
- BS EN 13041:2000 - Soil improvers and growing media. Determination of physical properties. Dry bulk density, air volume, water volume, shrinkage value and total pore space

Further methods are under development by CEN TC 223. The current status of this work is given on:
http://www.cenorm.be/CENORM/BusinessDomains/TechnicalCommitteesWorkshops/CENTechnicalCommittees/WP.asp?param=6204&title=CEN/TC%20223

Some methods are also given in the WRAP/BSI PAS 100 guidance "Specification for Compost" (2002, http://www.wrap.org) and in the British Standard for Topsoil (BS EN 3882: 1994). British Standards are available from: http://www.bsonline.techindex.co.uk.

Physical and chemical analytical methods have also been elaborated by the United States Environmental Protection Agency (USEPA 1973 and 1989).

4.3 Chemical Methods

Chemical analyses of composts and compost feedstocks may be carried out for a variety of purposes:

- environmental impact assessment, the most common analyses are those for trace elements and nitrogen compounds and also odour, but also may encompass toxic organic compounds and possibly measurements of redox potential (although oxygen demand is more commonly assessed as part of an assessment of "stability") – see the Critical Review Sections: *Sampling and analysis – Biological Methods* and *Product quality and environmental impacts --Maturity & stability*.
- product quality, the most common assessments are of pH, conductivity, organic matter content, nitrogen, phosphorous and potassium (total / extractable), but assessments for calcium, magnesium and other plant nutrients may be carried out.

A range of chemical techniques have been applied to assess compost "maturity" (Avnimelech *et al.* 1996 , Chanyasak and Kubota 1981 & 1982, Chefetz *et al.* 1996). However, this application is usually research orientated and does not form part of day to day operations at composting plants. Compost maturity assessments are discussed further in the Critical Review Section, *Product quality and environmental impacts - Maturity & stability*.

- prediction / monitoring of performance, most usually oxygen availability (e.g. Van der Gheyns *et al.* 1997), but potentially also pH, nitrogen content - see the Critical Review Section, *Biology of Composting - Optimisation.*
- A range of chemical assessments may also be applied to assess the impact of composts on soils, for example impacts on cation exchange capacity, pH and organic matter transformations - see the Critical Review Section, *Product quality and environmental impacts.*

These purposes may result from compliance needs for guidelines, standards and regulations, or for research and development processes. For day to day composting operations these measurements are mostly applied to final products, except where they form part of process prediction or monitoring. On occasion chemical compositions for feedstocks or interim process materials may be necessary, for example where a problem identified with a product is being tracked back through the process. Research interests in feedstock chemical data relate to fate of compound studies, environmental burden assessments and modelling of compound flows through waste management processes. Recent advances in chemical analytical approaches may allow finger-printing of contamination problems and subsequent identification of sources (for example see NICOLE 2004, US EPA 2004). Combined bioassay and chemical extraction techniques (*Toxicity Identification Evaluation - TIE*) offer the possibility of identifying both the specific nature of generally observed toxicity problems, and identifying the contamination source (NICOLE 2004).

A number of standard protocols for physical measurements exist for composted products. However, it must be borne in mind that these protocols do not take into account the likely range of particle sizes in composted fractions of MSW. As a "rule of thumb" it may advisable to limit their use to products that have been screened 10 mm or less. For product streams with larger particle sizes, it may be advisable for these measurements to be made on sized fractions (as suggested in the Critical Review Section, *Sampling and analysis – Sampling*).

Those presenting or using chemical analytical data should always bear in mind the possible impact of sampling errors and that different laboratories can report different analytical data for the same samples (Bourque *et al.* 1999). These problems may make both the interpretation of data difficult and prevent comparisons of different composts or products being made. This issue is discussed further in the Critical Review Section, *Sampling and analysis – Sampling.*

Guidance is available from the British Standards Institution, based on the work of the European Centre for Normalisation (CEN, http://www.cenorm.be) Technical Committee 223. Available standards are:

- BS EN 13037:2000 - Soil improvers and growing media. Determination of pH
- BS EN 13038:2000 - Soil improvers and growing media. Determination of electrical conductivity
- BS EN 13039:2000 - Soil improvers and growing media. Determination of organic matter content and ash

- BS EN 13650:2001 - Soil improvers and growing media. Extraction of aqua regia soluble elements
- BS EN 13651:2001 - Soil improvers and growing media. Extraction of calcium chloride/DTPA (CAT) soluble elements
- BS EN 13652:2001 - Soil improvers and growing media. Extraction of water soluble nutrients and elements
- BS EN 13654-1:2001 - Soil improvers and growing media. Determination of nitrogen. Modified Kjeldahl method
- BS EN 13654-2:2001 - Soil improvers and growing media. Determination of nitrogen. Dumas method

Further methods are under development by CEN TC 223. The current status of this work is given on:
http://www.cenorm.be/CENORM/BusinessDomains/TechnicalCommitteesWorkshops/CENTechnicalCommittees/WP.asp?param=6204&title=CEN/TC%20223

Some methods are also given in the WRAP/BSI PAS 100 guidance "Specification for Compost" (2002, http://www.wrap.org) and in the British Standard for Topsoil (BS EN 3882: 1994). British Standards area available from: http://www.bsonline.techindex.co.uk.

Odour assessment has been reviewed by Agency guidance published in 2002 (Environment Agency 2002).

Physical and chemical analytical methods have also been elaborated by the United States Environmental Protection Agency (USEPA 1973 and 1989).

No British Standard methods are available for toxic organic compounds. CEN TC 292, on *Characterization of Waste*, has a large programme of standards development work for the sampling and chemical analysis of waste streams, including for a number of organic compounds. (Web link:
http://www.cenorm.be/CENORM/BusinessDomains/TechnicalCommitteesWorkshops/CENTechnicalCommittees/CENTechnicalCommittees.asp?param=6273&title=CEN%2FTC+292).

Its scope of work encompasses: *Standardization of procedures to determine the characteristics of waste and waste behaviour, especially leaching properties and standardization of subsequent terminology.* Its work specifically excludes the setting of limit values and the setting of specifications for products and processes. Available standards largely relate to chemical analyses, in particular for leaching tests. Work in progress includes sampling protocols and further chemical determinations.

Lagenkamp and Luca (2001) review prospects for harmonised techniques for soil and sewage sludge. A series of guidelines for contaminated site assessment produced by the Dutch Ministry of Housing, Spatial Planning and Environment (VROM) include guideline values and measurement techniques for a wide range of organic substances (VROM 2000).

4.4 Biological Methods

Biological analyses of composts and compost feedstocks may be carried out for a variety of purposes:

- environmental impact assessment, the most common analyses are those for potential pathogens and allergens – see also the Critical Review Sections: *Product quality and environmental impacts - Microbial and pathogen issues* and *Health and Safety, Emissions and Emissions Control - Bioaerosols & other health risks*;
- product quality, the most common assessments are of human and animal pathogens, content of weed propagules, stability, maturity and phytotoxicity, and on occasion of parasites (for example *Ascaris* and *Toxicara*) and plant pathogens see also the Critical Review Sections: *Product quality and environmental impacts - Microbial and pathogen issues* and *Product quality and environmental impacts - Maturity & stability*;
- prediction / monitoring of performance, - see the Critical Review Section, *Biology of Composting - Optimisation.* Evaluation of biodegradability has become an important appraisal method, in particular for evaluating the use and fate of "biodegradable" plastics - see the Critical Review Section, *Feedstocks and composition - Biological characteristics*.

These purposes may result from compliance needs for guidelines, standards and regulations, in particular for compliance with Animal By-product regulations, or for research and development processes. Composting research work has included a number of experiments where composting is simulated, ranging from very small scale simulations to larger simulations using 50 to 100 kg of material. Another area of composting research making intensive use of microbial analyses is appraisals of microbial population dynamics and microbial activity (e.g. Potter and Harrman 1997, Peters *et al.* 2000, Vallini *et al.* 1989 and, of course, Waksman *et al.* 1939).

Centralised composting processes result in the release of micro-organisms into the surrounding atmosphere. Conditions currently being set in the waste management licences specify that facility operators must sample for these micro-organisms around the site. The Composting Association has developed a protocol to provide guidance on meeting regulatory conditions and carrying out the necessary assessments (Gilbert *et al.* 1999).

The most usual product quality biological assessments of are of human and animal pathogens, content of weed propagules, stability, maturity and phytotoxicity. Standard methods for pathogen appraisal have been specified in the *Animal By-Products Regulations 2003* (SI 2003/1482), which enact the *EC Animal By-Products Regulation* (EC 1774/2002). Some methods are also given in the WRAP/BSI PAS 100 guidance *Specification for Compost* (http://www.wrap.org). Methods are reviewed by Jones and Martin (2003). The use of indicator organisms is discussed by (Jones and Smith 2004). Plant pathogen assessment is reviewed by (Noble and Roberts 2003).

Compost maturity, stability and phytotoxicity are inter-related properties (Anid 1986, Inbar *et al.* 1990).

- Stability refers to the degree of biological decomposition. Composts stimulate high microbial activity in soil, where their content of readily degradable carbon is high they may cause oxygen deficiency and a variety of indirect toxicity problems to plant roots. Such composts can also be odorous because they remain biologically active, if oxygen is limited will begin to degrade anaerobically, which can be exacerbated if the compost is packed in bags.

- Maturity refers to the ability of a compost to support plant growth. Over composting relatively easily degradable materials are mineralised or converted into slowly degradable "humified" forms. In young composts intermediate breakdown products and degradable materials remain such as fatty acids and ammonia compounds. These compounds are odorous, and may also be inhibitory to plant growth. High concentrations of soluble nutrients present in immature composts support growth of Salmonellae and/or other pathogens which depend on free nutrients to grow (Inbar *et al.* 1990). Some stages of plant growth can be sensitive to conductivity, depending on the plant species. "Young" composts may have higher conductivity than older composts which have been subject to leaching processes, for example through exposure to rainfall.

- Phytotoxicity refers to the potential for detrimental effects of compost on plant growth. Composts may have phytotoxic effects because they contain high levels of certain trace elements or organic pollutants. This effect is unrelated to compost stability or maturity. Young composts may contain substances inhibitory to plant growth related to the breakdown and degradation processes still taking place (as described above) or because naturally occurring inhibitory substances such as phenolics from certain woody materials have not yet had time to degrade.

Compost stability and maturity assessments include chemical analyses, microbiological assays and higher plant bioassays. Compost respiration rates (assessed on the basis of oxygen uptake) as an estimate of microbial activity is the most common approach to compost stability assessments and also rates of composting (Hoitink and Frost 2002, Lasaridi and Stentiford 1999, Pressel and Bidlingmaier 1981, Richard *et al.* 1993, Swannell *et al.* 1993, Zimmerman and Richard 1992). Bio-assays based on effects on germination are the most common techniques used for assessing compost maturity and phytotoxicity based on the work of Zucconi *et al.* (1981). Grundy *et al.* (1998) proposed methods to determine weed seed contamination in composts based on sieving and flotation. The Composting Association has developed a standard test that combines a compost maturity/phytotoxicity assessment with a very simple and easy assessment of the content of weed propagules in the compost: *A method to assess contamination by weed propagules and phyto-toxins in composted organic materials. CATM/2000/01* (TCA 2000). Stability and maturity assessment methods are included in the WRAP/BSI PAS 100 guidance *Specification for Compost* (2002, http://www.wrap.org), and standard methods for the UK have been proposed by ADAS Consulting 2003.

A wide range of test protocols have been developed for examining biodegradability in composting systems (e.g. European Commission Project 1996, Itavaara *et al.* 1997, Pagga 1999, Satkofsky 2002). A European Quality Standard has been produced EN 13423 – *Packaging requirements for packaging recoverable through composting and biodegradation.* A certification scheme in the UK is operated by The Composting Association (http://www.compost.org).

Process simulations are used to try and model the biological activity of the composting process at a manageable scale that can be replicated. Replication is important to be able to distinguish experimental from random effects. Unfortunately, because of the thermogenic nature of composting, and the variability of compost feedstocks laboratory scale simulations can be unreliable, and great caution is required to interpret their results. Larger scale simulations (> 50 kg scale) are seen as more reliable, although more expensive and complex to operate. optimising the compost process for complex solid material such as municipal solid waste (MSW), is fraught with difficulties. The research must be carried out at a scale large enough for the sampled material to represent the waste accurately, but small enough to allow the process conditions to be easily replicated in different reactors (Petiot and de Guardia 2004, Magelhaes *et al.* 1993, Swannell *et al.* 1993).

5. Biology of Composting

5.1 Terms and Definitions

The terms "compost" and "composting" have a wide colloquial usage. *Composting* may be used to describe any process of biodegradation of organic materials into a product of some kind, whether carried out in the presence or absence of air. *Compost* may be used to describe many different types of growing media, soil improver or mulch.

Compost and *composting* may be used in this sense in some regulations (for example the Waste Management Licensing Regulations 1994). The Composting Association (TCA) reports the following Defra definition for "compost" as *biodegradable municipal waste which has been aerobically processed to form a stable, granular material containing valuable organic matter and plant nutrients which, when applied to land, can improve the soil structure of soil and enhance its biological activity"* (TCA 2001).

WRAP summarises the current definitions of compost used in the UK as follows (WRAP 2002): *There are no obvious legal definitions of compost in the UK. The definition used in the TCA standards is: 'Material that has been subjected to controlled, self-heating biodegradation under aerobic conditions and stabilised such that it is not attractive to vermin, does not have an obnoxious odour and does not support the regrowth of pathogens and their indicator species. Compost that has been subject to a screening process may be classified in terms of its particle size grade, from fine to coarse.'*

WRAP continue: *The DETR Report of the Composting Development Group on the Development and Expansion of Markets for Compost defines compost as: 'Biodegradable municipal waste which has been aerobically processed to form a stable, granular material containing valuable organic matter and plant nutrients which, when applied to land, can improve the soil structure, enrich the nutrient content of soil and enhance its biological activity.'*

From a scientific and technical standpoint "composting" and "compost" have a narrower meaning. A number of technical definitions and descriptions have been proposed (CIWM 2002, European Commission 2001, Zucconi and de Bertoldi 1986, Zucconi *et al.* 1987). The key features of these definitions are as follows:

- *Compost* is the product of *composting* - and not other processes such as anaerobic digestion or mixing.
- *Composting* is a biological process in which complex solid organic feedstocks are oxidised to a biologically stable residue, with the liberation of water, carbon dioxide, inorganic ions and heat. It is aerobic and is characterised by a period of elevated temperature caused by heat generated by the biological process.

The term *stable*, used in this context, refers to a product in which all of the readily degradable organic material has been fully decomposed. The compost product is not completely resistant to any further microbial breakdown; further decomposition will occur when, for example, the compost is applied to the soil, although at a far slower rate, depending on the *maturity* of the compost. *Stability* and *maturity* are defined in the Critical Review Section, *Sampling and analysis - Biological methods*.

5.2 Process Description

Composting microbiology has been the subject of much investigation over the past 80 years or more (e.g. Waksman *et al.* 1939). There have been a large number of reviews of the composting process, its microbiology and optimisation, including: Anon 1991, Bardos and Lopez Real 1989, Biddlestone *et al.* 1981, Brunt *et al.* 1985, De Bertoldi *et al.* 1983 & 1988, CIWM 2002, Finstein and Morris 1975, Finstein *et al.* 1986, Golueke 1972, Gotaas 1956, Lacey 2002, Newport 1990, Palmisano and Barlaz 1996).

The composting process can be considered as taking part in three distinct phases, which are delineated by the different temperatures at which the process takes place:

- an initial phase taking place at temperatures close to ambient (*mesophilic*, up to 40^{o}C)
- a phase at elevated temperatures, where biological activity causes heating to thermophilic temperatures - 50^{o}C or more
- a maturation phase, following thermophilic activity where more complex substrates are degraded at a slower rate (hence a slower rate of heat generation).

There are three different type of decomposer organisms (Dindahl 1978):

- first level consumers: true decomposer or primary organisms that feed and digest directly from the waste debris
- second level (secondary) consumers that feed on the initial composer and
- third level consumer (tertiary) which prey on the second group and upon each other.

A range of organisms are included, in particular: bacteria, actinomycetes, fungi, protozoa, annelids, arthropods. The thermophilic phase is dominated by bacteria, actinomycetes, and a few fungi (Finstein and Morris 1975), when temperatures as high as 70 to 80^{o}C may be reached if an uncontrolled build-up of heat within the composting material is allowed to continue (depending on the size of the composting mass).

Composting is mediated by a diverse community of micro-organisms, many of which are not individually capable of fully mineralising the compostable materials (mineralisation refers to the process of full decomposition of organic materials to carbon dioxide, water and ions). Degradation during composting may proceed via a series of intermediate compounds degraded by different sets of organisms. These intermediate compounds (as well as the feedstocks themselves) may be phytotoxic and/or odorous. These intermediate organic products may either serve as substrates for other micro-organisms or may remain, for a period of time, in the compost residue. Organic intermediate breakdown products which are known to be toxic to plants and which have been identified in immature composts include tannins, polyphenols, ethylene, ethylene oxide, aliphatic acids, various aromatic compounds and sulphides. The thermophilic stage is largely “fuelled” by readily degradable substrates such as proteins, starches, and later cellulose (Biddlestone and Gray 1982, Forsyth and Webley 1948, Jeris and Regan 1973), and is mediated by a relatively small range of micro-organisms, compared with that carrying out degradation at mesophilic temperatures (Peters *et al.* 2000, Strom 1985). Some organisms are active at both mesophilic and thermophilic temperatures (Waksman *et al.* 1939).

The thermophilic stage of the composting process comes to an end as the readily degradable substrates are exhausted, and the temperature of the composting material falls to ambient levels. Further composting, (*maturation* or *curing*) takes place close to ambient temperatures. As temperatures fall from thermophilic ranges fungal activity resumes (Anid 1986). During this stage the majority of degradation of complex polymers such as lignin, and lingo-cellulose takes place (mainly through the activities of basidiomycete fungi), phytotoxicity abates and nitrogen in the form of biomass, compost residue and ammonia begins to be oxidised to nitrate, *nitrification* (de Bertoldi *et al.* 1983, Zach *et al.* 2000). As temperatures fall further the compost will be invaded by a range of animals, not able to tolerate the higher temperatures of the thermophilic stage (Bechmann and Schriefer 1988).

Humification is assisted by the activity of soil mesofauna (invertebrates and other animals), which assist decomposition by reducing in size any agglomerations of organic matter, increasing the surface area available to microbial attack and promoting the processes by which the organic matter is incorporated fully into the soil (Beachman and Schriefer 1988, Dindal 1978).

Temperatures may fall as microbial activity reduces owing to a result of lack of available moisture or oxygen. In these circumstances if oxygen becomes available again (for example as a result of turning), or moisture (as a result of wetting), rapid composting will recommence. This can result in a series of periods of thermophilic activity, before maturation proper takes place. If composts are used when the composting activity has abated because of lack of moisture or oxygen, the compost is generally unstable / immature, and can cause damage to plants and is likely to be odorous or capable of generating odour.

A stable, mature compost is ready for general use. The final product of the composting process is a mixture of the recalcitrant organic residues which persist after the initial rapid stage of decomposition has subsided. Most of the readily degradable organic material will have been converted into carbon dioxide and water, and much of this water and the water already present in the feedstock, or added during composting, will have been driven off during the thermophilic stage. Although composted material can be considered as stabilised, it will continue to degrade further, although this process may take many years to complete. Once the compost has been applied to soil, further breakdown of the organic residues occurs and they become assimilated into the soil structure (Morel *et al.* 1986). This process is known as *humification*. Stehouwer (2004) wrote a good introductory review about soil biological processes.

The organisms necessary to carry-out composting are already present in mixed-MSW. There has been a large number of studies of inoculation of wastes with bacterial cultures of one sort or another, or with finished composts, to promote more rapid composting. Many report that these have not been able to demonstrate any substantial process benefit (Finstein and Morris 1975, Finstein *et al.* 1986, Golueke 1954), although there are some reports of benefits of using finished compost as an “inoculum” (Jeris and Regan 1973).

5.3 Process Optimisation

For MSW streams, the composting process is principally affected by:

- availability of substrate
- availability of oxygen - the minimum oxygen requirement for rapid composting is quoted as around 10%
- availability of moisture - at levels below 25% biological activity within the compost is severely retarded and at 10% or less it effectively stops
- temperature - thermophilic stage.

Other conditions, such as pH, conductivity and the presence of toxic compounds are not likely to significantly impact the composting of mechanically segregated (or source segregated) fractions of MSW. The optimum pH for composting is pH 6 to 8 (CIWM 2002, Nakasaki *et al.* 1993) which is the usual pH encountered in MSW being composted.

Given that the feedstocks contain readily biodegradable matter the key process controls for composting MSW are aeration (for cooling and oxygen supply), moisture and temperature. These factors tend to be inter-related, and are also affected by how the physical nature of the feedstock affects the free flow of fluids (water and gases). These affects are likely to change as the feedstock degrades and so its physical nature changes. In addition the nature of the composting process has an important bearing on air supply, temperature and moisture content.

C:N ratios are often discussed as an important process control parameter. For example, a nitrogen rich waste might be added to a waste that is carbon rich and low nitrogen such as straw. However, for the practical composting of putrescible rich mechanically segregated MSW of source segregated MSW, C:N ratio do not generally require any intervention. However, if the MSW stream is *very* rich in paper and card, it may be advisable to add a nitrogen rich amendment such as sewage sludge.

CN Ratio

This is the ratio of carbon to nitrogen. A simplified picture is that organisms use "fixed" carbon to provide energy, and nitrogen to build cellular components made of proteins. If fixed carbon and nitrogen are in balance then the organism has enough energy to make use of all the nitrogen available to grow and reproduce. Where there is not enough carbon, nitrogen will be released during decomposition, typically as ammonia. Where there is an excess of carbon, organisms will absorb nitrogen from the environment to support the extra growth and reproduction that the energy from the carbon affords. In reality the situation is far more complex. For example, some organisms are able to fix molecular nitrogen from air, and others degrade nitrogen sources to release gaseous nitrogen or nitrogen oxides that are lost to atmosphere. The carbon (and indeed nitrogen) will vary in its availability to micro-organisms, particularly as some substances are more rapidly degradable than others. Measurements of "total" carbon and nitrogen used to calculate it may bear little resemblance to what is actually available to micro-organisms. Use of CN ratios is at best a rule of thumb
.

Far more important in terms of feedstock composition are moisture content, and the physical structure of the material. This should be free draining to allow easy movement of air and water. Particle size should be relatively small (e.g. <50 mm), as large items will take time to degrade and may be anaerobic at their core. It is also important that the material contains a good proportion of slowly compostable materials, as these will help maintain an open structure in the composting mass over time. Conversely, rapidly degradable materials are important for stimulating a rapid increase in process temperatures and the onset of thermophilic temperatures. Once these temperatures have been reached, they can be maintained by the lower rates of activity from the degradation of the more slowly degradable materials because of the relatively high thermal inertia of composting materials. This is due to the high heat capacity of water and low thermal conductivity of organic materials.

Temperature is a key process control parameter. Higher temperatures are associated with greater decomposition (Richards *et al.* 1993). Increasing temperatures (providing moisture and oxygen availability are not limiting) accelerates biochemical (e.g. degradation) processes, doubling every $10^{o}C$ rise. It also changes the microbial composition of the community of organisms carrying out the composting. As a rule of thumb organisms operating up to $45^{o}C$ are called mesophilic, and those beyond this temperature are called thermophilic, as described above.

A principal aim of process control for composting is to maintain a steady thermophilic phase until all readily degradable materials are exhausted. There are two reasons for this; firstly to ensure the most rapid and extensive degradation, and secondly to sanitise the compost. Compost feedstocks may contain a variety of pathogenic organisms (Epstein 1998). Sanitisation describes the processes in composting that destroy harmful micro-organisms, in particular those that are pathogenic to plants or animals, including man.

Several processes combine to assist sanitisation, including: thermal inactivation, microbial antagonisms, sorption and predation by other organisms (Burman 1961), de Bertoldi *et al.* 1988, Knoll 1959 and 1963). Thermal activation is a function of both temperature and the length of exposure to the elevated temperature. Similar processes (thermal inactivation and decay) act to eliminate viable weed propagules, seeds and root fragments (Grundy *et al.* 1998).

Of these, thermal inactivation is judged the most important from a regulatory standpoint, largely because it is the easiest to observe, although microbial antagonisms and competition may be the dominant sanitising effect (de Bertoldi *et al.* 1983), although the direct evidence of antibiotic production during composting is limited (Kuester *et al.* 1981). Control of process temperatures plays a key role in the composting of mechanically segregated fractions of MSW following the recent implementation of controls for animal pathogens.

Current legislation classifies biodegradable waste in the household waste stream as “Catering Waste” and as such, requires it to be composted to a specific set of conditions that comply with the Animal By-Products Order. This is a statutory order introduced in the wake of the BSE and foot-and-mouth Epidemics. The aim of the order is to prevent the re-occurrence and spread of these diseases by preventing the distribution of pathogens that can be carried in compost that has been improperly stored or processed, and which is subsequently spread on grazing land.

These regulations apply to mechanically segregated MSW, if composts are to be applied to land where livestock including birds have access, which effectively means that these regulations apply unless the composting is a pre-treatment before landfill or thermal treatment. The requirements for composting mechanically segregated MSW within these regulations are:

- enclosure of the waste reception and first stage composting process
- that the composting process divided in to two distinct process stages
- *that each of these stages will be required to meet specified time-temperature conditions*
- separation of the clean and dirty sides of the process requiring separate equipment or rigid sterilisation procedures for equipment used either side of the composting process

There is a difficult trade-off between composting rate and sanitisation in that temperatures above 65^{O}C can only be tolerated by a limited range of organisms. Most (but not all) evidence suggests that decomposition rates are highest at 60^{o}C or lower (Bardos & Lopez-Real 1989, de Bertoldi *et al.* 1983, Forsyth and Webley 1948, Gray *et al.* 1971, Jeris and Regan 1973, Miller *et al.* 1989, Niese Neumeyer,-Seekatz 1979, Smith *et al.* 1987, Strom 1985, Stutzenberger *et al.* 1970 and 1971, Suhler and Finstein 1977, Tansey and Brock 1978, Waksman *et al.* 1939, Webley 1948).

However, a number of investigations of thermal inactivation of pathogens in compost – but not all - suggest temperatures a little higher than 60^{o}C are required, including for inactivation of parasites such as *Ascaris* (Andrews *et al.* 1994, Banse and Strauch 1966, de Bertoldi *et al.* 1988, Gotaas 1956, Gray *et al.* 1971, Knoll 1963, Krogstad and Gudding 1975, Lofgren 1979, Morgan and MacDonald 1969, Stentiford *et al.* 1985, US EPA 1971, Wiley 1962, Wiley and Westerberg 1969). Finstein *et al.* (1987) suggest that maintaining a temperature between 55 and 60^{o}C for at least three days throughout the compost volume is likely to maximise rates of decomposition, while still achieving an acceptable degree of thermal inactivation of pathogens. This suggestion is supported by other workers in the field (Biddlestone and Gray 1982). Temperatures of 55^{o}C also appear adequate to control weed propagation. However, weed seeds may remain viable in the edges of compost piles, or may be carried onto finished compost by wind (Grundy *et al.* 1998).

Most, but not all, plant pathogens are also eliminated by the composting process. There is also some evidence that composts may protect plants against some plant pathogens, and that water extracts of compost, “compost tea” have a similar protective effect (Scheuerell and Mahaffee 2002). See Critical Review Section, *Product quality and environmental impacts - Microbial and pathogen issues* for further information.

A further complication in compost sanitisation is that many organisms that mediate the composting process, particularly actinomycetes and the fungal species *Aspergillus fumigatus* produce spores which are allergenic (Clark *et al.* 1983, Lacey 1997 and 2002), and there may also be risks from airborne bacteria, including from the endotoxins in the cell walls of Gram-negative types (Lacey *et al.* 1990. Consequently composting creates a potential health and safety issue (TCA 2004), discussed further in the Critical Review Section, *Health and Safety, Emissions and Emissions Control - Bioaerosols & other health risks*.

To be active, composting micro-organisms require both air and water, whose availability therefore affects the rate of decomposition. Typically air is provided to the composting materials in one of more of the following ways:

- via passive diffusion through the composting mass, which may be assisted to some degree by convection through the composting pile

- by regularly turning the compost, so that it is physically broken up cooled and new air is incorporated into the composting mass
- by forced aeration, which may be *negative* or *reversed* (sucking air through compost), *positive* (blowing air through compost), or occasionally a combination (EC Project 1990, Lofgren 1979, Sesay *et al.* 1998).

Passive diffusion will not supply adequate oxygen to support controlled composting. Aeration by turning does support a controlled composting process, but the oxygen supply is rate limiting for the compost. Forced aeration can, in theory, supply abundant oxygen. However, even in aerated systems methane generation has been noted indicating some areas of anaerobic degradation (Swannell *et al.* 1993). Aeration also allows control of process temperatures by evaporative cooling (Bach *et al.* 1987) which allows better process temperature control than turning alone and which may also help dry the compost (Finstein *et al.* 1986). Aeration to control temperature provides adequate oxygen for microbiological processes. Forced aeration also helps distribute heat through the composting materials (de Bertoldi *et al.* 1983). Air may also be re-circulated to reduce heat loss from the composting materials (Koenig and Bari 1998). Maintenance of aerobic conditions is also a vital part of odour control (Noble and Dobrovin-Pennington 2002).

Temperature feedback control systems have been used to control aeration, switching fans on above a set temperature (say 60^{o}C) and off at lower temperatures - say 55^{o}C (Eccles and Stentiford 1987). The effectiveness of this *temperature feedback* control is limited by the high degree of variability in temperature in composting MSW materials (Atchley and Clark 1979). Variation in temperature is not only related to obvious factors such as depth in the pile, (for example surfaces are cooler - Avnimelech *et al.* 2004), but also includes a large, apparently random, element. The effect of this is that temperature feedback control is at best approximate, as indeed is temperature logging for the purposes of compliance with standards and regulatory controls, for example those relating to the *Animal By-Products Order*. Aeration on an intermittent basis without temperature feedback control can result in very high temperatures being reached, greater than 80^{o}C for composting sewage sludge and wood chips according to Finstein *et al.* (1987).

In practice fans are on almost constantly during the first week or two of composting, and still compost temperatures climb well above set points (e.g. de Bertoldi *et al.* 1982, Sikora and Sowers 1985). An alternative process control loop has been to use feedback based on oxygen levels in the composting mass. Indeed limiting oxygen availability has been proposed as a means of temperature control (Citterio 1987, EC Project 1991), however, the effectiveness of this approach - given the thermal inertia of the composting materials and the high volumes of air input - seems questionable (Finstein *et al.* 1986, Haug 1986). Oxygen feedback control might be combined with temperature feedback in systems where air can be re-circulated (for example to maintain process temperatures for a longer period of time), although thermal inertia may make this kind of sophisticated process control hard to achieve in practice. Other process control parameters that may be monitored using sensors include humidity and carbon dioxide levels (EC project 1990).

Often the technical literature will refer to the “Rutgers” and “Beltsville” approaches to composting. These refer to aeration approaches. The Beltsville approach uses intermittent aeration on the basis of a timer only (Epstein 1997, Willson 1987). The “Rutgers” approach is that of Finstein at al (1987) which applies temperature feedback control with a set point of 55^{o}C or thereabouts, as well as intermittent aeration.

Forced aeration must be undertaken with great care. Forced aeration can create fissures in the compost mass through which the majority of the air will pass rather than permeate the composting materials. This effect is known as channelling (Finstein *et al.* 1986). There are problems in aeration related to the height of the pile being aerated. In part this is because to supply air to the composting mass an ever increasing volume of air must be pushed (or sucked) through the base of the pile, so the for tall piles an excessive volume of air must be blown through a relatively small volume of material at the base. The problem of aeration is also in part related to the relative compaction of material towards the bottom of tall compost piles, which reduces the interstitial spaces between compost particles and so the ability of air and water to pass through. This reduced porosity leads to a greater risk of anaerobic zones developing within the composting material, and an increased risk of channelling. The risk of channelling is increased by increasing air pressure to achieve high air flow volumes from the base of silo type reactors, and the high flow rate may also dry the materials out sufficiently to prevent composting. Maximum heights of 2 to 3 m have been recommended (de Bertoldi *et al.* 1988, Finstein *et al.* 1987). Modelling of compost aeration has been reviewed by Mathsen (2004).

Negative aeration is often used so that the air drawn through the composting mass can be captured for odour treatment. However, its performance in controlling the composting process for MSW fractions is not as good as positive aeration (Stentiford 1992 and 1993, Stentiford *et al.* 1985). Negative aeration delivers less air supply than positive aeration, for the same power consumption, because the movement of air also drives moisture in the same direction. this can lead to condensation and water-logging in the vicinity of the vents the air is being withdrawn from. The effect of this is not only to reduce oxygen supply in the local area, but through out the composting mass. Positive aeration is able to deliver a greater air supply as moisture is driven away from the vent to the edges of the pile with the movement of the air. Using techniques such as covering piles with finished composts means that odour problems can be contained. Not all researchers favour positive aeration over negative aeration, e.g. Willson (1987) expresses a contrary point of view.

Positive aeration systems are often associated with drying out of the compost (EC Project 1991, Finstein *et al.* 1986, Lofgren 1979), particularly in the vicinity of vents, to such an extent that composting ceases before the material is stabilised. There are MBT process designs that exploit this drying effect to assist refining for one of two reasons, either the dried organic material is treated to remove inerts such as batteries and then remoistened and allowed to continue composting, or the refined dried organic matter is used as an alternative fuel. However, another consequence of this drying can be that the compost can almost set solid, making its handling and processing (for example downstream refining) more problematic.

For MSW optimal starting moisture content appears to be 50 to 65% by mass (Biddlestone *et al.* 1981, Finstein and Morris 1975, Jeris and Regan 1973, Wiley and Pearce 1955, Schulze 1961). Although mixed MSW feedstocks are typically already at an optimum moisture content (around 60% by mass) at the start of processing, moisture control during the composting can be quite difficult. Furthermore, very dry compost is hard to rewet (Finstein *et al.* 1986). Water may be irrigated on to the compost surface, although this may not be advisable for reverse aeration systems, or may be injected into the compost. The use of active compost piles to treat on site drainage water or even landfill leachate may be possible. Too much water is as bad as too little. If moisture levels during composting are too high the interstices between the particles of the composting material can fill with water, excluding air and bringing about anaerobic conditions. Moisture contents greater than 70% have been found to be sub-optimal for shredded MSW (Biddlestone *et al.* 1981, Wiley and Pearce 1955). The key issue from a microbiological point of view is the microbial availability of water (Miller 1989). Hence, for fractions with a high glass and inerts content, a relatively low moisture content may still support composting. It may be more appropriate to consider moisture content in the compostable components of the MSW fraction being composted. However, little information is available to provide a process control benchmark. A further problem is that moisture content within piles of composting materials is highly variable (Rynk 2000).

While many authors (e.g. de Bertoldi *et al.* 1983) believe that turning is inadequate for oxygen supply to composting, windrow turning alone remains commonly used, albeit perhaps with longer treatment times than for systems employing forced aeration.

However, for forced aeration systems there may be advantages in intermittent turning (Gray *et al.* 1971, Illmer and Schinner 1997), not only to allow a better application of water and homogenisation of moisture content, but also to ensure that pile edges are mixed in for the next leg of the composting process, to expose fresh surfaces to microbial attack (Biddlestone and Gray 1982) and to reduce the impact of channelling. In practice there are composting systems such as some in-vessel approaches and aerated static piles where there is no turning. In these systems the maturation of the compost becomes very important to allow a mixing step, and rewetting for example by rainfall. The two stage composting required for mechanically segregated MSW under the animal by-product regime has been applied using a static first stage, and then windrow turning for the second stage composting (although so far only for separately collected wastes). If no turning is employed then edges of compost piles can be covered with previously made compost to provide thermal insulation or incorporated into subsequent composting piles (Finstein *et al.* 1987).

Loss on degradation over composting of mechanically segregated MSW streams can be as 30 to 40% by mass on a dry matter basis (Bardos 1989, Hagenmaier and Krauss 1982). However, if composts are matured outside the loss of mass will be less as they absorb rainfall.

6. Pre-Processing Methods

Pre-processing is applied during MSW composting for one or more of the following reasons.

- **To increase the proportion of compostable materials in the feedstock –** Glenn 1991 – MSW contains a high proportion of non-compostable or poorly compostable material, hence composting the whole MSW stream is inefficient and leads to a very low grade of compost. See also the Critical Review Section, *Feedstocks and composition - Physical characteristics*.
- **To improve feedstocks for other recovery options** Removal of compostable materials (and materials removed in parallel such as glass) can improve the efficiency of down stream sorting processes to recover energy and dry recyclables in mechanised plant (Anon 1991, Barton 1983, 1984 and 1986, Barton and Poll 1983, Barton and Wheeler 1988)
- **To reduce levels of contamination by inerts and trace elements**. MSW contains items which may be hazardous in a finished compost, for example glass

which may be sharp or plastics which can injure grazing animals, and also give the compost an unsatisfactory appearance. It also contains levels of trace elements which could restrict, or eliminate, the usefulness of the finished compost. Pre-processing (often combined with post processing, or refining) is used to control the levels of hazardous items and substances in composts, for example exploiting known differences in contaminant distribution, such as the tendency of fines (<5-10 mm) to be enriched with trace elements. See also the Critical Review Sections: *Feedstocks and composition - Physical characteristics*, *Refining* and *Product quality and environmental impacts*

- **To recover other recyclable or re-usable materials (such as ferrous metal)**. Many of the non-compostable fractions of refuse may potentially be recovered for other purposes, for example recycling or energy recovery. Poorly compostable materials such as paper and card may also be better recycled or combusted for energy recovery. As a rule MSW processing takes place in a plant that, as far as possible, integrates several processing routes to divert fractions of the waste to the most appropriate recovery approach. See the Critical Review Sections: *Feedstocks and composition - Physical characteristics* and *Composting: Past and Present*.
- **To condition the feedstock to make it more easily compostable.** Large items will only degrade slowly, and may also degrade anaerobically beneath their surface. Compostable materials may be embedded in non-compostable items such as plastic bags. Conditioning liberates the compostable material and controls the size of particles to support a more efficient biological processing step. See the Critical Review Section, *Biology of Composting - Process Optimisation*. Pre-processing with chemical amendments, for example to control pH or change CN ratios has been applied for MSW feedstocks, but is uncommon.
- **To mix materials,** ensuring even and thorough distribution of the moisture, nutrients and substrates.
- **To reduce contents of pathogens and parasites, for example by the suggested use of autoclaving.** Pre-processing using microwave irradiation or autoclaving to kill pathogens has been trialled, mainly at pilot scale, but is not in widespread use, nor considered necessary Some of these processes are described in the Environment Agency Waste Technology Data Centre at http://www.environment-agency.gov.uk/wtd/.

Most of the pre-processing techniques that are applied are mechanical in nature. There are two broad categories: shredding and separation. Separation technologies exploit differences in properties between components of interest. For example MSW fractions that pass through a 50 mm screen tend to be enriched in putrescibles. Separation is achieved by exploiting one or more differences in size, shape, density or electro-magnetic properties. Shredding or pulverisation is typically achieved by attrition, usually in knife mills or hammermills. However, water based systems have been applied, most frequently the combined shredding and screening approach "wet pulverisation", but various maceration techniques have also been applied, rarely at practical scales. For MSW streams "debagging" is also necessary, as wastes are often contained in one or more plastic or paper bags. This may be achieved by pulverisation or shredding, or using spikes in rotating trommel screens that pierce and rip sacks.

In many cases an MSW processing plant, such as an MBT facility, will include several of these processes arranged in various "circuits". There are two broad families of approach that depend on the initial step taken to deal with the input MSW:

- size reduction by milling or shredding
- trommel screening to achieve separation into size ranges followed by subsequent separations.

This chapter discusses the following pre-processing methods in more detail:

- Separation technologies (handpicking, size and density based techniques, use of electric / magnetic fields)
- Size reduction approaches
- How size reduction and separation are combined
- Other conditioning approaches
- Materials handling issues.

This chapter is not intended as a comprehensive review of mechanical and other waste separation technologies, which have been discussed elsewhere. A review of MBT plants is the subject of another major SET project (see http://www.sitaenvtrust.co.uk/).

6.1 Separation Technologies

Separation of MSW prior to composting typically includes a combination of techniques, drawn from handpicking, size and density based techniques, and using electric and/or magnetic fields.

6.1.1 Hand Picking

Handpicking of refuse is perhaps the earliest and most prevalent handling process. In MSW composting plants handpicking encompasses activities such as the removal of large or unsuitable items from process streams (for example mattresses, large dead animals, stones), clearing materials handling blockages and also dedicated handpicking lines (Cross 1991, Ernst 1988, Manios and Syminis 1988, Sabater and Penuelas 1986).

Hand picking lines are usually installed after some size separation and magnetic screening of the refuse has taken place and is applied larger size fractions (such as plastics, paper and card, metals). In a typical hand picking line materials are transferred in a wide slow moving conveyor past individual "stations" where operatives stand and remove items of value according to a particular scheme. These items are then dropped down chutes where they are collected in skips or other receptacles before baling and sale. In the UK items which are handpicked are those of relatively high value to the plant operator, for example various plastics and possibly paper and card.

There are some who feel that handpicking is a somewhat unsavoury aspect of MSW processing, carrying problems of health and safety (Powell 1992) – for example from discarded hypodermic needles - and low self esteem. Others have the point of view that it is the a cost effective means of recovering resources from mixed MSW streams and is a source of unskilled or even sheltered employment. However, where it is used, hand picking is such an important part of the process that the use of poorly motivated labour can have a significant detrimental effect on the overall process.

6.1.2 Size Separation

Size separation is usually carried out by screening. Screens can be made from bars, mesh, wires or plates slotted with holes, or flexible plastic "stars". They may be flat, or curved for example, into a drum or trommel screen (Glaub *et al.* 1984, Harrison 1965).

Screens made from bars are usually used for screening jobs that require a robust design, particularly for sorting larger heavier items such as rubble. The bars are arranged in a three dimensional array. Large items roll off, and the undersize passes through the array. The other types of screen are effectively two dimensional and material passing through the apertures is "undersize" and material that does not is "oversize". The area of apertures may be referred to as a "bed".

Flat bed screens are typically inclined from the horizontal so that oversize rolls off. Mostly screens shake or vibrate to agitate the materials being screened and so assist the pass through of undersize and the motion off the screen of oversize. The angle of inclination affects the performance of the screening. A smaller angle means that the amount of time larger particles spend on the screen (residence time) is longer. The advantage of a long residence time is that a higher proportion of aggregates will be broken up into their constituent particles; the advantage for a shorter residence time is higher throughput. However, a large angle of inclination also affects the effective screen size, as the aperture becomes more oblique to material falling on to it. The throughput is a function of both the angle of inclination and the rate of agitation and how the agitation takes place. Flat bed screens can be more economical in terms of use of space than trommel screens.

The screening action of trommel screens tends to be more effective as the rotation allows multiple falls of material, and are less susceptible to "blinding" – see the Critical Review Section, *Pre-processing methods - Materials handling issue*s. Trommels are also inclined so that oversize materials pass along them. Trommel screens may include a series of "screen plates" of different apertures so that different size fractions can be removed. They may also include spikes to act as bag bursters and so liberate the individual MSW components. (Other debagging approaches are reviewed by Ballister-Howells – 1992 & 1993) Internal flights or vanes lift material up the sides of the rotating drum from where they fall by gravity. Throughput and screening efficiency are related to: screen sizes, the nature of the screen plates, angle of inclination and speed of rotation. A further effect of trommel screens is that the speed of rotation and the fall of materials will break brittle materials such as glass and ceramics. This effect may be exploited for the removal of non-combustible glass and ceramics from the "oversize" which can then be more easily used in energy recovery. Trommel screen principles are described in detail by Barton (1983), Barton and Wheeler (1988) and Wheeler *et al.* (1989).

The shape of individual MSW items has an important bearing on both their separation and their effect on the separation process. For example for a 50 mm screen a 150 mm long rod of 20 mm diameter may or may not pass through depending on whether it falls to the aperture side on or end on. If a material is very pliable a large item may be pushed through the screen by the force with which it strikes the screen. Paper of plastic film may be carried through a screen by a denser object falling through. Some materials, for example textiles may cause problems in screens by becoming entrained in apertures or on spikes, see the Critical Review Section, *Pre-processing methods - Materials handling issue*s.

A number of mechanistic models have been devised for estimating likely screen performance, mainly based on empirical observations of existing plant. These relate estimated feedstock compositions observed from size / category analyses – see the Critical Review Section, *Sampling and analysis - Physical methods* - to projected screening performance.

6.1.3 Density Based Separation

Density based separations of MSW fall into three basic categories:

- ballistic separators
- systems where items fall in air
- systems where items fall in water

Separation is achieved by the effect of frictional forces on the momentum of moving particles in the MSW stream being treated. This effect is a function of both shape and density. Consequently, separation on density is more effective where the size range of the materials to be separated is controlled. Hence density separation tends to follow screening and/or size reduction steps.

Ballistic separators work by imparting kinetic energy to the items in the MSW stream being treated. In effect the MSW items are flung into the air. Those that carry furthest tend to be denser (US EPA 1971, Wiley 1963). Often the ballistic separation is based on a fast moving conveyor belt which flings items into the air. A "splitter plate" separates two recovery chutes from the end of the conveyor, and is positioned where the degree of separation between "lights" and "heavies" is greatest. Ballistic separators have been applied to improving MSW feedstocks for composting (EC Project 2001), for example, might be used to separate batteries from a putrescible-enriched <50 mm fraction of MSW (Wheeler 1993). A problem for this separation technology as a pre-process step in composting is that some compostables (for example potatoes) are relatively dense and compact, and so could behave in the same way as a reject (such as a battery). An approach that has been used to try and overcome this problem is that the waste stream is flung against a plate, and the separation is based on the amount of deflection from this plate. A more complex approach is where materials are dropped on to a rotating drum or spinning cone, and the resulting trajectory differences bounce glass, metal and stones away from the compost. The rationale for this approach is that compostables tend to be softer and less elastic, so even if relatively dense will not bounce as far.

There are two basic approaches to separating items falling in air: air classification and air-tabling (Abert 1985, Boettcher 1972, Enery 2001, New and Papworth 1988, US EPA 1971). Both use a fan to create a column of air moving upwards, light materials are blown upwards, and dense materials continue to fall. In an air classifier the air column is usually oriented vertically. The air carrying light materials such as paper and plastic, enters a cyclone separator where the entrained materials loose velocity relative to the air stream, because of centripetal forces and their relative density compared with air, and fall out of the air stream. Air tables use the flow of air to "fluidise" the MSW stream on a shaking table. The table is inclined. Lighter materials are carried by the air to one end of the table. Denser materials are agitated down the slope of the table to a different edge. Air tabling can only be applied to carefully controlled size ranges, and is more likely to be of use for graded compost materials than feedstocks. Some air classification units, again more applied to products rather than feedstocks, integrate air classification and a screen plate to separate: "heavies", fine "lights" coarse "lights". Separations in air are not absolute, in particular because the shape of individual components and whether or not they are agglomerated, or sticking to materials of other densities, affects performance. For example, a process aim is to separate glass as “heavy” and compost as “light”. However, glass splinters may end up in the “light” stream, and aggregations of soil or compost in the “heavy” stream. The optimisation of air classification and air tabling depends on air flows and how materials are introduced to the air flow. Performance is critically affected by moisture content, as water is relatively dense and allows some materials to stick to others. The degree of separation (efficiency) is related to yield. For example higher yields inevitably mean a greater amount of “contrary” material in the stream being recovered. Air based separation systems for feedstocks are most commonly applied for the extraction of light high calorific value materials for combustion, and is not used greatly for the size ranges used as compost feedstocks (> 50-70 mm). It has been widely used for refining composted materials.

Density separation in water is less common, but are and have been used (Anon 1984, Birch 1980). The approaches to the use of water in separation are similar to the use of air: elutriation, where the waste stream falls against a rising current of water – analogous to air classification, and wet tabling which employs the same principles as air tabling. In this case the table has and has gently tapering ridges. Denser materials are carried along the ridges to the other end of the table.

Elutriation based techniques have been applied to feedstock preparation. There are several problems with the technique:

- air pockets in the heavy fraction may cause carry-over of materials.
- the elutriator gathers sediment which can interfere with the operation of the elutriator, for example by gradually filling it, and which decompose anaerobically which causes odour
- the need for process water treatment
- the impact of the entrained water on downstream composting (the feedstock may greatly exceed optimal initial moisture contents).

Wet tabling has been applied, with some success, to glass removal from compost (Wheeler 1990). It does however wet the compost which must then be dried both to facilitate its transport and use, and to maintain its stability. If the compost is not dried it may become anaerobic with a subsequent loss in product quality.

Mineral processing technologies include a technique known as “froth flotation”. In this technique minerals are treated in such a way that materials of interest react with the film of a forth generated in a mineral slurry. As this froth forms it is carried over a weir to achieve separation. Froth flotation has been trialled for the recovery of glass from MSW (Burton and Hortin 1976).

6.1.4 Use of Electric or Magnetic Fields

Magnetic fields can be used to remove ferromagnetic materials from the waste stream - i.e. iron and steel (Abert 1985, ASME 1992, EC Project 2001, Exley 1985). Not all steels can be removed by magnets, for example stainless steel may be only weakly magnetic. Mineral processing technology includes paramagnetic separation techniques that can recover other metals such as copper, but these do not have a known application for MSW management.

Magnetic fields are usually applied via electro-magnets so they can be switched on or off to allow the removal of collected magnetic material. Magnetic separations for MSW streams are applied to materials on a conveyor belt. The magnetic field may be applied by a belt itself being magnetic, via an overhead magnet or via a drum at the conveyor. Overhead magnets may either be movable, e.g. it can be moved over a receptacle and switched off to allow collection of the separated items, or they may be magnetic belts. Magnetic belts carry attached metals to a blade that scrapes them off the belt so that they fall into a chute or receptacle. Drum magnets at the end of the belt work because as the belt is drawn over them metals are deflected, so that magnetic and non-magnetic materials can be collected in separate chutes. Magnetic separation efficiency is sensitive to the depth of waste, as small ferrous items will not stick to the magnet if they are buried in non-ferrous materials, while larger ferrous items can drag non-ferrous items like paper and plastic along. Hence the separation works best on controlled size ranges of well liberated materials. However, as the technique is relatively cheap it may be applied at several points in a processing circuit. Magnetic separations may be applied both during pre-processing and refining.

Eddy current separation uses powerful electric fields to separate non-ferrous metals, in particular aluminium (ASME 1992, Exley 1985). This technology works by inducing repulsive (magnetic) forces in electrically conductive materials. Eddy current separators are located after magnetic separation to minimise contamination by ferrous materials. Eddy current separation is most commonly applied with an integrated MBT plant.

Removal of metal items from feedstocks by magnetic and eddy current techniques is generally unable to substantially reduce the loading of composts by trace elements. This is in part because the techniques are not able to remove all discrete metallic objects such as batteries, in part because part of the toxic metal burden is associated with other components such as plastics or cosmetic products, and in part because small metal items may be entrained in organic materials (Critical Review Section, *Feedstocks and composition - Chemical characteristics*).

6.2 Size Reduction Approaches

There are three major types of size reducing devices used in municipal waste processing, although occasional use is made of other techniques (Abert 1985, Anon 1987, Gray *et al.* 1971, Koch *et al.* 2004, Ruf 1974, Von Hirschheydt 1986):

- hammermills
- shear shredders, and
- wet pulverisation.

Hammermills consist of rotating sets of swinging steel hammers through which the waste is passed (tub grinders use a rotating tub to feed a horizontal hammermill). They are energy and maintenance intensive. The hammers need frequent resurfacing or replacement. In MSW processing applications they must be housed in specially designed chambers as propane tanks and other flammable materials can cause serious explosions. Hammermills shatter items such as glass and batteries, which can complicate the refining of subsequently produced compost.

Shear shredders usually consist of a pair of counter-rotating knives or hooks (each of which is several centimetres thick), which rotate at a slow speed with high torque. The shearing action tears or cuts most materials, although thin flexible items like film plastic may slip through the gaps between the knives. This tearing may help open up the internal structure of the particles, enhancing opportunities for decomposition. Shear shredders consume less energy and are less destructive than hammermills, but still can break apart contaminants and make subsequent recovery difficult.

Wet pulverisation makes use of rotating drums where MSW is mixed with water, or wet materials such as sewage sludge by tumbling them along the rotating cylinder (Griffin 2000). As in a trommel screen internal flights or vanes lift material up the sides of the rotating drum from where they fall by gravity. The unit will also act as a bioreactor as degradation usually commences rapidly within the drum (Sabater and Penuelas 1986). Wet pulverisation residence times may be 12 to 72 hours depending in part in whether the system is being used as a first stage of composting. The material that leaves the drum is by no means fully composted, and is highly biologically active. Where the drum is being used as a "bioreactor" aeration may be included to prevent the onset of anaerobic conditions. If used as a composting pre-process, wet pulverisers usually include screen plates at the outlet end, to separate "compostable" fraction from an oversize which will be largely "inerts". Examples of wet pulverisation used to initiate composting are described by: Anon 1984, Apotheker 1991, Barazzetta *et al.* 1987, Canarutto *et al.* 1991, Celardin *et al.* 1990, de Bertoldi *et al.* 1990, Farrell 1997, Gray *et al.* 1973, Harrison 1965, Hart 1968, Hughes 1977 and 1980, Le Bozec 1988, Lutz 1979 and 1982, Pringle and MacDonald 1999, Scott 1961, Stead and Irwin 1980. This list is just a selection from many papers in the technical literature going back some 40 years or more.

A recently opened plant in Leicester uses ball milling, which uses a trommel screen loaded with steel balls to both pulverise and screen the rubbish (http://www.biffa.co.uk).

6.3 Process Integration

Size reduction is important to optimise downstream composting: to maximise its rate and to avoid undegraded materials persisting through to the end of the process. However, reducing particle size also reduces the pore size, limiting the movement of oxygen required for composting.

There are two strategies employed for the treatment of MSW prior to processing for the extraction of recyclables, compostables and energy. The first is to use shredding or hammermilling to achieve a general size reduction of all of the waste, illustrated in Figure A. The second approach is to use a trommel screen as the first process step, illustrated in Figure B. (e.g. Anon 1987, Billecoq 1981, Colon and Kruydenberg 1978, EC Project 1990, Kermode and Wells 1988, Koch *et al.* 2004, Wiley 1963).

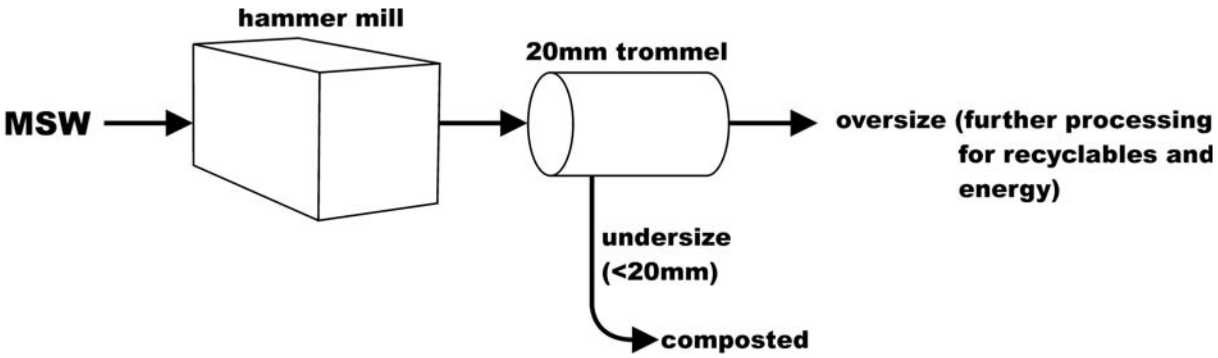

Figure A Pre-Shredding Approach

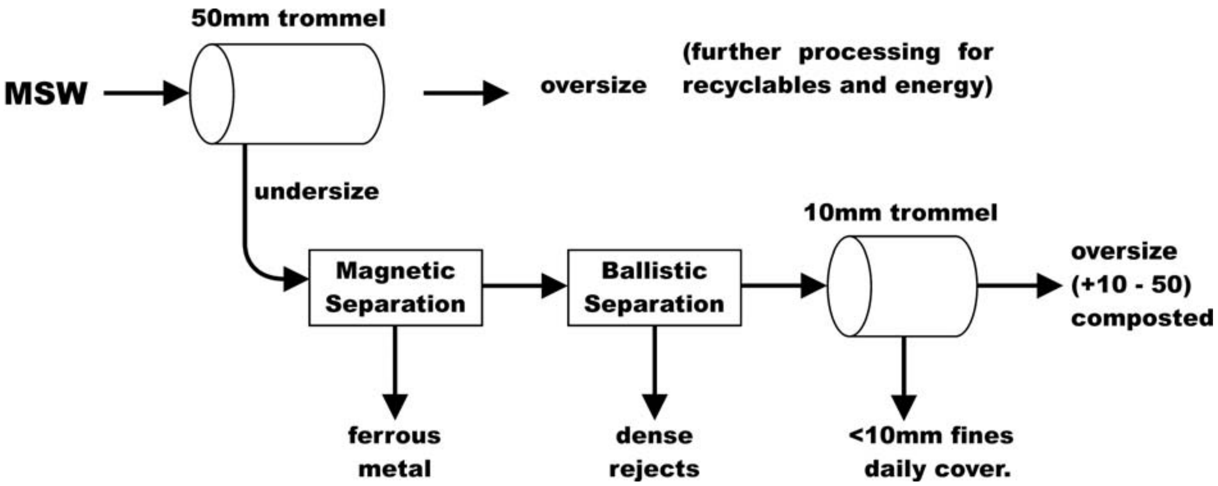

Figure B Pre-Screening Approach

The rationale behind hammermilling or shredding as a first step is to minimise the effects of size and shape on subsequent density based separations, and to allow easier "materials handling". The size reduced fraction may then be screened at a fine screen size (20 mm or so) to further enhance the performance of downstream magnetic and density separations (Barton *et al.* 1990). The undersize may be composted (Anon 1984, Anon 1990, Catto 1999, Millbank 1976), typically with little further treatment as the disintegrated material is rather hard to process mechanically. This approach is often referred to as "front end pulverisation". A problem with this approach is the difficulty it causes for the subsequent removal of inerts (Harrison 1965, Lofgren 1979, Wheeler 1990). For example glass separation from the compost is certainly made more difficult although trials have indicated that wet tabling could achieve low glass contents in a refined compost product (Wheeler 1990). Other reports suggest that front end-pulverisation to very fine particles (2 mm or so) may enhance compost quality (Krauss *et al.* 1987, Von Hirschheydt 1986), masking the appearance of glass and producing a compost with relatively low levels of trace elements. The toxic element content of the organic matter in such composts is not clear, and their glass content will tend to bring the overall total levels "down".

Using a trommel screen as the first process step removes a putrescible rich undersize without milling or shredding. The screen is often also operated in such a way as to break glass and ceramics into the undersize as well. The trommel screen undersize may then be further treated (typically by ballistic and/or magnetic separation, and occasionally water based density separations) before it is composted (Bardos 1989, Bidlingmaier and Alt 1987, Newport *et al.* 1993, Wheeler 1992 and 1993, Zuliana *et al.* 1986). The oversize may then be screened again, for example to facilitate handpicking. The remainder may then be size reduced and separated using metallic and density based separations to separate fractions for recycling and/or energy recovery (Bagstam 1979, Noyon and Begnaud 1990). The different effects of shredding on different types of components in the MSW fraction may be combined with screening to achieve further separations.

The use of wet pulverisation (Pringle and MacDonald 1999) as opposed to trommel screening may increase the amount of paper and card that passes through into the undersize. However, it reduces the quality of the oversize for further recovery of recyclables. This approach is often referred to as "front end screening".

Extensive work has been carried out on the relative benefits of front end screening and pulverisation by the former Warren Spring Laboratory and the University of Leeds in the 1970s and 1980s (Barton 1983, 1984 and 1986, Barton and Poll 1983, Barton and Wheeler 1988, Ege and New 1988, Newport *et al.* 1993, Stentiford 1992 and 1993, Wheeler 1992 and 1993). Their experience shows that front end pulverisation greatly limits the scope and effectiveness of down stream energy recovery and recycling operations. Its impact on compost quality is less clear. One would expect that the liberation of the contents of batteries would increase the heavy metal content of the compost compared with a front end screening approach. Observations of compost quality indicate that this is not necessarily the case, see the Critical Review Section, *Feedstocks and composition - Chemical characteristics*.

The importance of removing glass before the composting process is not clear. Some advocate its removal as far as possible (Anon 1984). On the other hand glass removal is easier from compost which is more friable, and the glass content may help the porosity of the compost and hence the movement of air and water thorough the composting materials.

Two feedstock processing innovations have been suggested to try and improve the potentially toxic element content of composts derived MSW fractions. The first is to operate the composting process to achieve maximum drying (see the Critical Review Section, *Biology of Composting - Optimisation*), then to refine the dried part-composted material, and then to rewet the refined material and allow composting to continue. The rationale for this approach is that the dried and partly degraded material is easier to refine than the raw feedstock, and that early refining might limit opportunities for metal leaching into compost. Indeed it is suggested that biological processing might be the front-end before mechanical processing to ease the recovery of other recyclable products and downstream energy recovery, "biological mechanical treatment" (Cooper 1998, Frith 2004).

The second suggestion is to screen the feedstock at 10 mm to eliminate the toxic element enriched <10 mm fines, and then to screen the finished compost at 10 mm. Materials after composting that are < 10 mm should be largely degraded organic matter. The <10 mm fines initially removed might have low grade applications such as daily cover in landfill.

6.4 Other Conditioning Approaches

Maceration of compostable fractions has been suggested as a means of accelerating biodegradation (Dumons 1995, EC Project 2003).

Pre-processing trials using water jets and sonication of compostable materials have been carried out - in this case prior to digestion (Everest 1994)

Autoclaving and microwave irradiation have been considered as techniques for sanitisation of MSW prior to composting (Defra 2004, Environment Agency Waste Technology Data Centre at http://www.environment-agency.gov.uk/wtd/).

None of these techniques have found widespread practical applications in MSW management, although large scale trials of microwave irradiation and autoclave treatments have been carried out, and processes are commercially available.

6.5 Materials Handling Issues

MSW fractions are difficult materials to move through mechanical processes. Their range of densities, size and shape mean that they are difficult to convey, difficult to deliver to process steps (e.g. air classification) and difficult to recover. Particular problems include the following.

- Textiles can become entangled in moving parts. The generation of "ragtails" of entwined textiles mixed up with other MSW components is a problem for trommel screens and particularly for wet pulverisation drums (Hughes 1977). A more recent problem for trommel screens is unspooling video tape.
- Materials can "bridge". Bridging is where materials have become stuck together so that they form a bridge over a chute. Materials falling to the chute fall over this bridge and end up blocking conveyors and/or tumbling out onto the process floor.
- Materials can cause blinding on screens, which is where materials stick to the screen and gradually close the screen apertures reducing the yield and efficiency of the screen. This is particularly a problem for wet materials, and for fine screens (for example screens used for combined air classification and screening in compost refining)
- In rotating systems materials can be compacted into balls (Hughes 1980, Stead and Irwin 1980), and similar problems may occur with turned windrows (Insley and Carnell 1982).

MSW process plants therefore require constant monitoring, with regular minor maintenance and cleaning to ensure process efficiencies and plant availability.

Dealing with materials handling can be a particular problem for the compostable fraction as anecdotal evidence seems to suggest that bypasses operated in RDF plants while bridged chutes are dealt with, led to the diversion of oversize material to the compostable fraction.

Materials handling issues in MSW separation are discussed in the Warren Spring Laboratory reports referenced in the Critical Review Section, *Pre-processing methods - Process Integration*.

7. Composting Techniques

Composting techniques and their context have been widely reviewed, e.g. Anon 1989 and 1991, Bidllingmaier and L'Hermite 1989, Border 1999, Brunt *et al.* 1985, CIWM 2002, Composting Association 2001, de Bertoldi *et al.* 1986, Diaz *et al.* 1993 and 1996, DTI 2000, EC 2002, Efstathios and Stentiford 2004, EC 2002, Epstein 1997, Environment Agency 2001, Finstein *et al.* 1987, Golueke 1972 and 1974, Hansen 1996, IWM 1994, Jackson *et al.* 1992, Kitto 1988, Lindeberg 1997, Newport 1990, Obeng and Wright 1987, Pescod 1991, Wiley 1963, Wix 1961. A useful general web link is the Environment Agency's web page: the *Waste Technology Data Centre* at: http://www.environment-agency.gov.uk/wtd/

The main aims of the composting techniques reported in the literature include one of more of the following:

- to provide a location for composting to take place which is convenient for both inputting and removing materials and holding materials while they compost
- to optimise the composting process - typically to achieve the fastest possible throughput, which needs to be balanced with achieving the greatest stability and maturity in the product
- to contain the composting process – for example to prevent access by animals and birds, to prevent the escape of odour, to protect the process from the extremes of the weather
- to further mix materials, ensuring even and thorough distribution of the moisture, nutrients and substrates.

From a processing point of view composting is often considered in two phases:

- a rapid "active" phase that includes composting to the end of the thermophilic processes, and
- a longer period of "maturation" occurring at mesophilic temperatures – see the Critical Review Section, *Biology of Composting - Process Optimisation*. Maturation tends to be a slow process taking 3 to 6 months (Bagstam 1979). Maturation benefits from moisture management and occasional turning.

The "active" phase may be further broken into two steps, for example an "in-vessel" treatment followed by an open aeration treatment.

Many composting systems incorporate artificial aeration, others incorporate mixing or turning, and some both. Biological processes in systems that rely on turning alone may be limited by oxygen supply. Systems that do not include some form of turning, agitation or mixing may suffer from problems in moisture control and poor processing at surfaces or interfaces with containment systems (edge effects) and a lack of process homogeneity - see the Critical Review Section, *Biology of Composting -Process Optimisation*. From the point of view of an optimal composting process some combination of aeration and mixing / agitation seems best.

Composting approaches can be divided across four basic categories:

1. The traditional compost heap as used by farmers and gardeners, where the only aeration is provided by diffusion, assisted by convection currents as the waste self-heats. The main problems are that the system can quickly become anaerobic and therefore odorous and inefficient and results in a poor quality product and is not considered further in this review.

2. Using turned windrows, where elongated piles (windrows) are formed and turned according to a regime which aims to maximise the rate of degradation. Turning has the advantage of exposing fresh surfaces to degradation processes.

3. Aerated piles, where air is forced through heaps of compostable materials. Aeration is controlled according to temperature or time or both, to maximise degradation. Aeration may be positive (blowing) or negative (sucking). No mixing of the waste is carried out once the pile has been constructed (hence 'static'). The compost piles may be "static piles", or may be turned intermittently, for example in bay systems.

4. "In-vessel" systems, most of which utilise turning or forced aeration or both. These are generally variations and combinations of the basic control methods of mechanical turning and forced aeration, although the fact that the composting material is enclosed means that the ability for control of the process may be enhanced.

These categories should not be regarded as absolute. For example mechanically agitated systems typically have one surface open, to allow access by mixing screws for instance, however they tend to be described as "contained systems". However, this categorisation is a convenient way of describing composting approaches in generic terms.

The requirements of the Animal By-Products Order and the EC Regulation that it is derived from have an important bearing on how composting techniques can be applied to mechanically segregated fractions of MSW, and is discussed in detail by the Composting Association (2004). An important aspect, in terms of processing, is a requirement for two phases of thermophilic composting, for example an in-vessel treatment followed by a turned windrow treatment. In practice this is not far removed from what has always been the case for MSW composting: a high throughput reactor based treatment (most frequently in rotating drum reactors) followed by a second phase of treatment including composting and aeration. The reasons for this have been largely economic, in that the cost of containing the entire thermophilic processing in-vessel would be astronomical, and in part accidental. The proponents of many in-vessel systems believed they could achieve very rapid completion of composting, whereas in practice the processes continued to occur at the rate biology dictated.

Composting is often taken to include "vermicomposting", which is the digestion of waste materials by worms (CIWM 2002). This has been applied to mechanically segregated fractions of MSW, but is not reviewed here.

Composting may be combined with anaerobic digestion in "hybrid systems" (CIWM 2002, Kayhanian *et al.* 1991, Rogers *et al.* 1992, Von Felde and Doedens 1999), which allow both for some methane recovery and the benefits of composting in producing a dry friable product.

The remainder of this section covers:

- turned windrow approaches

- open aerated systems (e.g. static piles, bay systems)
- contained systems (including: vertical units, horizontal units, reactors with compost agitation)

7.1 Turned Windrow Approaches

Long piles of feedstock (windrows) of about 2 to 3 m high and 3 to 6 m or more wide are constructed, with a roughly triangular cross section. These are constructed on an area known as a composting “pad”. These windrows are arranged in rows, and are allowed to degrade. The process is accelerated by turning the feedstock, manually or using a front loader or specialized machinery. Although this process has the advantage of simplicity it does have some drawbacks. The main disadvantage is that a large land area is required to cope with the long process retention time (at least three months in the UK, excluding maturation on stockpiles). The composting pad must be “hard standing” such as concrete or asphalt, since soil surfaces will be rapidly eroded by the windrowing process.(Composting Association 2001, CIWM 2002, Environment Agency 2001). A range of alternative (i.e. not concrete) hard-standing approaches are described by Riggle 1997, and an example of the use of recycled materials in pads is provided by Anon 2004.

Composting may be retarded or may be incomplete if anaerobic conditions are able to develop in some parts of the heap. Turning of the composting material is necessary to aerate the material to ensure that anaerobic conditions do not occur. The required frequency of turning is determined by the activity of the pile and more active composting requires more frequent turning. To a point the, converse is also true that more frequently turned compost windrows are more active as the oxygen levels are maintained closer to atmospheric levels. In the early stages of composting, turning two or three times a week is appropriate as this is a reasonable compromise between maintaining pile temperature and keeping the oxygen level high enough to avoid anaerobic conditions. Odour problems from windrow turning of MSW fractions is a real risk (e.g. Lofgren 1979, Von Hirschheydt 1986). Some commercial operations do turn less frequently than this (once a week), which runs a higher risk of producing odours, and may slow the process slightly. Later in the composting process the turning rate should be reduce (once per week) so that temperatures are maintained above sanitisation temperatures. Obviously an operation with changing frequencies of turning is more difficult to manage, so many operators operate to weekly turning throughout. Windrow turning operations may take place in buildings (e.g. Kuhlman *et al.* 1993).

There are no specific suppliers of systems for this technology, but individual items of plant that are required can be identified as front end loaders, turning machines, shredders and screens. The requirements of the Animal By-Products Order mean that for mechanically segregated fractions of MSW an open turned windrow is inappropriate as a first stage of a composting system unless it takes place in a building that prevents access by birds and animals, but it could follow treatment in a covered static pile or in-vessel system.

Examples of turned windrow facilities – not all of which are still operating - have been reported by: Abboud and Heidman 2002, Anon 1994, Avnimelech *et al.* 2004, Celardin *et al.* 1994, de Bertoldi *et al.* 1982, Insley and Carnell 1982, Kuhlman 1990, Kuhlman *et al.* 1993, Le Bozec and Resse 1987, Lofgren 1979, Manios and Syminis 1988, Soliva *et al.* 1984, Wheeler 1992. A number of these are composting stages subsequent to processing in rotary compost reactor (see Critical Review Section, *Composting Techniques - Contained Systems - Rotating Drums*).

7.2 Open Aerated Systems

Aerated static pile systems (CIWM 2002, Environment Agency 2001) do not employ mechanical turning. Aeration is provided by fans or blowers which force air through the composting material, using either positive aeration (blowing air outwards from the base or centre of the pile) or negative aeration (sucking air inwards from outside the pile) or a combination of both. Aeration may be provided through perforated pipes set within the piles in low cost systems, or the piles may be built on specially constructed floors set above a venting system. As for windrows it is important that operations take place on a hard wearing surface.

It is usually necessary to cover the perforated pipe or grid with material such as straw or wood chips to prevent the air inlets from becoming blocked with small particles from the compost feedstock. The piles may be covered with inactive material, such as recycled compost, to reduce odour emissions and to retain heat during the thermophilic stage of the process, since otherwise the surface layers of the pile would be unlikely to maintain temperatures in the thermophilic range.

Aeration is controlled according to time and often temperature (e.g. aeration occurs when measured composting temperatures exceed a fixed level say 55^{o}C) – see the Critical Review Section, *Biology of Composting -Process Optimisation*.

Aerated systems allow faster composting than windrow systems, so the land requirements for a similar throughput of feedstocks are lower, and this can provide a significant cost benefit over windrow composting where space is at a premium. However, aerated static pile composting also suffers from some disadvantages. Even with temperature-feedback controlled positive aeration, it can be difficult to ensure temperature control and adequate aeration and moisture levels throughout the pile, and intermittent turning is likely to be beneficial to compost quality.

One way of achieving turning is aeration in bays. Material can then be moved from bay to bay, say at weekly intervals which achieves a turning or mixing effect.

Examples of open aerated systems – not all of which are still operating - have been reported by: Abboud and Heidman 2002, Babos 1981, Bagstam 1979, Barazzetta *et al.* 1987, Canarutto *et al.* 1991, Cross 1991, de Bertoldi *et al.* 1982, European Commission Project 1990, Hughes 1977, Lutz 1979 and 1982, Mooss 1980, Sabater and Penuelas 1986, Willetts 1979 (a bay system). The Warren Spring Laboratory and University of Leeds carried out a substantial programme of test work for "pilot-scale" aerated static pile composting over the late 1980s and early 1990s (Newport *et al.* 1992 and 1993, Stentiford 1992 and 1993, Stentiford *et al.* 1985 and 1986, Wheeler 1992 and 1993 – pilot scale bay systems. A number of these are composting stages subsequent to processing in rotary compost reactor (see Critical Review Section, *Composting Techniques - Contained Systems - Rotating Drums*).

7.3 Contained Systems

A wide variety of engineered systems exist for carrying out composting under contained conditions (Anon 1986, CIWM 2002, Environment Agency 2001). Contained systems do just that, there are no open or exposed surfaces for the compost. Contained systems are also called *in-vessel* systems and the composting vessel may be referred to as a *reactor* or *bioreactor*.

In-vessel systems are intended to provide greater control of the composting process, allowing the temperature, moisture content and air supply to be tailored closely to the requirements of the decomposition process, and usually enable better control of emissions such as odour and leachate. Low retention times (often less than 14 days) are often employed in in-vessel systems. Typically the processing time allowed is insufficient for completion of the thermophilic composting stage, and further compost processing is required for materials leaving the compost reactor (e.g. Abboud and Heidman 2002, Hortenstine and Rothwell 1973, Koenig and Bari 1998).

The costs of in-vessel composting for say 21 to 28 days can often be prohibitive. However, a short duration might be adequate as a first stage of a two stage composting approach intended to comply with animal by-product regulations.

There are a variety of contained systems used in composting. The principle categories that have been applied to treating mechanically segregated fractions of MSW at practical scales are: horizontal systems, mechanically agitated systems, vertical systems, rotating drum systems. Systems currently available in the UK have been reviewed in detail by the Composting Association (2004).

There are other process variants, including aerated “digesters” (e.g. Anon 1999) and passively aerated cage systems (CIWM 2002, Von Hirschheydt 1986), but these have not been widely applied to mechanically segregated MSW.

7.3.1 Horizontal Units

Composting material is contained and aerated in a long, horizontal reactor, usually built of concrete. There are several ways in which materials may be moved in and out of the reactor:

- Materials may be loaded and unloaded by a front end loader, or conveyor system or combination (loading equipment must be cleaned in compliance with animal by-product regulations between handling of raw and treated material)
- Materials may be moved by a plug flow system where a hydraulic ram moves material through the reactor, discharging material that has spent some time in the reactor. The ram then withdraws to create a void space for new material to be input.
- Materials may be moved along a reactor by a moving floor system.

In most systems, forced aeration occurs along the length of the reactor floor. The advantage of a horizontal system is that the height of the composting materials is typically less than 2 to 3 m, which is important for achieving optimal aeration (see the Critical Review Section, *Biology of Composting -Optimisation*. Tunnel reactors are gaining widespread acceptance in the UK.

Examples of horizontal reactor or tunnel composting – not all of which are still operating - have been reported by Bardos 1987, Catto 1999, Cooper 1998, EC Project 1991, Mathsen 2004, Pringle and MacDonald 1999, Pringle and Svoboda 2002.

Flender (1982) describes the recovery of heat from a horizontal compost reactor, and its use for landfill leachate treatment, in parallel with composting.

7.3.2 Mechanically Agitated Systems

Feedstock is agitated mechanically to aerate and mix it. A wide variety of commercial systems are available. These systems generally rely on batch, rather than continuous processing. The main disadvantages are in ensuring adequate aeration, as in windrowing systems: insufficient turning prevents proper aeration. Therefore a number of systems combine mechanical agitation with forced aeration. These systems can be expensive to install, operate and maintain, but are generally highly effective.

Examples of in-vessel systems using mechanical agitation – not all of which are still operating - have been reported by: Butters 1980, Hortenstine and Rothwell 1973, Mousty and Reneaume 1984, Mousty and Levasseur 1987, Newport *et al.* 1992 and 1993 (a 1 tonne size pilot scale system), Zuliana *et al.* 1986.

7.3.3 Vertical Units

Composting material is enclosed and aerated in a vertical reactor (also known as “silos”, “towers”). Although capital costs tend to be high, the approach is intended to allow composting to take place on a small land area. However, many vertical reactors have suffered from serious compost process difficulties. The vertical reactors may either have a continuous depth (e.g. Anon 1990), sometimes referred to as silos, or they may be staged systems, in effect a series of stacked in-vessel reactors (e.g. Atchley *et al.* 1979).

The weight of composting material in silo-based or like systems can be sufficient to cause compaction of the material at the base of the reactor, and impede aeration (de Bertoldi *et al.* 1988, Stentiford and de Bertoldi 1988). The degree of compaction can be sufficient to prevent the materials discharge equipment of the system from functioning. Compaction usually impedes effective aeration, resulting in extensive anaerobic regions developing in a composting mass, and a greatly reduced efficiency of decomposition (see the Critical Review Section, *Biology of Composting -Process optimisation*). Removal of anaerobic materials, which may need to be manually removed, can cause extensive odour emission. Examples of these problems have occurred both abroad (e.g. Lofgren 1979) and in the UK (e.g. at the former Secondary Resources facility at Castle Bromwich, Birmingham).

Two approaches have been taken to *try* and reduce the extent of compaction and aeration difficulties in these silo-based or silo like systems. The first, mainly applied to existing reactors, is supplementary aeration above the base of the reactor, or by including a rotating rabble arm at the base.

Examples of vertical reactor systems – not all of which are still operating - have been reported by: Anon 1990 and 1996, Farneti *et al.* 1981, Easter 1982, Gothard 1961, Hart 1968, Le Bozec . and Morvan 1986, Lofgren 1979, Von Hirschheydt 1986.

7.3.4 Rotating Drums

Rotating drum systems are the most common in-vessel composting approach, although they only initiate composting and do not complete thermophilic processing. Feedstocks are introduced into one end of a slowly rotating drum, inclined at about 5 degrees from horizontal. Moisture may be supplied as water or as sewage sludge. Aeration is promoted by the tumbling action of the materials. Air injection and moisture addition systems have also been used on occasion. The combination of physical attrition and microbial degradation causes "wet pulverisation" of the material. Retention times vary from 4 to 6 hours to 2 to 3 days. This length of time does not permit a significant amount of composting activity to take place, but the drum does allow the homogenisation and screening of materials for subsequent composting (Barazzetta *et al.* 1987, Le Bozec 1988). Consequently, rotating drum systems are usually combined with either aeration in static piles or windrow turning to complete the most active (thermophilic stages) of composting (e.g. Canarutto *et al.* 1991, Celardin *et al.* 1990, Hughes 1977, Mooss 1980). The rotating drums used are the same equipment that is used for wet pulverisation – see the Critical Review Section, *Pre-processing methods - Size Reduction*, however operating conditions such as retention times, may be altered to enhance the systems composting "performance".

Examples of rotating drum systems – not all of which are still operating - have been reported by: Anon 1984, Apotheker 1991, Bagstam 1979, Barazzetta *et al.* 1987, Canarutto *et al.* 1991, Celardin *et al.* 1990, Cross 1991, de Bertoldi *et al.* 1982 and 1990, de Haan 1981, DTI 1992, Ernst 1988 and 1990, Farrell 1997, Gray *et al.* 1973, Harrison 1965, Hart 1968, Hughes 1977 and 1980, Kubota *et al.* 1984, Le Bozec 1988, Lutz 1979 and 1982, Mooss 1980, Pringle and MacDonald 1999, Sabater and Penuelas 1986, Scott 1961, Stead and Irwin 1980, Teensma 1961, Zuliana *et al.* 1986. This list is just a selection from many papers in the technical literature going back some 40 years or more.

8. Refining and Packaging

Compost refining techniques include adaptations of the separation and size reduction techniques already described in the Critical Review Sections: *Pre-Processing Methods - Separation Technologies* and *Pre-Processing Methods - Size Reduction*. In addition, operations may include the production of fine pellets (around 5 mm diameter) from composts, and/or bagging of the compost (Newport 1990). A number of developmental techniques have also been evaluated, for example the use of electric fields or chelating agents for the removal of trace elements from composts.

For the most part the "product" is the organic rich fraction. However, dense fractions with low organic content (for example rich in glass and ceramics) may be of use in landfill as daily cover or in drainage layers.

This chapter considers:
- separation processes applied in refining
- fine milling and pelleting
- mixing and bagging
- other techniques (largely experimental).

8.1 Separation Processes Used in Refining

Separation processes are used in compost refining to remove "inerts" such as glass and plastics, and in parallel increase organic matter content. The techniques used have already been described in the Critical review Section, *Pre-Processing Methods*, and include

- sizing techniques – principally screening using flat screens and on occasion trommels. See the Critical Review Section, *Pre-Processing Methods - Separation Technologies - Size Separation*. Screen sizes often used are:
    - 25 mm to separate a coarse grade which is re-composted or rejected
    - 10 mm to produce a soil improver grade of compost from a coarser grade which may find a low grade use (e.g. Celardin *et al.* 1990)
    - 5 mm to produce a fine grade of compost
- density separations - principally using air classification or air tables (stonors). See the Critical Review Section, *Pre-Processing Methods - Separation Technologies - Density Separation*. Air classification may be used to remove dense items such as glass or pottery fragments, and also to remove very light items such as plastic film. Sophisticated pieces of equipment have been designed which combine density separation with screening. The application of wet systems is (obviously) rare.
- magnetic separations are reviewed in the Critical Review Section, *Pre-Processing Methods - Separation Technologies - Electric/Magnetic*. During refining they are used to remove ferrous metal from compost fractions, although these may also be recovered by density separations. The use of eddy current separators in compost refining appears to be infrequent.

There appears always to be a "trade-off" between product quality and product yield (Bardos 1989). The separations of organic matter and inerts achieved are not perfect. Hence if a greater level of inerts removal is required, the yield of finished compost is lower, as inevitably some organic matter will be carried over into the reject fraction by the separation process.

The removal of inerts such as glass does seem to be accompanied by an increase in compost content of nitrogen and phosphorous, but also by an increase in concentration of trace elements. See the Critical Review Section, *Feedstocks and Composition – Chemical Characteristics*.

The pre-processing approach selected has a considerable bearing on the ease of refining. Composts produced from shredded or pulverised feedstocks are harder to refine (remove inerts from) than those produced from compost fractions produced by screening, see the Critical Review Section, *Pre-processing methods - Process Integration*. However, as produced, they may have a lower trace element concentration, perhaps as a result of a higher content of paper and inerts, see the Critical Review Section, *Feedstocks and Composition – Chemical Characteristics*.

Reports and papers dealing in detail with the application of separation technologies to compost refining include: Babos 1981, Bardos 1989, Boettcher 1972, King 1990, New and Papworth 1988, Newport *et al.* 1992 and 1993, US EPA 1971, Von Hirschheydt 1986, Wheeler 1990 and 1993.

8.2 Fine Milling and Pelleting

Residual glass can remain a problem in composts produced from mechanically segregated fractions of MSW, even after refining using separation technologies – see Critical Review Section, *Refining and Packaging - Separation Processes Used in Refining*. Residual glass content can be pushed higher by a desire to increase compost "product" yields. Two approaches that have been used to disguise residual glass and render it relatively harmless: fine milling (e.g. Brunt *et al.* 1985, Gogue and Sanderson 1975, Hagenmaier. and Krauss 1982, Lutz 1982, Mooss 1980) and pelleting (e.g. Anon 1984, Hortenstine and Rothwell 1973, King 1990, New and Papworth 1988, Wheeler 1993).

Pelleting is carried out by extruding the compost under pressure through a die, the assembly that carries this out is called a pellet mill. a 5 mm diameter aperture has been found to produce compost pellets of reasonable size and appearance. The pelleting process is strongly dependent on the compost moisture content. If it is to dry pellets will not form, if it is too wet the compost will be extruded like spaghetti. The compost is heated by the pelleting process. Compost pellets have been found to breakdown only relatively slowly in soil applications and as a growing media. This was found to be beneficial for soil improvement but detrimental in use of the compost in a growing media (Dunn *et al.* 1995, Nortcliff and Baker 1994).

Both fine milling (to 0.2 to 0.5 mm) and pelleting are energy intensive processes and require significant capital investment, which can substantially increase production costs.

8.3 Mixing and Bagging

Composted products from mechanically segregated MSW have been mixed with other materials to produce growing media type products, for example bulk amendments such as sand (e.g. Bagstam 1979), or materials added to improve the fertiliser value of the compost (e.g. Rainbow and Wilson 1997). However, unless composts can be produced to a very high quality, the production of growing media products from mixed waste fractions may be an unrealistic aspiration. See the Critical Review Section, *End-uses - Growing Media*.

Bagging plant varies in the level of automation, from simple manual bagging plant to fully automated production lines. No UK producer is currently bagging composts made from mechanically segregated fractions of MSW. Typically green waste compost is bagged at 40 to 50 litre volumes. This is less than the 80 litre bags common for peat based products. The smaller bags are used because green waste compost is denser than peat based materials, and experience shows that the smaller size bag is most manageable. Anecdotal evidence suggests that in the UK bagging is typically carried out by subcontractors. As well as the costs of the process plant, or its hire, bagging costs will also encompass art and design and printing and also transportation of loose and bagged materials.

It is important that compost to be bagged is both stable, and dry, e.g. less than 20% moisture (Schulze 1961) to prevent biological activity continuing to an extent that it will cause the compost to become anaerobic and odorous. Even where composts are dry and stable, it is important to design the compost bags so that the composts can "breath", so that any residual activity does not give rise to anaerobic conditions.

8.4 Other Techniques

A range of techniques have been trialled to remove metal ions from composts to reduce sodium ion or trace element contents. Techniques that have been trialled experimentally include electrochemical techniques, extraction techniques using chelating agents and the use of plants – phyto-extraction (Baek *et al.* 2000, Ciba *et al.* 1999, Jorgensen 1993).

9. Health and Safety, Emissions and Emissions Control

Health and safety, emissions and emissions control issues for composting of mixed and separately collected MSW fractions have been extensively reviewed (e.g. CIWM 2002, Deportes *et al.* 1995, Efstathios and Stentiford 2004, Epstein 1996, Forster *et al.* 2001, Gillett 1992, Newport 1990).

In 2004 the Composting Association produced a *Guide for Site Managers* on *Health and Safety at Composting Sites*, which provides comprehensive guidance. Also in 2004 Defra released a detailed *Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes*. This describes in detail the possible health effects that might be attributable to composting operations. In 2001 the Environment Agency released *Technical Guidance on Composting Operations*, which covered potential environmental impacts of composting and the regulation of the process.

There are a range of operations encompassed in composting mechanically segregated fractions of MSW:

- waste collection
- pre-processing
- composting
- refining
- distribution
- use.

Composting and its ancillary operations should only take place with the advice of recognised health and safety officers, and must be compliance with appropriate health and safety law and regulations. This document does not provide advice that can be used as definitive in the development of health and safety policies and guidelines. Applicable regulations and legislation includes (not an exhaustive list):

- Health and Safety at Work Act 1974
- The Management of Health and Safety at Work Regulations 1999

- Environment Agency Position on Composting and Health Effects, August 2001
- Control of Substances Hazardous to Health Regulations 2002 (COSHH)
- Noise at Work regulations
- Animal By-Product Regulations 2003
- Reporting of Injuries Diseases and Dangerous Occurrences Regulations 1995 (RIDDOR)

See Composting Association 2004 for further information.

This chapter aims to point out the key issues connected with health and safety, emissions and emissions control, and to provide case studies, examples and review references related to the composting of mechanically segregated MSW. The following topics are covered:

- leachate
- odour / volatile organic compounds (vocs)
- dust
- bioaerosols and other health risks
- vermin / birds / insects
- fire risks.

Other issues include noise, litter which may be blown off site and hazards presented by amendments and chemicals used (such as pesticides), machinery and transport, which are not covered by this review. Further information is available from: Composting Association 2004, Environment Agency 2001, Mays *et al.* 1973, Williams 1999). Note that litter can present a direct hazard to foraging animals (Mays *et al.* 1973).

See also the Critical Review Sections: *Product Quality and Environmental Impacts,* in particular: *Product Quality and Environmental Impacts - Microbial and Pathogen Issues.*

From a sustainability point of view one should consider the overall balance of inputs and outputs around the composting operation. Inputs include energy, materials, water, for example. Outputs include emissions such as carbon dioxide, nitrogen compounds, potentially hazardous substances etc. See the Critical Review Section, *Operational and Strategic Issues.*

9.1 Leachate

The term "compost leachate" is colloquially used to describe liquids draining from compost piles or piles of other stored materials. This water arises from two sources: water liberated by the physical and biological degradation of organic material, and rain water that has percolated through the compost pile. Where piles are protected from rain, little leachate is produced. The main concerns for leachates are (a) that they tend to be odorous, (b) that they may act as a vector for organisms, (c) that pooled leachate supports the proliferation of insects such as flies and mosquitoes, and that the leachate contains dissolved substances that may have a negative environmental impact. Leachates tend to have a high conductivity, and a high biological and chemical oxygen demand from soluble organic matter, for example fatty acids. They tend to have relatively high content of ammonia compounds (changing to nitrate depending on the age of the compost). They also contain dissolved trace elements. Leachate composition varies according to the age of the compost, and the composition of the feedstock.

In the UK leachate emissions must be captured by a drainage system for treatment, which may be on site or leachates may be removed by tanker for off site treatment. Leachates may also be discharged to sewers, if suitable consents exist and appropriate pre-treatment put in place. Good site management dictates that leachate is not allowed to pool on the surface where it can be a noxious hazard and support the proliferation of insects, neither can it be allowed to drain into the subsurface. Compost leachate has been used to add moisture to compost piles, to both help optimise the composting process and deal with the leachate (e.g. Flender 1982). A variety of conventional wastewater treatments can be applied to compost leachate.

Note: *Run-off* is generally used to describe water that has fallen onto the pile (for example, rainwater) but has not percolated through, or that has fallen onto the site surface without touching the pile. While run-off may contain lower concentrations of pollutants than leachate, its separate collection and treatment for windrows and aerated static piles is rarely practicable. However, separate collection of leachate is practical for contained systems. Although the volumes collected *may* be too small to make separate treatment an economic proposition, it could reduce off site treatment costs where leachate is removed by tanker. Condensation in buildings housing composting operations may also require collection and treatment.

References: CIWM 2002, Diaz and Trezek 1979, Environment Agency 2001, Leita and Nobili 1991, Mott MacDonald 1999, Muesken and Bidlingmaier 1992, Ulen 1997.

9.2 Odour and Volatile Organic Compounds

Odour from composting plants arises from the feedstocks, the composting process itself and the product as it is refined (Muesken and Bidlingmaier 1992). Finished compost should not have an unpleasant odour, rather it should have an earthy smell (produced by actinomycetes). The compounds that cause unpleasant odours include nitrogen compounds, such as ammonia, sulphur compounds and mercaptans, and a variety of volatile organic compounds (VOC) such as fatty acids which are often released by biodegradation. The generation of odorous compounds is exacerbated under anaerobic conditions, as production of hydrogen sulphide, mercaptans and VOC is enhanced (Eitzer 1995, Kim *et al.* 1995, Kissel *et al.* 1992 and 1993, Kryzmien *et al.* 1999).

The production of odour is the probably the most frequent cause of serious and widespread neighbour complaints, and is reported in the literature as early as 1961 (Gothard 1961). While odour may not be directly injurious to health (Wheeler 2001) it reduces the quality of life for those affected (Warde-Jones 1996). Odour problems may be far-reaching, and affect quite distant neighbours (Kruger 1986). Odour complaints have led to composting plant closures (Libbey 1991), so odour is a very serious issue for compost operators.

Mitigation measures for odours include at the out set good site management practice. This encompasses: ensuring that feedstocks are rapidly processed, that compost stockpiles are managed to ensure that they do not become anaerobic, that litter is regularly removed before it rots further and that the composting process is optimised so that decomposition is as fast, and as aerobic, as possible. Machinery should be maintained, and any breakdowns rapidly dealt with. It may be important to be selective about the nature of feedstocks accepted for mixing with MSW fractions, for example sewage sludge and manures may exacerbate odour risks.

Even if good odour management can be assumed, it is important to have ready prepared a strategy for dealing with any incident likely to cause an odour release, including a pro-active approach to informing site neighbours (CIWM 2002).

Mitigation measures for chronic odour problems include the use of commercially available odour-masking agents (CIWM 2002). These work by spraying fine aerosols of chemicals into the air to absorb and neutralise odorous substances; their use can be timed to coincide with operational activities. However, some neighbours may find these agents themselves noxious.

Compost process odour can be contained in in-vessel systems, and potentially by screening compost piles with finished compost (Brunt *et al.* 1985) or, it is claimed, by commercially available compost covers. Air emissions from contained compost systems is typically treated using dry and wet scrubbers and biofilters (Federal Environment Agency – Austria 1998, Williams 1995). Odour emissions may also arise from leachate storage, which may be controlled in part by aeration.

Emissions from composting such as ammonia and water vapour can have a corrosive effect on buildings, which may require adaptation to cope with these emissions (Tyler 2000).

9.3 Dust

Dust can be defined as tiny, solid particles that can be carried by air currents. Dusts contain particulate matter and also biological agents (bacteria and spores) described further in the Critical Review Section, *Bioaerosols and Other Health Risks*. Dust is produced as composts, feedstocks and composting materials are agitated, for example during compost turning, movement, or refining, or pre-processing of the MSW feedstocks (Diaz *et al.* 1976, Fiscus *et al.* 1978).

The formation and release of bioaerosols and dusts can be controlled in a number of different ways, the easiest of which is through good site design and management. Enclosing a biological process and treating exhaust gases (such as through a biofilter or chemical scrubber) will significantly reduce the concentrations of bioaerosols released into the environment, although worker exposure may be increased significantly (CIWM 2002, Weisweiler *et al.* 1986). Other control measures include: adjusting the moisture content of degrading materials to prevent them drying out, ensuring a site is kept clean and the use of misting sprays.

Research carried out on behalf of the Environment Agency suggested that measured inhalable dust concentrations at a number of out door composting facilities were below the legal occupational exposure standards and as such it was concluded that dusts do not pose a health risk to plant operators or the general public (Forster *et al.*, 2001, Wheeler *et al.*, 2001). See also: Gladding 1995.

9.4 Bioaerosols and Other Health Risks

There are a variety of health hazards in composting operations. The risks these hazards pose depends on the linkage of a hazard via a “pathway” to a receptor. For example:

- hazard – pathogenic organisms in feedstock

- pathway – ingestion of materials (for example from unwashed hands)
- receptor – compost site workers.

The risk posed is a function of the probability and scale of any effect. For compost workers there may be a variety of potential health risks, for example exposure to leptospirosis (transmitted via rat urine), exposure to allergens in composts and dusts and exposure to pathogens (Defra 2004, Sanders and Ray 1976). This is not an exhaustive list, and these risks cannot be ignored. There are plenty of cases of health impacts on composts and MSW plant workers in the literature (Lundholm and Rylander 1980, Powell 1992, Sigsgaard *et al.* 1989). Pathogens may be a hazard in feedstock materials, but seem unlikely to pose a risk in properly composted products, although plant and animal parasites cannot be ruled out (Andrews *et al.* 1994, Fiscus *et al.* 1978, Gaby 1975). Compost sites should make a formal risk assessment for their operations. Further guidance on health and safety at composting plants is provided in Composting Association 2004. In the UK Hazard Analysis and Critical Control Point (HACCP) strategy is usually employed to minimise risks from plant and animal pathogens and parasites in compost products, and also to control other risks (Evans 2003). HACCP is based on the identification of all processing steps, determining which of those steps have a controlling influence on risks, determining the best means of managing such *Critical Control Points* and employing this information in an overall production strategy to minimise risks. It is a process design tool that complements the role of QA, which is the standardisation of operating procedures, including checks that operations are performed in a consistent, traceable manner and that performance is satisfactory. Process planning activity should be based on an assessment of risk, and should identify which hazards are of such a nature that their elimination or reduction to an acceptable level is essential to the maintenance of product integrity.

Composting sites may pose risks to other human receptors as well as site workers (Wheeler *et al.* 2001). The Environment Agency in their 2001 *Position on Composting and Health Effects* concluded that the most likely risk is from the generation of “bioaerosols”. Bioaerosols are micro-organisms and spores suspended in the air. There are two principal impacts: (a) “Gram negative” micro-organisms contain a toxin in their cell walls – endotoxin (b) many actinomycetes and fungi have spores that can trigger serious allergic reactions (Lacey 2002, Lacey and Williamson 1989). Suspended micro-organisms have been reported to spread as far as 1,000 m from compost processing sites (Burge and Millner 1980). However, in the UK 250 m is used as a benchmark in siting composting facilities: facilities should be more than 250 m from the nearest “receptor”, unless a site specific risk assessment demonstrates that risks are negligible (CIWM 2002). Bioaerosols from composting plants have been extensively researched, e.g.: Clark *et al.* 1983, Crook *et al.* 1988, Danneberg *et al.* 1997, Epstein 1994, Fiscus *et al.* 1978, Lacey *et al.* 1990, Lacey and Williamson 1989, 1991 and 1995, Nersting *et al.* 1991. Further guidance on appraising bioaerosol risks is provided in Composting Association 2004.

There has been much concern about the exposure of human populations to toxic substances contained in composts derived from mechanically segregated MSW. Contents of trace elements and organic substances are discussed in the Critical Review Sections: *Product Quality and Environmental impacts - Trace Elements* and *Product Quality and Environmental impacts - Organic Pollutants*. However, no formal risk assessments have been carried out. A more significant issue is the principal of soil protection, which has been interpreted by a growing lobby of people to mean that the content of trace elements (and toxic organics) in soils should show net increase over time.

Other key receptors are water and the wider environment. Leachate from composting operations must be contained and managed, see the Critical Review Section, *Health and Safety, Emissions and Emissions Control - Leachate*. Migration of nitrogen from composts, and their loading of trace elements, inerts, toxic organics and even plant nutrients such as phosphorous may all cause environmental impacts from compost use. The key principal must be that compost use is beneficial and does not lead to unacceptable emissions. This topic is discussed further in. the Critical Review Section, *Product Quality and Environmental Impacts*.

Composting operations themselves have an environmental impact (for example odour, noise, dust, visual intrusiveness), and an environmental impact assessment may be a requirement for gaining planning permission and licensing. Composting operations may also have wider economic and social effects, for example blighting property, or having a negative effect on neighbouring property values. Those near existing and proposed composting facilities will have legitimate fears and concerns about operations, which requires dialogue (rather than monologue) to resolve. It may be prudent to engage in stakeholder consultations at an early stage in the development of a composting proposal, to avoid confrontational and expensive arguments in due course (Halstead and Whitcombe 1994).

9.5 Vermin / Birds / Insects

Problems with flies, persistent birds and vermin do occur at composting facilities. Good site management can reduce the chances of serious problems. Flies, vermin and birds cause nuisance problems, and are also a possible cause of contamination of finished composts by pathogens. Feedstocks should be processed as quickly as possible, and composting should be optimised to be as rapid as possible. Ensuring exposure of all of the composting mass to thermophilic temperatures will remove insects, larval stages and eggs from the compost. Rapid transition to compost will remove potential food sources for nuisance insects such as flies, and also form mammals such as mice and rats and birds. Colonisation of maturing composts by a variety of soil animals (insects, annelids etc) is almost unavoidable, and ultimately likely to be beneficial. Site cleanliness is very important in reducing the attractiveness of the site to vermin and birds, and reducing fly populations. Litter and undegraded feedstock, pools of liquid, should all be avoided. Contained composting may have some benefit in reducing the surface area of feedstock during early stages of composting. Insect control by pesticides is a possibility, but it may not be in keeping with composting operations to use pesticides on a continuous or regular basis. Mice and rats can be dealt with by baited traps and a variety of bird scaring devices - of varying effectiveness - are available (Alvarez *et al.* 1972, Bechmann and Schriefer 1988, Block 1988, Brunt *et al.* 1985, Gaby 1975, Gotaas 1956).

9.6 Fire Risks

Fires involving materials being stored or processed in bulk can have severe impacts on the local communities and the environment. It is important that site managers at municipal recycling facilities (MRFs) are aware of all the potential fire hazards that exist on their sites in order for them to produce a comprehensive fire safety plan and an effective risk assessment (Manchester and Bardos 2004).

There are a number of potential fire hazards at composting sites, resulting from the operations for compost preparation and refining, and the storage of materials. The possible sources of ignition include: sparks form vehicles and processing operations, lightening, arson, cigarettes and also the spontaneous combustion of materials stored in bulk (Anon 1988, Buggein and Rynk 2002, Rynk 2000, Rynk and Bloc 2000, Willson 2002).

10. Product Quality and Environmental Impacts

Composts derived from mechanically segregated MSW have several properties which may be of potential benefit for soil improvement and restoration or in growing media, as well as a pre-treatment prior to landfill. These are:

- a limited (and slowly available) content of plant nutrients, such as nitrogen, phosphorous, potassium, calcium, magnesium and trace elements
- stabilised organic matter
- a liming effect
- biological activity.

Not all of these benefits are suitable for all applications, see the Critical Review Section, *End-uses*.

However, composts derived from mechanically segregated MSW also may have several properties which might be deleterious for these applications, and which may cause wider environmental impacts from the compost application. These might include:

- excessive trace element contents
- excessive content of toxic organic compounds
- lack of stability or maturity
- impacts from migration of nitrogen and enrichment of phosphorous or nitrogen immobilisation
- deleterious organisms
- excessive content of “inerts”

This chapter reviews the following compost properties and the significance to compost applications and the wider environment:

- physical properties
- major chemical properties
- trace elements
- organic pollutants
- inerts
- microbial and pathogen issues
- maturity and stability.

Note moisture contents of finished, matured refined MSW-derived composts tends to be 40 to 60% on a fresh weight basis, bulk density 500 kg.m^{-3}.

10.1 Major Chemical Properties

The major chemical properties of MSW derived compost affecting product quality are:

- its content of major and minor plant nutrients: nitrogen, phosphorous, potassium, calcium, magnesium in particular
- its effect on pH
- its effect on redox
- its organic matter (carbon) content
- its conductivity (and sodium content).

Composts derived from mechanically segregated fractions of MSW contain low, but useful, concentrations of plant nutrients, in particular potassium and phosphorous. *Total* contents are typically (Anon 1984, Bardos 1989, Bengton and Cornette 1973, Newport *et al.* 1992 and 1993, Wheeler *et al.* 1992 and 1993):

- N - nitrogen 0.5 to 1.5% in dry matter
- P – phosphorous 0.2 to 1.0% in dry matter
- K – potassium 0.2 to 1.2% in dry matter.

The bibliography contains more than 40 references reporting plant nutrient contents, mainly NPK. In some cases contents may be reported as oxides (K_2O and P_2O_5), in which case the amounts reported would be higher as oxygen content is included. Positive effect on compost yield have been observed resulting from applications of MSW-derived composts. Composts derived from animal manures or sewage sludge have a higher NPK content, and usually generate a better crop response when comparative trials are carried out. However, there occasional reports of better yields using MSW-derived composts, and combined fertiliser and compost applications generally tend to outperform either amendment on its own. Some investigation of the effects of MSW-derived composts on crop quality have also been carried out, and qualities appear to be comparable (e.g. Anon 1998, Cabrera *et al.* 1989, Duggan and Wiles 1976, EC 2002, Garner 1962 and 1966, King *et al.* 1977, Mazur *et al.* 1983). Further examples are given in *Table A* in the Critical Review Section, *End-uses - Soil Improvement*. Gallardo-Lara *et al.* (1990) investigated MSW-derived composts as a treatment for sulphur deficient soils.

Only a small proportion of the nitrogen and phosphorus contained in mature composts is in inorganic – and so readily plant available - forms (Morel *et al.* 1986). The majority is bound, for example in biomass, and is released gradually. This gradual release may be a desirable property for some applications, where some fertilising effect is desired over time - for example energy forestry (Bardos *et al.* 2001), rather than a rapid effect at the start or middle of the growing season.

A possible cause for concern about environmental impacts is the leaching of nitrate and phosphorous from soils amended with MSW-derived composts to groundwater and surface water (Alza *et al.* 1999, Mamo *et al.* 1999, Murillo *et al.* 1989). The Department for Environment Food and Rural Affairs has released Guidelines for Farmers in Nitrate Vulnerable Zones (Defra 2003).

Some reports have found that MSW derived composts have immobilised nitrogen and caused deficiency symptoms in test plants / crops (e.g. Duggan and Wiles 1976, Sims 1990). This immobilisation is thought to be due to an excess of carbon substrates over nitrogen. The carbon substrates are thought to stimulate soil microbial growth, which then absorbs nitrogen to support that growth. It is therefore likely to be a feature of composts with a high ratio of carbon to nitrogen (CN > 30). These high CN ratios are likely to be a feature of young (immature) composts, or composts containing a high proportion of woody and paper materials which only degrade slowly through the composting process. The effect is temporary, as the biomass dies back nitrogen will be released. The biological activity of the compost may also have benefits on general nutrient turnover in the soil "soil fertility" - (Mazur *et al.* 1983, Werner *et al.* 1988).

Young composts and composts with a high CN will have a high oxygen demand in the soil, which can also affect the soil environment, lowering redox conditions which can affect trace element availability and soil pH, and also removing soil oxygen from root systems (Inbar *et al.* 1990).

MSW-derived composts can have a significant liming effect owing to their content of magnesium and calcium, and for very acid soils the buffering effect of the soil organic matter added. This liming effect may be advantageous for some soil improvement activities (Telman *et al.* 1973).

The major component of compost of interest to compost users is its organic matter content. It is the addition of organic matter to soil which has beneficial effects on soil structure condition, workability, water holding and fertility (via its effects on soil biology and the soil cation exchange capacity) see the Critical Review Section, *End-uses - Soil Improvement*. The organic matter content of MSW-derived composts is very variable depending on how the MSW feedstock was processed prior to composting, and refined afterwards. Organic matter content may vary from as little as 30% to as much as 70% of the dry matter, typically measured as loss on ignition (Bardos 1989, Morel *et al.* 1986, Newport *et al.* 1992 and 1993, Scott 1961, Villar *et al.* 1993). A number of investigations of the nature of this organic matter and its humification have been carried out (Chefetz *et al.* 1996, Gonzalez-Prieto *et al.* 1993, Gonzalez-Vila and Martin 1985, Inoko *et al.* 1979) although the practical relevance of these is not always clear. The major components found tend to be lignins and celluloses.

There is also considerable debate about the value of organic matter return to soil as a means of providing a net absorption of potential atmospheric carbon dioxide (EC 2002). It has been estimated that soil carbon sequestration could meet at most a third of the global annual increase in atmospheric CO_2-carbon, at current emission rates. While this seems like a substantial impact, the effect is dependent on on-going land management to maintain high soil organic matter contents, and the effect is limited in its duration (Anon 2004).

Conductivity of all composts including MSW-derived composts (e.g. Van Assche and Vyttebroeck 1982), tends to be high compared with peat of soil. A proportion of this conductivity is due to the sodium content of the compost. Excessive sodium contents may degrade soil structure, but this does not appear to be reported problem for MSW derived composts. High conductivity is not suitable in growing media, so typically waste derived composts have to be diluted to formulate growing media mixes see the Critical Review Section, *End-uses – Growing Media*. Immature composts are likely to have a higher conductivity (Avnimelech *et al.* 1996).

10.2 Trace Elements

The trace element composition is one of the most extensively researched and reported aspects of composts derived from mechanically segregated MSW. This bibliography includes over 150 entries. Key points and references are reviewed in this section. In general papers discuss:

- "total" trace element contents, typically trace elements extracted using strong acids such as concentrated nitric acid
- how trace element contents vary depending on how trace elements are extracted from compost, for example in water only extracts, extracts using dilute calcium chloride, extracts using chelating agents such as EDTA and DTPA, which are seen as providing information on which compost components trace elements are "bound" to, and
- the uptake of trace elements by plants (and mushrooms).

A series of references are summarised in Table A. Methods of trace element analyses are discussed in the Critical Review Section, *Sampling and Analysis*.

Table A: Selection of References Relating to Trace Element Content of Composts Derived from Mechanically Segregated MSW

"Total" trace element contents described	Trace element contents in different compost fractions described	Plant uptake of trace elements described (many also include fractionation studies)
Anon 1984, Bardos 1989, Bengton and Cornette 1973, Cabrera 1989, Celardin *et al.* 1990, Clark 1973, Colon and Kruydenberg 1978, Cook and Beyea 1998, de Haan 1972 and 1981, Duggan and Wiles 1976, Dyer and Ranzi 1987, Ege and New 1987, EC 2002, Furrer and Gupta 1983, Genevini *et al.* 1987, Giusquiani *et al.* 1988, Gonzalez-Vila *et al.* 1982, Gothard 1959, Gray and Biddlestone 1980, Hernando *et al.* 1989, Hortenstine and Rothwell 1973, Johnson 1970, King *et al.* 1977, Krauss *et al.* 1987, Krauss and Wilke 1995, Kreft and Bidlingmaier 1996, Lutz 1979, Mooss 1980, Newport *et al.* 1992 and 1993, Olaniya *et al.* 1992, Rugg *et al.* 1992, Scott 1961, Stentiford *et al.* 1985, Ulen 1997, Van Roosmalen *et al.* 1987, Villar *et al.* 1993, Walker and O'Donnell 1991, Wheeler 1990, 1992 and 1993, Wheeler and Bardos 1992, Wong 1985.	Canarutto *et al.* 1991, EC 2002, Giusquiani *et al.* 1988, Leita and Nobili 1991, Lustenhouwer and Hin 1993, Murillo *et al.* 1989, Petruzzelli 1985 and 1989, Tisdell and Breslin 1995.	Andersson 1975/76, Andersson 1984, Anid *et al.* 1983, Anid 1986, Baldwin and Shelton 1999, Berthet *et al.* 1989, Canet *et al.* 1997,Chu and Wong 1987, de Haan and Lubbers 1983 and 1984, EC 2002, Fritz and Venter 1988, Giordano and Mays 1977, Gogue and Sanderson 1975, King *et al.* 1977 Liebhardt and Koske 1974, Lineres and Petruzelli 1988, Mills *et al.* 1986, Purves and Mackenzie 1973, Shiralipour *et al.* 1992, Sims 1990, Stead and Irwin 1980 and 1981, Telman *et al.* 1973, Van Assche and Vyttebroeck 1982, Wong *et al.* 1983, Wong and Chu 1985, Wong and Lau 1985, Zhang *et al.* 1998.

Levels of many trace elements: in particular arsenic, boron, cadmium, copper, lead, mercury, nickel, selenium, zinc tend to be elevated in composts derived from mechanically segregated fractions of MSW compared with composts made from materials separated at source. The origin of this elevated metal content, and how it is affected by pre-processing and refining is reviewed in the Critical Review Section, *Feedstocks and Composition - Chemical Characteristics*. Contents of aluminium, iron, manganese and other metals also tend to be elevated.

The environmental significance of these elevated trace element contents is not known in an unequivocal way, with much debate continuing. The relationship between trace elements contents and risks to human health and the environment are a matter of some contention. Formal risk assessments developed by the US EPA for sewage sludges have been applied to MSW-derived composts (Logan *et al.* 1999), and result in "threshold" concentrations somewhat higher than those considered acceptable by most current European compost standards. The UK "CLEA" guidance on soil assessment in the context of contaminated land remediation includes detailed information about the toxicology of a number of trace elements (and toxic organics), but this information has not been derived or used in the context of compost to land applications *per se*. The CLEA web ink is http://www.defra.gov.uk/environment/landliability/clea2002.htm.

However, risk assessment is not seen as necessarily the appropriate yardstick for determining acceptable levels of trace elements in organic materials applied to land, for example by the EC Soil Strategy drafting papers (http://forum.europa.eu.int/Public/irc/env/soil/home). An alternative philosophy is related to soil protection, which at its most stringent is expressed as no net increase in trace element (or toxic organic burdens) in soils over time. Limit values based on this philosophy will have a much lower set of threshold concentrations for trace elements in organic matter than purely risk based assessments, as removal of trace elements from soil in crops or by leaching are slow processes (e.g. Dyer and Ranzi 1987).

There are two tenets for the soil protection position. The first is that it is not a sustainable use of soil to leave future generations with soil in a poorer condition (i.e. with a higher trace element content) than now. The second relates to a concern about "critical loads". This tenet is that, while soil can buffer the trace elements it acts as a sink for, this buffering capacity is not infinite, and as soil reaches its buffer capacity further changes may cause very large environmental impacts, for example a "sudden" and massive release of trace elements to plant available forms. This buffer capacity is not well established, and is also vulnerable to environmental changes itself, such as soil acidification. Therefore, inputs of trace elements to soils should be strictly controlled. However, information on the effects of trace elements on soil processes is conflicting, with many reports finding tolerance to quite high trace element contents (e.g. Giusquiani *et al.* 1994), while others find that some processes, in particular nitrogen fixation, are sensitive to soil trace element content. It also appears that trace element migration down the soil profile, for example to groundwater is also limited (e.g. Mays and Giordano 1989).

A counter argument is that relying on a single decision making criterion such as soil protection alone may not achieve sustainable development because the "wider costs" of achieving that soil protection may mean that environmental (and also social and economic) impacts occur elsewhere. These impacts could conceivably be more serious than those that might arise from elevated trace element contents in soils.

Another approach to the derivation of limit values is based on what is the lowest reasonably achievable level of contamination (Composting Association 2000). The latter is referred to as the "as low as reasonably achievable" or "ALARA" approach.

This is a continuing debate, and it looks like the end point will be a compromise, with perhaps an emphasis towards soil protection. A possible approach is that the risk assessment is based on the soil where the compost is to be used, to provide maximum application rates, rather than on trace element contents in the composts themselves.

The literature on trace element composition of MSW- derived composts is not consistent. It is clear that trace element levels are elevated, say compared with soils. In some cases phytotoxic effects from undiluted compost, particularly on germination, have been reported. These are attributed to boron in several papers, but may also be related to the compost maturity and stability, as well as its conductivity. Many papers report that regular application of MSW-derived compost applied to land leads to accumulation of trace elements in the topsoil. However, reports on the "availability" of these trace elements to plants are not consistent. Some articles report that levels of plant available zinc and copper increase, and increases in plant available cadmium, nickel and even lead have been reported. A number of reports suggest that availability is limited by the organic matter content of the compost (although this effect may be time limited) and that older composts tend to have less available trace elements. Conversely, other reports suggest that both total and available concentrations of trace elements in composts increase over time.

No clear picture emerges about the significance of the "fractionation" of metals in composts. Some articles suggest that particular extracts may be predictive of plant availability, others find the converse. Direct observations of plant uptake also present a mixed picture. Zinc and copper uptake are most commonly reported, and overall it may be that uptake is greatest for roots, followed by leaves, followed by fruit and seeds. However, uptake data appears to be strongly related to the specific conditions of each experiment, such as the source and nature of the compost, how the compost is treated/diluted, and the types of plants grown in it. The importance of any differences between metal uptake from other organic matter sources, for example manures or source segregated materials, is not clearly known. The dietary significance of any elevated trace element content in plants is often (but not always) assumed to be negligible, but no unequivocal information is available (although the CLEA work may serve as a useful platform for further assessment).

10.3 Organic Pollutants

Elevated levels of toxic organic compounds have been found in composts derived from mechanically segregated MSW (and from source segregated MSW, and in sewage sludge). There are divided views over significance of the elevated levels of these micro-organic pollutants in MSW-derived composts. Several commentators believe that they do not pose significant risks, while others suggest that MSW-composts should not be used as a precautionary measure. Limit values for micro-organic pollutants are being discussed by the EC at present for a forthcoming sewage sludge (revised) / biomass Directive. Some of the limit values proposed are so low that they preclude the use on land of almost all sewage sludges, and this is seen by some as not very sustainable, and also unnecessary from a risk assessment point of view (EC 2002, Friege 1992, Grossi *et al.* 1998, Smith 2000 and 2001, Vogtmann and Fricke 1992). The same arguments about risk assessment and soil protection approaches are being debated for micro-organic pollutants as for trace elements (discussed in the Critical Review Section, *Product Quality and Environmental Impacts - Trace Elements*).

Many organic pollutants are degraded by the composting process, and this degradation appears to be a facet of compost maturation over time. Chlorinated organics such as organo-chlorine pesticides, PCBs and highly substituted VOCs tend to be only slowly degradable in compost (under aerobic conditions). Dioxins also are only poorly degradable. As well as biodegradation, irreversible immobilisation to organic matter and losses to volatilisation may be significant routes for micro-organic pollutant losses from composts (Buyuksonmez *et al.* 1999 and 2000, EC Project 2003, Martens 1982, Regan *et al.* 1998, Rynk 2000, Stegmann *et al.* 1993).

Measurements of micro-organic pollutants in compost is a complex task, and the measurements themselves are expensive and subject to some uncertainties. Relatively few investigations have been carried out compared with trace element studies of MSW-derived compost. Table B lists reports in the literature for various categories of micro-organic pollutant. Other references are available in the bibliography listing. The data in these reports should be assessed with great caution. Comments such as “levels of total PAH” may be misleading as individual PAHs vary greatly in their toxicity, and the age of the compost sampled is not always discussed.

Table B Reports of Toxic Organic Compounds in MSW-Derived Composts

Compound	References
dioxins, furans and PCBs	Cook and Beyea 1998, Deportes *et al.* 1995, Friege, Grossi *et al.* 1998, Harms and Sauerbeck 1983, Krauss and Wilke 1995, Lahl *et al.* 1991, Malloy *et al.* 1992 and 1993, Muller *et al.* 1974, Tosine *et al.* 1985, Wilken *et al.* 1982
PAHs	Cook and Beyea 1998, Ellwardt 1977, Grossi *et al.* 1998, Hagenmaier *et al.* 1986, Harms and Sauerbeck 1983, Joyce *et al.* 1998, Martens 1982, Muller and Korte 1975, Overcash *et al.* 1993, Wischmann and Steinhart 1997
pesticides and herbicides	Buyuksonmez *et al.* 1999 and 2000, Carnes 1972, Muller and Korte 1975, Regan *et al.* 1998, Rynk 2000 and 2002
VOCs	Brown *et al.* 1997, Kim *et al.* 1995
Others	Gonzalez-Vila *et al.* 1982, Magalhaes *et al.* 1993, Malloy *et al.* 1992 and 1993, Overcash *et al.* 1993, Stegmann *et al.* 1993

The UK “CLEA” guidance on soil assessment in the context of contaminated land remediation includes detailed information about the toxicology of a number of toxic organic compounds, but this information has not been derived or used in the context of compost to land applications *per se*. The CLEA web ink is
http://www.defra.gov.uk/environment/landliability/clea2002.htm.

The Dutch Ministry of Housing, Spatial Planning and Environment has also published information on the risk assessment of toxic organic compounds in soil, again in the context of contaminated land (VROM 2000).

10.4 Inerts

Inerts are materials in the compost which are effectively not biodegradable, such as: glass, stone, metals, and plastics. Pre-processing and refining greatly reduce the levels of inerts in composts derived from mechanically segregated fractions of MSW, but do not fully eliminate them. See the Critical Review Sections: *Pre-Processing Methods* and *Refining and Packaging*.

Inerts pose a variety of problems in compost products:

- sharps – fragments of glass and hypodermic needles are sharp and present a hazard during compost handling (Kendle 1990)
- visual impacts both in the product and the landscapes of treated areas – for example glittering from glass (Clark 1973, Soliva *et al.* 1984, Von Hirschheydt 1986)
- hazards to grazing animals (Mays *et al.* 1973) which may be harmed by ingesting inerts
- hazards to wildlife, for example birds and soil fauna (Stamatiadis and Dindal 1986)
- litter, for example wind blown plastic film (note see also the Critical Review Section, *Feedstocks and Composition - Biological Characteristic*s about the debate over biodegradable plastics).

Inert materials may be disguised by pelleting or fine milling – see the Critical Review Section, *Refining and Packaging - Fine Milling and Pelleting*. Inert materials may be eroded over time *in situ*. However the effect is slow (Page and Leonard 2002). Inert contamination may also be rendered invisible by plant growth, for example grass cover. Inert materials are also a major cause of trace element contamination of MSW derived composts, particularly small fragments, however this contamination appears to be largely irreversible even after compost refining – see the Critical Review Section, *Feedstocks and Composition - Chemical Characteristics*.

10.5 Microbial and Pathogen Issues

Microbial and Pathogen Issues

Human infections and illness from compost production and use may well be rare, but have been recorded, Control of risks from animal pathogens are the subject of recent regulations, see the Critical Review Section, *Health and Safety, Emissions and Emissions Control - Bioaerosols & Other Health Risks*. Many plant pathogens are destroyed during the composting process, although some *may* persist (see The Composting Association Information Sheet 21 *Plant Pathogens – Honey fungus*, available via http://www.compost.org.uk). On the other hand compost use has been found to suppress a wide rage of plant diseases.

Human and animal pathogens are likely to be rare or absent in properly made and matured composts derived from MSW. The destruction of pathogens during the composting process is referred to as *sanitisation* - see the Critical Review Section, *Biology of Composting - Process Optimisation*. Parasitic organisms *may* persist (Noble and Roberts 2003), and a risk assessment may be appropriate, particularly if sewage sludge has been used in the composting mix. Finished composts, from all sources, will contain opportunistic pathogens such as pseudomonads and *Aspergillus*. These are part of the microbial community that mediates the composting process, and so cannot be avoided. Those most at risk from opportunistic pathogens are the elderly and people with compromised immune systems. Opportunistic pathogens exist in other media such as the soil, and risk assessments for product users and compost operators may be necessary, along with instructions for use (Andrews *et al.* 1994, Gaby 1975, Jager *et al.* 1994, Jones and Martin 2003, Knoll 1982, US EPA 2001).

The most likely human health hazard from (*any*) compost is use is that posed by bioaerosols released when compost, particularly dry compost, is agitated. This hazard has been reviewed in the Critical Review Section, *Health and Safety, Emissions and Emissions Control - Bioaerosols & Other Health Risks*. A risk assessment for product use may be necessary, and based on this the provision of suitable instructions for use.

Composts are not unique in these microbial and pathogen issues which affect a wide range of materials, for example wood chips, topsoil, etc. The risks posed by composts and composting have been described by the US Environmental Protection Agency (US EPA 2001) as follows: *There is very little potential for properly prepared, finished compost to affect public health or animals. The data regarding workers at composting facilities have shown that workers have not been affected over the past 20 years. Workers are the most exposed individuals to pathogens and bioaerosols. Workers need to exercise proper hygienic practices. In conclusion, properly designed and operated non-green feedstock composting facilities should not present a public health or worker health threat*.

Composts also have beneficial microbial properties. Composts may exert a beneficial effect on soil microbial activity, developing soil fertility (Stehouwer 2004). Of particular interest are the observations that MSW-derived composts (and other types of compost) may suppress plant pathogens such as nematodes, rots and some virus infections (D'Errico and Di Maid 1980, EC 2002, Hunt *et al.* 1973, Logsdon 1993, Noble and Roberts 2003, Serra-Wittling *et al.* 1997, Tilston *et al.* 2002, US EPA 1997, Van Assche and Vyttebroeck 1982). This suppression may also be mediated by aqueous extracts of compost, so-called "compost tea" (Scheuerell and Mahaffee 2002).

Note: information on persistent weeds and composting has been compiled in the Composting Association Information Sheet 15 *Composting - Noxious Weeds*, available via http://www.compost.org.uk.

In the UK Hazard Analysis and Critical Control Point (HACCP) strategy is usually employed to minimise risks from plant and animal pathogens and parasites in compost products, and also to control other risks (Evans 2003) – see the Critical Review Section, *Health and Safety, Emissions and Emissions Control - Bioaerosols and Other Health Risks*.

10.6 Maturity and Stability

Composts which are mature and stable have the widest range of potential end-uses, and are easiest to handle, transport and manage, although some uses may be tolerant of composts which are not fully stabilised or matured (such as soil forming for land restoration) – see the Critical Review Section, *End-uses*.

Compost maturity, stability and phytotoxicity are inter-related properties:

- Stability refers to the degree of biological decomposition and potential to degrade further
- Maturity refers to the ability of a compost to support plant growth
- Phytotoxicity refers to the potential for detrimental effects of compost on plant growth.

They are discussed in detail, along with test methods, in the Critical Review Section, *Sampling and Analysis - Biological Methods*.

Composts which have poor stability cannot be stored easily, are subject to further changes in the properties, may be odorous, may generate significant amounts of carbon dioxide (and methane) over storage, will interfere with plant growth by stimulating microbial activity that competes with the roots for oxygen, and possibly nitrogen. The most reliable tests of stability observe oxygen utilisation or carbon dioxide emissions of test samples (ADAS Consulting 2003, EC 2002).

Composts which are immature contain agents which interfere with plant growth. A wide variety of such agents have been detected including fatty acids, ammonia and phenolics (Chanyasak *et al.* 1982, Chanyasak and Kubota 1981, Wong 1985, Zach *et al.* 2000). These agents often are generated by ongoing degradation of the compost. Hence there is a strong linkage between maturity and stability. It has also been suggested that thermophilic organisms release toxins, which are gradually degraded during maturation (Anid 1986). It is also possible that ethylene, a plant signalling agent, produced in anaerobic zones in the compost may affect root growth.

A range of maturity tests have been proposed, including looking at changes in CN ratios, changes in ammonium content, cation exchange capacity, changes in organic matter composition, conductivity, sugar content (ADAS Consulting 2003, Avnimelech *et al.* 1996, Chanyasak and Kubota 1981, Harada and Inoko 1980, Harada *et al.* 1981, Hirai *et al.* 1986, Inbar *et al.* 1990, Inoko *et al.* 1979). The common feature of these tests is that
they require sophisticated laboratory analyses,

- they are dependent on a range of site and measurement specific factors making comparison of different products difficult (Morel *et al.* 1986)
- and their interpretation is rather subjective.

The most practical test of compost maturity is to use is seen as seedling emergence (ADAS Consulting 2003, EC 2002), which emerged as an approach in the early 1980s (Stentiford And Pereira-Neto 1985, Zucconi *et al.* 1981). Note that poor seedling emergence tests may also be due to high conductivity in composts.

11. End-uses

The broad classes of end-uses that MSW-derived composts have been used for (CIWM 2002, Efstathios and Stentiford 2004, Newport 1990) are:

- soil improvement - enhancing soil structure, condition and fertility
- growing media – as a component of mixes used to grow crops in containers
- mulches – used to suppress weed growth and conserve water
- restoration – used for “soil forming” and soil improvement

- landfill applications – restoration and improvement of landfill covers and as a daily cover material
- other applications – such as manufactured top soils and “top dressings”, in turf production, as a fill material, for tree planting, and as a fuel

Composting as a process is being used, or considered for use, as a pre-treatment prior to landfill in several European countries. This is in part a response to the EC Landfill Directive.

These are discussed in turn in this chapter. In addition this chapter reviews current developments in standards for composts and advice about compost marketing.

An important facet of end-uses for MSW-derived composts is to ensure that the quality, and perhaps the *perceived* quality, of the compost is appropriate for the end-use envisaged. There has been a lot of debate, particularly in the wake of developing interest in MBT composting, about so-called “lower grade” uses (Centemero *et al.* 1999, DETR 1998, Godley *et al.* 2002, US EPA 1994, Walker and O'Donnell 1991, Wheeler *et al.* 1994 and1996). “Lower grade” uses are applications thought of as more tolerant of some of the contamination problems of composts derived from mechanically-segregated MSW. However, it is dangerous to make very simple assumptions about the market place for composts. “Lower Grade” compost may not be seen as suitable by those managing applications such as landscaping (Kendle 1990). Some feel it has no use on the land (Hammer 1992). “Lower Grade” is a contentious term. Some believe that *any* compost derived from mechanically segregated MSW should be described as *lower grade*. Others feel that distinctions between compost quality grades should be made on the basis of the compost product composition, rather than the feedstock it was produced from. The term “lower grade” is also though of as pejorative, and therefore one that should not be used.

In the UK the current regulatory situation *appears* to be that composts produced from source segregated composts will more readily seen as recycled products than composts produced from mechanically segregated composts, as discussed in the Critical Review Section, *Operational and Strategic Issues - Regulations Standards and Guidelines for Compost Products*. Consequently, taking into account both the current regulatory climate *and* the sensitivity over the term *lower grade*, the following might be a better broad classification of compost types, by application.

- **Premium Grade** - freely usable for agricultural and horticultural applications, or in the manufacture of formulated products such as “composts” for home use, turf, pot plants etc. These applications may still be subject to over-arching regulations such as those controlling the application of nitrogen to land, but can otherwise be freely traded by any organisation without specialist expertise.

- **Regulated Grade** – composts suitable for applications such as use in remediation, restoration, agriculture, forestry, short rotation coppice (SRC) and non food crops where either an element of specialist expertise is necessary in trading and use or there is ongoing regulation of the application or both. These applications can make beneficial use of recycling organic matter to land. However, biological, chemical or physical hazards remain a regulatory concern, for example controls on trace elements or animal pathogens.

- **Engineering Grade** – composts used where access is strictly limited, and other risk management measures are already in place, for example uses such as daily cover, or as engineering fill material - for example in bunds and sound barriers, or as pollution control measures such as biofilters.

MSW-derived composts are unlikely to meet requirements for "premium grade" compost as concerns over their contents of inerts trace elements and possibly organic pollutants (see Critical Review Sections: *Composting: Past and Present* and Product *Quality and Environmental Impacts*) Some degree of regulation of their use seems inevitable (see Critical Review Sections: *End-uses - Standards and Guidelines* and *Operational and Strategic Issues*).

Note: In addition dense reject fractions are often produced during MSW-derived compost refining, which may have some possible uses, for example as engineering fill or in drainage layers.

11.1 Soil Improvement

A *soil improver* is a material that is added to soil, usually outdoors, in order to improve one or more soil properties (Composting Association 2001).

The principal benefits of compost addition leading to soil improvement result from its organic matter content, its microbial content and its content of plant nutrients (see the Critical Review Section, *Product Quality and Environmental Impacts - Major Chemical Properties*). These inputs may have a direct effect, for example a fertilising effect, or an indirect effect, for example stimulating soil microbial activity resulting in the development of humic materials and enhanced soil functions (such as fertility).

The effects of soil improvement are:

- minor changes in soil texture (the balance of mineral particles in the soil between sand, clay and silt)
- significant changes in soil structure, such as enhanced porosity and strength, resulting from increased soil organic matter content, which results in more workable and resilient soils, and for finely textured soils improved drainage
- significant changes in soil condition, largely resulting from soil organic matter changes, including enhanced cation exchange capacity, enhanced plant nutrient buffering and availability, enhanced pH buffering (as well as liming effect) and enhanced water holding capacity
- a degree of improvement in plant nutrient status (from the its content of plant nutrients, typically in a "slow release" form) the improvement effect on soil; condition and fertility may also enhance the effectiveness of other fertilisers added to the soil
- significant impacts on soil microbiology, both from the organic matter input and possibly the biomass input, including improved plant nutrient turnover and availability, and possibly suppression of plant pathogens (see the Critical Review Section, *Product Quality and Environmental Impacts - Microbial and Pathogen Issues*).

Nutrient levels tend to be less than for synthetic fertilisers, and so it would be wise to highlight the other benefits of compost-based products (CIWM 2002). Without regular applications (say annually), the soil improvement effect will gradually diminish with time as organic matter is degraded, which may be faster in sandy soils (Levi-Minzi *et al.* 1985) and under arid conditions (Pascual *et al.* 1998). Soil improvement effects used to be seen as gradual with no early economic benefit to the grower (MAFF 1976). However, many of the references in *Table A* below reveal rapid and far reaching benefits (i.e. measurable benefits within one to two years).

References relating to soil improvement by MSW-derived composts include: Avnimelech *et al.* 1990, Avnimelech and Kochva 1997, EC 2001 and 2002, Gallardo-Lara and Nogales 1987, Giusquiani *et al.* 1988, Jakobsen 1995, Khaleel *et al.* 1981, Murillo *et al.* 1989, Perucci 1990, Schoemakers 1985.

Key market sectors for waste derived composts have been identified by CIWM (2002) as agriculture, landscaping, forestry, horticulture, land restoration, and construction. Table A lists reports for MSW-derived compost use for each of these applications.

Table A MSW-Derived Compost Use for Soil Improvement by Sector – Example References

Sector	References
Agriculture, and horticulture	Anon 1998, Bryan and Lance 1991, Cabrera *et al.* 1989, Celardin *et al.* 1990, Chu and Wong 1987, Duggan and Wiles 1976, Dunn *et al.* 1995, Florensa *et al.* 1985, Fritz and Venter 1988, Furrer and Gupta 1983, Giordano and Mays 1977, Hortenstine and Rothwell 1973, Jakobsen 1995, King *et al.* 1977, Mamo *et al.* 1999, Mays *et al.* 1973, Poran 1996, Roe *et al.* 1993, Sainz *et al.* 1998, Schultz and Romheld 1997, Shiralipour *et al.* 1990, Sims 1990, Stead and Irwin 1980, Telman *et al.* 1973, Tietjen and Hart 1969, Van Assche and Vyttebroeck 1982, Wong *et al.* 1983, Wong and Chu 1985, Zhang *et al.* 1998
Landscaping (including grassland)	Garcia *et al.* 1991, Kendle 1990, Murillo *et al.* 1995, Sanderson 1980, US EPA 1997
Forestry (including energy forestry)	AEA Technology and r3 environmental technology limited 2004, B9 Energy and Shanks First 2002, Bardos *et al.* 2001, Bengton and Cornette 1973, Insley and Carnell 1982, Maynard 1988, Shiralipour *et al.* 1990, Smith *et al.* 1979, Tienken and Dreves, E. 1987, US EPA 1997 and 1999
Land Restoration (including at landfill sites)	B9 Energy and Shanks First 2002, Bardos *et al.* 2001, Bending *et al.* 1999, Duggan and Scanlon 1974, Dunn *et al.* 1995, Insley and Carnell 1982, Norland and Veith 1995, Nortcliff and Baker 1994, Sellers *et al.* 2002, Stapleton 2000, Stout *et al.* 1982

11.2 Growing Media

A *growing medium* is a material used to grow plants in containers, such as pots and growing bags, where the plants are confined and depend on the growing medium for most of their requirements (Composting Association 2001). Growing media have a range of uses: propagation, potting, ornamental plantings, growing bags, ericaceous composts, nursery stock and blocking compost. Different characteristics are required for each. In some cases, growing media are branded as 'multi-purpose compost'. Such products are in great demand but are difficult to develop. Failure to meet product claims will lead to disappointment, loss of faith in the product and possibly legal action being taken against the manufacturer. It is unwise therefore, to attempt to market such a product unless it has been developed and manufactured with the benefit of specialist expertise (CIWM 2002).

Since the 1970s the majority of growing media production has used peat as the major constituent. A wide variety of alternatives to peat are available (Verdonck 1983). The consumption of peat to produce growing media in the UK is now slowly falling, and the consumption of peat alternatives is increasing - the same is true for soil improvers (ODPM 1999). There is great interest in support for accelerating a move away from peat based products for a variety of environmental reasons (English Nature and RSPB 2002).

MSW-derived composts have been used as a component of mixes used to grow crops in containers, mainly for ornamentals, trees and landscaping plants. They have also been used in growing media for horticultural crops, in particular tomatoes. Reports in the literature are mainly of propagation, potting, ornamental plantings, growing bags and for nursery stock. In nearly all cases MSW-derived composts have formed less than 30% of the growing media mix. Problems with their conductivity, physical properties, pH and boron content preclude higher addition rates. Even, at these relatively modest proportions the performance of growing media containing MSW-derived compost is not always as good as generally available alternatives, (see: Biddlestone and Gray 1991, Castillo *et al.* 2004, Chong 1999 and 2000, Dunn *et al.* 1995, Fitzpatrick 1981 and 1989, Gogue and Sanderson 1975, Lumis and Johnson 1982, Maynard 1988, Sanderson 1980, Siminis and Manios 1990, Stead and Irwin 1981, Stentiford *et al.* 1985, Van Assche and Vyttebroeck 1982).

Recent guidelines have been produced by WRAP (WRAP 2004) for the *specification of composted green materials used as a growing medium component*. These specifications **exclude** composts produced from mechanically segregated fractions of MSW (http://www.wrap.org.uk).

11.3 Mulches

Mulching is where materials are laid on the soil surface to suppress weed growth, conserve water and/or maintain soil temperatures or protect plants against frost. Sheets of paper, and also plastic film are used as mulch. Granular materials such as composts and woodchips can also be used as mulches and have the advantage of allowing movement of air, and infiltration of water. Mulching may also be used to control and runoff, particularly in combination with the establishment of vegetative cover. Mulching may also be combined with coppicing for the long term maintenance of energy forestry. Mulches typically need to remain in place for several months at least so a minimum period of longevity is expected. Mulching is seen as a potential application for waste-derived composts (Agassi *et al.* 1998, Bardos *et al.* 2001, CIWM 2002, Hoogerkamp and Verhoek 1976, Roe *et al.* 1993, Tardy 1996). Pelleted compost tends to persist for longer than unpelleted compost (Dunn *et al.* 1985) and so may have some advantages as a mulch.

Mulching is related to soil improvement, in that mulches are gradually incorporated into the soil and may have consequent soil improvement effects. The limitations on using MSW-derived compost as a mulch are therefore the same as those for using it as a soil improved, discussed in the Critical Review Section, *End-uses - Soil Improvement*. A further concern for mulching applications may be: the degree to which a mulching material may be a fire risk, and their stability under windy conditions – they should remain in place. This characteristic will depend on particle size and on density. Matured composts used as mulches should have a relatively low calorific value (Anon 1987) and, if so, would therefore have relatively limited risks of ignition. This may not be true for raw or immature composts.

11.4 Restoration

Restoration is, perhaps, a special case of soil improvement. It is slightly different because the organic matter may initially be used in a different way, for example for "soil forming" where the surface cover is so unlike topsoil that reasonable plant growth is not possible. Restoration may also make use of the organic matter content of the compost as part of a risk management strategy to stabilise site contamination problems. Example articles are listed in Table A in the Critical Review Section, *End-uses - Soil Improvement*.

Soil forming material: parent material for new soil used as a substitute for, or supplement to, natural soils in the course of land reclamation (Bending *et al.* 1999, Stapleton 2000). Bending *et al.* implied that soil forming materials were inorganic in nature and would be supplemented by organic amendments. The term is often also used to describe the organic amendments. An emerging soil forming activity of great contemporary interest is in the establishment of biomass crops, possibly in conjunction with the rehabilitation of derelict or contaminated land (Bardos *et al.* 2001).

The stabilisation benefits of organic matter application in restoration may be buffering of pH and redox changes in the subsurface (which may limit the further release of contaminants, for example from pyretic materials, and stabilisation/immobilisation of trace elements and organic compounds, as well as supporting the consolidation of the surface and consequent management of erosion. Any such effects would need to be applied in the context of an overall risk management strategy for the site being restored (AEA Technology and r3 environmental technology limited 2004, Bardos *et al.* 2001). The trace element and content of toxic organic substances in the compost used would need to form part of this risk management strategy.

11.5 Landfill Applications

MSW-derived compost applications in landfill are primarily for restoration or improvement of the landfill cap and use as a daily cover material. The restoration benefit of organic matter is largely related to its performance as a soil improver for low grade subsoils placed over the landfill cap, or for soil formation over the landfill cap (Dunn *et al.* 1985). Example articles about MSW-derived compost use in land fill restoration are listed in Table A in the Critical Review Section, *End-uses - Soil Improvement*.

Landfill sites have a requirement for inert cover throughout their operating life, in order that the refuse tipped during the course of a working day may be covered over at the end of the day to prevent access by flies and vermin, and the wind dispersal of the tipped refuse. MSW-derived composts may be used as this daily cover material, instead of virgin materials such as topsoil or sand (Anon 1986, Cossu *et al.* 1995, Pohland and Graven 1993). It is not clear whether use as "daily cover" is regarded as recycling under current UK regulations (SEPA 2002). Dense reject fractions from compost processing may also be useful as daily cover, or as a granular fill / drainage medium.

11.6 Other

A variety of other applications for MSW have been trialled, with varying degrees of success, including manufactured "top dressings", for turf production, as a fill material in sound barriers, as a biofilter material, compressed for use in building panels or impermeable barriers, for restoring wetlands (Benson and Othman, 1993, Breslin 1995, CIWM 2002, Cossu *et al.* 1985, Lutz 1981, Spencer 1992, US EPA 1997 and 1999, Zimmerman 1975).

An emerging approach in the UK is to use composting as a process step in producing a refuse derived fuel. In this approach the composting process is operated to maximise its drying effect (see Critical Review Section, *Biology – Process Optimisation*). The dried MSW is relatively little degraded and is more easily separated to produce an RDF fraction. The type of pre-processing applied to the MSW may be different in this type of MBT scenario, for example it may be desirable for paper, card and plastic to end up in the fuel fraction so the majority of the MSW is shredded before composting (Cooper 1998, Jager *et al.* 1998).

11.7 Pre-treatment For Landfill

Composting as a process is being used, or considered for use, as a pre-treatment prior to landfill in several European countries. This is in part a response to the EC Landfill Directive. The opportunity for composting as a pre-treatment is as follows

- Loss in mass and increase in bulk density over composting increases landfill lifetimes
- The composting process may reduce the nuisance effect of the waste (litter, odour, attractiveness to insects, birds and vermin)
- The composted material *is seen as* having a lower potential to generate landfill gas and landfill leachate, and so provide a treatment route that complies with the landfill Directive, depending on the waste acceptance criteria agreed for the landfill
- The composting pre-treatment may facilitate the recovery of other recyclable materials such as ferrous metal

However, the majority of studies of composted MSW indicate that it still has the capacity to generate landfill gas and landfill leachate, which may limit the effectiveness of composting as a pre-treatment, compared with incineration for example. However, the volumes of landfill gas and leachate per tonne of MSW received must surely be lower, given the mass loss over composting. The composted waste may also show a more rapid stabilisation in the landfill site than uncomposted MSW. From a philosophical standpoint, composting as a pre-treatment for landfill is seen by some as a waste of potentially recoverable organic material.

References: Bockreis and Steonberg 2004, Chang 1993, Defra 2004, Frechen 1993, Greenpeace 2001, Hartz 1973, Koller *et al.* 1998, Lechner and Klaghofer 1981, Lechner *et al.*

2004, Mostbauer and Heiss-Ziegle 2004, Muller *et al.* 1998, Robinson *et al.* 2004, West *et al.* 1998, Wheeler *et al.* 1999, Zach *et al.* 2000.

12. Operational and Strategic Issues

This chapter covers the role MSW composting can play in sustainable development, regulations standards and guidelines for compost products and the composting process, and compost marketing. While this chapter has separated product and process for presentational purposes, many of the product standards are dependent on specified processing conditions being met.

12.1 MSW Composting and Sustainable Development

The concept of sustainable development gained international governmental recognition at the United Nation's Earth Summit conference in Rio de Janeiro in 1992. Sustainable development has been defined as: "…. *Development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland 1987). Underpinning this approach are three basic elements of sustainable development: economic growth, environmental protection and social progress. In the UK "resources" is separated out from "environment" as a distinct element on its own. Stakeholder involvement in decision making is also seen as an important aspect of achieving sustainable development.

At a strategic level, the re-use of mechanically segregated MSW as composts appears to serve the needs of sustainable development, for example by substituting for primary fertiliser resources and improving the efficiency of use of those resources, and protecting soil organic matter levels. However, these benefits do not come without a cost, which includes environmental impacts, such as the spreading of trace elements and "inerts" to soil, economic impacts such as the cost of MSW-composting, and social impacts such as the general acceptability of this approach. It is also important to consider the sustainability of MSW-composting at an individual project level. Even if it is accepted as the best strategic approach for an area, the establishment of each composting plant will have environmental, economic and social consequences, some positive, and some negative. A vast number of papers have been written about the sustainability, and wider environmental, economic and social impacts of MSW- composting, including costs and benefits (for example: Barton 1997, Brunt *et al.* 1985, Cabinet Office Strategy Unit 2002, Crowe *et al.* 2002, Defra 2004, DETR 2000, Dougherty 1998, EC 1997, 2002 and 2003, EC Project 2004, Favoino 2002, Greenpeace 2001, Hogg 2001, House of Commons 1998 and 2003, Land Use Consultants 2002, Lechner *et al.* 2004, Metcalf *et al.* 2000, ODPM 2002, Smith *et al.* 2001, US EPA 1998, 1999 and 2002, White 1995).

EC and UK policy drives targets for the recycling of organic wastes, including by composting. For example, the Landfill Directive requires that by 2010, the amount of biodegradable waste landfilled be reduced to 75% of the amount landfilled in 1995. Defra have also set up "quality of life" indicators to measure how far local authorities are able to achieve sustainable development, and these include measurements of waste recycling and composting (ODPM 2004).

12.2 Regulations Standards and Guidelines for Compost Products

Definitions of compost and composting are discussed in the Critical Review Section, *Biology - Terms and Definitions*. This report has described compost uses as: *Premium Grade, Regulated Grade* and *Engineering Grade*, see the Critical Review Section, *End-uses*. Table A outlines available standards and guidelines has been divided into sections for these three grades in the UK. In general standards are only available for Premium Grade applications in the UK. Composts that are sold in to the soil improver markets or are incorporated in growing media may wish to comply with industry standards for these products.

Table A: References for Regulations, Standards and Guidance of Possible Relevance to Compost Products

Grade	References
Premium Grade	• BS 3882, 1994 British Standard for top soil and top soil substitutes (BSI 1994) • WRAP / BSI PAS 100 • WRAP guidelines for the specification of composted green materials used as a growing medium component • EU Ecolabel AHWG Revision of ECOLABEL criteria for Soil Improvers (EC 2001)
Regulated Grade	• Contaminated land guidance (see below) • safe compost matrix” • Soil Ameliorants for Landscape Planting
Engineering Grade	• safe compost matrix”
All	• PD CR 13455:1999: Soil improvers and growing media. Guidelines for the safety of users, the environment and plants • PD CR 13456:1999: Soil improvers and growing media. Labelling, specifications and product schedules • 96/716249 DC, Soil improvers and growing media. Specifications. Product schedules (prEN 12578), Draft for Public Comment, • Suggested compost quality criteria in the EC Biowastes Working Document. Second Draft, now superseded by a draft discussion document on biowastes and sewage sludge which no longer contains the suggested compost quality criteria • EC Nitrate, Water Framework and Groundwater Directives (see below)

Key recent issues and debates are: the work of

- CEN TC 223
- EC discussions on soil strategy, biowastes and sludges
- EC Nitrate, Water Framework and Groundwater Directives (and possibly other Directives and revisions, for example relating to Integrated Pollution Prevention and Control, Environmental Liability and Environmental Impact Assessment)
- Contaminated land guidance

- the BSI/WRAP PAS 100 guidance and further WRAP guidance.

CEN TC 223. CEN is the European standards organisation to which BSI is the UK's representative member. CEN standards and reports are published in the UK by BSI in the UK. CEN Technical Committee 223 *Soil Improvers and Growing Media* has established a number of analytical standards for measuring the performance standards in these product for the whole range of materials, from peat to vermiculite and encompassing waste based materials (see the Critical Review Section, *Sampling and Analysis*). In addition the committee has published two technical reports that discuss the safety issues and labelling, specification and vocabulary. The reports do not have the status of standards as they represent areas where consensus could not be gained. Of particular interest for waste based composts is the safety report that outlines the safety issues and the appropriate methods of addressing these through appropriate limit values. The chapter on potentially toxic elements (heavy metals etc) only discusses the approaches to the setting of limits due to the technical difficulties in the area. The CEN standards set out a series of analytical methods which largely underpin the TCA standard mentioned earlier and the BSI PAS - 100.

EC discussions on soil strategy, biowastes and sludges. The EC has been considering compost standards since the late 1980s (de Bertoldi *et al.* 1990, Jackson *et al.* 1992, Zucconi and De Bertoldi 1986 and 1987). The EC Biowastes Working Document was a particularly important document as it represented a discussion ahead of a Directive on biowaste that the EC had committed itself to deliver in 2004 (EC 2002). This document set out a series of quality thresholds for composts, considering two classes of compost (or digestate) for materials segregated at source, and a set of thresholds for materials produced from mechanically segregated MSW, called *stabilised biowaste*. The term compost was reserved for materials from source segregated feedstocks. The so-called stabilised biowastes was seen as a material that would require regulated use, where as "Class 1" composts from source segregated materials could enjoy unregulated use. The biowastes discussions were integrated with ongoing discussions on revising the Sewage Sludge Directive, and developing an EC Soil Strategy in 2003. Clearly these are inter-related areas of policy. However, the latest discussion document (EC 2002 and 2003) no longer includes the specific suggestions on compost and "stabilised biowaste" thresholds, so the status of these thresholds is now unclear. However, the provenance and derivation of the quality thresholds in the former document were not explained.

EC Nitrate, Water Framework and Groundwater Directives. For any compost product, applications to agricultural land will be controlled by the EC Nitrate Directive, to limit the potential migration on nitrogen to groundwater (Defra 2003). The Directive is based on total nitrogen, not the availability of nitrogen. Hence, the "slow release" benefits of compost nitrogen are ignored. See also links from
http://www.defra.gov.uk/environment/water/quality/nitrate/default.htm
The EC Water Framework and Groundwater Directives are likely to have a wider impact on the use of organic matter to land. These Directives aim to prevent any deterioration in water quality, and so could conceivably lead to controls on phosphates, and even trace element emissions, from organic matter applied to land. Developments are posted on:
http://forum.europa.eu.int/Public/irc/env/wfd/home

Contaminated land guidance. Where compost is being used in the restoration of contaminated land, its use will need to be guided by the risk management principles set out in Part IIA of the Environmental Protection Act. Risk assessment guidance was published by

Defra and the Environment Agency in March 2002, and is downloadable from http://www.defra.gov.uk.

BSI/WRAP PAS 100 — Specification for compost. PAS 100 was developed from guidance published by the Composting Association (Composting Association 2000). The Composting Association and WRAP offer an accreditation service for producers (see http://wrap.org.uk). PAS 100 specifies the minimum requirements for the process of composting and the quality of the end product and refers to normative documents where appropriate. The PAS has sections covering scope, normative references, terms and definitions, process control, input materials, composting activity, sanitization, stabilization, compost quality requirements, product preparation, compost sampling and analysis, final product storage, labelling and marketing, monitoring and traceability. There are two annexes that specify methods for assessing contamination by weed propagules and phytotoxins in compost, and for the determination of particle size distribution and physical contaminants. There are two further annexes providing guidance on process control planning and implementation, and designation and labelling for different end-uses.

Compliance with BSI/WRAP PAS 100 also requires that processing is carried out according to certain requirements. For example its sanitisation requirements are based on hazard analysis and critical control points – see the Critical Review Section, *Health and Safety, Emissions and Emissions Control - Bioaerosols and Other Health Risks*.

Standards developed by BSI, WRAP and the Composting Association do not recognise composts derived from mechanically segregated wastes as high grade materials (premium products as described in this report). Indeed, composts derived from mechanically segregated MSW are specifically excluded as possible compost feedstocks by some of these standards. This is connected with concerns that such higher grade uses are not able to tolerate the comparatively elevated levels of trace elements and inerts in mechanically segregated MSW composts. This same distinction is made by the former EC discussion document on biowastes (EC 2002). No allowance is made for an argument that with suitable pre-processing and refining a mechanically segregated MSW compost could meet the quality thresholds in these standards and guidelines.

Regulated and *engineering* grades end-uses are generally agreed to be the only realistic opportunities for the use of mechanically segregated MSW compost in the UK. However, there are serious regulatory and policy impediments to these end-uses in the UK. The current policy and regulatory situation creates a high degree of uncertainty for the successful and sustained use of lower grade composts to land in the UK, even if environmental assessments were to indicate overall positive benefits. The causes of this uncertainty include the following.

1. It is possible that ongoing regulation of a product would mean that it is still perceived as a controlled waste by the regulator. Furthermore these uses might be considered a form of landfill under the definitions of the Landfill Directive. There is no clear framework for making these decisions, which so far appear to have been left to *ad hoc* local decisions, and the courts (see also point 3)

2. It is not clear if re-use as *regulated product* or *engineering material* would constitute beneficial re-use as defined under *1994 DoE guidance on the Environmental Protection Act 1990: Part II, Waste Management Licensing, The Framework Directive*

on Waste. This sets as a benchmark that: *the "recovered material can be used as a raw material in the same way as raw materials of non waste origin by a person other than a specialised recovery establishment or undertaking"*. This may not be seen to be the case for either *regulated products* or *engineering materials*, whose re-use is likely to require at least an element of specialist expertise This has a serious commercial and political impact in that these re-uses may then not qualify for recycling credits, and possibly may not even feature in the achievement of recycling targets.

3. The Waste Management Licensing Regulations (as amended 1994) lack clear definitions as to what compost actually is, and which materials can be applied safely to land. It is not obvious when, or under what conditions, a material which has been through a composting process ceases to be a waste (or indeed, whether it actually does). Consequently, the exemptions under Schedule 3 of the WMLR, some of which allow the application of wastes – including "compost" to land as long as there is no harm to human health or the environment, lack specificity (WRAP 2002).

4. If under the Landfill Directive re-use as *regulated products* or *engineering materials* are considered landfill, then Customs and Excise would be obliged to make a ruling on the landfill tax liabilities of these materials.

5. The Scottish Environmental Protection Agency has published a consultation on what benchmarks would need to be met for a compost to be seen as a product rather than a waste (SEPA 2002). The benchmark suggested is the Composting Association standard (now superseded by BSI/WRAP PAS 100). This standard is intended for horticultural grade material. A lower grade of compost can be used in landfill restoration, based on a site specific risk assessment, but would still be regarded by SEPA as a waste. Unless a compost meets the horticultural grade benchmark, only the losses of mass due to degradation would then count towards recycling performance indicators.

In September 2004 the Scottish Environmental Protection Agency published a "position" paper which reiterates the view that composts produced from mixed waste sources are ineligible for current quality standards. Such compost remains a waste, but may be applied to land in applications such as landfill restoration, providing a risk assessment has been carried out The compost remains a waste, and the site where it used may require permitting. The paper includes an indicative standard for mixed waste compost, that encompasses a range of trace elements, "impurities" and faecal coliforms. This is consistent with the suggestion above of premium and regulated grades of compost.

For a discussion about definition of waste recovery and disposal operations at a European level, see Sander *et al.* 2004.

12.3 Regulations Standards and Guidelines for the Compost Process

Key legislation relating to composting plants is has been summarised by the Composting Association (2001) and CIWM (2002). Humphrey and Hadley (2000) provide a general overview of UK environmental legislation. Health and safety issues are discussed in the Critical Review Section, *Health and Safety, Emissions and Emissions Control*. A large volume of technical literature discusses the planning and implementation of composting facilities, for example: Halstead and Whitcombe 1994, Land Use Consultants 2002, Metcalf *et al.* 2000, Muller *et al.* 2004, ODPM 2002. The Office of the Deputy Prime Minister has published a detailed review of *Planning for Waste Management Facilities* (ODPM 2004), which includes detailed guidance on composting, MBT and digestion facilities.

As a general rule planning applications will always be required for a composting operation where waste materials are brought onto a site via the public highways for treatment and the operation exceeds 28 days in any one year. A composting site will also be a waste management site. There is a legal requirement to obtain a Waste Management Licence from the Environment Agency to carry out commercial composting operations. Waste Management Licensing requires the holder of the licence to put a number of important provisions in place. These include using competent staff, financial provision and duty of care.

In terms of process regulation the most critical issues of concern are those of environmental protection and health and safety. These can be separated into three main hazard groupings: biological hazards (such as animal, human and plant pathogens, and allergens in bio-aerosols) chemical hazards (content of toxic substances) and physical hazards (such as the content of sharp objects, or physical objects that might be consumed by grazing animals).

The requirements on the process are currently managed through the waste licensing process which is enforced by the Environment Agency (Environment Agency 2001). The waste management license is specific to each site and thus can account for the site specific aspects but the principle environmental factors that are considered are:

- wastes accepted
- odour
- noise
- litter
- water / leachate management
- record keeping
- operations (opening times, staffing etc).

Like other development projects, proposed waste management projects of any size are subject to detailed scrutiny of their likely environmental impacts under the Environmental Impact Assessment (EIA) regulations (DETR 2000). Waste management operations are subject to Integrated Pollution Prevention and Control (Defra 2002). Some waste management companies have accepted Environmental Monitoring Systems (EMS) to bring about better management and minimisation of environmental impacts once operations have been initiated (IWM 1998). The debate about composting as a pre-treatment prior to landfill is covered by the Critical Review Section, *End-uses – Pre-treatment for Landfill*.

The EU Animal By-Products Regulation ((EC) No. 1774/2002) has applied since 1 May 2003, although Defra have only been able to enforce it in England since 1 July 2003. The Animal By-Product Regulations (ABPR) have detailed process control requirements, although guidance on these is still out to consultation. They identify several broad classes of materials on the basis of the potential animal pathogen risks they pose. MSW is seen as a low risk group, falling under the category “catering wastes”, since it will contain food wastes from kitchens. The use of composting is permitted for catering wastes, but the regulations require a two barrier approach (i.e. two thermophilic stages) for the composting of mechanically segregated MSW, if the compost is to be applied to land. The Composting Association has produced guidance on the animal by-product regulations and gaining approval for processes (Composting Association 2004). The Defra web link for the animal by-product regulations is: http://www.defra.gov.uk/corporate/consult/animalbyprod2/index.htm

12.4 Marketing

Key market sectors for waste derived composts have been identified by CIWM (2002) as agriculture, landscaping, forestry, horticulture, land restoration, and construction. The CIWM guidance goes on to describe the likely requirements of each of these sectors. Detailed guidance on compost markets and marketing has also been provided by DETR 1997, 1998, Wheeler *et al.* 1994 and 1996. In 2003 the Composting Association published a *Practical Guide to Compost Marketing and Sales*. This manual focuses on the marketing of compost in bulk form, providing, amongst other information on sales and marketing strategies, and is principally concerned with composts made from source-segregated materials.

Composts made from mechanically segregated fractions of MSW have been effectively excluded from markets for premium grade applications in the UK. Regulatory uncertainty also makes it unclear how secure markets are for regulated products. It is clear that even though MSW-derived composts are excluded from BSI/WRAP PAS 100, they should aim to meet its quality thresholds, as this may be the only realistic opportunity to demonstrate to regulators that the compost is indeed a product and its use can be permitted and count as recycling. An alternative approach might be to carry out site specific risk assessments for each envisaged compost use. The development of a "safe compost matrix", proposed by Godley *et al.* 2003, may offer wider opportunities in the medium term. Zero value for the composted products should be assumed as a matter of course, and may even be a best case scenario. The development of a "safe compost matrix", proposed by Godley *et al.* 2002, and the development of an EC sludge and biowaste Directive, may support wider uses of MSW-derived composts in the UK in the medium term.

Alternative markets might include pre-treatment for landfill or pre-treatment prior to energy recovery, see Critical Review Sections: *End-uses - Pre-treatment For Landfill* and *End-uses – Other*.

From the point of view of marketing composts from mechanically segregated MSW it is essential to have a clear idea of likely end-uses, and the *real* opportunities (i.e. markets) for those end-uses at the earliest stages of planning, and certainly well before any significant investment in time and money has been made.

13. Conclusions

Among many findings, the review identified the following key points:

Composting past and present: past and recent UK and European composting experience shows a cycle of interest and then disinterest in composting of MSW, at present, while it is generally agreed that composts made from source segregated materials are likely to make higher quality composts, there is increasing interest in composting mechanically segregated MSW feedstocks as part of an "MBT" process. MBT, or mechanical biological treatment, allows a range of secondary materials to be recovered, including compost, albeit of a lower grade.

Feedstocks and composition: the physical, chemical and biological characteristics of mechanically segregated MSW are highly variable. Contamination of the compostable fraction by trace elements and "inerts" – i.e. non-compostables - appears to be an intractable problem, with residual inerts and elevated trace element contents remaining in the refined compost. The "best" composts made from mechanically segregated MSW are similar in trace element content to the poorest composts produced from source segregated materials.

Sampling and analysis: MSW is a highly heterogeneous and variable material. Specialist approaches are needed for its sampling, sample preparation and analysis.

Biology of composting: the key biological effects are decomposition including a period of decomposition at elevated (Thermophilic) temperatures. The compost is sanitised by a correctly optimised composting process. The dominant process variables are aeration, temperature and moisture, and it can be difficult to sufficiently aerate the composting mass to control temperatures and so maximise processing rates, without over-drying it.

Pre-processing methods: a wide variety of technologies for compost feedstock preparation (separation technologies such as, hand picking, size separation, density based separation, use of electric or magnetic fields) have been developed over the past 50 years or more. Size reduction plays an important role in pre-processing before composting, with size reduction by screening *without* shredding largely preferred.

Composting techniques: the principal techniques used in MSW composting are turned windrow approaches, open aerated systems, and contained systems (vertical and horizontal reactors and agitated systems). In the past rotating drum reactors followed by aerated piles or turned windrows was the dominant composting approach. Each approach has advantages and disadvantages. However, rotary compost reactors are rarely used for long enough to do more than mix and condition the feedstock, and initiate the thermophilic stage of composting. Operating problems appear to be most frequently reported for vertical continuous or silo type reactors.

Refining and packaging: refining uses similar separations to pre-processes, residual content of inerts may remain a problem. This may be masked by fine milling or pelleting.

Health and safety, emissions and emissions control: the principal emissions and health and safety issues are leachate, odour and volatile organic compounds, dust, bioaerosols and other health risks, vermin / birds / insects and fire risks. These can all be effectively controlled in a well managed and planned composting operation.

Product quality and environmental impacts: The dominant benefit of composts arises from their organic matter content, although they do contain useful amounts of plant nutrients and may have a significant liming effect. Concerns about contents of trace elements and inerts have limited the use of composts made from mechanically segregated fractions of MSW in the past. An emerging concern is exists with elevated levels of toxic organic compounds reported where tests have been carried out, although the significance of these is still being debated.

End-uses: for composts produced by from mechanically segregated fractions of MSW are likely to incur some form of ongoing regulation, possibilities might include soil improvement and soil forming for restoration, daily cover in landfill management, as a pre-treatment prior to landfill and perhaps as a pre-treatment for energy recovery.

Operational and Strategic Issues: MSW composting could play a role in sustainable waste management. However, regulations, standards and guidelines for compost exclude products made from mechanically segregated fractions of MSW from “premium grade” markets in the UK. The possible lower grade uses for compost, mentioned above, are currently subject to regulatory uncertainty. This regulatory uncertainty is perhaps the most critical issue affecting the implementation of MBT systems in the UK, and the provision of clear benchmarks and guidance should be undertaken as a matter of some urgency by the regulators and policy departments concerned.

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