Objective 2

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2.1 Introduction

Composting is an excellent example of the practical use of biotechnology. It involves a highly complex biological process, involving many species of bacteria, fungi and actinomycetes, which coverts a low-value material into a higher value product. A wide range of biowastes can be composted including materials generated by agriculture, food processing, wood processing, sewage treatment, industrial and municipal waste.

Interest in composting has developed relatively slowly across the world. Prior to 1970 there were very few composting operations except for those producing compost for the mushroom industry. Interest then started to develop in the composting of biosolids, followed by the idea that composting could provide an alternative to landfill as a route for the management of biodegradable waste. Much of the early work was carried out in the USA where there are now over 3,500 green waste composting facilities (ODEQ, 2001). Within Europe, Austria, Germany and the Netherlands are well advanced in terms of green waste composting, whereas the UK is currently lagging behind (Hogg *et al.*, 2002; SU, 2002). In 1998 there were 910,000 tonnes of waste being composted in the UK (Gilbert and Slater, 2000~~tion, 1998~~) with approximately 25% of the material coming from non-municipal sources (74% of this from trade and other commercial sources, 15% from agriculture, 11% from other non-municipal sources).

Composting is seen as a key process in the waste hierarchy in the UK (SU, 2002) and markets for compost have an important role in reducing the volume of biodegradable municipal waste going to landfill.

Increasingly, farmers and growers are diversifying into offering composting facilities to local companies and waste authorities. In 1999 there were 65 on-farm sites in the UK, which processed 8% of the total material composted (Slater *et al.*., 2001). Small on-farm composting operations are often exempt from waste management licensing as the amount of waste they compost is below the specified threshold and the compost is used on-site. Partnerships between companies, local authorities, farmers and growers are seen as a way of making on-farm composting more cost-effective at a local level while minimising transport costs (DTI, 2001).

However, amendments to the Animal By-Products Order 1999 which were introduced in 2001 effectively banned the composting of catering waste by making it illegal to spread the compost produced from this material on land where animals (including wild birds) may have access. This has halted progress in the use of compost on agricultural land. The recently issued draft Animal By-Products (Amendment) (England) Order 2002 specifies system requirements to enable the composting of catering waste and its spreading on land.

The development of markets for compost products remains a key challenge to the promotion of a greater uptake of composting. Each of those countries which have encouraged composting most strongly has in place a statutory standard supported by systems for quality assurance.The publication of the PAS 100 Specification for Composted Materials in November 2002 was an important step towards a British Standard for compost (BSI, 2002).

The recently published strategy for tackling the waste problem in England (SU, 2002) recommends that DEFRA should continue to encourage the development of quality standards for compost, and should develop a bio-strategy addressing amongst other issues:

- making available a soil map showing where compost may benefit agricultural land;
- the provision of advice to farmers on the agricultural and environmental benefits of compost;
- the contribution compost can make as a carbon sink for the UK climate change programme; and
- the scope for extending farm environment schemes to cover the improvement of soil quality through the application of compost.

The use of carbon sequestration into soil is soil one of the few tools for changing the balance of carbon in the atmosphere and can therefore help the UK in meeting the strategic goals of the climate change agreements. To make an appreciable difference there will need to be large-scale and comprehensive use of compost because much of the carbon in compost will be mineralised in the soil and returned to the atmosphere as CO_2 (SU, 2002). A proportion though, will be retained in the soil for the medium term, perhaps up to 100 years during which time other abatement can be sought. If this is considered together with the other benefits of compost then it becomes an attractive option. For example, intensive farming and inorganic fertilisers have depleted the soil of carbon reserves and thereby increased the carbon balance in the atmosphere (SU, 2002). This can be reversed by intensive applications of good quality compost material produced from organic waste.

There has been a considerable amount of work throughout the world to develop composting systems for both conventional and organic agricultural systems (Diver, 2001; DTI, 2001), although few of these have been developed with UK agriculture specifically in mind. The CMC (Controlled Microbial Composting) system developed in Austria is now being developed by a range of growers and research workers for use in UK organic agriculture (Section 2.4.6).

Greater progress has been made in the mushroom composting industry where tighter time schedules and more discerning quality parameters have prompted technological innovation Burden (2001). Highly automated systems and strict hygiene arrangements are used to control the conversion of wheat straw and chicken manure into safe, productive compost for mushroom growing.

There is little research specifically on composting in organic farming and production systems, therefore most of the information is based on studies carried out in conventional farming system. However, composting and the use of composted products, e.g. composted manure, forms a major component of soil fertility management in organic farming systems. There is great potential to learn from the range of experience reported in the broader scientific literature. This requires greater effort to be put into technical transfer of current knowledge on composting to inform organic farmers and growers, and regulators about issues of concern.

2.2 Definitions

Biowaste (biodegradable waste) is any waste that is capable of undergoing anaerobic or aerobic decomposition, such as food and garden waste, paper and paperboard.

Compost is solid particulate material that is the result of composting, that has been sanitized and stabilized and that confers beneficial effects when added to soil and/or used in conjunction with plants.

Composting is a process of controlled biological decomposition of biodegradable materials under managed conditions that are predominantly aerobic and that allow the development of thermophilic temperatures as a result of biologically produced heat, in order to achieve compost that is sanitary and stable.

Compost extract is the filtered product of compost mixed with any solvent (usually water), but not fermented. This term has been used in the past to define water extracts prepared using a very wide range of different methods. In the past, the terms “compost extract”, “watery fermented compost extract”, “amended extract”, “compost steepage” and “compost slurry” have all been used to refer to non-aerated fermentations. "Compost extract", "watery fermented compost extract" and "steepages" are approximate synonyms defined as a 1:5 to 1:10 (v:v) ratio of compost to water that is fermented without stirring at room temperature for a defined length of time. "Amended extracts" are compost extracts that have been fermented with the addition of specific nutrients or microorganisms prior to application.

Compost tea is the product of showering recirculated water through a porous bag of compost suspended over an open tank with the intention of maintaining aerobic conditions. The product of this method has also been termed "aerated compost tea" and "organic tea".

In the past, the term "compost tea" has not always been associated with an aerated fermentation process. It is important to distinguish between compost teas prepared using aerated and non-aerated processes, therefore the terms aerated compost tea (ACT) and non-aerated compost tea (NCT) are used in this review to refer to the two dominant compost fermentation methods. ACT will refer to any method in which the water extract is actively aerated during the fermentation process. NCT will refer to methods where the water extract is not aerated or receives minimal aeration during fermentation apart from during the initial mixing.

Green and wood waste is vegetable waste from gardens and municipal parks, tree cuttings, branches, grass, leaves (with the exception of street sweepings), sawdust, wood chips and other wood waste not treated with heavy metals or organic compounds.

Humus is the more or less stable dark coloured fraction of the soil organic matter remaining after the major portions of added plant and animal residues have been decomposed.

Manure is animal excrement which may contain large amounts of bedding.

Maturity is the degree of biodegradation at which compost is not phytotoxic or exerts negligible phytotoxicity in any plant growing situation when used as directed.

Municipal Solid Waste (MSW) is solid waste from households.

Sewage sludge (also referred to as biosolids) is residual sludge from sewage plants treating domestic or urban waste water and from septic tanks and other similar installations for the treatment of sewage.

Slurry consists of dung, urine and water with only small amounts of bedding.

Stabilization is a process of biological activities that together with conditions in the composting mass give rise to compost that is stable.

Stable, stabilized, stability is the degree of biodegradation at which the rate of biological activity under conditions favourable for aerobic biodegradation has slowed and microbial respiration will not resurge under altered conditions, such as manipulation of moisture and oxygen levels or temperature.

Vermicompost is the material that is egested from earthworms as casts then further decomposed and matured in the vermicomposting system.

Vermicomposting is the process of using selected species of earthworms to help compost input materials, and vermicompost as the material that is egested from earthworms as casts then further decomposed and matured in the vermicomposting system.

2.3 The Composting Process

2.3.1 Principles of composting

Composting relies upon an indigenous population of microorganisms from the environment carried by most organic materials. microorganisms are, in general, inefficient in trapping energy released during the oxidation of organic substrates. Energy that is not biochemically captured in the catabolic degradation of substrates is dissipated to the environment as heat. This is not normally noticed when the material is spread over a large area of ground. But compost piles restrict the dissipation of heat, leading to an increase in temperature (Zibilske, 1998).

Microbial populations change during the process through the following stages:

- mesophilic stage (20-40^{o}C)
- thermophilic stage (>40^{o}C)
- stabilisation or curing stage (cooling period).

The mesophilic population starts the process, oxidising readily available substrates such as proteins, sugars, starch. As the temperature increases, thermophilic microbes develop. These consist of only a few genera of bacteria e.g. *Bacillus subtilis*, fungi e.g. *Aspergillus fumigatus*, and actinomycetes e.g. *Streptomyces spp*. (Strom, 1985)

This is the period of fastest decomposition, and more resistant compounds such as lignin are degraded. This is the first stage in humus formation, which continues during the maturation phase. It is also likely that pesticides and other organic contaminants will be broken down during the thermophilic stage by hydrolysis and oxidation reactions (Deportes *et al.*., 1995). The high temperature and intense hydrolytic enzyme activity may also lead to the denaturing of DNA and thereby reduce the risk of any GM material which might be present entering into the farming system.

As the temperature rises towards 70 ^{o}C pathogenic microorganisms and weed seeds are killed, but once above this temperature the process becomes self-limiting and microbial activity decreases. Energy and nutrients become exhausted and the compost cools, mesophiles re-invade the compost together with worms and arthropods. Turning the compost can re-introduce mesophiles from the cooler outer parts of the pile. Nitrifiers become established and this leads to the formation of nitrate, lowering potentially phytotoxic ammonium-nitrogen levels. This is known as the maturation phase, and can last up to 6 months.

PAS 100 (BSI, 2002) specifies, for conventional composts, the minimum requirements for the process of composting, the selection of input materials, and the quality of the composted materials.

The Soil Association Standards (SA, 2002) emphasise the beneficial effects of composting and storage of manures in reducing pathogen loads and in producing a stabilized product. A temperature >55 ^{o}C for three days, achieved by turning the material, is recommended for destroying most weed seeds, pathogens, chemical residues and antibiotics.

2.3.2 Factors influencing the composting process

Temperature is the main factor that controls microbial activity during composting. Heating is essential to enable the development of a thermophilic population of microorganisms which is capable of degrading the more recalcitrant compounds (natural and anthropogenic), and to kill pathogens and weed seeds (Boulter *et al..*, 2000).

Aeration has an indirect effect on temperature by speeding the rate of decomposition and therefore the rate of heat production. The air requirement depends upon the type of waste (type of material, particle size), the temperature of the compost and the stage of the process. Air supply can be controlled to some extent by the use of a system of aeration. Under natural conditions warm air diffuses from the top of the windrow drawing fresh air into the base and sides (Hellmann *et al..*, 1997). Aeration is further encouraged by periodic turning of the windrow. Alternatively, air may be actively forced into the pile, usually within a closed or in-vessel system with the aim of maximising the rate of microbial decomposition. This is relatively costly, but is useful for materials that pose health risks. Forced aeration has also been used successfully on static piles giving a high degree of process control (Sesay *et al..*, 1997).

Microbial activity is influenced strongly by moisture content: activity decreases under dry conditions, and aerobic activity decreases under water-logged conditions due to the resulting decrease in air supply. The recommended optimum water content is 40-60% on a mass basis (Epstein, 1997).

Changes in moisture content are related to aeration and temperature; in an aerated static pile system approximately 90% of the heat loss is due to evaporation of water (Sesay *et al..*, 1997). Systems which actively encourage aeration can lead to desiccation and result in a decrease in the rate of decomposition in windrow composting (Itavaara *et al..*, 1997).

The compost must be kept aerobic to avoid the production of odours. Moisture is essential but if the compost is too wet then anaerobic conditions develop. Anaerobic conditions are also undesirable because of the loss of N by denitrification. There may also be a build up of organic acids, such as acetic acid, which can be toxic to plants.

The carbon:nitrogen ratio (C/N) is important in determining in general terms the rate of decomposition of organic materials (Section 2.6.1). The optimum C/N ratio for the feedstock material is around 25:1.

2.3.3 Feedstocks for composting

PAS 100 (BSI, 2002) requires that the types of input material going into the composting process are known and listed. It is expected that criteria will be established for the acceptance or rejection of loads arriving at the site. Presence of unacceptable levels of contaminants, including material types not permitted in the waste management licence, should be part of the set of criteria.

For the purpose of the PAS 100 input material can be of any solid, carbon based, biodegradable material that has been separately collected from non-biodegradables, or that has not by other means been mixed, combined or polluted with other potentially polluting wastes, products or materials. Quality requirements are specified for the end-product in terms of human pathogens, potentially toxic elements, physical contaminants, and weed propagules.

Prior to composting, feedstocks may be treated or processed to improve the composting process. This may involve shredding or grinding the material to produce particles of the optimum size, mixing to produce a uniform feedstock, adding water, or adding nitrogen. This pre-composting stage is normally carried out in a day. Wood chips or shredded green waste are used in some systems to improve the physical structure of the composting mix. Larger pieces of wood can be removed by screening during the post-composting stage (DTI, 2001).

2.3.3.1 Conventional feedstocks

Composting can be used to treat the following types of solid organic waste (DTI, 2001):

Agriculture e.g. manures, crop residues
Catering e.g. food scraps (subject to Animal By-Products Order)
Construction and demolition e.g. discarded wood
Food and drink processing e.g. vegetable waste, fats
Engineering e.g. oils and grease
Horticulture e.g. discarded plant material
Landscaping and amenity e.g. green and woody plant waste
Paper and board manufacturing e.g. offcuts and surplus materials
Retail e.g. biodegradable packaging
Sewage treatment e.g. dewatered sewage sludge
Textiles e.g. natural fibres.

Annex I of the second draft proposal for an EU Directive on the Biological Treatment of Biowastes [Ref] lists “biowastes” which are “in principle suitable for biological treatment”, using classifications in the European Waste Catalogue [Official Journal of the European Communities. 23 July 2001 (2001/573/EC)]. However, future legislation (e.g. the Animal Byproducts Order) may only permit composting activity with certain conditions if input material is from a source that contains catering wastes, animal by-products or materials of animal origin.

2.3.3.2 Permitted feedstocks for organic systems

Products authorized by UKROFS exceptionally for use in soil conditioning and fertilization are given in Table 2a. The list includes uncomposted and composted manures, subject to certain restrictions, together with composted bark and vegetable matter, vermicompost, and fermented seaweed. The exception for use of composted household waste expired on 31st March 2002.

Table 2a. Permitted feedstocks for organic systems (UKROFS, 2001)

Name Compound products or products containing only materials listed hereunder:	**Description, compositional requirements, conditions for use**
Farmyard manure	Product comprising a mixture of animal excrements and vegetable matter (animal bedding). Need recognised by the inspection authority or inspection body. Indication of the animal species. Coming from extensive husbandry*.
Dried farmyard manure and dehydrated poultry	Need recognised by the inspection authority or inspection body. Indication of the animal species. Coming from extensive husbandry*.
Composted animal excrements, including poultry manure and composted farmyard manure included	Need recognised by the inspection authority or inspection body. Indication of the animal species. Factory farming origin forbidden.
Liquid animal excrements (slurry, urine, etc.)	Use after controlled fermentation and/or appropriate dilution. Need recognised by the inspection authority or inspection body. Indication of the animal species. Factory farming origin forbidden.
Composted or fermented household waste	Product obtained from source separated household waste, which has been submitted to composting or to anaerobic fermentation for biogas production. Only vegetable and animal household waste. Only when produced in a closed and monitored collection system, accepted by the Member State. Maximum concentration of PTEs as given in Table 2d. Only during a period expiring on 31 March 2002. Need recognised by the inspection authority or inspection body.
Mushroon culture wastes	The initial composition of the substrate must be limited to products of the present list.
Dejecta of worms (vermicompost) and insects	

Composited or fermented mixture of vegetable matter	Product obtained from mixtures of vegetable which have been submitted to composting or to anaerobic fermentation for biogas production. Need recognised by the inspection authority or inspection body.
Products and by-products of plant origin for fertilizers (for instance, oilseed cake meal, cocoa husks, malt culms, etc.)	
Seaweeds and seaweeds products	As far as directly obtained by: (i) Physical processes including freezing and grinding (ii) Extraction with water or aqueous acid an/or alkaline solution (iii) Fermentation
Sawdust and wood chips	Wood not chemically treated after felling
Composted bark	Wood not chemically treated after felling

*Only in the sense of article 6 (4) of Council Regulation (EEC) No 2328/91, as last amended by Regulation (EC) No 3669/93.

2.4 Composting systems

Descriptions of the main types of composting systems can be found in the EA Draft Technical Guide to Composting Operations (EA, 2001) and the BIO-WISE Review of Composting Technology (DTI, 2001). There is a large number of different composting systems available, ranging in technological sophistication and therefore in cost. There are open systems (windrow and aerated static pile) which are relatively simple to operate and low cost, and a number of contained systems which have options for moving the material, supplying forced air, and operating on a continuous or batch system.

The processing costs typically range from £17-£20 per tonne of feedstock for open windrow composting systems to £14-£25 per tonne for contained systems. Typical composting times are shown in Table 2b.

2.4.1 Open windrow

Windrow composting is the most common of the technologies currently used in the UK. It takes between 12 and 20 weeks to complete and consists of forming the mixture of raw materials into long narrow piles or windrows, which are turned and re-mixed on a regular basis. The height of windrows ranges from approximately 1 m for dense materials such as manures to approximately 3.5 m for less dense materials such as leaves. The width of windrows varies from 1.5 to 6 m with the shape determined normally by the equipment used to form the windrows. Specialised turning machines produce low wide windrows and machines with front-end buckets produce tall windrows.

Table 2b. Typical composting times for selected feedstock materials and composting methods (EA, 2001)

Method	Materials	Composting time (weeks)	Maturing time (weeks)
Passive composting	Leaves Manure	104-156 26-104	N/A N/A
Windrow – infrequent turning	Leaves Manure	26-52 16-32	16 4-8
Windrow – frequent turning	Manure	4-16	4-8
Passively aerated windrow	Manure + Bedding Fish waste + peat moss	10-12 8-10	4-8 4-8
Aerated static pile	Sludge + wood chips	3-5	4-8
Rectangular agitated bed	Sludge + green waste, Or manure + sawdust	2-4	4-8
Rotating drum	Sludge and/or solid wastes	0.5-1	8 (+windrowing)

The composting process depends upon a good supply of oxygen, therefore air must be able to move through the windrow. This will depend upon the size and shape of the windrow, the porosity of the material, and its water content. Feedstock material is usually shredded to ensure the correct porosity. A windrow constructed of low density materials such as leaves can be much larger than a windrow constructed of wet dense manure. Anaerobic areas can occur near the centre of the windrow if it is too large, too dense or too wet, and these areas will release odours when the windrow is turned. On the other hand, small windrows lose heat quickly and may not achieve high enough temperatures to kill pathogens and weed seeds.

Turning releases trapped heat, water vapour and gases and also mixes the materials, breaks up large particles and restores the pore spaces eliminated by decomposition and settling. Turning also exchanges the material from the outside of the windrow with that from the interior. This helps to ensure that all material receives equal exposure to the air at the surface and to the high temperatures inside the windrow thereby providing a uniform treatment process.

2.4.2 Aerated static pile (covered and uncovered)

This process is used widely in the USA, Germany, France and other European countries, but is not yet used to any significant extent in the UK. Aerated pile composting typically takes 8-13 weeks and involves the provision of aeration using a blower to supply air to the pile. This gives a greater degree of control over the composting process.

The composting material is placed on top of a perforated pipe or platform. In passive systems, natural convection will aerate the pile. Air may be blown upwards (positive aeration) or sucked downwards (negative aeration). Negative aeration also enables the exhaust air to be treated via a biofilter to remove odours. Once the pile is formed, it will require no turning or agitation and provided that the air supply is sufficient and uniformly distributed, the active composting period may be completed in approximately 3 to 5 weeks. The pile may be covered or uncovered, a factor which has important implications for the circulation of air within the pile.

2.4.3 In-vessel

In-vessel composting refers to a group of composting systems, which range from enclosed halls to tunnels and containers or bins. In-vessel systems attempt to create optimum conditions for the microorganisms thereby giving improved control of the composting process and accelerating decomposition. As in all composting systems the supply of air to all the material being composted is a key factor in determining the effectiveness of the process.

In the UK there are at least seven contained composting systems in operation, and they are becoming increasingly popular. This is mainly due to increasing pressure at the planning and licensing stages for new facilities to provide evidence of pathogen, odour and bioaerosol control, which cannot be guaranteed in an open windrow system.

In vessel systems normally process material through the active composting phase and through to stabilization which typically takes 14 days. The maturation phase is normally carried out in piles or windrows, which requires suitable hard-standing areas. Small, in-vessel systems have been developed in the UK, for example the Sirocco, which was part-funded by the DTI and the BOCF.

Horizontal systems are more widely used than vertical systems in the UK. For example, a continuous tunnel or batch tunnel can process 10-400 tonnes. Batch tunnel systems have been developed from technology used for the production of mushroom compost with the option of recirculating the air.

Although the quality is higher and variability less (within and between batches) when composts are produced in these systems, their cost currently precludes their use in organic agriculture. The real value of such systems lies in effective treatment of dangerous organisms (e.g. plant, animal and human pathogens) within high risk wastes. These systems will certainly be considered in future to treat certain types of wastes (e.g. kitchen waste).

2.4.4 Controlled Microbial Composting (CMC) (covered windrow)

The Controlled Microbial Composting® (or CMC®) process was developed by the Luebke family in Austria and involves the production of compost in covered windrows (1.2 x 1.8 m approx. x any length) over a 6-8 week period (Driver, 2001). The feedstocks are carefully chosen to include a balance of well structured materials and should have a C/N ratio of around 30. They are mixed, water is added if necessary and covered with a waterproof, breathable membrane. The windrows are monitored daily for CO_2, moisture levels and temperature and the windrows are turned with a purpose-built compost turner every time the temperature exceeds 60^{o}C. This often means that the windrows are turned daily at the start of the process. Compost maturity is estimated by measuring temperature and CO_2 emission from the windrows.

2.4.5 Vermicomposting

Earthworms will break down sewage sludge and other organic wastes (Neuhauser *et al.*, 1980). The ‘tiger’ or ‘brandling’ worm *Eisenia foetida* has received most attention, and work at Rothamsted showed that it could grow well in a wide range of wastes including pig and cattle solid and slurries, horse manure and potato waste (Edwards *et al.*, 1985). Worms are useful in converting agricultural wastes into useful soil conditioners, but also the worms can be harvested and processed into a nutritious protein feed supplement for fish, poultry and pigs.

E. foetida prefers a pH of 5, temperatures <35 ^{o}C, and it will not enter poultry waste with high ammonia content. Batch systems treating up to 2 tonnes of waste in worm beds to a depth of one metre have been tested, but are labour intensive. The amount of soluble P, K and Mg appears to be increased, and worm-processed animal wastes have been shown to be suitable as plant growing media.

2.4.6 Compost extracts and teas

A considerable amount of work has been carried out to develop improved methods for preparation and use of compost extracts and teas for use as fertilizers and to assist crop protection. Most of this work has been done in the United States and much of it by commercial companies. There is some confusion as to exactly what is meant by compost teas and compost extracts.

The term *compost tea* is used in this review to describe the product of showering recirculated water through a porous bag of compost suspended over an open tank with the intention of maintaining aerobic conditions (Riggle, 1996). Several commercial companies have developed machinery for the preparation of compost teas in this way under highly aerated conditions.

The terms *aerated compost tea* (ACT) and *non-aerated compost tea* (NCT) will be used in this review to refer to the two dominant compost fermentation methods. ACT will refer to any method in which the water extract is actively aerated during the fermentation process. NCT will refer to methods where the water extract is not aerated or receives minimal aeration during fermentation apart from during the initial mixing. The term *compost extract* has been used in the past to define water extracts prepared using a very wide range of different methods (Scheuerell and Mahaffee, 2002).

The production of ACT and NCT both involve compost being fermented in water for a defined time period. Both methods require a fermentation vessel, compost, water, incubation and filtration prior to application. Nutrients may be added prior to or following fermentation and additives or adjuvants may be added prior to application.

There is vigorous ongoing debate regarding the benefits of aeration during compost tea production (Brinton *et al.*, 1996; Ingham, 1999). Aerated production methods are associated with shortened production time. Non-aerated methods are associated with low cost, low energy input and many documented reports of successful plant disease control (Weltzein, 1991). It is possible that NCTs can cause phytotoxicity and that the production of NCTs provides an ideal environment for the growth and reproduction of human pathogens, however there is limited evidence to prove either of these claims at present.

Several companies now offer fermentation units that produce aerobic compost tea by suspending compost in a fermentation vessel and aerating, stirring or recirculating the liquid (Diver, 2001).

NCT has generally been made by mixing one volume of compost with between four to ten volumes of water in an open container. The mixture is stirred as it is made up, then it is left for at least 3 days at 15-20^{o}C with minimal or no stirring (Weltzein, 1991; Brinton *et al.*., 1996).

Compost teas can be made in quantities ranging from a few litres to several thousand litres in a single batch depending on the size of the fermentation vessel.

See also Section 4.6.4.

2.5 Environmental impacts

Composting is a process based on the management of microorganisms naturally present in waste materials. In addition to the positive beneficial effects of this process on the environment, there are a number of potential negative impacts. The waste material may contain within its microbial population organisms which are potentially pathogenic to humans, animals and plants. This is currently a major concern (Gale, 2002) and is considered further in Section 2.7.1. The composting process may generate byproducts which have potentially negative impacts on the environment, in particular gaseous byproducts. Ammonia may be volatilized as ammonium released from N-rich materials by microbial activity accumulates in the compost. Depending upon the redox conditions, microbial decomposition of organic materials will lead to the production of CO_2, N_2O, or CH_4 (Hellmann *et al.*, 1997). All of these three gases contribute to the greenhouse effect, but their net contributions to global climate change differ.

2.5.1 Ammonia

The majority of manures generated by the UK livestock industry (approximately 90 million tonnes per year) come from dairy and beef farming (73 million tonnes per year). These manures represent a significant nutrient resource of around 280,000 tonnes of N, 50,000 tonnes of P, and 250,000 tonnes of K (Smith *et al.*, 2001b). It also represents an important source of organic matter.

Manures can act as a source of pollution to water and air, with an estimated 117,000 tonnes of ammonia emissions from dairy and beef systems (DEFRA, 2002a). Emissions from FYM heaps increase to a maximum in the first few days of storage as the bacteria cause the temperature to rise. Most of the emission from FYM heaps takes place within the first 30 days of storage, unless the heap is turned, or forked, to encourage composting and more ammonia is emitted. Heavy rainfall reduces emissions by slowing the composting process, but it may increase drainage from the heap and the movement of water-borne pollutants down through the soil. There may be a further peak of ammonia emission when the heap is broken up before being spread on the land.

Dairy farms are estimated to produce manures in the form of approximately 65% slurry and 35% farmyard manure, and beef units 20% slurry and 80% farmyard manure (Smith *et al.*, 2001b). Straw-based waste management systems are assumed to have less environmental impact than slurry, but preliminary results from controlled experiments suggest that total emissions of ammonia are similar for the two systems (Chambers *et al.*, 1999). Farmyard manure contains a smaller proportion of soluble N than slurry; this means that the nutrients in FYM are available at a slower rate for plant uptake, and also are less susceptible to leaching (Smith *et al.*, 2002).

2.5.2 Greenhouse gases

CO_2 is one of the products of aerobic respiration, but in contrast to CO_2 produced by fossil fuel combustion, CO_2 derived from degradation of plant materials does not contribute to global warming because it had been previously removed from the atmosphere by photosynthesis. N_2O is a product mainly of the microbial reduction of NO_3^- under anaerobic conditions (denitrification) but also to some extent via nitrification. CH_4 is a product of the microbial reduction of CO_2 under anaerobic conditions. The release of N_2O and CH_4 to the atmosphere contributes to the enhancement of the greenhouse effect (Hellmann *et al.*, 1997). The flux of CH_4 to the atmosphere can be avoided if the material is subject to anaerobic digestion in which the CH_4 is collected and used as a source of energy.

Composting is an aerobic process which depends essentially on the supply of O_2 to the microorganisms within the pile, but anaerobic conditions can develop in poorly managed systems. It can be concluded therefore that well-managed aerobic composting systems should not make a significant contribution to greenhouse gas emissions, whereas poorly managed systems which become anaerobic can contribute to N_2O and CH_4 fluxes.

Smith *et al.* (2001a) analysed the carbon balance implications of the range of waste management options for municipal waste in the EU from 2000-2002. It was concluded that source segregation of municipal solid waste followed by recycling (for paper, metals, textiles and plastics) and composting/anaerobic digestion (for putrescible wastes) gives the lowest net flux of greenhouse gases, compared to other options for the treatment of municiipal solid waste. In comparison with landfilling untreated waste, composting/anaerobic digestion of putrescible wastes and recycling of paper produce the overall greatest reduction in net flux of greenhouse of gases.

Vegetation and soils currently absorb around 40% of global CO2 emissions from human activities. This has raised the possibility that carbon could be sequestrated through the creation of carbon sinks. The use of composted biowaste in agriculture and horticulture can also improve the organic matter content of soil and as a result soil carbon sequestration.

2.5.3 Leachate

Several studies have indicated that leachate produced from both green and non-green feedstock composting operations may contain high concentrations of pathogens, organic compounds, nutrients, and/or metals, which can negatively impact water quality (ODEQ, 2001). Management practices should be implemented to minimize the amount of wastewater produced, and recommended protection mechanisms should be constructed to protect water resources.

2.5 Effect of composting on chemical parameters of the finished product

Composting involves converting waste material into a product that has been stabilized and that confers beneficial effects when added to soil. The process therefore involves a range of chemical transformations mainly carried out by microorganisms. Stabilization is achieved by the conversion of readily biodegradable organic compounds into less biodegradable products, in particular humus. This may also involve the stabilization of organic forms of N and P, for example by incorporation into microbial biomass. As a result these elements are less likely to be lost to the environment in leachate and gaseous emissions (See Section 2.5.1). Phosphorus is likely to be present largely in an organic form.

Potassium is unlikely to be changed significantly during composting. Manures contain significant amounts of K in the form of soluble salts which are vulnerable to leaching losses. The accumulation of salts during the composting process is due to the reduction in mass and moisture content of the material and, coupled with the formation of nitrate during the maturation phase. The resultant high salt content may cause a problem if the compost is applied to young seedlings. This is best indicated by the electrical conductivity of the material.

2.6.1 Nitrogen

Transformations of N during the composting process are important in determining the N content of the compost product and losses of N. The fate of N in feedstock materials will depend upon the biodegradability of the materials and the ratio of C/N within the biodegradable fraction (this will also affect the losses of C to the atmosphere as CO_2). The C/N ratio of a range of materials is shown in Table 2c.

Table 2c. C/N ratio of a range of feedstock material for composting

Material	C/N ratio	Material	C/N ratio
Urine	2	Pig manure	5
Poultry manure	10	Lawn clippings	12
Kitchen waste	12	Farmyard manure	14
Seaweed	19	Garden waste	20
Horse manure	25	Weeds	30
Bracken	48	Straw	80
Woody prunings	100	Bark	100
Newspaper	200	Cardboard	500

Materials with a low C/N ratio such as poultry manure result in an excess of N for microbial growth and this is released as ammonium which can be volatilized into the atmosphere as ammonia gas (Finstein and Morris, 1975). Materials with high C/N ratios such as straw will not contain adequate amounts of N to support microbial growth, therefore the decomposition process will slow down. The composting process can be optimised by combining materials with complementary N contents. In extreme cases, it may be necessary to add N fertilizer to re-activate the process.

During the curing stage, if aerobic conditions are maintained, the compost is re-colonised by nitrifying bacteria, and ammonium is oxidised to nitrite and nitrate (Catton, 1983).

2.6.2 pH

pH varies within a compost pile, but there is a general trend for the pH to decrease (become more acidic) during the early stages of decomposition and then to increase (Finstein and Morris, 1975). The initial decrease in pH is due to the formation of organic acids that are formed during rapid degradation which can occur prior to composting (Hellmann *et al.*, 1997). This subsequent increase in pH is due to volatilization of organic acids, and to accumulation of ammonia.

The optimum pH for decomposition is 6.5-8.5 but in order to avoid excessive ammonia losses in aerated compost systems the pH should be <7.4 (Hoitink and Kuter, 1986). pH<5 is unfavourable for bacteria, and will prevent a number of important processes including colonization of compost by bacterial biocontrol agents (Hoitink *et al.*, 1997). If a compost pile includes a large amount of bark the low pH of this material (pH 4.5-5.2) should be balanced by the addition of ammonium-containing materials such as poultry manure to increase pH (Hoitink and Kuter, 1986).

The final compost product normally has a pH of between 7.0 and 8.5 with a liming value that can help to maintain soil pH on light land.

2.6.4 Potentially toxic elements (PTEs)

The feedstock materials used for composting may contain a range of potentially toxic elements (PTEs) and limit values have been established in many countries, in many cases based on the range of values used for sewage sludge. Upper limits for conventional compost are given in the PAS 100 (BSI, 2002) and limits for organic compost derived from household waste are given in UKROFS regulations (UKROFS, 2001) (Table 2d).

Table 2d. Upper limits for conventional compost (PAS 100) and organic compost (UKROFS)

Element	Upper limit (mg kg^{-1} dry matter)	
	PAS 100	UKROFS
Cadmium (Cd)	<1.5	<0.7
Chromium (Cr)	<100	<70
Copper (Cu)	<200	<70
Lead (Pb)	<200	<45
Mercury (Hg)	<1	<0.4
Nickel (Ni)	<50	<25
Zinc (Zn)	<400	<200

The UKROFS standards follow Annex II/A of EC regulation 2092/91/EEC on organic farming. This contains a list of admissible fertilisers and soil improvers which includes pure plant and vegetable materials (plant compost, park and garden waste compost). Following amendment from 29 July 1997 (EC regulation 1488/97/EEC) composted household waste was also permissible, with a transition period until March 2002. This amendment is linked to limit values for heavy metals and the requirement that the raw material must be obtained from a closed and controlled collection and processing system. The need of farms for the compost has to be recognised by the inspection body. Heavy metal limits are lower that the PAS 100 limit values.

2.6.5 Organic contaminants

The waste material used for composting may contain a large number of organic contaminants (pesticides, pharmaceuticals, industrial contaminants). The fate of these compounds during the composting process will largely determine their presence in the finished product. Only the most stable compounds are likely to persist in the compost due to the length of time taken for the composting process, the intense microbial activity, and the high temperature. For example, the pesticide diazinon which has a persistence in soil of 12 weeks was not found in compost, whereas pentachlorophenol which may persist in soil for 5 years is found in compost (Deportes *et al.*, 1995).

Data on the concentration of major types of organic contaminants in composts have been reviewed by Deportes *et al.* (1995) and Buyuksonmez *et al.* (1999). Contaminants were selected which were likely to cause concern due to their resistance to biodegradation, toxicity to organisms, and tendency to accumulate in the food chain (O'Connor *et al.*, 1991). Polyaromatic hydrocarbons (PAH) are stable compounds with a long half-life in soil. The total PAH content of compost ranges from 1-250 mg kg^{-1} with individual compounds such as naphthalene present at concentrations up to 41 mg kg^{-1}. Following application of compost to soil none of the seven PAHs that are known carcinogens were found a concentrations exceeding the critical values (O'Connor *et al.*, 1991). Laboratory studies have shown that the co-composting of pig manure and PAH-contaminated soil caused a 90% reduction in the concentration of phenanthren and anthracene, with most of this occurring during the thermophilic phase (Wong *et al.*, 2002).

Chlorinated hydrocarbons range from 0.02-1.1 mg kg^{-1} with volatile solvents present at concentrations as high as 0.1 mg kg^{-1}. Polychlorinated biphenyls (PCBs) are highly persistent compounds and have been detected in composts at concentrations ranging from 0.0007-5 mg kg^{-1} (Deportes *et al.*, 1995).

Organophosphate and carbamate insecticides, and most herbicides were only rarely found in a study of feedstock materials and compost samples in the US (Buyuksonmez *et al.*, 1999). Organochlorine compounds are most resistant to degradation during composting.

Overall it appears that composting can be considered to be essentially similar to a biologically active soil environment in which degradation is accelerated (Buyuksonmez *et al.*, 1999). However, the bioavailability of compounds may be different due to the high content of organic matter in compost, which may sorb compounds, making them less bioavailable. Little is known about the bioavailability of pesticides in compost.

The fate of a particular pesticide during composting may involve partial degradation to intermediate metabolites, volatilization, adsorption and humification, depending upon the compound, composting conditions and the microbial community. The supply of carbon and energy in composting material stimulate the breakdown of recalcitrant xenobiotics either directly or via cometabolism.

Animal wastes from intensive farming and treated sewage often contain traces of therapeutic agents (compounds that are used to cure or prevent diseases). These compounds are likely to behave in the same way as pesticides in the environment, and may maintain residual activity in manure and biosolids, but have been largely overlooked (Jjemba, 2002). The quantities of therapeutic agents used in some countries are similar in magnitude to the quantities of pesticides (Hirsch *et al.*, 1999). Partially metabolised residues are excreted in faeces and urine and together with residues in leftover livestock feeds enter the waste stream. Manure and biosolids may contain residues that remain stable and survive treatment processes.

The growth and development of crop plants such as *Medicago sativa* and *Zea mays* and non-crop plants such as *Plantago major* were adversely affected by sulphadimethoxine in laboratory studies (Migliore *et al.*, 1995; Migliore *et al.* 1997) and nodulation and growth of *Phaseolus vulgaris* in soil was reduced by chlorotetracycline (Batchelder, 1982). There is a need to obtain field data on types and concentrations of pharmaceutical compounds in manure and biosolids, and in soil in order to understand potential impacts on crops in the field (Jjemba, 2002). The European Union has proposed that the concentration of pharmaceutical compounds should not exceed 10 μg kg^{-1} before further evaluation of a specific compound is considered (Spaepen *et al.*, 1997), but further work is needed to justify this, including studies on the impacts of these compounds on soil microbiological processes.

Some countries (but not the UK) have established limit values for organic pollutants e.g. the upper limits for PAHs are 3 mg kg^{-1} dry weight in Denmark an d 10 mg kg^{-1} dry weight in Luxembourg (Hogg *et al.*, 2002) . In Germany and the Netherlands no limit values for organic compounds are provided because of the low level that has been detected in composts derived from the source-separated materials . Only very low levels of pesticides have been detected in bio-waste and green waste in Germany and Luxembourg.

In some countries regulations exist concerning the use of pesticides in gardens, partly related to concerns for the fate of these compounds once composted. Denmark, with its high rate of composting of garden waste, has recently implemented a ban on the use of garden pesticides.

In the US there is concern that certain herbicides (e.g., chlorpyralid and picloram) are very persistent to degradation, and may decompose slower in compost than in natural soils (Hogg *et al.*, 2002).

Organic compounds are also derived directly from the compost itself. For example, fatty acids and methylated esters may be produced by microorganisms during the composting process. The quantities are small however, and are not considered to be dangerous (Gonzales-Vila *et al.*, 1982). Of greater concern are volatile organic compounds which cause odours. These are mainly due to sulphur compounds such as methyl mercaptan, which is produced from the amino acid methionine under anaerobic conditions (Catton, 1983).

2.7 Effect of composting on the biological parameters of the finished product

Compost is a biological product (unlike peat-based products) which contains a wide range of microorganisms that are beneficial to plants and the environment. The feedstock materials for composting are generally wastes from a wide range of agricultural, municipal and industrial sources, and in many cases these materials will contain a number of microorganisms which are pathogenic to humans, animals and plants.

Feedstock materials may also contain weed seeds e.g. from animal feeds or bedding material. The thermophilic conditions during composting should eliminate weed seeds. The PAS 100 (BSI, 2002) indicates that there should be no more than 5 weed propagules per litre of compost product.

Composting is an intense thermophilic microbial process which when managed correctly will provide a microbially-rich product which is safe from pathogens. There has been concern over the fate of human pathogens in sewage sludge (ADAS, 2001), and more recently attention has been focussed on the risk associated with composting catering waste containing meat. A risk assessment has been carried out for DEFRA (Gale, 2002) and a draft statutory instrument published for consultation (DEFRA, 2002b) which specifies the processing systems and parameters that can be used for the composting of catering waste.

2.7.1 Human pathogens

A human pathogen can be defined as any virus, microorganism, or substance capable of causing disease. There are two main categories: (a) primary pathogens and (b) secondary or opportunistic pathogens. The major types of pathogens are shown in Table 2e.

Table 2e Major types of human pathogens (ODEQ, 2001)

Primary Pathogens	**Secondary Pathogens (Bioaerosols)**
Bacteria	Fungi
Viruses	Actinomycetes
Protozoa	Endotoxin
Helminths: nematodes (roundworms) and cestodes (tapeworms)	

Prions and endotoxins are examples of a pathogenic non-organism. A prion is a protein that when normal, is harmless and occurs in the brains of all mammals, including humans. However, they can be transformed to abnormal, deformed prions that can turn normal prions into deformed prions and result in Bovine Spongiform Encephalopathy (BSE). Endotoxins are heat-stable, phospholipid-polysaccharide-protein complex macromolecules which form part of the cell wall of gram-negative bacteria. They are found in organic dusts and can form allergic reactions (ODEQ, 2001)

The recent risk assessment on the use of composting to dispose of catering waste focussed on transmissible spongiform encephalopathy (TSE) agents, the exotic pig viruses, *E. coli* 0157, campylobacters, salmonellas, Newcastle disease and parasites (Gale, 2002).

Mixed food waste which includes produce waste, kitchen waste (vegetative), and table waste (mixed food waste containing meat, grease and dairy products) may include the following pathogens (ODEQ, 2001):

Salmonella spp., a gram-negative bacterium widespread in animals, especially poultry and swine. It is present in water, raw meats, raw poultry, and raw seafood. The most common species are *S. typhi*, *S. enteritidis*, and *S. typhimurium*. Salmonellosis is a food poison-type illness. *S. typhi* produces typhoid or typhoid-like fever.

Escherichia coli O157:H7 is a serotype of *E. coli*. *E. coli* is a normal inhabitant of the intestines of all animals, including humans. A minority of *E. coli* strains is capable of causing human illnesses. It has been associated with undercooked or raw meat, vegetables, fruit, juices, and cheese.

Shigella spp is a gram-negative bacterium that causes bacillary dysentery. It is associated with a range of foods.

Listeria monocytogenes is a gram-positive bacterium that is commonly isolated from soil, silage, and other environmental sources. It is associated with unpasteurised dairy products and meat.

Yersinia enterocolitica is a gram-negative bacterium that is found in meats and raw milk.

Vibrio cholerae Serogroup Non-O1 infects only humans and is associated with shellfish.

Campylobacter jejuni is a gram-negative bacterium that is believed to be one of the leading cause of bacterial diarrheal illnesses It has been isolated from cattle, chickens, birds, and flies. It has been associated with raw chicken, milk, and water supplies.

Staphylococcus aureus is a gram-positive bacterium that is associated with a range of foods.

Hepatitis A Virus is an enterovirus and is associated with contaminated fruit, vegetables and water.

Norwalk Virus Group is transmitted via contaminated food and water

Cryptosporidium parvum is a protozoan parasite that infects humans and many animals, including calves, cows, sheep, goats and deer. The infective stage of the parasite is an oocyst.

Giardia lamblia is a protozoan parasite that is associated with contaminated water and foods.

Composting can be very effective in the destruction of pathogens (Epstein, 1997). The main mechanism of pathogen destruction during composting is the effect of high temperatures over a long period of time. Many countries have schemes in place which require, either through statutory standards or through voluntary schemes, the compost material to be raised to a minimum temperature for a minimum period of time. Where the compost is in open-air windrows, this will be a longer period of time, and these temperature regimes are often linked to requirements for turning.

In addition, the composting process involves considerable changes in the biochemistry of the composted material. Antagonistic effects and breakdown of the mesophilic microbial biomass in the maturation phase can play a significant role in the elimination of pathogens and in the prevention of recolonisation of the compost by pathogens.

2.7.1.1 Composts

Feedstock materials for composting may contain plant, animal and human pathogens, and countries which have statutory composting standards in place normally have testing criteria in place for the content of pathogens. Indicator organisms are used to identify the presence or absence of pathogens. It is impractical to monitor all of the pathogenic organisms that could be present in a feedstock and the effectiveness of the composting process on their destruction so pathogen testing usually involves testing for the presence of specific indicator microorganisms.

Since *Salmonella spp*. are often present in non-green feedstock and they are relatively resistant to temperature their destruction is a good indication of the absence of other pathogens. Parasites and viruses should be destroyed prior to the destruction of faecal coliforms or *Salmonella spp*. Furthermore, the laboratory methods used to test for these organisms are not expensive.

The effectiveness of the individual composting procedure in destroying pathogens can be determined in a variety of ways (Hogg *et al.*, 2002). Samples of microorganisms may be introduced to a batch at the start of the process and their survival evaluated upon completion of the process (e.g. in Germany, Luxembourg).

Indirect test criteria can be used for a plant in practical operation through monitoring and recording the temperature of each composting mass daily. Standards are typically set in the form of a minimum temperature requirement for a minimum period of time. For example the PAS 100 (BSI, 2002) recommends the following alternatives:

- ≥55°C for at least 14 days in windrows with at least five turnings,
- ≥65°C for at least 7 days in windrows with at least two turnings,
- ≥60°C for at least 7 days an aerated static pile with insulating layer (no turning),
- ≥60°C for at least two days for in-vessel systems,
- ≥70°C for at least 1 hour for in-vessel systems.

However, the size of individual particles is an important factor in determining the effectiveness of the process, particularly in relation to meat. Gale (2002) assumed in the risk assessment that there would be no pieces of meat >40 cm. A further precaution is not to allow animals to graze on land to which composted catering waste has been applied for a period of 2 months (Gale, 2002).

In most countries a combination of a specified temperature–time regime and end product tests (typically using *Salmonella spp* and *E. coli*) is used to guarantee sanitisation. The PAS 100 recommendations above are in general agreement with the second draft of the EU Biowaste Directive. The PAS 100 states that *Salmonella spp* shall be absent in a sample of 25 g compost and the concentration of *E. coli* shall be less than 1000 colony forming units (CFU) per gram.

It is interesting to note that 10 years of experience and research on Salmonellae and Enterobacteriaceae (*E. coli* and other coliform bacteria) in Austria have given no evidence of any compost-derived disease problem in practice (Hogg *et al.*, 2002).

During composting, some of the nitrogen is transformed into ammonia. Several studies have shown that ammonia is toxic to a variety of organisms (Taylor, *et al.*., 1978; Ward and Ashley, 1976). Poliovirus 1, Coxsackievirus, and Echovirus can be inactivated by ammonia and the rate of viral inactivation by ammonia in sludge is increased by heating.

2.7.1.2 Recolonisation of compost by pathogens

The indigenous microorganism population in compost is very large. Webley (1947) found that for grass compost, the maximum number of bacteria was 2.6×10^{11} per gram of fresh weight. When the food source for organisms becomes limited, the indigenous microorganisms are much better able to utilize the limited food supply than pathogens. Under these conditions, the pathogen populations die. Millner, *et al.* (1987) reported that the presence of metabolically active bacteria and actinomycetes resulted in the death of salmonellae in compost. Proper maintenance of aerobic conditions and moisture encourages the proliferation of the indigenous microorganisms.

Recontamination of compost with pathogens can occur when a finished compost is contaminated by dirty equipment or the introduction of feedstocks containing pathogens. Viruses, helminths, and protozoa cannot regrow outside their specific host organisms, however, bacteria *Salmonella spp.* and faecal coliforms can. Recontamination can be detected when compost is tested using these bacteria as indicator organisms. A stable product will be unfavourable for recolonisation, therefore it is important to ensure that products have reached this stage (See Section 2.7.5)

2.7.1.3 Bioaerosols

Bioaerosols can invade and infect humans. Inhalation of dust from organic material can cause respiratory problems. The three major illnesses from bioaerosols are inflammation, allergy, and infection (Epstein, 1997). The bioaerosols of greatest interest in relation to composting are the fungus *Aspergillus fumigatus*, endotoxin, and organic dust.

Aspergillus fumigatus is thermotolerant and, therefore, survives the high temperatures normally obtained during composting. It is ubiquitous and is associated with decaying organic matter and soil throughout the world. It has been found in homes, potted plants, dust, parks, woods and wood chips, lawns, compost, agricultural environments, and many other common locations (Millner, *et al.*., 1994; Epstein, 1997) and therefore, it will be found in non-green feedstock composting operations.

Endotoxins are heat-stable, phospholipid-polysaccharides –protein complex macromolecules. They are part of the cell wall of gram-negative bacteria and are therefore ubiquitous since gram-negative bacteria are throughout the environment. Organic dust contains endotoxin.

The major concern is for workers since they are exposed more frequently and to higher concentrations than the general public. *Aspergillus fumigatus* and endotoxin can be collected using an Anderson sampler. Measurements are usually made at several locations both upwind and downwind during the different composting operations. Emissions of bioaerosols can be minimised by maintaining moist conditions during
composting or moving of material.

2.7.1.4 Animal manures

Studies at the catchment level and field trials have indicated that livestock excreta could act as significant sources of faecal indicator organisms for recreational waters and water supplies (Kay *et al.*, 1999; Vinten *et al.*, 2002). The potential importance of this pathway for transfer of pathogens is illustrated by the fact that there is around 30 times more livestock manure recycled to agricultural land than biosolids, with livestock manures applied to 3.9 million ha per year and biosolids applied to 80,000 ha (Nicholson *et al.*, 2002).

There has been a large increase in the number of reported cases of food-borne illness over the past 20 years, mainly due to Salmonella, Campylobacter, verocytoxin-producing *Escherichia coli* (VTEC) and Listeria (Pell, 1997; Jones, 1999). Although it is very difficult to determine the exact routes of infection, a significant number of these cases involve contaminated food or water. This may be due in part to contamination of food during primary production, and the on-farm use of animal manures containing pathogenic microorganisms may be one possible route of contamination.

In a recent study of around 1000 livestock waste samples taken from around Great Britain 5.5% of samples contained Salmonella, 15.3% contained *E. coli* 0157, 16.7% contained Campylobacter, 29.4% contained Listeria (Hutchinson *et al.*, 2002). Solid manures offer the best opportunity for pathogen control using extended storage in heaps. Manure heaps encourage the formation of thermophilic conditions in which reduction in pathogen loads can be achieved ranging from 2 to 6 log reductions in indicator *E. coli* numbers (Nicholson *et al.*, 2002). This can be best achieved with minimum costs if the manure is stored in heaps in the field (although precautions would have to be taken to minimise water pollution risks). Turning and mixing of manure should be encouraged to promote thermophilic conditions. A storage period of one month is likely to be adequate to ensure the elimination of most pathogens. The treatment of slurry is more problematic because options such as landfilling or anaerobic digestion are costly (Nicholson *et al.*, 2002).

2.7.2 Plant pathogens

In contrast to the vast literature on survival of human pathogens during composting of municipal wastes and sewage sludge there are few data on survival of plant pathogens during composting (Bollen, 1985). More interest has been focussed on the disease-suppressing properties of compost (Section 4.6).

In reviewing the literature, Bollen (1985) concluded that the chances of survival of fungal pathogens are very low. Even pathogens such as *Verticillium dahliae*, which form resistant sclerotia that persist in soil for more than 10 years, are eradicated by composting (Yuen and Raabe, 1979). Nematodes such as potato cyst nematode seem to be very susceptible to composting, possibly due to organic acids produced (Bollen, 1985).

The very few data on survival of plant viruses indicate that these pathogens are more resistant to composting than fungi and nematodes (Bollen, 1985). Gale (2002) reported there was evidence that some nematodes, spores from certain plant pathogenic fungi produce hardy resting spores and plant pathogenic viruses may survive the composting process. Five pathogens were identified as being of particular concern (Gale, 2002):

Sclerotium cepivorum (white rot of onions)
Plasmodiophora brassicae (club root)
Polymyxa betae (vector of beet necrotic yellow vein virus which causes Rhizomania)
Potato spindle tuber viroid
Pepino mosaic virus.

Bacillus species and their antibiotics isolated from composts are known to have antifungal activity against phytopathogenic fungi (Phae *et al.*, 1990). A review of the survival of plant pathogens during composting is currently being undertaken by HRI for WRAP, but was still in progress at the time of this report.

2.7.3 Enzyme activity

The composting process involves the microbial degradation of simple compounds (e.g. sugars and organic acids) and and more complex polymers e.g. protein and lingo-cellulose. These involve catabolic reactions which depend upon a range of endocellular and extracellular enzymes. It is expected that the period of intense microbial activity will be associated with higher levels of activity of oxidoreductase and hydrolase enzymes (Epstein, 1997).

However, studies on MSW have indicated little change in the activity of endo-cellulase and glucosidase during the first 80 days of composting and low levels of acid- and alkaline-phosphatase following an initially high level during the first few days (Hermann and Schann, 1993)

2.7.4 Stability and maturity parameters

There is no general agreement on definitions of stability and maturity. Stability is usually defined either as a stage in the composting process, or as a rate of activity. Compost maturity is usually associated with the readiness of the material for its intended use (agriculture, horticulture, landfilling). ADAS have recently undertaken an assessment of the options and requirements for stability and maturity testing of composts commissioned by WRAP, and due to be published on the WRAP website during February 2003.

Compost stability is an important characteristic and under certain conditions, immature, poorly stabilised composts can cause problems. Continued active decomposition when these composts are added to soil or growth media may reduce the oxygen concentration in the soil-root zone, reduce available nitrogen, or lead to the production of phytotoxic compounds (Brinton and Evans, 2001). Ensuring stability of compost also reduces the potential for recolonisation of the material by human pathogens such as *Salmonella spp.* (Section 2.7.1.2).

Tests have therefore been developed to evaluate the maturity of compost materials and many countries have in place some form of measurement for stability as part of compost standards (Hogg *et al.*, 2002). However, there is no clear agreement on the best approach exists. Methods include seed germination and plant growth, the amount of heat that the material can produce in a closed container (self-heating test or ‘Rottegrad’), or by measuring microbial respiration in the compost by oxygen consumption or carbon dioxide production.

Brinton *et al.*. (2001) reported that volatile organic acids (VOA) and respiration using CO_2 techniques correlated well with cress germination and container plant growth. Ammonia and VOA effects were stronger at root emergence stages while oxygen depletion and sulphide effects were longer lasting. Self-heating correlated to germination and growth over a limited range only. They suggested that maturity is best indicated by two or more unrelated analyses.

Stability is normally achieved by the end of the actively managed composting phase. The period required to achieve this will depend upon the types of feedstock materials, and management of the composting process.

2.8 Conclusions and recommendations for future work

Composting is an excellent example of the practical use of biotechnology. It involves a highly complex biological process, involving many species of bacteria, fungi and actinomycetes, which coverts a low-value material into a higher value product. A wide range of biowastes can be composted including materials generated by agriculture, food processing, wood processing, sewage treatment, industrial and municipal waste. However, regulations place restrictions on the materials that can be used in organic farming and production systems. The basis for these regulations should be based on current scientific understanding.

There is little research specifically on composting in organic farming and production systems, therefore most of the information is based on studies carried out in conventional farming system. However, composting and the use of composted products, e.g. composted manure, forms a major component of soil fertility management in organic farming systems. There is great potential to learn from the range of experience reported in the broader scientific literature.

This requires greater effort to be put into technical transfer of current knowledge on composting to inform organic farmers and growers, and regulators about issues of concern.

Composting is seen as a key process in the waste hierarchy in the UK and markets for compost have an important role in reducing the volume of biodegradable municipal waste going to landfill. The use of carbon sequestration into soil is soil one of the few tools for changing the balance of carbon in the atmosphere and can therefore help the UK in meeting the strategic goals of the climate change agreements. To make an appreciable difference there will need to be large-scale and widespread use of compost. Further research is needed to quantify the short-term benefits of compost use in soil in terms of carbon sequestration.

There has been a considerable amount of work throughout the world to develop composting systems for both conventional and organic agricultural systems although few of these have been developed with UK agriculture specifically in mind. The CMC (Controlled Microbial Composting) system developed in Austria is now being developed by a range of growers and research workers for use in UK organic agriculture). However, UK organic farmers are not using composting to any significant extent at present. Research is needed on the CMC system to enable it to be compared with alternative systems developed in the UK.

Empirical relationships exist between process variables such as C/N ratio of input materials, moisture contents, aeration status and the quality of the finished product. There is a need to establish more rigorous process models that enable the composting of a variety of materials by a variety of alternative methods in order to produce finished compost of a suitable quality for a number of different purposes (growing media, soil conditioner etc).

A considerable amount of work has been carried out to develop improved methods for preparation and use of compost extracts and teas for use as fertilizers and to assist crop protection. Most of this work has been done in the United States and much of it by commercial companies. There is an urgent need for research on the efficacy of these products and risk assessments on the colonisation of non-aerated compost teas by human pathogens.

Effective monitoring tools are required to enable different composting systems to be managed to ensure that conditions are such that they will minimise the risk of the production of greenhouse gases (N_2O and CH_4), ammonia, and organic acids.

Source segregation of municipal solid waste followed by recycling (for paper, textiles etc) and composting should be encouraged as this gives the lowest net flux of greenhouse gases, compared to other options for the treatment of municipal solid waste.

The feedstock materials used for composting may contain a range of potentially toxic elements (PTEs). Upper limits for conventional compost are given in the PAS 100 and limits for organic compost derived from household waste are given in UKROFS regulations. These limits should take into account the bioavailability of PTEs in compost immediately following incorporation into soil and over time as the compost is decomposed.

The waste material used for composting may contain a large number of organic contaminants (pesticides, pharmaceuticals, industrial contaminants). The fate of these compounds during the composting process will largely determine their presence in the finished product. Only the most stable compounds are likely to persist in the compost due to the length of time taken for the composting process, the intense microbial activity, and the high temperature.

Overall it appears that composting can be considered to be essentially similar to a biologically active soil environment in which degradation is accelerated. However, the bioavailability of compounds may be different due to the high content of organic matter in compost, which may sorb compounds, making them less bioavailable. Research is needed on the bioavailability of pesticides in compost.

Animal wastes from intensive farming and treated sewage often contain traces of therapeutic agents (compounds that are used to cure or prevent diseases). These compounds are likely to behave in the same way as pesticides in the environment, and may maintain residual activity in manure and biosolids. Research is needed on the fate of therapeutic agents in compost.

There has been concern over the fate of human pathogens in sewage sludge, and more recently attention has been focussed on the risk associated with composting catering waste containing meat. A risk assessment has been carried out for DEFRA and a draft statutory instrument published for consultation which specifies the processing systems and parameters that can be used for the composting of catering waste.

It is impractical to monitor all of the pathogenic organisms that could be present in a feedstock and the effectiveness of the composting process on their destruction so pathogen testing usually involves testing for the presence of specific indicator micro-organisms (typically *Salmonella spp* and *E. coli*).

Bioaerosols are also a concern, particularly the fungus *Aspergillus fumigatus* and endotoxin. Emissions of bioaerosols can be minimised by maintaining moist conditions during composting or moving of material.

Livestock excreta can act as significant sources of faecal indicator organisms for recreational waters and water supplies. There is around 30 times more livestock manure recycled to agricultural land than biosolids indicating that this is a potentially important pathway of transfer of pathogens.

Manure heaps encourage the formation of thermophilic conditions, particularly if turned and mixed, in which large reductions in pathogen loads can be achieved. A storage period of one month is likely to be adequate to ensure the elimination of most pathogens.   Stacked manures should be encouraged as a means of reducing pathogen transfer.

In contrast to the vast literature on survival of human pathogens during composting of municipal wastes and sewage sludge there are few data on survival of plant pathogens during composting. More interest has been focussed on the disease-suppressing properties of compost.

The chances of survival of fungal pathogens are very low. Even pathogens that persist in soil for years are eradicated by composting. Nematodes such as potato cyst nematode seem to be very susceptible to composting, possibly due to organic acids produced. The very few data on survival of plant viruses indicate that these pathogens are more resistant to composting than fungi and nematodes. Research is needed on the survival of plant pathogens in compost, together with the development of diagnostic kits to assist in quality assurance of the finished product.

Feedstock materials may also contain weed seeds e.g. from animal feeds or bedding material. The thermophilic conditions during composting should eliminate weed seeds.

Compost stability is an important characteristic and under certain conditions, immature, poorly stabilised composts can cause problems. Continued active decomposition when these composts are added to soil or growth media may reduce the oxygen concentration in the soil-root zone, reduce available nitrogen, or lead to the production of phytotoxic compounds. Ensuring stability of compost also reduces the potential for recolonisation of the material by human pathogens such as *Salmonella spp.*. Research is needed on methods for determining stability of composted materials.

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