

# Literature review: Compost stability – impact and assessment



A review of the current information regarding:

- The influence of the various processing factors and operational conditions of in-vessel systems on the stability of the resulting composts.
- The impact of compost stability on compost storage and end use, with an emphasis on agriculture and growing media.
- The range of compost stability tests in use in the UK and Europe.

This report should be read alongside Final report: Compost stability - impact and assessment, covering the laboratory and field research aspects of this project

WRAP's vision is a world where resources are used sustainably.

Our mission is to accelerate the move to a sustainable resource-efficient economy through re-inventing how we design, produce and sell products; re-thinking how we use and consume products; and re-defining what is possible through re-use and recycling.

Find out more at [www.wrap.org.uk](http://www.wrap.org.uk)

**Document reference: WRAP, 2015, Banbury, Literature review: Compost stability impact and assessment, Prepared by Dimambro, ME., Steiner, J., Rayns, F., Wallace, P.**

**Written by:** Dr Mary Dimambro and Dr Joachim Steiner (Cambridge Eco), Dr Francis Rayns (Garden Organic) and Dr Phil Wallace (Phil Wallace Ltd)



Phil Wallace Ltd

---

**Front cover photography:** Compost

While we have tried to make sure this report is accurate, WRAP does not accept liability for any loss, damage, cost or expense incurred or arising from reliance on this report. Readers are responsible for assessing the accuracy and conclusions of the content of this report. Quotations and case studies have been drawn from the public domain, with permissions sought where practicable. This report does not represent endorsement of the examples used and has not been endorsed by the organisations and individuals featured within it. This material is subject to copyright. You can copy it free of charge and may use excerpts from it provided they are not used in a misleading context and you must identify the source of the material and acknowledge WRAP's copyright. You must not use this report or material from it to endorse or suggest WRAP has endorsed a commercial product or service. For more details please see WRAP's terms and conditions on our website at [www.wrap.org.uk](http://www.wrap.org.uk)

# Executive summary

Since the development and introduction of compost stability testing in the 2005 edition of PAS100, industry practices and scientific studies have progressed significantly. Over the last 10 years, a greater amount of food waste has been collected and processed through in-vessel composting systems, and economic pressure has resulted in shorter processing times followed by the field storage and spreading of younger, less mature composts. This review was undertaken to assess the more recent literature and industry practices within a regulatory context where composts may be spread to land under different regimes. The four main research questions regarding IVC composts with a range of stabilities are summarised below.

This literature review is the first phase of project OMK009, and has been used to inform the next project phase of site and laboratory work.

## **1. The influence of processing factors and operational conditions within in-vessel systems on the stability of the resulting composts**

Important processing factors for in-vessel composting systems include aeration, porosity, structure, pH, moisture, the C:N ratio and microorganisms. During the early phase of composting, volatile organic acids (VOAs) are produced and the pH of the material drops. With adequate aeration, these acids are either broken down by microorganisms or become volatilised. However if poor aeration causes the development of anaerobic conditions within part or most of the material, VOAs may persist and cause offensive odours and will potentially inhibit the composting process as a whole.

Low temperatures are another factor that can lead to an accumulation of volatile organic acids. Unless the initial temperature increases sufficiently, the appropriate thermophilic microbiological community required to degrade VOAs may fail to establish, hence allowing VOAs to accumulate.

In addition, under acidic conditions, ammonia is not volatilised but remains in solution either as dissolved ammonia gas or ammonium. As conditions change later in the process (for example, the material is removed from the vessel and managed as an outdoor windrow), pH and temperature increases resulting from increased oxygen availability and microbiological activity can result in a flush of ammonia from the material. Materials containing greater amounts of food waste are more likely to present these problems than materials containing greater amounts of green waste.

The site and laboratory work undertaken as phase 2 of this project, was therefore designed to consider the effects of aeration and temperature during composting in conjunction with material characteristics such as feedstock composition, C:N ratio, pH, ammonium and other nutrients, microbial activity and communities. The focus of phase 2 was to consider these factors in relation to compost stability over time, in order to assess any correlation and improve both process control and regulatory understanding.

## **2. The impact of compost stability on compost storage, with an emphasis on agriculture and growing media (including horticulture)**

Despite extensive searching, no published work was found which has examined the potential for leaching or odour generation from in-field compost storage heaps for either immature or mature IVC composts in the UK.

To greatly reduce the risk of leachates entering ground or surface water, the Nitrate Vulnerable Zones (NVZs) regulations (in addition to CoGAP) includes specific rules regarding construction and placement of storage piles of compost. Moreover, the range of rules relevant to PAS or non-PAS composts also specifies where in-field storage of composts can occur to minimise the likelihood of leaching.

It is possible that less mature composts stored in the field might pose a pollution risk, if the stabilisation phase of the composting process was minimised or if it had 'stalled' due to inadequate moisture or aeration, or had become anaerobic due to a lack of structure within the pile. However, the literature suggests that after the first few weeks of composting the amount of leachate produced is small. Further research could indicate if a pH or stability test of the material might indicate its condition and likelihood of causing a pollution incident, either in storage or after spreading. Addition of lime or pH adjustment may mask this, however.

Bagged composts have been reported to pose problems of malodours, flies and fire during storage. It is possible that these issues described by the general public could, in part, be a result of the compost being bagged prior to being mature and stable. However, no academic literature was identified to corroborate anecdotal feedback from members of the public regarding the use of IVC composts in bagged growing media.

## **3. The impact of compost stability on compost end use, with an emphasis on agriculture and growing media (including horticulture)**

Regarding the use of immature compost in agriculture and field horticulture, the literature data obtained does not fully reflect the diversity of composts (feedstock, processing method, stability), application timings, crops and soil types necessary for comprehensive conclusions to be drawn for the UK. However, the information gathered on immature composts does provide an indication as to the types of effects which could be anticipated.

The majority of published research regarding the use of immature composts in agriculture and field horticulture on a range of crops and soil types has been undertaken in Germany, with some work also from Luxemburg and Canada. These trials generally refer to composts as being fresh (Rottegrad II-III in the German stability classification system) or mature (Rottegrad IV-V). The main aspects of compost use which were investigated were crop performance, nitrogen, soil properties and pollution.

### ***Crop yield***

Agricultural and field horticultural trials regarding the use of fresh composts have generally shown agronomic benefits on crop yield (i.e. wheat, barley, rye, oilseed rape, maize, asparagus, beetroot, sugar beet, cauliflower, lettuce, spinach, chard) and soil properties when fresh and mature composts have been used.

In some trials there were no differences in yield response when comparing fresh and mature composts, and in others fresh compost crop yield was greater. In some cases the addition of

inorganic fertiliser to fresh and mature compost was observed to increase yields more than when compost was used alone.

However, for very salt sensitive crops such as lettuce and spinach, a combination of both negative, neutral and positive yield effects were observed in one study when fresh and mature composts of a range of maturities were incorporated only to a depth of 3 to 4 inches on a range of soil types.

### ***Soil nitrogen***

Yield effects were in some instances linked to the available N released (mineralised) within the growing season both during the year of application and in subsequent years. In turn, N release was associated with a number of factors including the C:N ratio of the compost and the soil, the soil organic matter and the soil type. Initial N lock-up (immobilisation) has been observed in some pot and field studies when using fresh composts, and/or composts with a C:N ratio >20:1, but this is temporary, with re-mineralisation being observed subsequently. However, other fresh composts have been observed to have a higher N release rate than mature composts. Several authors indicate that the N release rate may be influenced by the compost feedstock, with some fresh composts containing a proportion of biodegradable municipal waste (BMW, which includes kitchen and garden waste) or poultry manure releasing more N than fresh or mature green waste composts.

As with mature composts, N mineralisation rates for fresh composts were observed to be much higher during the warmer summer months than during the winter. Crop yield reductions due to N immobilisation are usually avoided by applying and incorporating the compost well in advance, such as in the autumn before a spring sown crop. Indeed even for using mature composts with salt sensitive crops, a period of several weeks between compost application and sowing is recommended in the UK, as with manures or NPK fertilisers (WRAP, 2004b).

Not all publications described the full set of compost properties (such as stability, feedstock, application timing) and/or trial design in detail (such as compost incorporation depth, time between compost application and sowing, soil type), hence no specific comparisons with UK systems could be made.

In a field, little compost is applied in relation to the volume of soil present due to nutrient loading limitations. However, in growing media, compost may be used at a third or even more as part of a mixture. Hence initial N lock-up effects following use of fresh composts were more readily observed in pot studies than in field trials. Where pot studies involved several cuts of grass over a number of months, initial N lock-up was in several cases observed for fresh BMW and green waste and mature green waste composts at the start of the experiment and the first grass harvest, with re-mineralisation observed in later harvests. The application of inorganic N was generally observed to counteract this initial N lock-up effect for both fresh and mature composts.

### ***Soil properties***

In the field situation, both fresh and mature composts have been observed to supply carbon as a source of energy for soil microorganisms, and nutrients, leading to increased soil microbial activity, improved soil organic matter and fertility. Positive effects on soil physical properties such as aggregate stability, pore volume and water holding capacity have been observed in some studies where fresh composts were applied annually for at least two years. In some instances, effects were more pronounced for mature composts and/or in sandy soils than heavier soil types. Due to application limits restricting total application volumes, these beneficial effects generally become more apparent with regular applications of fresh or mature compost over many years.

### ***Pollution: Water and air***

There are specific rules in the UK to safeguard the environment from ground and surface water pollution, such as nitrate leaching, following the application of composts. By tailoring compost and additional N fertiliser application rates to match the requirements of the crop (e.g. using RB209), leaching should be minimised. Within NVZs the maximum compost application rate is 250 kg N/ha/year or 500 kg N/ha once every two years. This equates to approximately 23 to 33 t FW/ha/year or 46 to 66 t FW/ha bi-annually for UK green waste and BMW composts respectively.

Where fresh composts were applied at very high application rates (>200 t/ha in one year or 300 t/ha over a four year period, both much greater than permitted NVZ limits in the UK) some nitrate leaching was observed in light sandy soils, but not in heavier soil types such as clay silt. However, the use of fresh and/or mature composts in agriculture at application rates comparable to those permitted in the UK did not generally result in significant nitrate leaching for a range of crops and soil types.

No publications were available considering the release of GHGs during the application of IVC composts in the field or thereafter. However, the use of compost directly enhances soil carbon, and can reduce emissions from agriculture by reducing the need for chemical fertilisers, minimising cultivations and the need for irrigation, and so the GHG balance was considered positive.

## **4. The range of compost stability tests in use in the UK and elsewhere – with particular reference to those required by compost specifications other than PAS100 in Europe**

A number of tests to assess for compost stability/maturity have been developed and investigated over the past 25 years. They have been used for garden waste, food waste, manure, sewage sludge and various industrial wastes. The most commonly cited tests are self-heating (Dewar test) and oxygen uptake rate (OUR test), which are both proposed as EU end of waste compost stability tests. Thus it was recommended to include those two stability tests as part of a stability test comparison in the laboratory work phase of this project.

For the majority of EU countries, there are currently no legal requirements with regards to compost stability testing with exception of Ireland and Flanders. Specific voluntary stability limits are defined in Germany, Flanders, Ireland and the UK. The only countries which have a distinction between compost end use and stability are Germany and Luxembourg, where a specific quality assurance scheme (BGK) suggests the use of fresh compost in agriculture, mature compost in horticulture, and substrate (very mature) compost in growing media. This is not a legal requirement.

The results of this literature review have been used to recommend the final selection of stability test methods for the laboratory and field work, and also to facilitate interpretation of the data arising.

# Contents

<b>1.0</b>	<b>Introduction and background</b>	<b>11</b>
1.1	Compost stability considerations and definitions	11
1.2	Compost stability test development for PAS100	14
1.3	Objectives	14
1.4	Methodology	14
<b>2.0</b>	<b>In-vessel composting systems</b>	<b>17</b>
2.1	Environment Agency regulations for in-vessel composting	18
2.2	The Animal By-products Regulation and the compost sanitisation process	19
<b>3.0</b>	<b>Processing factors</b>	<b>20</b>
3.1	Processing factors: Oxygen content and aeration	21
3.2	Processing factors: pH and VFAs/ VOAs	22
3.3	Processing factors: pH and ammonia	23
3.4	Processing factors: Use of additives to influence pH	23
3.5	Processing factors: Moisture content	24
3.6	Processing factors: Feedstock	26
3.7	Processing factors: Micro-organisms	26
3.8	Links between stability and odour	29
3.9	Volatile organic compounds emitted during composting	30
3.9.1	Volatile organic acids emitted during composting	31
3.9.2	Volatile organic sulphur compounds emitted during composting	31
3.10	Reducing compost odour	32
3.11	Emission of greenhouse gases and ammonia during composting	33
<b>4.0</b>	<b>The regulatory requirements and literature regarding compost stability and compost storage</b>	<b>36</b>
4.1	Compost storage rules: All composts	36
4.2	Compost storage: PAS100 composts	37
4.3	Compost storage: Non-PAS composts	38
4.4	The potential for leaching of immature composts stored in-field	39
4.5	Greenhouse gas and ammonia emissions of immature composts during in-field storage	40
4.6	Storing bagged compost	41
<b>5.0</b>	<b>The regulations regarding compost end use in the UK</b>	<b>42</b>
5.1	Compost end use: Rules for all composts	42
5.2	Compost end use: Rules for applying PAS100 composts	44
5.3	Compost end use: Rules for non-PAS composts	44
<b>6.0</b>	<b>The impacts of compost stability on compost end use</b>	<b>45</b>
6.1	Immature compost use in growing media	46
6.2	Crop growth and yield	47
6.2.1	Compost use in agriculture and field horticulture	48
6.2.2	Immature compost use in agriculture and field horticulture	48
6.2.3	Fresh and mature compost use in agriculture and field horticulture:	
	Germany	51
6.3	Nitrogen mineralisation	55
6.3.1	Glasshouse and laboratory trials: Nitrogen mineralisation	55
6.3.2	Immature compost use as a mulch	58
6.3.3	Field trials: Nitrogen mineralisation	58
6.4	Nitrate leaching	61
6.5	Soil physical properties	63
6.6	Soil microorganism activity and diversity	65
6.6.1	Fresh compost: Soil microorganism activity and diversity	66
6.7	Greenhouse gas emissions during and after compost application	67

6.8	Odour during and after compost application .....	68
6.9	Weeds .....	68
<b>7.0</b>	<b>Compost stability tests in the UK and further afield.....</b>	<b>69</b>
7.1	Germination/ plant growth .....	70
7.2	Respiration methods.....	71
	7.2.1 Dynamic respiration test.....	71
	7.2.2 Static respiration tests – measuring oxygen uptake.....	71
	7.2.3 Static respiration tests – measuring carbon dioxide production.....	72
7.3	Self-heating test .....	73
7.4	Spectroscopy .....	73
	7.4.1 Humic acid fractionation .....	75
7.5	Chemical methods: Ammonium and nitrate .....	75
7.6	Biochemical enzyme activity and DNA analysis.....	75
7.7	Dissolved organic carbon .....	76
7.8	Other chemical stability methods.....	76
7.9	Summary of stability test methods.....	77
<b>8.0</b>	<b>EU stability tests.....</b>	<b>78</b>
8.1	Proposed EU-wide compost stability criteria.....	78
8.2	UK compost stability criteria .....	79
8.3	EU country-specific stability requirements .....	79
8.4	Current compost stability limits and corresponding end uses.....	81
	8.4.1 Oxygen uptake rate.....	81
	8.4.2 Solvita Test .....	81
	8.4.3 Self-heating test .....	82
	8.4.4 Respiration Activity (e.g. AT 4).....	83
<b>9.0</b>	<b>Conclusions .....</b>	<b>83</b>
<b>10.0</b>	<b>References.....</b>	<b>86</b>

# Glossary

ABP	Animal by-products
ABPR	Animal By-Products Regulations
AR	Aeration rate
AT	Austria
BE	Belgium
BG	Bulgaria
BOD	Biological Oxygen Demand
Biowaste	German BMW including food waste and garden waste
BMW	Biodegradable Municipal Waste (source-separated)
C:N	Carbon:nitrogen ratio
CO <sub>2</sub>	Carbon dioxide
COD	Chemical Oxygen Demand
CoGAP	Code of Good Agricultural Practice
CPs	Chlorinated paraffins
CY	Cyprus
CZ	Czech Republic
DE	Germany
DGGE	Denaturing Gradient Gel Electrophoresis
DK	Denmark
DM	Dry matter
DW	Dry weight
DOC	Dissolved organic carbon
DON	Dissolved organic nitrogen
EA	Environment Agency
EC	Electrical conductivity
EE	Estonia
EoW	End of waste
ES	Spain
EU	European Union
EEM	Excitation–emission matrix
FA	Fulvic acid
FI	Finland
FM	Fresh matter
FR	France
FRI	Fluorescence regional integration
FT-IR	Fourier-transform infra-red spectroscopy
FW	Fresh weight
GHG	Greenhouse gas
GR	Greece
HA	Humic acid
HBCD	Hexabromocyclododecane
HU	Hungary
Humified	Chemically stable humus
IE	Ireland
IT	Italy
IVC	In-vessel composting
LT	Lithuania
LU	Luxemburg
LV	Latvia
MBT	Mechanical Biological Treatment
MC	Moisture content

MSW	Municipal Solid Waste
MT	Malta
NH <sub>4</sub> -N	Ammoniacal nitrogen
NIRS	Near infrared reflectance spectroscopy
NL	Netherlands
NO <sub>3</sub> -N	Nitrate nitrogen
NO <sub>x</sub>	Oxides of nitrogen
NP	Nonylphenol
NVZ	Nitrate Vulnerable Zone
OM	Organic matter
PAHs	Polycyclic aromatic hydrocarbons
PARAFA	Parallel factor analysis
PCBs	Polychlorinated biphenyls
PBDEs	Polybrominated diphenyl ethers
PCDD/F	Dibenzofurans
PFAS	Perfluorinated alkyl substances
PL	Poland
PT	Portugal
QPC	Quality Protocol for Compost
RH	Relative humidity
RO	Romania
SE	Sweden
SK	Slovakia
SI	Slovenia
TBBPA	Tetrabromobisphenol A
TVOC	Total volatile organic compounds
WHC	Water holding capacity
VOA	Volatile organic acid (same meaning as VFA)
VOC	Volatile organic compound
VOSC	Volatile organic sulphur compound
VFA	Volatile fatty acid
VS	Volatile solids

## Acknowledgements

Many thanks to the European compost experts who provided information on the current status of composting in the EU and their relevant country.

Many thanks to Ulrich Schmutz (Garden Organic), Jim Frederickson (Open University), Thomas Aspray (Heriot Watt University), Ralph Noble (East Malling Research) and the Project Steering Group (David Tompkins and Jacks Guinness (WRAP), Kathy Nichols (EA), Kiara Zennaro (ORG)), who provided assistance in the compilation of this review.

## 1.0 Introduction and background

Confidence in the use of composts in agriculture, field horticulture and growing media has been improved by the introduction of the UK compost quality specification BSI PAS100 in 2002, and the subsequent introduction of the Quality Protocol for Compost (QPC). These have been effective in enhancing the confidence of growers, farm assurance schemes, processors and supermarkets, and also in deregulating the use of quality-assured compost. From 2005 onwards, PAS100 has required that compost stability be tested and that assured composts comply with a minimum limit for stability. The limit is intended to represent a baseline for compost quality on which specific market sectors can build.

In the UK the number of in-vessel composting (IVC) sites is steadily increasing, with nearly 40% of organic waste composted in a process involving IVC in 2012. In 2012 there were 58 operational IVC sites (WRAP, 2013c) compared to 33 in 2009 and 23 in 2007/08 (Association for Organics Recycling, 2010). As the number of IVC plants in the UK has increased, so has the range of IVC techniques. For example, some IVC systems operate with a lower air supply than others, and the duration of the in-vessel phase may be one or two weeks (with turning) depending on the sanitization requirements of the Animal By-Products Regulations (ABPR). Subsequent storage and maturation of composts occurs both on and off the production site for supply to agricultural and growing media uses. The stability of the compost on delivery to the storage site, and its subsequent management (turning or the lack of it) or monitoring, may affect the quality of the end product and emissions to the environment. A better understanding of composting process effects on compost stability, and the relationship between stability and environmental risk, would greatly benefit both the regulator and the biological treatment industry at a time when commercial pressures are applied to process materials as rapidly as possible.

This introductory section considers how compost stability and maturity are defined, how the UK compost stability method for PAS100 was developed, and then highlights the key objectives and methodology for the literature review itself.

### 1.1 Compost stability considerations and definitions

The following definitions in the UK's Compost Quality Protocol are all relevant to this study (Environment Agency, 2012c).

**Sanitisation:** A biological process that together with the conditions in the composting mass gives rise to compost that is sanitary.

**Stabilisation:** Biological processes that together with conditions in the composting mass give rise to compost that is nominally stable.

**Maturation:** Period of lower rate biodegradation than in the preceding steps of composting (sanitisation and stabilisation). This step occurs after the actively managed period, either before or after any compost screening.

**Stable, stabilised:** Degree of processing and biodegradation at which the rate of biological activity has slowed to an acceptably low and consistent level and will not significantly increase under favourable, altered conditions.

The WRAP guide 'Compost Production for use in Growing Media – a Good Practice Guide' covers production and testing of composts and also includes the following, more in-depth definitions of maturation and stability (WRAP, 2011b):

**Maturation:** A period (within the composting process) of lower biodegradation than in the preceding steps of composting. The stabilisation continues but the rate of decomposition has slowed to the point that turning or forced aeration is no longer necessary. Some microbial activity and chemical changes, such as the oxidation of ammonium ions to nitrate, will continue. Beneficial soil micro-organisms that were inhibited or destroyed during the active composting process will begin to re-colonise the composted materials.

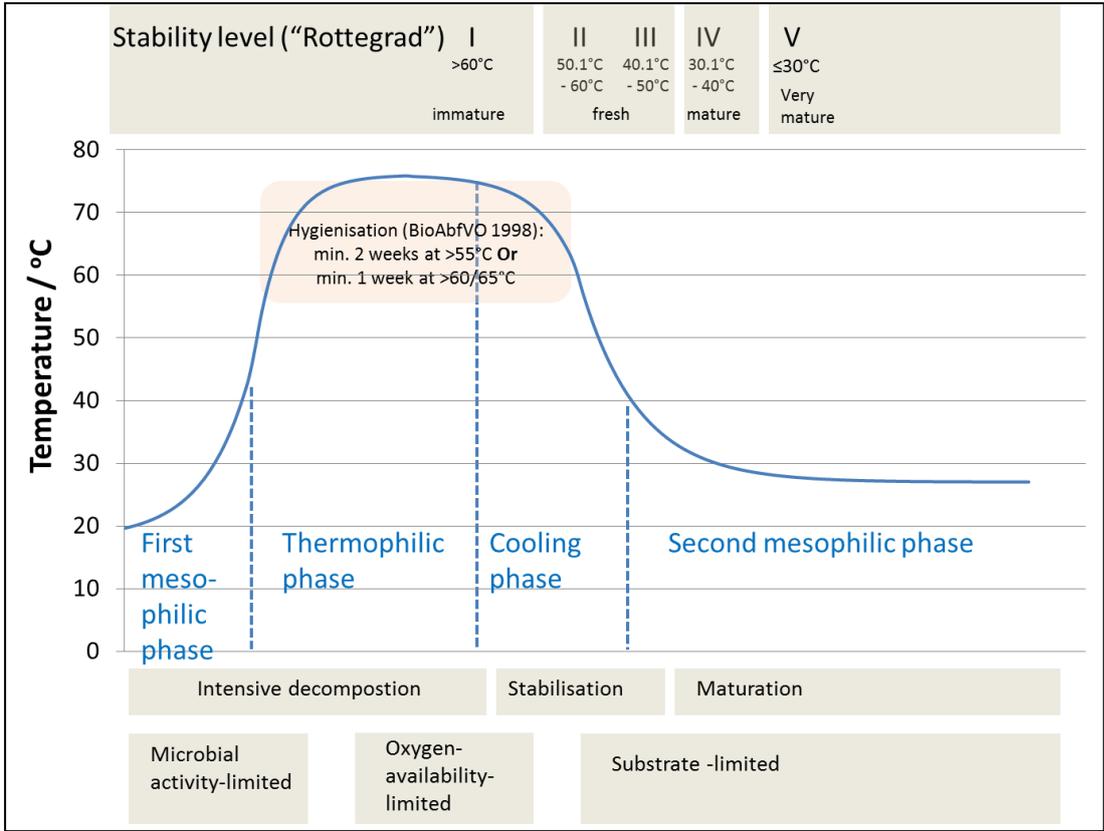
A **stable** compost is one in which biological activity and biodegradation has completed and slowed enough and will not resurge under altered conditions such as manipulation of moisture or oxygen levels, or through the addition of a source of water soluble nitrogen.

In some EU countries two main types of compost stability are characterised (Barth et al., 2008), namely:

**'Mature compost:** Fully humified compost, generally utilised and recommended in all applications, including sensitive applications' (described as being horticulture, constituents of growing media and use in potting soil);

**'Fresh compost:** Half matured compost but having passed thermal sanitisation (thermophilic phase) with a relatively high biological activity, and to be used in less sensitive applications such as arable land'.

**Figure 1** A diagram of the German Rottegrad classification for compost maturity. The graph shows temperature plotted over time. Translated and reformatted based on Körner (2009)



The voluntary German quality scheme administered by the Bundesgütegemeinschaft Kompost e.V.(BGK) defines compost stability in terms of level of decomposition termed Rottegrad (Kehres and Thelen-Jüngling, 2006). Further details of the BGK and other EU country specific schemes and stability requirements can be found in Section 8.3. This is

correlated to the time-temperature plot of a typical composting process (see Figure 1), and has been in use since 1984. This shows that the Rottegrad II-III composts (termed 'fresh compost' in Germany and herein), which are recommended for agricultural use, are not mature. Compost for horticulture is recommended to have Rottegrad IV or V, with compost for growing media Rottegrad V (Kehres and Thelen-Jüngling, 2006). Further details regarding the methodology of Rottegrad can be found in Section 7.3. The EU proposed limit for End of Waste for composts is Rottegrad III (or OUR 25 mmol O<sub>2</sub>/kg organic matter/h) (Saveyn and Eder, 2014), with further details in Section 8.1.

The relationship between compost stability and the Rottegrad system is shown in Table 1, This is for illustrative purposes only, as the UK PAS 100 baseline level of 16 mg CO<sub>2</sub>/g OM / is relatively high in terms of microbial activity, with a more stable 10 mg CO<sub>2</sub>/g OM / day recommended for growing media (WRAP, 2011b). A recent European Commission report suggested that a Rottegrad IV index is comparable with 15 mmol O<sub>2</sub>/kg OM/h or 16 mg CO<sub>2</sub>/g OM/day in a respirometric test (Anonymous, 2013c).

**Table 1** Compost stability definitions in a number of EU countries

	DE	DE & DK	DE	DK	Various	UK
	Rottegrad	Dewar	Respiration	Respiration	Oxygen uptake rate	PAS100 stability
	(Unit-less scale)	Temp (°C)	mg O <sub>2</sub> /g OM	mg O <sub>2</sub> /g OM	mmol O <sub>2</sub> /kg OM / hour	mg CO <sub>2</sub> /g OM / day
<b>Immature</b>	I	60-70				
<b>Fresh</b>	II	50-60	30.1-80	>40.0	25 (EU EoW)	
	III	40-50				16
<b>Mature</b>	IV	30-40	≤ 30.0	40.0-16.1	NL for GM: <15	For GM: 10
<b>Very mature</b>	V	≤30	≤ 20.0	16.0-6.1	IE: ≤10	
<b>Digestate</b>					50 (EU EoW)	

References for the table: DE (Kehres and Thelen-Jüngling, 2006), DK (Carlsbaek and Broegger, 1999), EU EoW (Anonymous, 2013c), IE (Anonymous, 2010b), NL (Stichting, 2009), UK (BSI, 2011; Llewelyn, 2005), UK recommended for GM (Growing Media) (WRAP, 2011b).

Notes: OM (Organic Matter) is in dry matter for all tests. OM = VS (Volatile Solids)

This is a comparison of varying definitions for maturity levels of composts, with the majority being for voluntary schemes, with further details in section 6. This table is for illustration purposes only

There are commercial pressures (reducing gate fees, increasing fuel costs) on UK compost manufacturers to process biodegradable wastes into compost as rapidly as possible for subsequent use in the agriculture and field horticulture markets. Composts spread in these markets may be PAS100 certified (which automatically requires stability testing) or non-PAS (as a waste, which does not require stability testing), with the PAS/non-PAS split currently being approximately 50:50 (WRAP, 2013c). For the UK regulators, biodegradable waste is considered to be fully recovered when it can be described as a compost and can be stored safely with minimum intervention.

## 1.2 Compost stability test development for PAS100

Following the introduction of PAS100:2002, a project was supported by WRAP to develop a compost stability test, which focussed on green waste composts produced via open windrow systems (ADAS, 2005). After a number of iterations the ORG 0020 test based on CO<sub>2</sub> evolution was adopted as the reference test method and incorporated into PAS100:2005. An upper limit was set at 16 mg CO<sub>2</sub> per g organic matter per day to cover all markets. This method involves passing a supply of CO<sub>2</sub>-stripped air through an incubation chamber holding the test sample, with CO<sub>2</sub> evolved by the sample being captured and measured as an indication of microbiological activity and hence compost stability. The test does not use an inoculum, and relies on the inherent microbial community to degrade the sample under test. Stability tests were reviewed again in 2009, with the subsequent report providing a good summary of the history of stability testing, including the development of tests in the US and Europe, at that time (Wood et al., 2009).

For growing media, prior to 2005, the 'Guidelines for the specification of composted green materials used as a growing medium component' had been developed, in which it was recommended that C:N ratio, the Dewar self-heating test and the nitrogen drawdown index (NDI) were utilised to assess the stability of a compost (WRAP, 2004a). Later, in the 'Guidelines for Specification of Quality Compost for Use in Growing Media' both the ORG 0020 and Solvita (a commercial kit to measure respiration) tests were recommended (WRAP, 2011c). Further details of these tests can be found in Section 7.0.

When the ORG 0020 test was developed, composts were produced predominantly from green waste in open windrows. The subsequent emergence of a range of IVC systems intended to process feedstocks containing food wastes, in combination with more rapid throughput, has recently caused the composting industry and its environmental regulators to question both the limit for the ORG 0020 test, whether this method is still fit for purpose and whether some kind of stability test should be required of composts that do not meet the PAS100 specification.

## 1.3 Objectives

The main objectives for this literature review were to consider:

1. The influence of the various processing factors and operational conditions of in-vessel systems on the stability of the resulting composts
2. The impact of compost stability on compost storage, with an emphasis on agriculture and growing media
3. The impact of compost stability on compost end use, with an emphasis on agriculture and growing media
4. The range of compost stability tests in use in the UK and elsewhere – with particular reference to those required by compost specifications other than PAS100 in Europe

The results of this desk study were used to recommend the final selection of stability test methods for subsequent laboratory and field work (WRAP, 2015), and also to facilitate interpretation of the results arising from that work.

## 1.4 Methodology

The review focussed on four main research areas as discussed below. Search terms were established, including synonyms, spelling variations and different combinations of terms as listed below. Searching was largely carried out using the ISIS Web of Science and Coventry

University 'Locate'<sup>1</sup>. These covered not only the principal agricultural databases, but also food-related databases, environmental science, water, pollution, toxicology and general science databases. A number of these databases also index grey literature.

In addition to the standardised interrogations of the highlighted academic databases, unstructured searches were also carried out using internet search engines (Google, Google Scholar, Yahoo, Google.de and Defra Science search).

Some literature was available from WRAP, EA ([www.gov.uk](http://www.gov.uk)) and ORG websites and sources, as well as the authors' databases and libraries. For objectives 1 and 2 the initial search focussed on publications specific to UK composting systems. Where sufficient information was not available, the search was extended to include European publications, with a focus on systems and processes which mirror those found in the UK, and then further afield.

The titles retrieved from these searches were screened, and then abstracts were downloaded. These abstracts were subjected to a second round of screening where useful papers were selected. Full text was obtained for these items. In addition, relevant publications cited in reports obtained during the searches were also obtained.

The key search terms are listed below. For each section (a, b, c), one or a combination of the terms highlighted in the general section (highlighted in blue) were used, in addition to the specific terms used for each topic listed in the rows below. For grey literature searches using internet search engines there are always an almost infinite number of hits, and so only relevant web pages were investigated, from at least the first ten pages of hits.

Biodegradable Municipal Waste (BMW), biowaste and Municipal Solid Waste (MSW) were in some cases used as search terms, as these materials tend to be composted in-vessel, and are terms used to describe a range of wastes depending on the country from which the publication arises. Where appropriate, searches were made both with the words spelled out in full and abbreviated (e.g. nitrogen and N).

In order to provide a UK regulatory context regarding composting, compost storage and application to land, documents regarding permits, exemptions and legislation were obtained from the [www.gov.uk](http://www.gov.uk) website, with documents regarding PAS100 and the compost Quality Protocol (CQP) obtained from the WRAP website ([www.wrap.org.uk](http://www.wrap.org.uk)).

### a) In-vessel composting systems

Topic	Search terms used and combinations thereof
General search terms used for this section	In-vessel composting / IVC / food waste compost / BMW / MSW / biowaste / stability / England / Scotland / Wales / UK
Oxygen	Oxygen
pH	pH / acidity / lime
Aerobic & anaerobic microorganisms	Microorganisms / aerobic microorganisms / anaerobic microorganisms / bacteria
Odour	Odour / smell / ammonia
Other processing factors	Temperature / moisture / C:N

<sup>1</sup> Web of Science: <http://wok.mimas.ac.uk/>. Locate: [http://cov-primo.hosted.exlibrisgroup.com/primo\\_library/libweb/action/search.do](http://cov-primo.hosted.exlibrisgroup.com/primo_library/libweb/action/search.do)

## b) The impacts of compost stability on compost storage

Topic	Search terms used and combinations thereof
General search terms for this section	Mature / immature / fresh compost / food waste compost / BMW / MSW / biowaste / England / Scotland / Wales / UK
In-field compost storage	Storage / in-field storage / pile in field / odour / leaching
Bagged compost storage	Bag(ged) compost / odour / smell / complaint / horticulture / growing media

## c) The impacts of compost stability on compost end use

Topic	Search terms used and combinations thereof
General search terms for this section	Immature / fresh compost / food waste compost / BMW / MSW / biowaste / agriculture / horticulture / England / Scotland / Wales / UK / Rottegrad / Kompost / Frischkompost*
Crop growth & yield	Crop growth / crop yield / crop response
Ground and surface water pollution	Compost application / field / leaching / pollution / runoff / nitrate / heavy metals / PTEs
Odour	Odour / smell / ammonia / compost application / spreading
N lock-up	Nitrogen / N mineralisation / nitrogen / N lock-up
Soil microorganism activity	Soil / microorganism / activity / enzyme / bacteria / diversity
Greenhouse gas emissions	Emissions / greenhouse gas / methane / carbon dioxide / nitrous oxide

\* Searches in Google.de

## d) Compost stability tests in the UK and further afield

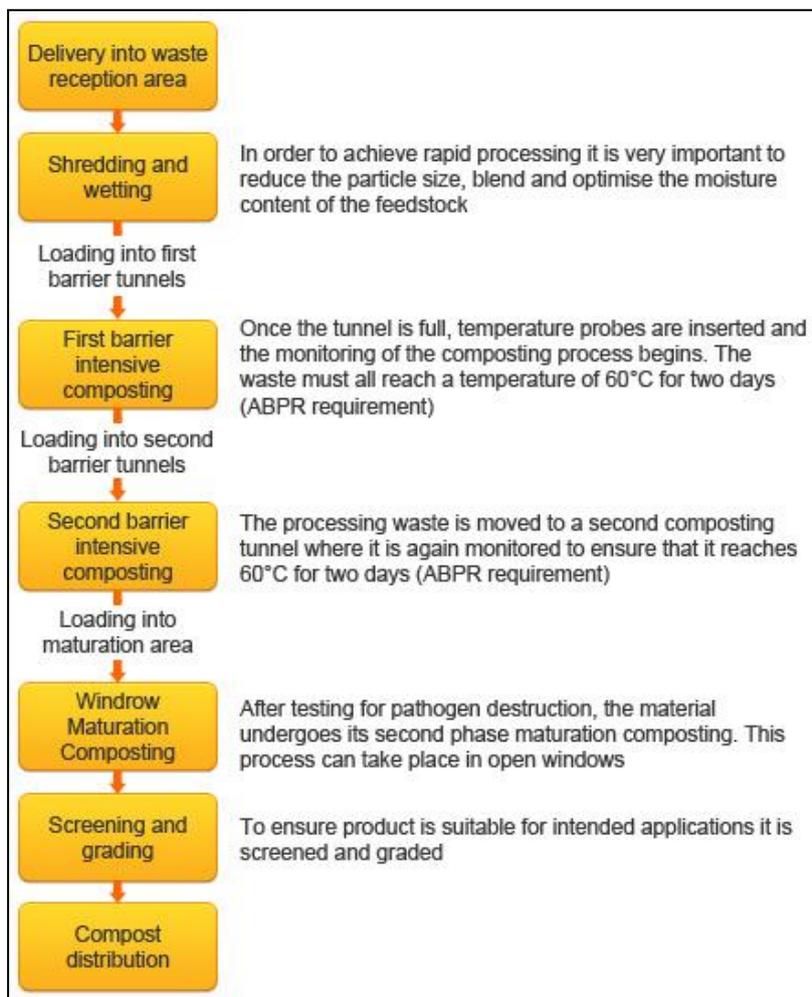
This section involved contacting EU experts directly, in addition to some literature searching specifically regarding stability test methods, using the searching methodology described above. Further details can be found in Section 8.0.

## 2.0 In-vessel composting systems

This section firstly highlights relevant UK legislation regarding IVC composting systems, and then examines the results of the literature searches on the influence of the various processing factors and operational conditions of IVC systems on the stability of the resulting composts.

The fundamental concepts of IVC systems are well understood, and a basic flow diagram of the process is provided in Figure 2, while the regulatory context is fully explained by Defra guidance (Defra, 2008).

**Figure 2** A flow diagram of an IVC tunnel process (IGD, 2012). This example is for the treatment of catering waste to national animal by-product regulations (ABPR)



There are many different IVC systems, as highlighted in a range of publications (Kokkora, 2008; The Composting Association, 2004), but they can be generally categorised into six types:

1. Containers
2. Silos
3. Agitated bays
4. Tunnels
5. Rotating drums
6. Enclosed halls

In-vessel systems are primarily used to compost materials that include food wastes defined as Animal By-Products (ABP). Such materials include kitchen wastes from households, as well as slaughterhouse residues and other low-risk material. Composting in-vessel helps to retain the heat necessary to comply with the regulatory sanitisation regimes required by the Animal By-Products Regulations (ABPR).

In general, it is well known that compost stability typically increases with composting time and effective process management (Short and Wallace, 2004) and this is also true for different enclosed composting systems. However, the relationships between process management and the characteristics of the composting waste as it passes through the various stages of IVC systems to achieve an acceptable stability are less well defined.

In the UK composting operations are regulated by the Environment Agency, and where ABPs are included, the Animal Health and Veterinary Laboratories Agency (AHVLA<sup>2</sup>). Details regarding these regulations are described below.

## 2.1 Environment Agency regulations for in-vessel composting

As a waste management (treatment) operation, composting sites need to obtain firstly planning permission from the Local Authority and then (depending on scale and intended feedstocks) either an Environmental Permit or Exemption from permitting from the Environment Agency. In 2012, 323 composting sites in the UK were operating under an environmental permit (WRAP, 2013c). A range of standard permits are available to fit different types of composting operation (see Table 2), although bespoke permits are also available to meet site-specific circumstances.

**Table 2** Exemptions and permits relating to the operation of open and closed composting systems in the UK

Permit or exemption code	Composting system	Feedstock quantity and notes	Reference
T23 exemption	Open & closed	<80t/yr Only specific wastes are allowed	(Environment Agency, 2014b)
SR2008No16 25kte permit	Open	<75,000t/yr	(Environment Agency, 2013b)
SR2008No17 75kte permit	Closed	<75,000t/yr	(Environment Agency, 2013c)
SR2012 No3 permit	Closed	<75 t/day = 27,000 t/yr	(Environment Agency, 2010b)
SR2012 No7 permit	Open	<75 t/day = 27,000 t/yr	(Environment Agency, 2012a)
SR2011No1 500t permit	Open & closed	<500t stored, treated & composted on-site at one time*. Only using the wastes listed in exemption T23	(Environment Agency, 2010a)
SR10No14 500t permit	Open & closed	<500t stored, treated & composted on-site at one time*	(Environment Agency, 2013e)

\*The total quantity of waste that can be in storage, physical treatment and composting at any one time under these standard rules may not exceed 500 tonnes.

<sup>2</sup> Please note that at the time of writing AHVLA were merging with the Plant Health Inspectorate to become APHA

**Box 1** Excerpt from the Standard Rules for composting in closed systems (Environment Agency, 2013c)

Operating techniques:

1. The storage, physical treatment and composting of wastes shall take place on an impermeable surface with sealed drainage system.
2. Each composting batch shall undergo an identifiable sanitisation and stabilisation stage.
3. The sanitisation of wastes shall take place in a closed system incorporating a bio-filter and/or equivalent abatement system.
4. The bio-filter and/or equivalent abatement system shall be specifically designed, operated and maintained to minimise the release of odour, bioaerosols and micro-organisms.
5. The storage, physical treatment and composting of wastes under anaerobic conditions shall be prevented.

## 2.2 The Animal By-products Regulation and the compost sanitisation process

IVC systems, treating source segregated household waste or equivalent which include animal based materials, must comply with the ABPR (Anonymous, 2011). The current EU regulation requires Category 3 ABP with a maximum particle size of 12 millimetres to be treated at 70°C for one hour (European Union, 2009). For composting plants treating only catering waste, and not other types of ABP (except manure, digestive tract content, milk, milk based products and colostrum), alternative national composting treatment standards have been established, termed Authorisation D6, as shown in Table 2 (Defra, 2013a). Further information on the ABPR can be found in the AHVLA guidance (AHLVA, 2012).

**Table 3** The time-temperature requirements for composting of catering waste in England (Defra, 2013a). National composting treatment standards for catering waste require that two stages (barriers) are used, but that both stages need not employ the same approach. This means that any of the three options listed can be used in combination with any other

<b>System</b>	<b>Composting in a closed reactor (option 1)</b>	<b>Composting in a closed reactor (option 2)</b>	<b>Composting in housed windrows</b>
Maximum particle size	400mm	60mm	400mm
Minimum temperature	60°C	70°C	60°C
Minimum time spent at the minimum temperature	2 days	1 hour	8 days (during which the windrow shall be turned at least 3 times at no less than 2 days intervals)

The Standard Rules for both open and closed composting systems state that “each composting batch must undergo an identifiable sanitisation and stabilisation step” (see Box 2) (Environment Agency, 2010a). In addition, the Rules state that for IVCs “the sanitisation of wastes shall take place in a closed system”

**It must be noted that these are the requirements for compliance with standard rules environmental permits – these are in addition to (not instead of) any requirements for compliance with the Animal By-Products Regulations.**

Each composting batch shall undergo an identifiable sanitisation and stabilisation stage.

Definition of sanitisation: The actively managed and intensive stage of composting, lasting for at least five days, characterised by high oxygen demand and temperatures of over 55°C, during which biological processes, together with conditions in the composting mass, eradicate human and animal pathogens or reduce them to acceptably low levels.

Definition of stabilisation stage: The stage of composting following sanitisation, during which biological processes, together with conditions in the composting mass, give rise to compost that is nominally stable.

Monitoring requirements for each batch:

- Monitoring equipment shall be available on-site and used as required to maintain aerobic conditions and ensure compliance with these standard rules.
- During sanitisation: Daily temperature measurements using a temperature probe.
- During stabilisation: Weekly temperature measurements using a temperature probe.

Operators typically tend to compost material in IVC systems for a minimum of one or two weeks until the particular sanitisation requirements of the regulations are achieved, with both one and two barrier systems in use.

### 3.0 Processing factors

In 2004 the then Composting Association in the UK produced a comprehensive guide to in-vessel composting (The Composting Association, 2004). This summarised the most suitable processing requirements for managed composting to achieve a stabilised compost output, including: aeration (oxygen content), moisture content, pH value, aerobic and anaerobic micro-organisms and other factors. Indeed, the main properties affecting the composting process have been highlighted by many compost researchers to include oxygen availability, temperature, moisture content, bulk density and porosity (Cooperband, 2002; Mohee and Mudhoo, 2005). The literature also makes some links between compost stability and odour. Odours are often due to ammonia (NH<sub>3</sub>) and volatile organic acids (VOAs) that are more abundant in the early stages of composting (Brinton 1998). These are discussed in more detail below, in the context of IVC composting of food wastes.

Crouch (2014) highlighted that:

'Care needs to be taken in interpreting the results of the many studies described in the literature as there is often a difference in composting technique, feedstock, climate, or scale between the conclusions drawn from a particular study and the composting operation in question. Due to the relative ease of operation and additional control possibilities, much of the work to date has been done using lab- or pilot-scale setups. Whilst these studies serve an important purpose in answering specific questions, the results can sometimes be of limited use when applied to full-scale composting operations. Due to the complex interactions occurring between the vast array of biological, chemical, and physical processes within the composting mass, it is often not possible to study just one parameter in isolation.'

### 3.1 Processing factors: Oxygen content and aeration

The supply of oxygen is a fundamental requirement for managed aerated composting, alongside other important factors such as carbon to nitrogen (C:N) ratio, structure and porosity, and moisture. Oxygen dissolved in the liquid layer surrounding the particles is used by the composting microbes. The ability of oxygen to dissolve is influenced by the oxygen concentration in the air spaces and temperature, with lower oxygen concentrations and higher temperatures reducing dissolved oxygen concentrations (Environment Agency, 2012b). The feedstock particle size will affect porosity, airflow and hence oxygen availability, with smaller particles having more surface area per unit volume, although if particles are too small porosity decreases and airflow within the compost pile will be restricted. A combination of feedstock particles sizes is recommended to create the most porous pile (Cooperband, 2002).

Aeration occurs naturally in well-constructed windrow systems with adequate structure and porosity in which warm, moist air convects from the top of the compost, thus drawing fresh air in from the sides and base (Litterick et al., 2003). To enhance aeration and oxygen availability, as well as ensuring that all material achieves desired sanitisation temperatures, windrows are turned. This improves the pile structure, and the oxygen introduced is consumed rapidly. As a general consideration, aerobic conversion of biological material is considered more efficient than anaerobic mechanisms, hence it is more likely that a stable product without significant odour potential will be produced at a site running under predominantly aerobic conditions than a site running largely anaerobically (Crouch, 2014; Michel and Reddy, 1998).

As highlighted in Box 1, a condition of the Standard Rules is that “the composting of wastes under anaerobic conditions shall be prevented”. Moreover, the Standard Rules define a closed composting system (IVC) as “a closed composting reactor or closed area (such as a building) in which waste is fully contained, and efficient air management abatement systems are demonstrated” (Environment Agency, 2010b; Environment Agency, 2013c). Hence in IVC systems air may be forced upwards or downwards through the material, and the material may be turned or agitated either within the enclosure or when emptying and filling – but whichever approach is used, the material must be kept in an aerobic state.

In systems that rely on forced aeration, the aeration rate is the major factor influencing the stability of the resulting compost, and naturally an increase in aeration would normally be expected to increase the oxygen concentration within the compost (Guo et al., 2012). The air should be provided in such a way that it is uniformly distributed through the composting mass and at a sufficient rate that it maintains aerobic conditions within the material itself. The oxygen concentration may need to be above 7% in the air spaces in the composting mass to avoid the generation of offensive anaerobic odours (Envar Ltd, 2010) and to ensure the water films surrounding the material are adequately oxygenated. While turning assists with the distribution of moisture and nutrients, it may result in a short term increase in microbial activity and a reduction in dissolved oxygen levels in these water films to 0.1ppm within a few hours of turning, with levels returning to 1-2ppm within a few days (Sauer and Crouch, 2013).

Recommended aeration rates for in-vessel composting plants were found to vary within a very wide range ( $6\text{-}24\text{m}^3 \text{ tonne}^{-1} \text{ h}^{-1}$ ) in the academic literature (Environment Agency, 2013a). Data from UK composting sites has shown that where dissolved oxygen levels are generally above 1 ppm, there are few odour problems, whereas sites with dissolved oxygen levels predominantly below 0.5 ppm are more likely to have odour problems during composting (Sauer and Crouch, 2013). However, an EA technical guide suggests that wet material such as food waste may require a dissolved oxygen concentration of at least 3 ppm

to prevent anaerobic conditions (Environment Agency, 2012b). Further information regarding odour during composting can be found in Section 3.8.

In a Japanese bench scale IVC study (Lu et al., 2001) composting of dog food, sludge, and woodchip was assessed at two different forced aeration rates. Aeration of 0.05-0.1 l min<sup>-1</sup> condition was deemed better than 0.2-0.4 l min<sup>-1</sup>, as the higher flow rate of air cooled the composting mixture significantly, as well as causing significant moisture loss through evaporation. The authors observed that the usual thermophilic composting process occurred at the 0.05-0.1 l min<sup>-1</sup> air flow rate, whereas composting at 0.2-0.4 l min<sup>-1</sup> air flow mainly resulted in a mesophilic process.

The initial carbon to C:N ratio of the feedstock is also an important factor (Michel et al., 1996). A summary of the C:N ratios of a wide range of feedstocks highlights the high (>100) C:N ratios of paper, cardboard and wood as compared to <55 for green waste including grass and leaves, and <20 for mixed food waste (Tompkins, 2005). Initial C:N ratios of 25–30 are considered ideal for composting (Kumar et al., 2010), although some studies demonstrate that lower initial C:N ratios are possible. For example, in a Chinese study, pig slurry and corn stalks were co-composted at different aeration rates (AR: 0.24, 0.48, 0.72 l kg<sup>-1</sup> dry matter (DM) min<sup>-1</sup>), different C:N ratios (15, 18, 21), and different moisture contents (MC: 65%, 70%, 75%) in 60 litre aerated vessels (Guo et al., 2012). A compost was considered stable when CO<sub>2</sub> emissions were <1 mg CO<sub>2</sub>-C g<sup>-1</sup> DM d<sup>-1</sup>. A compost was classed as mature when the germination index was >80% (via a petri dish cucumber bioassay using a compost extract).

The thermophilic phase (>50°C) with all treatments lasted longer than 7 days, being long enough to meet the Chinese national standard sanitisation requirements. The oxygen content and N losses (predominantly ammonia) increased with increasing AR from 0.24-0.48 l kg<sup>-1</sup> DM min<sup>-1</sup>, although no significant differences were observed between the moderate and high treatments (AR 0.48 and 0.72 l kg<sup>-1</sup> DM min<sup>-1</sup>). The compost with the lowest initial C:N ratio had the lowest germination index (53–66%), being significantly lower than the other treatments. AR was found to be the main factor influencing compost stability, while the C:N ratio mainly contributed to compost maturity. The MC (moisture content) had an insignificant effect on the compost quality. To economically treat pig manure, composting with an AR of 0.48 l kg<sup>-1</sup> DM min<sup>-1</sup> and a C:N ratio of 18 was recommended with a MC ranging from 65% to 75% (Guo et al., 2012).

### 3.2 Processing factors: pH and VFAs/ VOAs

Food waste contains readily biodegradable materials which are broken down into compounds with shorter carbon chains. Many of these are volatile organic compounds (VOCs). Amongst these compounds are volatile organic acids (VOAs), also sometimes termed volatile fatty acids (VFAs), many of which are odorous. During the initial phase of composting the microorganisms start to degrade the readily decomposable materials, with VOAs accumulating (including acetic, formic and butyric acid), thus causing the composting waste to be acidic until they are either decomposed themselves or volatilised (Brinton, 1998; Eklind et al., 2007). The PAS100 stability limit will not be achieved until the majority of the readily biodegradable materials in the feedstocks and their secondary metabolites have been biodegraded by the microorganisms. Normally, the initial acidic conditions that tend to form change to neutral/alkaline as a result. More information regarding VOCs can be found in Section 3.9.

Gajalakshmi and Abbasi (2008), in their analysis of solid waste management by composting, highlight that pH is a parameter that greatly affects the composting process. The range of

pH values suitable for bacterial development is 6-7.5, while fungi prefer an environment in the range of pH 5.5-8.

Low pH during the initial composting phase, specifically of food wastes, has been highlighted as prolonging the composting process and being correlated with high odour levels. A well-managed aeration system will help to create conditions that enhance the decomposition and volatilisation of the acidic compounds, and the pH of the compost will therefore rise above pH 7.

A poorly aerated in-vessel system, or even a badly constructed windrow that is not turned adequately, may remain largely anaerobic leading to acid conditions persisting. This can result in odour emissions when the materials are removed from the vessel for further processing / maturation. Thermophilic bacteria are less able to cope with acidic conditions than mesophilic organisms – which means that if temperatures rise too fast, acidic compounds may not be broken down. This can give rise to putrefaction of material, a subsequent release of foul odours and a delay in composting until stability is achieved (Gajalakshmi and Abbasi, 2008). Aeration at this stage can be as important for the cooling it provides as for providing oxygen (Sundberg et al., 2004).

### 3.3 Processing factors: pH and ammonia

Following the initial composting phase, as discussed above, there is a subsequent evolution of CO<sub>2</sub> and utilisation of VOAs. As stability increases during the stabilisation phase, the pH begins to rise and may exceed pH 8, which can in turn cause loss of N as ammonia.

Ammonia is a typical by-product of the aerobic decomposition of materials containing high levels of N, especially those with a low C:N ratio (<15:1). Under acidic conditions, the ammonia remains in solution as ammonium ions but as the pH rises and becomes alkaline, and if temperatures remain elevated above 45°C, the ammonia volatilises (Pagans et al., 2006) and may be emitted to the atmosphere unless scrubbed through the use of suitable technology. Therefore, if the in-vessel stage of composting remains acidic there is the potential for most of the ammonia to be emitted during a subsequent aerated phase on the windrow pad when the pH rises and if temperatures remain high.

Beck-Friis et al. (2001) investigated gaseous emissions during lab scale IVC of a mixed feedstock of BMW and chopped straw. They showed that the dynamics of NH<sub>3</sub> emission during composting were affected by the occurrence of VOAs, which seemed to control the pH and the microbial activity, and thereby the dynamics of immobilization and re-mineralisation of NH<sub>4</sub><sup>+</sup> in the material. Despite intensive aeration of the compost, VOAs remained during the first week of composting. When they disappeared, the thermophilic phase started and the pH increased rapidly to about 9, the microbial activity and NH<sub>3</sub> emissions simultaneously increased and the temperature increased above 45°C (Beck-Friis et al., 2001). This research may indicate the need for the microbial community to adapt to conditions, which takes time. A rapid increase in temperature may result in an imbalance, for a period of time, between the microorganisms able to survive higher temperatures but preferring non-acid conditions to be most active and the microorganisms that are able to degrade the VOAs, which might prefer lower temperatures.

### 3.4 Processing factors: Use of additives to influence pH

A combination of high initial aeration rates and the use of additives such as wood waste or recycled compost has been observed to rapidly overcome the low pH phase (Sundberg et al., 2013). These additives promote good structure and aeration, with the added benefit of the

recycled compost providing pH buffering – as well as the inoculation of the feedstock with appropriate compost microbes.

Addition of sodium acetate has been suggested as a way of increasing microbial activity during in-vessel composting of food waste, increasing pH from 5.2 to 5.5 due to its inhibition of the production of VOAs (Yu and Huang, 2009). This increase in pH and microbial activity increased the rate of degradation.

A recent study investigated the performance and feasibility of using different buffer agent combinations, with  $K_2HPO_4/MgSO_4$ ,  $KH_2PO_4/MgSO_4$  (added at the start of the composting process) and NaOAc (sodium acetate, added on day 4), in composting of food waste in 30 l bench scale vessels (Li, 2013). The food waste was a mixture of potato, carrot, ground pork, steamed rice and cooked soybean, with leaves and soil.

The  $KH_2PO_4/MgSO_4$  treatment had the lowest pH at the start of the trial of 5.3, with  $K_2HPO_4/MgSO_4$  having the highest pH of 6.5. In all treatments, the pH decreased initially during the first four days to below 4.5, due to the production of organic acids. All three types of agents were found to prolong the thermophilic stage. At the end of the trial (day 25, when all composts were at ambient temperature), the compost pH ranged from 9.3 for the NaOAc, 8.5 for the  $K_2HPO_4/MgSO_4$  treatment and control (no additives), and 7.6 for the  $KH_2PO_4/MgSO_4$  treatment. Moreover, application of  $K_2HPO_4/MgSO_4$  or NaOAc (the two alkaline additives) resulted in higher cumulative oxygen uptake rates than the other treatments, and a higher total organic degradation rate. The amendment of NaOAc resulted in a higher ammonia loss than the other two agents and the control. The authors concluded that  $K_2HPO_4/MgSO_4$  addition showed the most favourable influence on composting performance of food waste, demonstrating a pH buffering capacity during the composting process, and the potential to lead to the formation of struvite which would absorb ammonia into the compost and reduce ammonia emissions.

An American study investigated the composting of a mixture of 0%, 5% and 20% (w/w) biochar (produced from pine chips) with poultry litter (Steiner, 2010). Water was added to the feedstocks to achieve a MC of 60%. Composting was undertaken in a bench-scale aerated IVC system for 42 days. The 20% biochar treatment achieved a maximum composting temperature of 65°C more quickly than the other treatments, which only achieved <60°C. The 20% biochar treatment increased pH more rapidly during the 7 weeks of composting, with lower ammonia and H<sub>2</sub>S emissions than the other treatments.

In summary a range of additives offer the potential to overcome the low pH phase more rapidly and allow the compost to achieve stability more rapidly, although the majority have only been trialled in bench-scale systems.

### 3.5 Processing factors: Moisture content

WRAP guidance for production of compost intended to be used as a constituent in growing media recommends that the feedstock moisture content should be 51% m/m or greater immediately following batch formation (WRAP, 2011b). Guideline values suggested in PAS 100's Annex B are equal to or greater than 51% m/m during the sanitisation phase and at least 40% m/m during the stabilisation phase. Moisture content should not be greater than 65% m/m in order to ensure the composting pile has enough air available for the aerobic microbes (WRAP, 2011b).

Makan et al. (2013) evaluated the effect of initial moisture content of BMW in Morocco on the composting process in sealed 15 L IVC units over ten days. Air was injected into the IVC to reach the desired air pressure, and gases formed during composting were removed daily,

and fresh air added again to again reach the desired pressure. In the first phase of this study, five experiments were conducted to evaluate the initial air pressure effect (0.2, 0.4, 0.6, 0.8 and 1 bar) on the composting process. Secondly, experiments with different initial moisture contents of 55%, 65%, 70%, 75% and 85% were carried out. Relatively high moisture contents of 70-75% achieved the highest temperatures of >45°C and retained them for the longest time, compared to the other treatments. The authors highlighted that there is no single ideal moisture content for compost feedstocks, due to varying physical, chemical and biological characteristics which will each affect the relationship between moisture content and factors such as water availability, particle size, porosity and permeability. However, for the BMW used in this experiment, the initial feedstock moisture content of 75% and air pressure of 0.6 bar greater than atmospheric pressure was deemed most suitable for efficient composting, as it achieved a maximum temperature of 50°C (higher than the other treatments (but low compared with a commercial system due to the small scale of the reactor used)) and resulted in a final compost material with good physicochemical properties (pH of 6.2-7.2, EC of 2.5 mS/cm, ammonium content of 221 mg/kg DM, C:N ratio of 12.2). Due to these properties, the final compost was considered sufficiently mature to be used for agricultural applications by the authors (Makan et al., 2013).

A lower optimal moisture content is recommended by other authors but greater initial water content could be advantageous in a dry climate. In an industry guide for the prevention of and control of odours at biowaste processing facilities, a moisture content of 55-65% is considered optimal (The Composting Association, 2007). At below 40% moisture, decomposition is slowed down as it is too dry for microorganisms to function, and above 60% the material is too wet, air spaces are reduced and the heap becomes anaerobic (Miller and Jones, 1995). At other than optimal moisture conditions, the rate of stabilisation of the material is likely to be slowed. Moreover, high moisture levels will make the material very heavy and prone to structural collapse, thereby restricting air flow and causing channelling in production-scale systems. Also, a lot of energy is required to raise the temperature due to the high specific heat of water (Haug, 1993).

Moisture content also has effects on the passage of air through the material. For example, the relationship between compaction and permeability of various materials was modelled and with a moisture content of over 60%, air space can be less than 30%, requiring extra energy to force air through (Das and Keener, 1997). Where feedstock material is very wet, forced aeration in IVC systems may not provide sufficient oxygen for the whole mass, allowing the potential for pockets of very moist dense material, unless agitation is employed (Environment Agency, 2013a).

In the USA a two month trial compared two types of IVC forced aeration systems: Positive (air is blown up through the compost) and negative (air is drawn down through the compost) aeration (Nicoletti and Taylor, 2005). A range of factors were compared during the composting of a mixture of biosolids, sawdust and recycled compost. However, the aeration system did not influence the compost temperature, with rapid heating occurring initially in both systems, and achieving 55°C for 15 days. Moreover, there were no differences in oxygen levels and no H<sub>2</sub>S was observed, suggesting that the composting process was not at all anaerobic. Further technical advantages and disadvantages (e.g. capital costs, energy requirements, operational and maintenance considerations) of the two systems are discussed, with neither system being highlighted as significantly better than the other in all circumstances.

### 3.6 Processing factors: Feedstock

The type of feedstock used has also been found to influence the composting process and achievement of stability, although feedstock-specific issues tend to relate to their impacts on other factors (such as moisture, porosity and pH) rather than any more particular properties. As food waste contains greater amounts of readily available carbon and nitrogen, with lower C:N ratio, ammonia emissions and possibly also VOCs (including VOAs / VFAs) would be expected to be greater than with pure green waste. Greater MC and risk of putrefaction before managed composting starts, such as prior to and during collection, and in waste transfer storage, could be expected. More information regarding VOCs and ammonia can be found in Sections 3.9 and 0.

A UK study found that when the proportion of kitchen waste to the more fibrous green waste was increased to above 30% or alternatively the organic fraction of MSW was co-mingled with the kitchen and green waste, the bulk density was increased to such an extent that there was a limitation to the airflow during the IVC phase, which slowed down the overall composting process and rate of stabilisation (Fowles, 2010). The residence time in the composting vessel was therefore increased to address this. Mohee and Mudhoo (2005) analysed the physical properties of an IVC matrix, demonstrating a marked decline in pore space and increase in bulk density as the compost developed.

Moreover, slow decomposition during prolonged low-pH conditions was highlighted as a frequent process problem in food waste composting in Scandinavia (Sundberg et al., 2013), and also in general due to the presence of short-chain organic acids (Yu and Huang, 2009). The presence of these acids, and hence acidic conditions, leads to a reduced rate of composting and hence a delay in the attainment of suitable degree of stability until conditions change through e.g. enhanced aeration as seen in Section 3.2.

### 3.7 Processing factors: Micro-organisms

During composting the microbial community grows and changes in composition as the process progresses from mesophilic to thermophilic and then to the cooling phase. These changes in compost microbiology during the composting process are summarised below (based on Trautmann and Krasny (1997)).

'Different communities of microorganisms predominate during the various temperature phases. Initial decomposition is carried out by mesophilic microorganisms, which thrive at moderate temperatures. These microbes rapidly break down the soluble, readily degradable compounds, and the heat they produce causes the compost temperature to rise rapidly. Once temperatures exceed 40°C, the mesophilic microorganisms become less active and are replaced by thermophilic, or heat-loving microbes. During the thermophilic stage, high temperatures accelerate the breakdown of proteins, fats, and complex carbohydrates like cellulose and hemicellulose, the major structural molecules in plants. As the supply of these compounds becomes exhausted, the compost temperature gradually decreases and mesophilic microorganisms once again take over for the final phase of "curing," or maturation of the remaining organic matter. In a well-managed IVC system, temperatures are controlled by the removal of heat during the thermophilic stage using forced aeration, although this can lead to drying of the material.'

Microbial abundance, composition and activity change substantially during composting and compost maturity can be correlated with high diversity and low activity (Ryckeboer, 2003). The processing factors described above will all influence the activity of microorganisms, as summarised in Table 4; if conditions for microbial activity/diversity are optimised at each

stage of the composting process, then the fastest rate of stabilisation of the material will be achieved.

**Table 4** Examples of literature (bench scale studies) regarding the effects of processing factors during composting on micro-organisms

<b>Processing factor</b>	<b>Influence on microbial community</b>	<b>Reference</b>
Oxygen	Lower levels of oxygen result in slower increases in microbial populations, including thermophilic bacteria (predominantly <i>Bacillus</i> and <i>Thermus</i> )	Steger et al. (2005)
pH	Low pH and high fatty acids during the thermophilic phase of household waste composting reduced the microbial tolerance to thermophilic temperatures, thus slowing down microorganism activity	Smårs et al. (2002)
pH	Low pH (and high odour) conditions altered microorganism composition to include anaerobic or facultatively anaerobic species rather than typical thermophilic composting aerobic species	Sundberg et al. (2013)
pH	Low pH due to the short-chain organic acids contained in food waste (and generated as composting begins) will inhibit microbiological activity	Yu and Huang (2009)
Temperature	For maximum bacteria species diversity, optimum temperatures below 60°C were recommended	Strom (1985)
Temperature	At temperatures of over 60°C most aerobic microorganisms will die and anaerobic decomposition takes over	Ohio EPA (1999)
Moisture content (MC)	The ideal MC for microorganisms during composting is 55-60%, as, if higher, conditions may become anaerobic. Even at ideal MCs, anaerobic conditions are likely if compaction or small particle sizes lead to inadequate free space for air flow (porosity).	Ohio EPA (1999)
Feedstock	Feedstock type may influence populations of both thermophilic and mesophilic microorganisms	An et al. (2012)
Nitrogen	Too much nitrogen can cause accelerated microbial growth which will use up available O <sub>2</sub> and cause odours	Ohio EPA (1999)

Of course these processing factors do not influence the microorganisms independently but often in combination with one another. For example, during a Swedish bench scale trial focussing on the initial phase of food waste composting, high temperatures (46°C) and an initial pH of less than 6 were found to inhibit thermophilic microbial activity (Sundberg et al., 2004). However, by regulating the rise in temperature to only 36°C in a temperature-controlled water bath and raising the pH using sodium hydroxide to above 6.5, the composting rate was improved. At 46°C, the pH reduced further whereas at 36°C pH increased as the acidic compounds were able to be degraded by mesophilic microorganisms. Gajalakshmi and Abbasi (2008) observed similar effects, with the growth of active microorganisms inhibited by temperatures above about 40°C where short-chain fatty acids and low pH were present.

A recent study focussed on potential correlations between low pH, odour and microbial composition during food waste composting. Samples were obtained from both laboratory composting experiments and two large scale forced aeration composting plants in Sweden

and Norway (Sundberg et al., 2013). For the laboratory experiments, a 200 litre aerated compost reactor was used, with controlled temperature and oxygen. Two different temperature strategies were used: For the self-heating strategy the substrate was allowed to self-heat and when self-heating decreased, the material was externally heated to 55°C (thermophilic temperatures). In the cooling strategy, the substrate was allowed to self-heat to 38°C, and was then cooled by passing the recirculating air through a heat exchanger to maintain a temperature just below 40°C (mesophilic temperatures) until the pH of the condensate increased above 6. The temperature was then allowed to rise to 55°C. For both strategies 16% oxygen concentration was used in the reactor, and in addition one test was performed with the cooling strategy at 1% oxygen.

Commercially, the cooling can be achieved through increased aeration rate as long as moisture is not significantly reduced. On combining the results of the commercial and laboratory scale systems, there was a large variation in odour, with two basic groups identified, as shown in

Table 5. Samples of both groups were dominated by the typical composting microbes Bacillales and Actinobacteria (Group B, see Table 5). However, in the high-odour group (Group A, see table 5) the dominant microbes were anaerobic or facultatively anaerobic species (e.g. *Flavobacterium* spp. and *Sphingobacterium* spp.), which are not thermophilic composting species. Samples with high odour also contained lactic acid bacteria and *Clostridia*, which are known to produce odorous substances. Moreover, Group A, with a higher odour concentration had significantly higher total VOCs and acid concentrations than Group B.

**Table 5** Comparison of compost samples with odour concentrations of 74,000 ou<sub>E</sub>/m<sup>3</sup> and higher (Group A) and 41,000 ou<sub>E</sub>/m<sup>3</sup> or lower (Group B). (Sundberg et al., 2013) For variables marked with \*, Group A and Group B were significantly different at 95% confidence level.

	Group A	Group B
No of samples	11	10
Odour concentration (OU <sub>E</sub> /m <sup>3</sup> )	566,000 ± 425,000	16,600 ± 10,200
DM (% of fresh weight)*	46.3 ± 3.9	51.6 ± 6.3
pH	5.0 ± 0.4	8.0 ± 0.7
Tot-C (% of DM)	40.8 ± 5.4	37.3 ± 9.3
Tot-N (% of DM)	1.73 ± 0.16	1.84 ± 0.16
NH <sub>4</sub> -N (g/kg DM)	1.3 ± 0.6	1.3 ± 0.8
NO <sub>3</sub> -N (mg/kg DM)*	93 ± 58	8 ± 15
C/N-ratio	23.9 ± 4.8	20.1 ± 4.5
Total VOC <sup>*,a</sup>	630b ± 213	43 ± 62
Acetic acid in material (mmol/kg compost)*	46 ± 47	0 <sup>b</sup>
Lactic acid in material (mmol/kg compost)*	131 ± 28	0 <sup>b</sup>
Total acid in material (mmol/kg compost)*	190 ± 68	0 <sup>b</sup>

<sup>a</sup> Not measured at NSR, only 7 samples in Group A.

<sup>b</sup> All samples were below the detection limit of 9 mmol/kg compost for acetic acid and 6 mmol/kg compost for lactic acid

Thus it is possible if the temperature rises too rapidly in commercial IVC systems, or if aeration is insufficient – that the pH may remain low, adversely affecting the composting process and producing material with high odour concentrations. On the other hand, a well-managed IVC system takes all factors, physical and microbial, into account and optimises the composting process and hence the rate of stabilisation.

### 3.8 Links between stability and odour

The Environmental Permitting (England and Wales) Regulations 2010 (Anonymous, 2010a), considers an odour to cause pollution when “an activity which may give rise to an offensive smell noticeable outside the site where the activity is carried on”.

Defra has published ‘Odour Guidance for Local Authorities’ (Defra 2010) with a useful summary that refers to Section 79(1)(d) EPA, which defines any statutory nuisance (including offensive odours), as: “Any dust, steam, smell or other effluvia arising on industrial, trade or business premises and being prejudicial to health or a nuisance”.

An industry guide for the prevention and control of odours at biowaste processing facilities (Jacobs et al., 2007) provides practical guidance on ways of minimising the generation of odorous compounds, controlling emissions of these odours, and managing the impact of odours on the environment on site. This guide does not specifically cover field storage of composts. The Standard Rules regarding odour at compost sites are shown in Box 3. This highlights the need for IVC sites to include an odour abatement system such as a biofilter to minimise odour levels outside the site. A review regarding odour treatment options at composting sites can be found in Border (2002).

For many years, higher levels of odour (or odour intensity) have been noted to be most prominent during the first few weeks of composting (Brinton, 1998; Day, 1998). Odours identified during composting include ammonia and various VOCs, including VOAs (which are also termed volatile fatty acids VFAs) and volatile organic sulphur compounds (VOSCs) many of which are odorous. The following sections consider the dynamics of these compounds during composting, with a focus on IVC and food waste.

Odour during composting has been observed to have a relationship with biological stability (Scaglia et al., 2011), temperature and feedstock composition. Odour has been associated with at least three stages during the composting of source segregated household waste, with the odour derived from different compounds at each stage as summarised below (Delgado-Rodríguez et al., 2010; Environment Agency, 2013a):

#### **1. Shredding and mixing of feedstock**

- Volatilisation of terpene compounds ( $\alpha$ -pinene, 3-carene, and D-limonene) from botanical material and xenobiotic compounds (such as 1,1,1-trichloroethane, toluene and ethylbenzene).

#### **2. Initial composting**

- Aldehydes, alcohols, carbonyl compounds, carboxylic acids, esters, ethers, ketones, sulphides and terpenes.

#### **3. Thermophilic composting**

- If feedstock has a high N content → Ammonia.
- If anaerobic conditions occur due to incomplete or insufficient aeration → Reduced sulphur compounds.
- If incomplete aerobic degradation processes occur → Alcohols, ketones, esters and organic acids.

---

**Box 3** Standard Rules regarding odour at closed compost sites

Regarding odour, the Standard Rules (Environment Agency, 2013c) state:

The bio-filter and/or equivalent abatement system shall be specifically designed, operated and maintained to minimise the release of odour, bioaerosols and micro-organisms.

Emissions from the [composting] activities shall be free from odour at levels likely to cause pollution outside the site, as perceived by an authorised officer of the Environment Agency, unless the operator has used appropriate measures, including, but not limited to, those specified in any approved odour management plan, to prevent or where that is not practicable, to minimise, the odour.

### 3.9 Volatile organic compounds emitted during composting

VOCs which have been recorded during the composting of materials containing a proportion of food waste include: VOAs (e.g. formic acid, butyric acid (also known as butanoic acid), and iso-valeric acid), reduced sulphur compounds (e.g. dimethyl disulphide (DMDS), H<sub>2</sub>S, thiols), hydrocarbons (pentene, hexane, benzene, toluene, ethylbenzene, *p,m*-xylene, styrene, *o*-xylene), ketones (acetone, butanone, 2,3-butanedione), aldehydes (3-methylbutanal), esters (methyl acetate, ethyl acetate, ethyl hexanoate), and terpenes ( $\alpha$ -pinene,  $\beta$ -pinene, limonene, *p*-cymene,  $\beta$ -myrcene, 3-carene), many of which are common and can be produced normally under aerobic conditions (Font et al., 2011; WRAP, 2013b; Environment Agency, 2013a). However, some VOCs can be air pollutants, due to their malodorous and hazardous properties.

A review of the main types of VOC emitted in organic waste treatment facilities, including composting of BMW, found total VOC concentrations in composting halls, where food waste was included in the feedstock, to be 0.71-10.10 mg m<sup>-3</sup> (Font et al., 2011). This study also reviews the treatment methods applied to gaseous emissions commonly used in composting and anaerobic digestion facilities in addition to the methods used to detect and quantify VOCs.

In open windrow studies of biowaste and green waste, detectable VOC concentrations were predominantly found during the first week of composting: limonene (0.09–2.7 mg m<sup>-3</sup>; as a main component),  $\alpha$ -pinene (0.31–0.38 mg m<sup>-3</sup>),  $\beta$ -pinene (0.10–0.11 mg m<sup>-3</sup>), ethylacetate (0.06 mg m<sup>-3</sup>), ethanol (0.22–1.3 mg m<sup>-3</sup>), acetone (0.06–0.27 mg m<sup>-3</sup>) and 2-butanone (0–0.39 mg m<sup>-3</sup>) (Amlinger et al., 2008).

A study of VOCs emitted during composting of a range of materials obtained from the organic fraction of MSW found that yard wastes (assumed to be comparable to green waste) primarily produced terpenes, alkylated benzenes, ketones and alkanes, while food wastes primarily produced sulphides, acids and alcohols. Among 13 aromatic VOCs found in MSW composting facilities, toluene, ethylbenzene, 1,4-dichlorobenzene, *p*-isopropyl toluene, and naphthalene were in the largest amounts. All VOCs were emitted early in the composting process and their production rates decreased with time at thermophilic temperatures (Komilis et al., 2004).

In a Defra funded demonstrator project (Fowles, 2010) where the composting of BMW (a mixture of kitchen and green waste) in IVC tunnels was investigated, 27 VOCs were monitored during three composting phases. VOCs were observed to be highest during the warming up stage of tunnel composting and were likely to originate from the fresh feedstock. During this warming up phase the highest concentrations of the 23 VOCs detected

were 2-butanone ( $620 \text{ mg m}^{-3}$ ), limonene ( $390 \text{ mg m}^{-3}$ ) and 2-butanol ( $66 \text{ mg m}^{-3}$ ), with all other VOCs being  $<30 \text{ mg m}^{-3}$ .

During sanitisation, 15 of the 23 VOCs detected during warming up were detected again, with the majority at much lower levels during this second phase. A few VOCs had their highest levels during the sanitisation stages (comprising a two stage composting process, each with material achieving a minimum of  $60^\circ\text{C}$  for 48 hours), as compared to the warming up phase: Dimethyl disulphide ( $0.12 \text{ mg m}^{-3}$  as compared to  $0.10 \text{ mg m}^{-3}$ ), 2-nonanone ( $0.48 \text{ mg m}^{-3}$  as compared to  $0.35 \text{ mg m}^{-3}$ ), fenchone ( $0.69 \text{ mg m}^{-3}$  as compared to  $0.38 \text{ mg m}^{-3}$ ) and camphor ( $4.40 \text{ mg m}^{-3}$  as compared to  $1.00 \text{ mg m}^{-3}$ ).

Only one VOC (trimethylamine) was isolated only at the cooling down stage, and at a very low level ( $0.17 \text{ mg m}^{-3}$ ), being non-detectable during the other two phases. The total combined concentration of the VOCs measured was  $1185.9 \text{ mg m}^{-3}$  during the warming-up phase,  $321.59 \text{ mg m}^{-3}$  during pasteurisation and  $6.29 \text{ mg m}^{-3}$  during the cooling-down phase, showing a clear reduction in VOCs during the composting process (Fowles, 2010).

In summary, VOCs have been observed to be emitted predominantly during the early stages of composting, with levels greatly reducing during the maturation process.

The studies discussed in the following two sections focus on specific types of VOCs, firstly VOAs and then VOSCs.

### *3.9.1 Volatile organic acids emitted during composting*

VOAs are most abundant in immature compost and are often formed in anaerobic pockets of the windrow or heap, being utilised as an energy source later in the process. Transient low oxygen conditions almost always occur even in well managed composting systems. VOAs are often the cause of phytotoxicity. They can be detected by humans at very low concentrations in the air (Brinton, 1998). Thus it could be inferred that, as immature composts contain higher levels of a range of VOAs, it is more likely that there will be some odour emissions during application of immature composts than mature composts.

VOCs, including VOAs, can be collected and analysed using a range of methods including gas chromatography (Komilis et al., 2004; Smet et al., 1999). This currently requires specialised equipment and technical competence to enable robust conclusions to be drawn. As VOAs are produced generally during the early stages of composting, if there was a simple test for operators to be able to use to indicate the progress of their composting process, this could facilitate their ability to demonstrate that their compost is 'nominally stable'. The principles of the gas chromatography method used for measurement of VFAs in the PAS110 digestate residual biogas potential test (BSI, 2010) could possibly be applied to VOA measurement in composts.

### *3.9.2 Volatile organic sulphur compounds emitted during composting*

VOSCs are VOCs containing sulphur and mainly include organic reduced sulphur compounds e.g. methylmercaptan (MeSH), dimethyl sulphide (DMS), dimethyl disulphide (DMDS), carbonyl sulphide (OCS) and carbon disulphide ( $\text{CS}_2$ ) (Wu, 2010). VOSCs may comprise 35-38% of VOCs emitted during the composting of food waste (Komilis et al., 2004).

Bench scale 20 litre IVC systems were used to investigate the first 11 days of composting of the organic fraction of MSW mixed 2:1 (w/w) with lignocellulosic materials (D'Imporzano et al., 2008). At the end of the trial the oxygen uptake rate was below  $1000 \text{ mg O}_2 \text{ kg VS}^{-1} \text{ h}^{-1}$ . It was found that the highest odour production (sulphur compounds – as well as odourless

methane, and hydrogen – which are all indicative of strong anaerobic conditions) occurred during days 3-5 of composting. This coincided with both high microbial activity and high compost temperature, causing O<sub>2</sub> depletion in the material. Much lower odour levels were observed thereafter, together with lower levels of microbial populations, in this case.

In a bench scale study (Wu, 2010), food waste from three separate sources was composted for 41 days in aerated 11 litre reactors. Emission of 15 VOSCs from the food wastes totalled 409.9 mg kg<sup>-1</sup> (dry weight), with DMDS, DMS, methyl 2-propenyl disulphide, carbonyl sulphide and methyl 1-propenyl sulphide being the five most abundant VOSCs, comprising 75.5%, 13.5%, 4.8%, 2.2% and 1.3% of the 15 VOSCs released, respectively. The emission fluxes of major VOSCs peaked at days 2–4 and then decreased sharply until they levelled off after 10 days of incubation. For most VOSCs, over 95% of their emission occurred in the first 10 days. The production of VOSCs was induced mainly by microbial activity during aerobic decomposition probably due to anaerobic microsites within the waste particles.

In Belgium, aerobic composting of green/kitchen waste was compared with a two stage anaerobic/aerobic process and the emission of volatile compounds was measured. There were changes with time during the process. Emission of sulphur compounds occurred in the aerobic thermophilic stage, with dimethyl sulphide being the dominant compound (Smet et al., 1999). Anaerobic microsites were highlighted by the authors as potentially forming VOCs including sulphur compounds during active composting.

The presence of these VOSCs are an indicator of the degree of (lack of) stability of the material but are in themselves not an indicator of stability itself as their presence may be related to the composition of the initial feedstocks. Material preparation may also affect the presence of VOSCs as they tend to be produced under anaerobic conditions that can occur within microsites, even within an otherwise well aerated composting system.

### 3.10 Reducing compost odour

Sundberg et al., (2013) proposed an odour reduction strategy for the composting of food waste in which the low pH phase is rapidly overcome through high initial aeration rates and the use of additives such as recycled compost. During the early stages of composting, odoriferous compounds are generally present in low-pH conditions. These odoriferous compounds are degraded by mesophilic organisms. However, where excessive temperatures occur, the growth of these mesophilic organisms is inhibited, hence producing odours. A high aeration rate was observed to cool the compost and help overcome this inhibition of growth (Sundberg et al., 2013). Addition of recycled compost can help to inoculate the heap with an effective range of microorganisms and buffer pH (Sundberg, 2011), thus assisting the development of the mesophilic organisms and reducing odour.

Moreover, the addition of coarse, dry bulking agents such as compost oversize, is recommended for reducing odour by increasing porosity and reducing moisture in the feedstock (Ohio EPA, 1999).

A consideration, which has been investigated during the field and laboratory work phase of this project, was to test the compost pH, to establish whether the measurement of acidic conditions might indicate very unstable and potentially odorous material, whilst alkaline conditions might indicate adequately stabilised (but still immature) material. Unfortunately, the addition of lime at the beginning of the composting process would mask this (Chiang et al., 2007).

A well stabilised compost is likely to have a pleasant odour rather than an unpleasant one and the management of the composting process to reduce offensive odours will also lead to the production of a stable product.

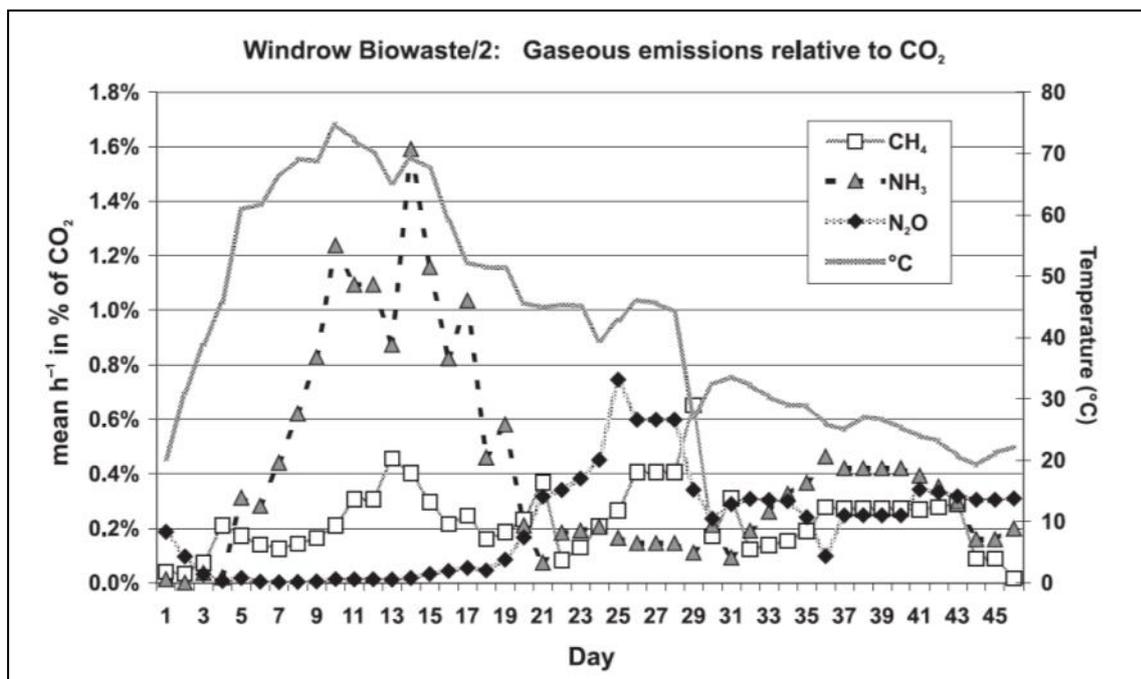
### 3.11 Emission of greenhouse gases and ammonia during composting

Due to the difficulty in monitoring ammonia and greenhouse gas (GHG) emissions (including methane and nitrous oxide) on a continuous basis, there are very few published studies derived from monitoring full size composting plants, with most ammonia and GHG emissions data obtained from laboratory-scale trials (Environment Agency, 2013a).

A summary of a recent UK composting report describes the interactions with ammonia within the composting process as follows (Environment Agency, 2013a):

“The mechanism for ammonia emission from in-vessel composting processes using low C:N ratio feedstocks follows this sequence. During initial stages of composting when carbon and oxygen are often limited, ammonium ions from microbial decomposition of proteins predominate due to the lower temperatures and acidic conditions that prevail. As both the temperature and the pH of the composting system increase, it is normal for increased concentrations of ammonia gas to be produced and stripped from the composting pile by high rates of air flowing through in-vessel systems and subsequently emitted to air. At thermophilic temperatures, the solubility of ammonia gas is only half that at mesophilic temperatures, meaning that as pile temperatures increase, ammonia can be emitted to air very readily. Ammonia emission from composting under well-aerated conditions is normal, especially with highly biodegradable feedstocks such as municipal solid waste. Furthermore, it is also typical for ammonia to be emitted to air during the early stages of composting.”

**Figure 3** Gaseous emissions relative to CO<sub>2</sub> production during open windrow composting of biowaste (Amlinger et al., 2008)



Emissions of nitrous oxide, ammonia and methane, from composting and MBT systems, have been examined in Austria and Germany (Amlinger et al., 2008). Gas emissions from three open windrow composting scenarios (green waste, biowaste and sewage sludge added once at the start of composting) and one backyard composting system (biowaste added weekly):

wooden composters 100 cm × 100 cm × 80 cm) were examined. The open windrows were turned once or twice a week, in contrast to the backyard system which was turned up to once every 12 weeks. The CH<sub>4</sub> and N<sub>2</sub>O emissions were higher from the backyard composting than for the open windrow composting. Biowaste, which contains a considerable amount of easily degradable kitchen waste, showed a typical decomposition dynamic in the open windrow system, with CH<sub>4</sub> peaks observed during thermophilic degradation, with N<sub>2</sub>O emission rates rising mainly in the mesophilic stages (Figure 3). From week 21 onwards, the gas emissions were stable at a low level. In contrast, the more lignin-rich green waste showed a more even and slow degradation pattern with constant gas emission levels over the entire trial period.

**Table 6** Specific measures and their effects on GHG and ammoniacal nitrogen emissions in closed/encapsulated composting systems with waste air treatment (box, tunnel, hall, etc.) reproduced from (Amlinger et al., 2008)

Measure	CH <sub>4</sub>	NH <sub>3</sub> <sup>a</sup>	N <sub>2</sub> O
Enhancing turning frequency or aeration rate	Positive; enhances O <sub>2</sub> -supply suppresses CH <sub>4</sub> formation	Higher aeration (eventually turning) may slightly increase NH <sub>3</sub> . This is also supported by: ■ increased NH <sub>3</sub> stripping ■ increased evaporation	Potentially negative; optimised O <sub>2</sub> supply at temperatures <45°C may enhance N <sub>2</sub> O formation as intermediate product of nitrification and denitrification
Temperature control: < 45-65°C after sufficient sanitisation	Positive; maximum CH <sub>4</sub> production takes place during the first intensive decomposition phase at high temperatures because of a facultative O <sub>2</sub> deficiency. CH <sub>4</sub> formation is clearly minimised below 45/50°C	Positive; maximum NH <sub>3</sub> formation during the thermophilic phase parallel to the CH <sub>4</sub> dynamics	Maximum N <sub>2</sub> O formation at 30-45°C; less at higher temperatures
Humidity control: should be maintained at 50-60% (w/w)	Positive; prevention of water logging and the creation of anaerobic zones	Excess of water may induce deoxidising conditions (denitrification) and an accumulation of NH <sub>4</sub> <sup>+</sup> , drying may then result in increased NH <sub>3</sub> emission	Excess of water may result in considerable O <sub>2</sub> deficiency during maturation; this induces denitrification of NO <sub>2</sub> <sup>-</sup> and NO <sub>3</sub> <sup>-</sup> to N <sub>2</sub> O
Biofilter	Neutral; only limited degradation (ca. 15%)	Positive; partial to complete degradation	Negative; considerable formation of as intermediate product of NH <sub>3</sub> degradation
Biofilter with preceding acid scrubber	Neutral; only limited degradation (ca. 15%)	Positive; effective elimination by acid scrubber systems	Neutral to slightly negative

<sup>a</sup> NH<sub>3</sub> emitted during the early stages of composting would no longer be available for N<sub>2</sub>O-formation at lower temperatures during the later stages of composting

The key recommendations provided for process management practices that minimise GHG and NH<sub>3</sub> emissions during composting are shown in Table 6. Many of these are the same

basic rules of compost quality management used to reduce odours and optimise decomposition and humidity. As a result, compost stability is more likely to also be achieved more rapidly.

Methane may be detected in the mass of material during the early phase of in-vessel composting due to anaerobic conditions, but this would be expected to oxidise rapidly within a well-aerated in-vessel system (Fowles, 2010).

Methane was measured at a UK IVC site with in-vessel aeration rates of 1.5 and 2.3 m<sup>3</sup> tonne<sup>-1</sup> h<sup>-1</sup>. The authors considered these aeration rates to be low for IVC systems, with piles likely to be oxygen-limited. The higher of these aeration rates produced a methane concentration in the in-vessel exhaust gas of greater than 1,000 ppmv, which indicates that piles were significantly anaerobic (Environment Agency, 2013a).

A Canadian study compared the emissions of N<sub>2</sub>O and CH<sub>4</sub> during the in-vessel composting of liquid pig manure and wheat straw in two systems, one with forced aeration (ground level) and the other without (Thompson et al., 2004). The lack of aeration increased CH<sub>4</sub> emissions to 24 times that of composting with aeration, but had no significant effect on N<sub>2</sub>O production. This suggests that when actively composting material is not aerated, CH<sub>4</sub> may be released.

In a study assessing the loss of nitrogenous compounds during the composting of mixtures of straw and different liquid manures (poultry, pig, cattle, and mixtures thereof), the greatest nitrogen losses, of 46.8-77.4% of the initial total nitrogen content, were caused by gaseous emissions in the form of NH<sub>3</sub> as well as small amounts (<5%) of NO<sub>x</sub> (Martins, 1992). The main factors which were attributed to the level of gaseous emissions were the total nitrogen content at the beginning of the composting period, the temperature of the compost material and heap rotation (turning). The greatest nitrogen losses were found in the N-rich poultry- and pig-straw mixtures which showed obvious temperature increases up to 40°C during the first few days of the composting period. A high pH value of >8 was considered to be promoting the emission of gaseous NH<sub>3</sub>.

Food waste composted in an aerated static pile was reported to have an N<sub>2</sub>O loss of <0.7% of initial N concentration (Beck-Friis et al., 2001). However no specific data on CH<sub>4</sub> emission from food waste compost was cited.

A review regarding the GHG emission balance of the composting process as a whole provided a summary of N<sub>2</sub>O and CH<sub>4</sub> emissions from composting operations with a range of feedstocks, predominantly manure, pig litter and straw (Brown et al., 2008). In a summary of eight studies, half of the composting systems had methane levels recorded as comparable to background levels or not detected. N<sub>2</sub>O emission levels varied greatly, but generally were increased when oxygen was limiting. In all studies reviewed by Brown et al (2008), GHG emissions were detected when the % moisture of the feedstock was at or above the maximum level for controlling aeration.

The 2008 review also states that "although anaerobic conditions may exist in a pile, high ammonia concentrations within the pile are sufficient to inhibit methanogenic bacteria. An additional safeguard against the release of any GHGs formed within a pile is the active aerobic microbial community on the surface of the pile. These organisms oxidize CH<sub>4</sub> before it is released into the environment" (Brown et al., 2008).

Another review paper included information on GHG emissions from the composting of green waste, manures and mushroom residues, indicating that methane is released in some cases

during the early stages of composting, although food waste was not referred to (Recycled Organics Unit, 2007).

In conclusion, composting can be an effective means of reducing GHG emissions from a range of waste materials, as compared to landfilling, even in the case where some GHGs are emitted during composting (Brown et al., 2008).

#### **4.0 The regulatory requirements and literature regarding compost stability and compost storage**

There are specific regulatory requirements regarding compost stability and storage prior to use. These are highlighted in Sections 4.1 - 4.3 to provide context for Sections 4.4 - 4.6. Some rules will apply whether the compost is stored on-site or in-field, and other rules are specifically for in-field storage. These rules are discussed below, firstly for all composts, followed by PAS100 composts and then non-PAS composts.

##### **4.1 Compost storage rules: All composts**

Composts containing ABPs must be stored away from farm animal feed, and farm animals should be prevented from accessing the stored compost (Defra and AHLVA, 2014b). There are no specific additional storage requirements with regards to the ABPR, provided the compost is either stored at the site where it was produced or where it will be used (Defra and AHLVA, 2014a).

In England, where land is situated in NVZs there are specific rules regarding placement of storage piles of organic amendments (termed organic manures in the NVZ guidance, which include composts) to reduce the potential for surface or groundwater contamination (Defra, 2013b), including a maximum storage duration of 12 months in one place. The rules relating to the temporary storage of composts in field heaps are shown in Box 4. For all farmland, including land outside NVZs, following Defra's Code of Good Agricultural Practice (CoGAP) is recommended for all composts (Defra, 2009b).

In neither PAS100, the CQP, nor the Standard Rules are there specific requirements regarding the configuration of the compost storage pile. The NVZ Regulations state that 'The field heap site must occupy as small a surface area as is practically required to support the mass of the heap and prevent it from collapsing'. If a storage pile is too large for natural aeration then the compost may become anaerobic. Moreover, if the compost is not stable then it is likely that the compost will continue to decompose, and water may evaporate due to the internal heat generated. There may be a small risk that the pile might produce a leachate which is independent of rainfall but this is less likely than the effect of prolonged periods of rain on leachate production, especially if the pile is poorly constructed. The two predominant considerations of leaching and gas emissions from immature composts during storage are discussed in Sections 4.4 and 4.5.

---

**Box 4** UK NVZ regulations regarding temporary storage of solid manure in temporary field heaps (Defra, 2013b)

This option applies if:

- they are solid enough to be stacked in a free-standing heap, and
- they do not give rise to free drainage from within the stacked material.

If you choose to store manure in temporary field heaps, you need to comply with the following rules.

YOU MUST ensure you do not build your field heap:

- within 10m of surface water (including ditches) or of a land drain,
- within 50m of a spring, well or borehole,
- on land likely to become waterlogged, or
- on land likely to flood.

YOU MUST also

- move any field heap at least every twelve months,
- leave a 2 year gap before returning to the same site, and
- keep a record of the sites used for field heaps, and the dates of use.

NEW RULE - Effective from 16 May 2014

From 16 May 2014 YOU MUST:

- not build or maintain a field heap within 30m of surface water (including ditches) if the land slopes steeply (12 degrees (1 in 5, or 20%) or greater)
- The field heap site must occupy as small a surface area as is practically required to support the mass of the heap and prevent it from collapsing

#### 4.2 Compost storage: PAS100 composts

For CQP compliant composts (which must automatically comply with the requirements of PAS100), the compost is not classed as a waste, and so the waste management rules (as described in Section 4.3) do not apply. These composts should have a maximum stability level of 16 mg CO<sub>2</sub>/g OM / day for agriculture and field horticulture. The CQP guidance for storage is shown in Box 5. This includes following the Fertiliser Manufacturers Association's<sup>3</sup> solid fertilisers code of practice (FMA, 1998). This generally includes the same rules as the EA Standard Rules (see Box 6) and the NVZ regulations (see Box 4), and also states: 'Sites for outdoor storage should be level and free from protruding stones. They should not be liable to flooding.'

---

<sup>3</sup> It should be noted that the FMA has now been amalgamated with the Agricultural Industries Confederation (AIC)

---

**Box 5** The Compost Quality Protocol guidance for storage (Environment Agency, 2012c)

- Producers, distributors and users should follow good practice for the storage, handling, application and use of quality compost as an agricultural fertiliser and in soil-grown horticulture.
  - Follow the joint Environment Agency/Fertilisers Manufacturers Association (FMA) guidance, *Protect the environment: the essential guide for storing solid and liquid fertilisers* (Environment Agency and FMA., 2012), to ensure the compost is stored in a manner that protects the environment.
  - Handle the compost as described in the FMA's Code of practice for the prevention of water pollution from the storage and handling of solid fertilisers (FMA., 1998) to ensure that its storage and handling does not cause harm to human health or the environment.
  
- If it appears that the material is being stored indefinitely with little prospect of use, the material will revert to being a waste and waste management controls will apply

#### 4.3 Compost storage: Non-PAS composts

For non-PAS composts the waste management requirements of the U10 and U11 exemptions, and the Standard Rules will apply, depending on the exemption or permit applicable to the composting operation (for the list of exemptions and permits related to composting see **Table 2**, and for spreading to land see **Table 7**). The maximum storage duration is 12 months.

In some instances composts will be stored on agricultural fields prior to use. For non-PAS composts (which should be at least 'nominally stable'), the Standard Rule in permit SR2010No4 will apply, as shown in box 6. However, 'nominally stable' is not defined in terms of measurable parameters, instead a definition of stable/stabilised is provided in process terms.

---

**Box 6** Excerpts of the Standard Rules relevant to storage prior to landspreading SR2010No4 (Environment Agency, 2013d)

Storage of wastes pending land treatment resulting in benefit to agriculture or ecological improvement. Limits:

- Secure storage of waste [compost], at the place where it is to be used for land treatment.
- No more than 3000 tonnes of waste [compost] shall be stored at any one time.
- Waste [compost] shall be stored for no longer than 12 months.

"Secure storage" means storage where waste cannot escape and members of the public do not have access to it.

The activities [storage and land spreading] shall not be carried out within:

- 10 metres of any watercourse;
- 50 metres of any spring or well, or any borehole used to supply water for domestic or food production purposes; and
- Groundwater Source Protection Zone 1.

Emissions to air, water or land:

- There shall be no point source emissions to land, except from the sources listed in the agreed deployment form.
- Emissions of substances not controlled by emission limits (excluding odour) shall not cause pollution. The operator shall not be taken to have breached this rule if appropriate measures, including, but not limited to, those specified in any approved emissions management plan, have been taken to prevent or where that is not practicable, to minimise, those emissions.

Odour:

- Emissions from the activities [storage and land spreading] shall be free from odour at levels likely to cause pollution outside the site, as perceived by an authorised officer of the Environment Agency, unless the operator has used appropriate measures, including, but not limited to, those specified in any approved odour management plan, to prevent or where that is not practicable, to minimise, the odour.

---

**Box 7** Excerpt of the Standard Rules for permits SR2012No7, SR2012No3 and SR2008No17\_75kte regarding compost stability (Environment Agency, 2010b; Environment Agency, 2012a; Environment Agency, 2013c).

Each composting batch shall undergo an identifiable sanitisation and stabilisation stage.

The stabilisation phase is defined as: The stage of composting following sanitization, during which biological processes, together with conditions in the composting mass, give rise to compost that is nominally stable.

The terms "*stable, stabilised*" are defined as: The degree of processing and biodegradation at which the rate of biological activity has slowed to an acceptably low and consistent level and will not significantly increase under favourable, altered conditions.

#### 4.4 The potential for leaching of immature composts stored in-field

Leaching of nitrate through soils into groundwater is an issue for water quality in the UK and the EU. The Nitrate Pollution Prevention Regulations 2008, under the EU Nitrate Directive (a part of the Water Framework Directive) has specific limits on the quantity and timing of N fertiliser and organic matures including composts. In the UK these regulations have been translated into the Nitrate Vulnerable Zones (NVZs) Regulations, as discussed in Section 4.1. This includes specific rules regarding placement of storage piles of both PAS100 and non-PAS compost at a minimum distance from water bodies including land drains to reduce the potential for surface or groundwater contamination (Defra, 2013b).

In addition, for non-PAS composts, the U10 and U11 waste exemptions and the SR2010No4 permit for spreading the compost to land have the following condition (Environment Agency, 2014a): The place where waste that is stored or land which is to be spread must be at least 10 metres from a watercourse and 50 metres from a spring, well or borehole. More details can be found in Box 6.

For mature composts, it is well documented that N availability is low. For example, in biowaste composts less than 5% of the N in compost is in readily-available forms (ammonium and nitrate) (Ebertseder and Gutser, 2003). The remainder of the N in composts, once applied to the soil, will slowly mineralise and become available to crops over a period of months to years (WRAP, 2011a). This indicates that during storage of mature, stable composts nitrogen leaching is unlikely to be significant, due to the majority of N being

bound in organic forms. Further information regarding N release following compost application can be found in Section 6.3.

No evidence was found in the literature to assess the potential for leachate run-off during storage of immature composts. Whilst it is difficult to exactly correlate incidents of odour and water pollution with field-stored piles, anecdotal observations suggest that this is an issue. However, there is information available regarding leaching during compost production.

A USA guide to composting recommended the avoidance of highly permeable soils as sites for compost windrows when composting is performed directly on the soil surface, due to the leaching of nitrates and other soluble nutrients which is most likely to occur during the compost curing (maturation) phase and storage (Cooperband, 2002).

Martins (1992) examined nitrogen losses occurring during composting of mixtures of straw and different liquid manures (poultry, pig, cattle, and mixtures thereof). During the composting period 9.6-19.6% of the initial total nitrogen was lost as leachates, with >70% of the leaching (predominantly ammonium-nitrogen) occurring within the first 10 days of the composting period. The greatest nitrogen losses were found in the N-rich poultry- and pig-straw mixtures which showed obvious temperature increases up to 40°C during the first few days of the composting period. This does suggest that provided the initial composting phase has been completed, leachate losses should not be significant, although the author does not discuss the potential for changes to leachate when a compost pile is no longer turned.

A recent review of compost leachates highlighted that: 'The exact chemical makeup of the leachate varies with the type of feedstock as well as age and maturity of compost. The initial leachate contains the highest concentration of dissolved and particulate matter and nutrients, with increased amount of water passing through the compost, the amount of leached materials decreases' (Chatterjee et al., 2013).

In a UK review of manure storage, most of the leachate being emitted from the manure pile was water already contained in the manure, rather than that added in the field by rainfall (MAFF, 1999). Even immature compost is a much drier material than farm yard manure, with lower available nitrogen, and so leaching is likely to be less of an issue for composts than for manures. For example, typical cattle farm yard manure has a dry matter content of 25% (Pain and Buss, 2002). For example, a recent WRAP study comparing four green waste and three green and food waste UK composts, all with a stability level of 11.8 mg CO<sub>2</sub>/g VS/day or less (measured by CO<sub>2</sub> evolution) found compost dry matter values of between 37 and 74% (WRAP, 2011a), which is within the range of what could be expected throughout the composting process and thus relevant for immature composts too (Makan et al., 2013; The Composting Association, 2007).

In summary, all composts are much drier materials than farm yard manure, with lower available nitrogen, and so nitrate leaching is likely to be less of an issue for composts than for manures.

#### 4.5 Greenhouse gas and ammonia emissions of immature composts during in-field storage

During the biodegradation of food and other similar organic wastes, water and carbon dioxide are produced, as well as ammonia (Fowles, 2010; Murphy and Power, 2006). Some of this water is lost as water vapour and helps to cool the material through evaporative cooling, as the air stream is drawn through the waste. Some may be lost as leachate (Fowles, 2010). This leachate may be acidic and have a high BOD and COD. There is the

potential for ammonia, CO<sub>2</sub>, water vapour and leachates to continue to be produced when the compost stored is not yet mature, but is still actively composting.

Although no specific literature was found regarding the in-field storage of immature food-waste-based composts, information regarding greenhouse gas (GHG) or ammonia emissions during composting in different systems was obtained, and is discussed in section 0. This could be used to consider whether similar circumstances would arise with immature compost heaps in-field which are not actively managed (for example, by turning).

Investigations into GHG impacts of biowaste management (Fischer and Sakrabani, 2011) covered processing and end use of composts derived from food waste but not specifically the storage phase. The release of N<sub>2</sub>O from compost during use is not well documented (Boldrin et al., 2009), and it was observed that "Emissions of N<sub>2</sub>O from applications of organic wastes will be very difficult to predict as they are dependent on a multitude of factors such as the waste characteristics and its decomposition, the microbial processes of nitrification and denitrification in the soil and the factors such as moisture, oxygen, and temperature that affect these process" (Defra, 2009a).

By following CoGAP for the storage and application of composts (being the same for all organic manures including PAS100 and non-PAS composts), GHG losses should be minimised. As for manures, if compost field heaps are shaped to shed rainfall they should remain drier and less likely to become anaerobic and hence release GHG, odour and ammonia.

#### 4.6 Storing bagged compost

Compost for retail is generally bagged and stored prior to purchase. Very little academic literature was found specifically relating to the storage of bagged compost, with no data specifically relating to IVC composts. The WRAP guidelines for compost use in growing media highlights that the: 'inclusion of food waste may increase the electrical conductivity of the finished compost and in practice the rate of inclusion of such materials should therefore be limited to a low percentage (<20% by volume)' (WRAP, 2011c).

Garden Organic runs an advisory service for its 20,000 members. Issues relating to growing media containing green waste compost as a peat alternative occur reasonably often, usually concerning heating, mould growth or unpleasant odours in the bags (Rayns *pers comm*, 2013), which could be due to instability – although it is impossible to be definitive given that green composts tend to constitute a minor percentage of growing media blends.

During the internet search on bagged compost, a number of articles were located, which focussed on bags of compost purchased by members of the public smelling of ammonia or just generally being very odorous (Anonymous, 2013a). It was not clear whether the bagged 'composts' being discussed were 100% compost or a product which included compost as one of several ingredients.

A UK trial assessed the storage of 11 bagged growing media mixes which included green waste compost, over a one year period. This trial showed that N is locked up (due to conversion of nitrate and ammonium into microbial biomass) during storage, and additions of base fertiliser prior to bagging were recommended, to adjust final N levels to those that were consistent with market requirements (Richardson and Rainbow, 2005).

Immature composts have been reported to pose problems of malodours and fire during storage, in addition to issues with flies and bags bursting (Mathur et al., 1993), and so it is

possible that the issues described above could be a result of the compost being bagged prior to being mature and stable.

The growing media and soil improver retail product supply industry is very conscious of the need for the quality of the ingredients to be high, including that the material should be stable during storage and not cause any of the effects noted above, which would result in adverse publicity and sales.

The PAS100 stability limit is 16 mg CO<sub>2</sub>/g OM / day, with lower values indicating greater stability. The WRAP guidelines for compost use in growing media recommends an upper limit of 10 mg and a target of 8 CO<sub>2</sub>/g OM / day (WRAP, 2011c). This is still higher than the level recommended by the authors of the ORG0020 method development report (Llewelyn, 2005), who state that "10 mg CO<sub>2</sub>/g VS/day appears to be a critical value below which composts can be generally considered to be complete and stable for most purposes. Stabilities of <6 mg CO<sub>2</sub>/g VS/day are desirable for growing media purposes or for any applications where self-heating would be a problem".

## **5.0 The regulations regarding compost end use in the UK**

This section focuses on the use of composts in agriculture and field horticulture. The rules and requirements for the application of composts are considered, firstly for all composts, then PAS100 composts and finally non-PAS composts. This provides regulatory context for Section 6, which focuses on the results of the literature searching on the use of composts with a range of stabilities.

Composts must be 'fit for purpose', defined as having all of the properties and characteristics necessary for their intended use(s). In the context of PAS100, 'fit for purpose' compost passes all PAS 100 obligatory tests and any additional requirements the composteer has committed to fulfilling in his/her quality policy or in a written agreement with a compost customer.

### **5.1 Compost end use: Rules for all composts**

There are a range of regulations and controls which need to be followed when applying composts. These include Cross Compliance Statutory Management Requirements (SMRs) under the Single Payment Scheme (RPA and Defra, 2013), and, if applicable Environmental Stewardship rules. The SPS will be replaced by the Basic Payment Scheme in 2015, which will include some new greening rules. As these are currently under development these are not considered further here (information on the new rules will be added to: [www.gov.uk/cap-reform](http://www.gov.uk/cap-reform)).

The current cross compliance requirement states that 'you must not apply any organic manures within 2 metres of the centre of hedges, a watercourse or field ditch. This also applies to land within 1 metre of the top of the bank of a watercourse'.

Where the land is in an NVZ, then the NVZ regulations must also be adhered to (Defra, 2013b), as outlined in Box 9. NVZs are included within Cross Compliance as SMR1 (previously SMR4). One key consideration regards the amount of N the crop can uptake and the N already supplied through soil organic matter, crop residues and organic manure.

In addition to the regulations, there is also the Code of Good Agricultural Practice (CoGAP) (Defra, 2009b), which details how to protect the water, soil and air. CoGAP recommends a

maximum application rate of 250 kg N/ha /year for organic manures including composts, with compost spreading recommendations the same as those for NVZs as shown in Box 9.

Moreover, following application of composts produced from ABPs, pigs must be prevented from accessing the land for two months and any other farm animal for 21 days. In addition, cut or harvested herbage cannot be used as feed for pigs for 2 months or any other farmed animals for 21 days, from land where the ABP compost was applied, (Defra and AHLVA, 2014b).

In addition to the regulations above, RB209 includes a section on nutrient supply from composts, which highlights that inorganic fertiliser N is still required when compost is used (Defra, 2010):

'The available field experimental data indicate that green compost supplies only very small amounts of crop available nitrogen and that inorganic fertiliser nitrogen application rates should not be changed for the next crop grown. In the case of green/food compost, the available experimental data indicate that around 5% of the total nitrogen applied is available to the next crop grown (irrespective of application timing). Following the repeated use of green and green/food composts long-term soil nitrogen supply will be increased.'

---

**Box 9** Excerpts from the NVZ regulations 2013-2016 regarding compost application to agriculture and field horticulture (Defra, 2013b)

### **Spreading composts**

YOU MUST NOT spread organic manure if you identify there is a significant risk of runoff getting into surface water (the guidance explains how to assess for this risk).

YOU MUST NOT spread organic manure [compost] when the soil is:

- Waterlogged, flooded, snow-covered, or frozen for more than 12 hours in the previous 24 hours.

YOU MUST NOT spread organic manures [compost]:

- less than 50 metres of any spring or well, or any borehole.
- within than 10 metres of any watercourse; except on land managed for breeding wader birds or as species-rich semi-natural grassland and under certain circumstances.

If you apply organic manure on bare soil or stubble (other than soil that has been sown). YOU MUST: incorporate compost into the soil as soon as practicable, and within 24 hours (unless it has been spread as a mulch on sandy soil) if the land is sloping and within 50 metres of surface water that could receive run-off from that land.

### **Application rate**

For composts, up to 250 kg N/ha/year can be applied [approximately 30-35 t compost/ha], or 500 kg N can be applied in any two year period either as a mulch or worked into the soil if the only organic manure you apply to a field is compost.

Before you apply organic manure to a field YOU MUST decide what an appropriate application rate would be by:

- Assessing the amount of crop available nitrogen likely to be supplied by the application of organic manure.
- Ensuring that this addition of nitrogen does not result in a breach in the N max limit [specified in the NVZ guidance for a range of crops].

## 5.2 Compost end use: Rules for applying PAS100 composts

CQP compliant composts (which must automatically comply with the requirements of PAS100) are deemed recovered and no longer waste, so can be supplied and used without the need for a waste permit or exemption for spreading. All CQP compliant composts should have a maximum compost stability of 16 mg CO<sub>2</sub>/g OM/day. The rules highlighted in Section 5.1 must also be adhered to where appropriate.

## 5.3 Compost end use: Rules for non-PAS composts

For non-PAS composts, which must be “nominally stable”, a range of Standard Rules apply (including those outlined in Box 10) and a permit or exemption will need to be obtained prior to storage on the land (see section 0) and spreading.

---

### **Box 10** UK regulations regarding the application of non-PAS compost to land (Defra, 2013b)

The U10 and U11 exemptions, and the SR2010No4 permit all state:  
The place where waste that is stored or land which is to be spread must be at least 10 metres from a watercourse and 50 metres from a spring, well or borehole.

In addition, for U10 and U11 exemptions, you must not spread waste if the land is:

- Waterlogged, frozen or covered with snow.
- Has been frozen for 12 hours or more in the 24 hours before you want to start spreading.

In order to apply non-PAS composts to land a deployment form must also be submitted, which must include a benefit statement (further details in Box 11). This involves an assessment that shows that the compost application will result in a benefit to agriculture or ecological improvement must be made prior to spreading. This assessment must be made by a person with appropriate technical expertise and contain evidence demonstrating the reasons for their opinion. For the Environment Agency permits, exemptions and Standard Rules discussed in this and subsequent sections, the assumption is that the application of compost meets the principles of waste recovery as set out in RGN13:

*‘The compost is applied to land as a form of waste recovery (rather than disposal), to achieve a beneficial outcome in an environmentally sound manner’* (Environment Agency, 2010c).

---

### **Box 11** Requirements for the benefit statement for the deployment of non-PAS composts with a SR2010No4 permit (Environment Agency, 2013f; Environment Agency, 2011)

The benefit statement must describe how the activity will result in benefit and demonstrate that the spreading of wastes for the purpose of recovery will not cause harm to the environment. If the land has been treated with other wastes, slurries or manures in the last 12 months this information should be included and taken into account when carrying out your benefit analysis.

The benefit statement uses the soil analysis, waste analysis and intended end-use of the land (e.g. cropping regimes) to describe the benefits and improvements that the spreading of waste provides. The statement should describe any potential negative impacts the activity may impart to the receiving soil and surrounding environment and include the operator’s management and operational procedures to manage and prevent such impacts before, during and after the activity. Application rates should be in-line with relevant standards e.g. RB209 (Defra, 2010).

**Table 7** Exemptions, permits and deployments relating to the land spreading of non-PAS composts in the UK

Permit or exemption code	Land type	Notes	Reference
SR2010No4 permit	Agricultural & non-agricultural land	Must also apply for aLPD1 deployment. For the use of equipment for storing compost and then applying to land. Max storage: 3000t Application: As agreed in the deployment form, and in any case a maximum of 250 t/ha/yr Max application area: 50ha per deployment	(Environment Agency, 2013d)
LPD1 deployment	Agricultural & non-agricultural land	Must first hold a SR2010No4 permit For applying compost. Benefit statement required.	(Environment Agency, 2011)
U10 exemption	Agricultural land only	Permitted composts: <ul style="list-style-type: none"> <li>▪ Compost produced only from list of waste and in the proportion stated in the T23 exemption, or worm compost from T26 exemption.</li> <li>▪ Used compost from growing mushrooms</li> </ul> Max storage: 500 t Application: Max 50t/ha/yr Max application area: Not stated	(Environment Agency, 2014c)
U11 exemption	Non-agricultural land only	As for U10 exemption	(Environment Agency, 2014d)

There is also an Environment Agency guidance note focussing on land spreading, and complying with the regulations (Environment Agency, 2013f).

There are therefore many regulatory factors to be taken into account when storing and then applying composted material to land. The receiving soil must benefit from the application, and the environment must not be harmed. Therefore the composted material must be fit for purpose. However, one benefit of applying composted material is to provide carbon as an energy source for soil microorganisms that, in turn, improves soil structure and related properties. The continued degradation of the carbon in the composted material when applied to soil is a natural process. The composting process extracts much of the energy before the material is applied to the soil and so the amount of stabilisation that occurs dictates how much residual energy remains for the soil microorganisms. The impacts of compost stability on compost use are reviewed in the next section.

## 6.0 The impacts of compost stability on compost end use

As described in Section 5, compost use in agriculture is regulated by specific annual application limits within NVZ regulations and CoGAP, in addition to crop nutrient requirements via RB209 guidelines. Specific application timings are not regulated for PAS100 or non-PAS composts, other than the ABPR requirements and the need for ground conditions to be suitable. However, both UK and German guidance highlights that due to the slow release of nutrients, composts can be applied post-harvest in the autumn (or before planting in winter-spring), with nutrients becoming available in the spring and in subsequent seasons (Rogasik and Reinhold, 2006; WRAP, 2004b).

The majority of information regarding the use of composts of different maturities comes from German studies. Approximately 33% of compost produced in Germany is 'Frischkompost' (fresh compost, Rottegrad II-III), 63% is mature (Rottegrad IV-V) and the rest is used as a mulch or for growing media (Meyer, 2009). In some cases, the reports published in German do not include specific data on the stability of the composts used, with the exception of stating that the compost was 'fresh' or 'mature'. In the discussion below, such instances are highlighted by stating that the stability was undefined.

In the following subsections, the effects of compost stability on crop growth and yield, nitrogen lock-up, soil physical properties, ground and surface water pollution, greenhouse gas emissions, odour and weeds are discussed. A significant body of work is available in German language literature, partly due to widely accepted compost stability levels (Rottegrad) having been defined by compost quality assurance schemes for several decades. Firstly immature compost use in growing media is explored, followed by compost application to agriculture and field horticulture.

### 6.1 Immature compost use in growing media

Very little literature is currently available regarding the use of immature composts specifically as a growing media ingredient because growing media manufacturers are unlikely to have used unstable composts in research, since they can be associated with high EC and organic acid content – which are undesirable characteristics for growing media constituents (WRAP, 2011b). However, research using composts with a range of maturities, including immature composts in various plant bioassays specifically for assessing compost maturity, was obtained and is included in section 0.

With composts considered mature and suitable for use in growing media, the compost is always mixed with a combination of other ingredients, such as bark, wood chip, wood fibre, coir, peat or soil to provide the physical and chemical characteristics required for good plant growth. A maximum of 40-50% by volume of compost is recommended, depending on the type of growing medium to be made and the plant species to be grown (WRAP, 2011b). This should result in a growing medium with a suitable balance of nutrient supply, porosity and aeration to support plant growth. Exploring the use of mature compost as a growing media ingredient further is beyond the remit of this desk study but is the subject of a separate WRAP report 'De-mystifying the use of PAS100 compost in horticultural growing media' (WRAP project code OMK005-002). The studies described below focus on immature composts.

When mixed with other growing media ingredients in pot trials, immature compost has been shown to exhibit adverse effects on plant growth to a greater extent than in the field, because in the latter the compost is always added as a very small proportion to the soil mass. These adverse effects in pot studies could be caused by high EC or high VOAs (WRAP, 2011b).

In-vessel biosolid compost of a range of maturities was mixed with peat and sand (approximately 2:1:1) to achieve an EC of 2 dS/m, and used as a growing media for sorghum-sudan grass (Brinton, 2000b; Brinton, 2002). The compost maturities were defined as; Phase I, "Uncured" when compost is discharged after the 21-day intensively turned phase (Rottegrad II); Phase II, "Semi-Cured" compost which has been cured for another 60-days in windrows under cover (Rottegrad V), and Phase III, "Cured" at the end of outdoor curing in open piles for 250 days (Rottegrad V). Immature compost (Phase I uncured) resulted, after 20 days, in restricted root growth and smaller shoots. This was attributed to high VOA content (2109 ppm in Phase 1 as compared to 993ppm in Phase 2 and 319ppm in Phase 3 compost) and low oxygen levels inhibiting root growth.

In a German pot study, fresh (70% biowaste 25% green waste, Rottegrad III, C:N 19) and mature compost (100% green waste, Rottegrad V, C:N 13), mushroom compost, horse manure and control (no amendment) were used to grow white asparagus (Bloom, 2003). The amendments were mixed with loamy sand soil to achieve a final C content of 4 t C/ha. A soil-only treatment was used as the control. The substrates were mixed nine days before one year old asparagus seedlings were planted in 25l pots. There were no significant effects of the organic amendments on the number of asparagus shoots. However, the fresh and dry weights were significantly lower for both the fresh and mature composts and the control, compared to the other amendments. The author commented that the asparagus did not grow well in any of the treatments in the pot study, attaining only a third of the yield obtained in a field study, which is described in section 6.2.3.

The influence of applying a layer of three MSW-biosolids composts as a mulch on the emergence of several weed species was evaluated in a number of greenhouse pot trials (Ozores-Hampton M, 2002). The three composts were:

- Three days old, having just exited the IVC (C:N 32:1).
- Eight weeks old, which had undergone subsequent open windrow treatment (C:N 30:1).
- Mature compost.

Both the three day and eight week old composts were considered immature due to the high C:N. The trials included investigating a range of mulch depths (2.5, 5, 7.5 and 10cm) and a number of weed species. Both immature composts were found to reduce the emergence of several economically important weed species, compared to a commercial growing media and an untreated control. The mature compost was only useful as a mulch when used at a depth of 10cm, whereas the two immature composts succeeded in completely suppressing some weeds when applied at a depth of 2.5cm, with an increasing thickness to 10cm resulting in weed suppression for longer in other species. The authors recommended that immature composts can be used to control weeds under conditions where spatial separation, for example in row crops, is maintained between the crop and the compost and phytotoxic fermentation products do not affect the health of the mulched plants and where odours associated with such partially stabilized products do not pose problems.

In a pot study, fresh and mature compost from vegetable, fruit and green waste (composted in enclosed systems) were mixed with a peat-perlite substrate at rates of 0, 10, 20 %; compost maturity was assessed using the self heating test and fluorescein diacetate hydrolysis to determine microbial activity (Tuitert, 1996). At the highest rate of 20%, mature compost suppressed *Rhizoctonia solani* in lupins (*Lupinus angustifolius*), but the immature (fresh) compost had no effect. The disease suppression was associated with high populations of certain microorganisms in the mature compost that were absent from the immature compost.

Pot studies regarding immature compost specifically focussing on N mineralisation are described in Section 6.3.1.

## 6.2 Crop growth and yield

Composts supply nitrogen and a range of other nutrients, improve soil structure and water holding capacity, which in many cases result in an increased yield. Plant growth can be reduced by compost application as a result of various directly toxic effects (e.g. herbicide contamination, VOAs, depletion of oxygen to the roots through competition from microorganisms). Plant growth may also be affected indirectly by nitrogen lock-up. To an extent some issues (especially nitrogen lock-up) can be ameliorated by fertiliser applications and this may be acceptable to farmers who are seeking soil improvement through the organic matter that compost contains.

This section focuses on the use of immature compost in agriculture and field horticulture, with a sub-section included specifically on German research as much of the work on fresh composts has been undertaken there.

### *6.2.1 Compost use in agriculture and field horticulture*

WRAP carried out a full literature review in 2004 on the benefits of the use of composts in agriculture (Wallace et al., 2004). At that time, predominantly green waste only was collected and composted, without food waste. The benefits of compost use were described, ranging from nutrient supply to plants, to the provision of organic matter for soil fertility effects and microorganisms for soil health. Constraints were also investigated such as soluble salt levels, potentially toxic element concentrations, compost immaturity and the levels of physical and biological contaminants in composts.

Results showed that repeated applications of green waste composts over a period of 2 to 10 years increased soil organic matter levels by an average of 12%, when compared with soils receiving no compost. Moreover, some increases in crop yield were also observed when compost (with or without inorganic N) was compared to untreated and inorganic fertiliser controls (Bhogal et al., 2009; Wallace, 2009; Wallace and Carter, 2007). A review of UK field trials in 2008 for WRAP (Wallace, 2008) highlighted that medium term, repeated compost use can result in improved crop growth and yield increases of 7% in cereals (Wallace, 2009).

A review summarising long term trial research (3-60 years) on composts (Diacono and Montemurro, 2010) also highlighted a range of benefits, the majority of which are now well known within the UK composting industry:

- An improvement in soil biological functions.
- Increased soil physical fertility through improved aggregate stability and decreased soil bulk density.
- Crop yield increases by up to 250% through long-term applications of high rates of municipal solid waste compost.
- Soil organic nitrogen content can be enhanced by up to 90%.

In a Defra report, using more stable composts was recommended, as immature (stability undefined) composts may continue to actively decompose when added to the soil, which may reduce the oxygen concentration of the soil-root zone, reduce available nitrogen or lead to the production of phytotoxic compounds (Litterick et al., 2003).

A Swiss study (Fuchs, 2008b; Fuchs, 2008a) investigated a range of six mature composts (all Rottegrad V) with different end uses (2 for agriculture, two for horticulture and two for protected horticulture/gardening). Composts were applied in the spring at a rate of 100m<sup>3</sup>/ha, but no information was provided regarding the time between compost application and sowing the maize crop. Even though all composts were mature (<16 mg O<sub>2</sub>/g organic dry matter with the AT4 test) there were differences in maize growth and yield. The general trend was that of all of the composts tested, those which were slightly less mature resulted in lower yields than the slightly more mature composts. With additional fertilization, however, it was possible to compensate for this effect, which was attributed to nitrogen lock-up. Nitrogen mineralisation is discussed further in Section 6.3.

### *6.2.2 Immature compost use in agriculture and field horticulture*

Regarding the use of immature (or fresh) composts in agriculture and field horticulture, a number of studies were identified from Europe and further afield, but few from the UK. Regulations regarding the application and use of non-PAS 100 composts in the UK are discussed in section 5.3.

One publication observed that immature composts (generally considered to be Rottegrad II-III), when added to the soil, will continue to decompose and utilise the oxygen in the soil. This may starve the plant roots of oxygen and also lead to anaerobic conditions that are conducive to H<sub>2</sub>S and NO<sub>2</sub><sup>-</sup> production and lead to the creation of organic acids that are phytotoxic to plant roots (Mathur et al., 1993). However, the field trial data discussed below generally demonstrates that the use of fresh composts does not detrimentally affect crop yield when compost application and subsequent crop establishment timings are managed appropriately.

In a UK study, the application of five composts of different origins and ages was trialled on a barley crop and subsequent winter wheat crop (Lillywhite et al., 2009). Composts used were:

- 1 x CLO made from the organic fraction of MSW, which was two weeks old (stability undefined but considered immature, C:N 32, NH<sub>4</sub>-N 657 mg/kg DM, NO<sub>3</sub>-N 2 mg/kg DM).
- 2 x horizontal IVC composts with subsequent open windrowing. Both included BMW and cardboard, had both undergone the IVC stage and subsequent open windrow composting (stabilities undefined, C:N 16 and 13, NH<sub>4</sub>-N 237 and 30 mg/kg DM, NO<sub>3</sub>-N 88 and 297 mg/kg DM).
- 1 x vertical composting unit (VCU) compost made from green waste, fruit and vegetable waste and cardboard. VCU for 1 week and subsequent open windrowing for 6 weeks (stability undefined, C:N 20, NH<sub>4</sub>-N 77 mg/kg DM, NO<sub>3</sub>-N 11 mg/kg DM).
- 1 x open windrow (OW) compost made from green waste, fruit and vegetable waste and cardboard (stability undefined, C:N 11, NH<sub>4</sub>-N 17 mg/kg DM, NO<sub>3</sub>-N 1188 mg/kg DM).

The IVC, VCU and OW composts were all obtained at the end of the composting process and were all at least six weeks old, as compared to the CLO which was only two weeks old. Further details regarding the composition of the composts can be found in the final project report (Dimambro et al., 2006). Composts were applied in year one only, and incorporated the day before sowing. The application rates were 250kg N/ha and 500 kg N/ha for all composts. The control treatment was zero fertiliser. In the second year 100 kg N/ha of ammonium nitrate fertiliser was applied to all plots.

In year 1, the OW and IVC composts at both application rates increased barley yield compared to the unfertilised control, with higher yield observed in the 500 kg N/ha treatments in all cases. However, the VCU compost and the CLO treatment resulted in reduced growth and yield in the year of compost application for both application rates, with a reduction in total N uptake observed compared to the control. For the CLO this was attributed to the high NH<sub>4</sub>-N (>2.2g/kg), high C:N (32:1) and high sodium content. The VCU compost had a relatively high C:N of 20, which may have caused some N lock-up. The following year, the wheat yield was better than the control for all treatments except for the 250 kg N/ha VCU compost treatment which was comparable to the control, (Lillywhite et al., 2009).

In California, 15 crop trials examined the effect of compost feedstocks, compost maturity (defined in Table 8), and soil texture on vegetable crops over a two year period (Buchanan, 2002). The fields were coarse sandy loam, fine sandy loam, sandy clay loam, and clay soils. Feedstocks for the 25 composts used were either green waste only or a combination of green waste and poultry manure (termed blend compost). The mature and/or moderately mature (maturing) composts consistently released a greater percentage of their total N content (assessed monthly for the duration of the trials), in comparison to immature or very mature materials. There was no correlation between compost C:N ratio and other maturity index parameters. No yield differences were observed in a number of trials where immature or very immature composts were applied either months or weeks prior to a crop planting. In other trials, reductions in yield were associated with the incorporation of immature and very mature composts into the soil, while yield increases tended to occur with the use of mature

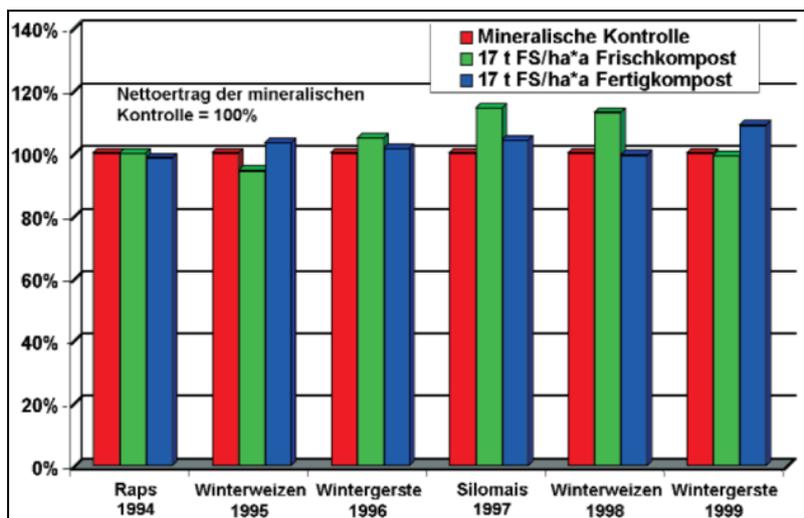
or maturing materials (Buchanan, 2002). Timing and depth of compost incorporation were stated as being important, as reductions in seedling emergence and N uptake were observed when immature green-waste compost was incorporated only to a depth of 3 to 4 inches. The crop response results from these trials are shown in Table 8. The author stated that: 'The data from 15 crop trials and 25 compost samples does not reflect the diversity of products, crops, and locations necessary for comprehensive conclusions.'

A study in Luxemburg compared fresh and mature compost (stability undefined) and inorganic fertiliser in a field trial over 15 years with an arable rotation of cereals, oilseed rape and maize. No significant differences between fresh and mature compost were observed (Figure 4), and it was concluded that as fresh compost is cheaper to produce it should be used in preference to mature compost in agricultural applications (Gröll, 2007).

**Figure 4** Yield data of the first six years of the Luxemburg trial

The treatment yields are shown as a % of the mineral fertiliser control (Anonymous, 2004)

Red = Inorganic fertiliser control  
 Green = 17 t/ha FW fresh compost  
 Blue = 17 t/ha FW mature compost  
 Raps = Oilseed rape  
 Winterweizen = winter wheat  
 Wintergerste = winter barley  
 Silomais = forage maize



**Table 8** Summary of crop response to composts of varied maturity status on different soils in California (Buchanan, 2002)

Compost Type	Maturity	Crop	Yield
<b>Sandy Soils (Coarse and Fine Sandy Loams)</b>			
Blend	VM	Baby lettuce	0
	VM	Baby lettuce	-
	VM	Baby spinach	+
	VM	Baby spinach	0
	IM	Baby spinach	0
	IM	Baby spinach	+
	IM	Baby chard	0
	MM	Baby mustard	+
Green Waste	MM	Baby Lettuce	+
	IM	Baby Lettuce	-
	IM	Baby Lettuce	-
	MM	Baby Spinach	+
	IM	Baby Spinach	0
	MM	Baby Spinach	0
	IM	Baby Spinach	-
	MM	Baby Spinach	-
	M	Baby Chard	0
	VIM	Baby Mustard	-
<b>Loamy Soils (Sandy Clay Loam)</b>			
Blend	M	Lettuce	+
	MM	Lettuce	+
	MM	Celery	+
Green Waste	M	Lettuce	0
	IM	Lettuce	0
	M	Celery	+
<b>Clayey Soils (Clay)</b>			
<b>Blend</b>	MM	Cabbage	+
	VIM	Lettuce	-
<b>Green Waste</b>	M	Cabbage	+
	IM	Lettuce	0

+ = Increased yield 0 = No difference in comparison - = Decreased yield

- VIM: Very Immature (C:N ratio is greater than 25, and/or stability test is greater than 12 C / unit OM / day [assumed to be 12 mg CO<sub>2</sub>-C/g VS/day], and/or NH<sub>4</sub> is greater than 500ppm and there is no nitrate present)
- I: Immature (Unstable compost, odours likely, high toxicity potential, immobilization (tie-up) of available nitrogen)
- MM: Moderately mature or maturing (stability test result is greater than 6 and less than 8 C / unit OM / day [assumed to be 8 mg CO<sub>2</sub>-C/g VS/day] and/or when nitrate is detected and is greater than 25 ppm N)
- M: Mature (Cured compost, Odour production not likely, limited toxicity potential, positive impact on available soil nitrogen)
- VM: Very Mature (well-cured compost, no continued decomposition, no odours, no potential toxicity, possible lower release of N than mature compost)

### 6.2.3 Fresh and mature compost use in agriculture and field horticulture: Germany

As highlighted above, the majority of work on fresh composts has been undertaken in Germany, with some trial work discussed below. Where the research publication included details of compost application timings and the level of maturity in Rottegrad this is highlighted. The Rottegrad system is defined in Table 1.

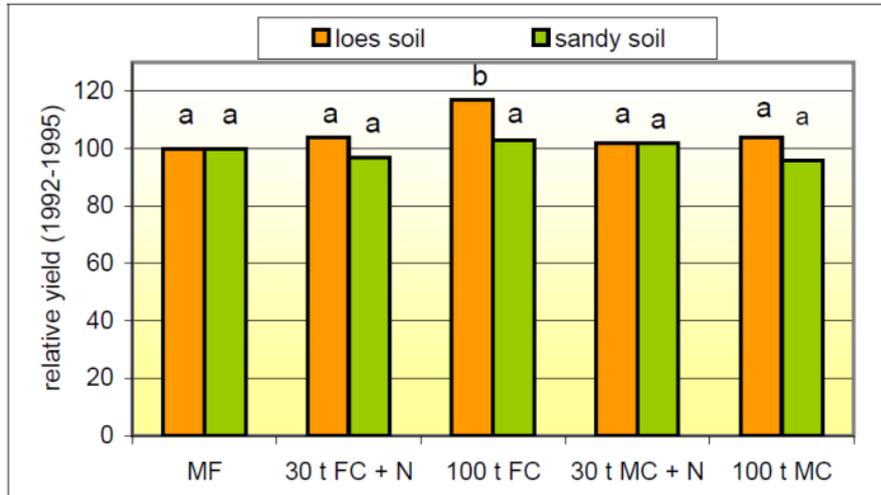
The effects of extremely fresh (Rottegrad I, composted for 12-25 days) and mature (Rottegrad IV-V, composted for four months) biowaste composts (75% kitchen and garden waste, 25% green waste in both cases) were compared with inorganic fertiliser on a range of crops (Petersen and Stöppler-Zimmer, 1999). In an arable trial, the composts were applied at two rates (30 t/ha with mineral N, and 100 t/ha compost only) on two soils. Compost was incorporated on the day before or the actual day of sowing. Crops grown were cauliflower, potatoes, beetroot and winter wheat. On a sandy soil there were no differences in yield between the mineral fertiliser and compost treatments within a four year period, whereas on a loess soil, application of 100 t/ha of fresh compost resulted in a significantly higher yield in comparison to mineral fertiliser and mature compost, as shown in Figure 5. Effects of these treatments on the soil are discussed in Section 6.5.

In a second trial, the same fresh (Rottegrad I) and mature (Rottegrad IV-V) composts (75% kitchen and garden waste, 25% green waste) were applied at 100 and 250 t/ha in a forsythia field. Compost was incorporated on the day before or the actual day of planting the one year old cuttings. There were no significant differences between treatments compared to inorganic fertiliser (Petersen and Stöppler-Zimmer, 1999). It was noted that the fresh compost at the 250 t/ha rate resulted in the greatest increase in the number of branches and plant weight, although this was not significant.

In a review paper, the potential explanation for these positive results found in the aforementioned Petersen & Stöppler-Zimmer studies is that fresh (Rottegrad I) compost supplies a slightly higher level of available nutrients (N, P and K) (Amlinger et al., 2007).

**Figure 5** Relative crop yield over 4 years (1992-1995) on two soil types

Key: MF = mineral fertiliser, FC = fresh compost, MC = mature compost. (Petersen, 1995)

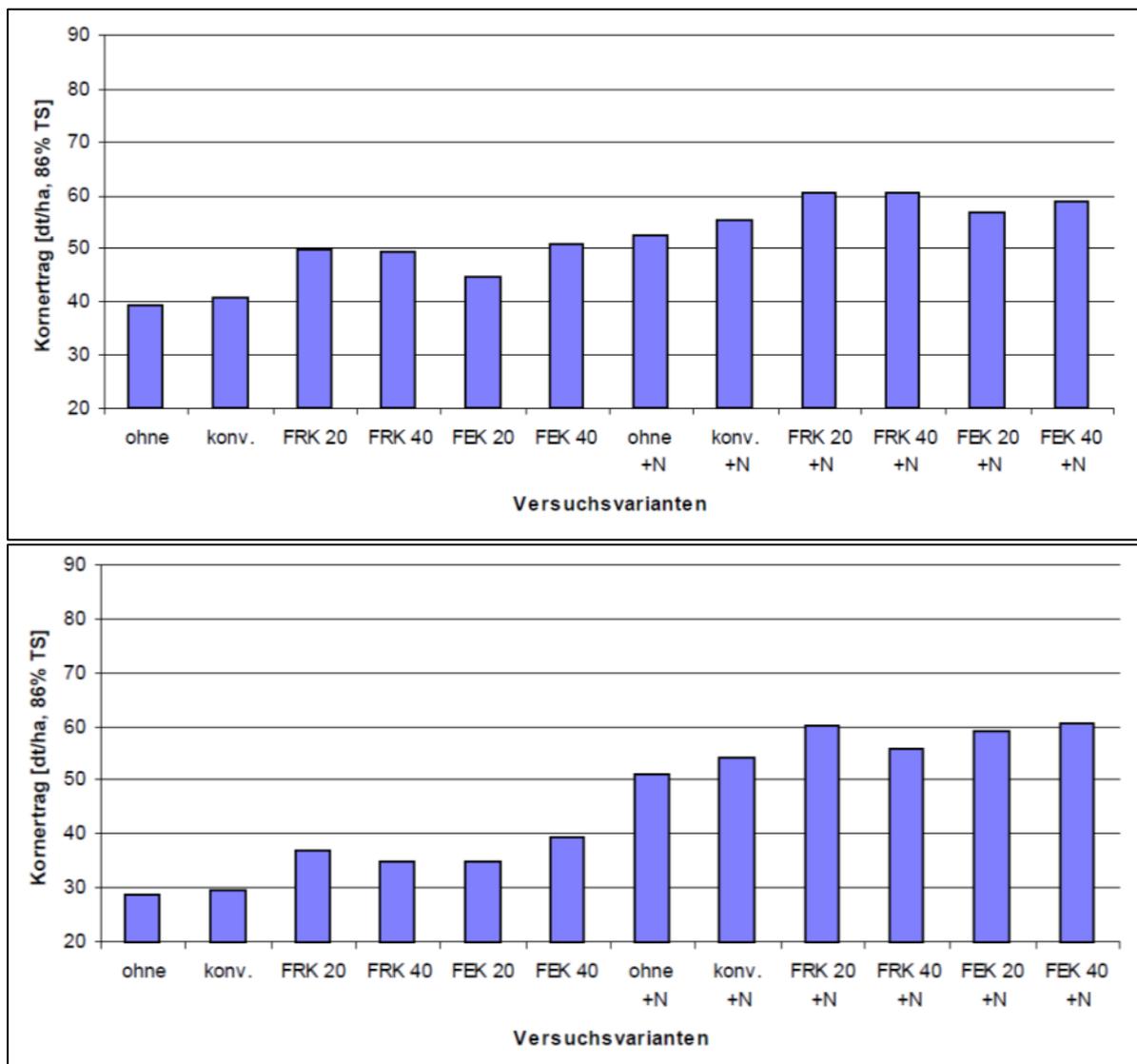


In a German review paper (Kasten, 1999), a number of compost use in agriculture trials were highlighted. These included comparative field trials in range of locations in Hestia, Germany. In the first year of compost application (fresh and mature composts, stability not defined) there was no effect on quality and yield of sugar beet. In the second growing season after compost application, however, there was a significant increase of 16% in yield of winter wheat in the fresh compost treatment compared to the unfertilized treatment (an average over seven sites). In one location, mature compost resulted in N immobilisation, which reduced the yield of spring barley by 20 % below the control (Asche and Steffens, 1995).

A German study compared the effect of 20 mm and 40 mm fresh and mature compost (stability undefined) addition on quality and quantity of a range of crops during 1996-1997 (Hartmann, 2002). The compost was produced from a mixture of biowaste and green waste. The fresh compost was the result of 14 days in an IVC unit, and the mature compost was at least 100 days old. The compost application rate was 40 t/ha FW (63-79 m<sup>3</sup>/ha) in year 1 and 33 t/ha FW (40-53 m<sup>3</sup>/ha) in year 2. There was also an unfertilised control and a standard NPK fertiliser treatment (nutrient concentrations not defined). The same six treatments were repeated with inorganic fertiliser added in all plots. The same trial was conducted at three sites with different soil types: Podsol, brown earth and para brown earth.

In both years, winter rye was grown in the podsol field. All of the compost treatments performed better than the zero control, with the addition of inorganic N to the compost treatments increasing yield further (see Figure 6).

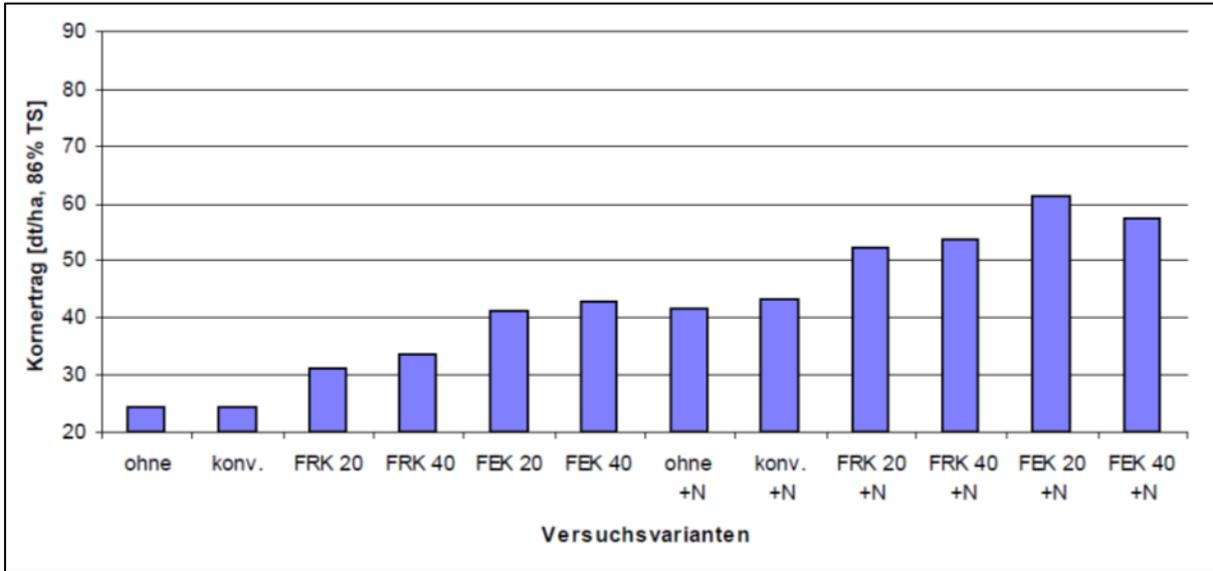
**Figure 6** Winter rye yield results in dt/ha DW from 1996 (year 1 above) and 1997 (year 2 below) from the podsol site. X axis: Control (ohne), conventional fertiliser (konv.), 20mm and 40mm fresh compost (FRK) and 20mm and 40mm mature compost (FEK), +N is the addition of inorganic N (Hartmann, 2002)



In the brown earth field, winter rye was also grown in year 1 and winter barley in year 2. For the winter rye the results were much less variable than at the para brown earth site, with

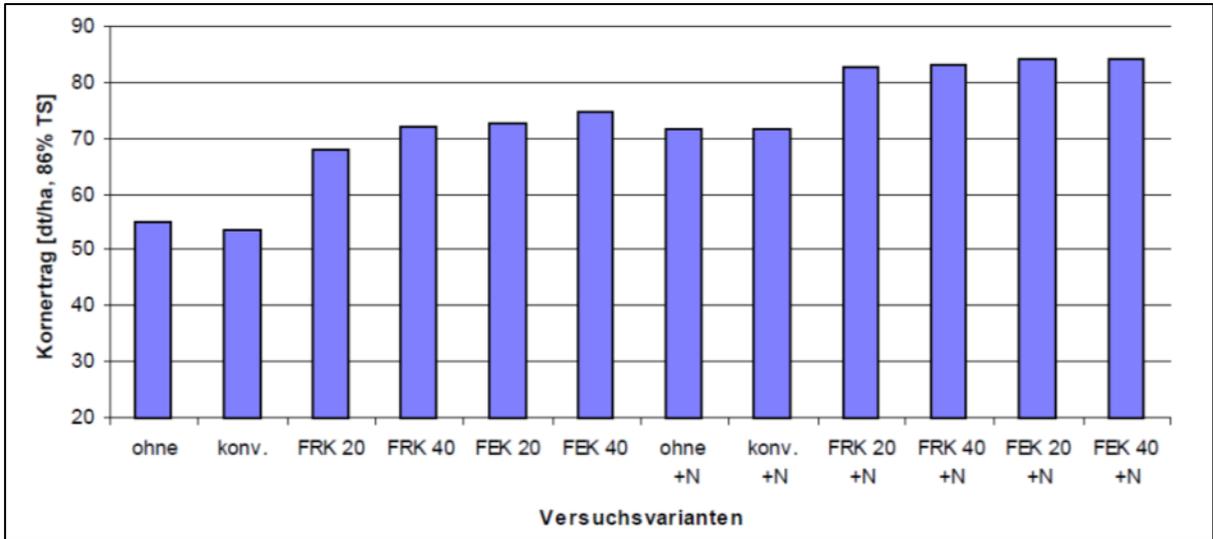
the 12 treatments having yields of 68-77 dt/ha DW. However, for the winter barley, there was a clear increase in yield from zero fertiliser to conventional fertiliser, and then composts. The compost plus additional N treatment increased yields further, as shown in Figure 7.

**Figure 7** Winter barley yield results in dt/ha DW from 1997 (year 2) from the brown earth site. X axis: Control (ohne), conventional fertiliser (konv), 20mm and 40mm fresh compost (FRK) and 20mm and 40mm mature compost (FEK), +N is the addition of inorganic N (Hartmann, 2002)



In the para brown earth field, potatoes were grown in year 1, with very little difference between treatment, with yields varying between 380-425 dt/ha. However, in year 2 winter wheat was grown, with clear yield increases with the use of compost, and again an even higher yield where inorganic N was added to the compost (see Figure 8).

**Figure 8** Winter wheat yield results in dt/ha DW from 1997 (year 2) from the para brown earth site. X axis: Control (ohne), conventional fertiliser (konv), 20mm and 40mm fresh compost (FRK) and 20mm and 40mm mature compost (FEK), +N is the addition of inorganic N (Hartmann, 2002)



The effects of different organic fertilizers on establishment, growth, yield and nitrogen balance of white asparagus were investigated in Germany (Bloom, 2003). In the spring in 1997, horse manure and composts were applied to the surface and then incorporated to 30 cm. There were two application rates, both being comparable to the quantity of carbon in the horse manure (200 dt/ha and 600 dt/ha horse manure C equivalent). In 1997 the two composts applied were biowaste compost (Rottegrad IV, C:N 13) and fresh green waste compost (Rottegrad III, C:N 26). Six days later, one year old white asparagus seedlings were planted.

In spring 2000 the treatments were re-applied on the existing asparagus crop in the low application rate plots only (200 dt/ha horse manure C equivalent) areas only, at the same rate. The two composts being a fresh biowaste compost (Rottegrad III, C:N 19) and a mature green waste compost (Rottegrad V, C:N 13). The whole field experiment was amended with the standard annual mineral basal fertilizer application (P, K, Mg) used under local farming conditions, each year.

During the first year of the trial the fresh compost caused a slight reduction in asparagus shoots (ferns) due to N immobilisation, but this was not statistically significant. In subsequent years there were no significant differences in yield in any of the treatments. The author concluded that:

- Composts are appropriate organic fertilizers for use in asparagus production.
- To ensure optimal crop growth, supplemental N fertilization, adjusted for soil-N is needed at the end of the harvest period, or at the start of fern development in the first year.

### 6.3 Nitrogen mineralisation

The first phase of microbial transformation of compost N in the soil is mineralisation, followed by ammonification, nitrification and denitrification. This complex process is reviewed comprehensively by Amlinger et al. (2003). The major part of total compost-N is bound within the organic N-pool, and so the quantity of N available to the crop and also therefore the quantity of N which has the potential to be leached out of the soil are both low (Husz, 1999). Hence, as highlighted in section 5.1 and RB209 (Defra, 2010), inorganic-N is generally still required. Indeed RB209 recommends that in the first year of green waste compost use, the total crop N requirement should be supplied with inorganic-N, or 95% when food waste composts are used.

To evaluate the mineralisation (availability) of compost-N, a range of experimental methods are used. Predominantly pot and field plot trials are undertaken to evaluate the N-efficiency in terms of comparative yield or N uptake, compared to an untreated control or inorganic fertiliser treatment. Assessments of N leaching on the field scale focus on assessing soil nitrate at specific depths (termed the leaching horizon), or using lysimeters or suction cups (Nortcliff and Amlinger, 2001b). A number of publications reporting on effects of immature composts on N mineralisation are discussed below; firstly glasshouse and then field studies.

#### 6.3.1 Glasshouse and laboratory trials: Nitrogen mineralisation

A Spanish glasshouse experiment assessed the nutrient availability of straw/horse manure compost sampled every four days over two months and mixed with soil (Blanco, 1997). No linear correlation was found between composting time and the potential of compost to improve rye grass yield; immobilisation of nitrogen in 'post-mature' compost was suggested.

A greenhouse pot bioassay was conducted to determine the percentage of short-term apparent bioavailable N in a highly matured organic 'refuse' compost (in Tenerife) and its relative efficiency in supplying inorganic N using ryegrass as a test crop. 'Highly matured' in

this study was defined by a composting time of 165 days, C:N ratio <12, cation exchange >67cmol/kg and humic acid:fulvic acid>1:6. Overall there was a positive net N mineralization over time but, initially, there was some immobilization of N, potentially caused by available soil nitrogen being used by the microorganisms to breakdown the organic materials supplied (Iglesias-Jimenez, 1993).

Spanish sewage sludge/cotton waste compost was mixed with soil at a rate equivalent to 48 t/ha, and used in a ryegrass bioassay. The compost was obtained at the end of the active phase (41 days old, C:N 9.9, NH<sub>4</sub><sup>+</sup>-N 208 mg/kg, NO<sub>3</sub><sup>-</sup>-N 526 mg/kg) and after maturation (100 days old, C:N 9.4, NH<sub>4</sub><sup>+</sup>-N 182 mg/kg, NO<sub>3</sub><sup>-</sup>-N 4192 mg/kg). The rye grass was harvested twice, and on both occasions there was no significant difference between the yield of the inorganic fertiliser control, and the soils amended with the two composts. The rye grass was assessed for total N concentration, to ascertain N uptake. The rye grass grown in the soil amended with 41 day old compost had similar total N uptake to mineral fertilizer. The greatest N uptake, and hence N fertilizer efficiency was found in the mature compost treatment, which was attributed to its high concentration of nitrate and, to a lesser extent, also to its mineralizable N (Bernal et al., 1998).

Yeast and lemon tree pruning compost in Spain was added to soil at a rate of 210g soil to 4.2g compost (w/w) and tested in a ryegrass bioassay. Compost samples were taken after 0 (fresh feedstock), 4 (during the thermophilic phase, C:N 30.6), 7 (end of the thermophilic phase, C:N 22.5), 9 (mesophilic phase, C:N 24.2), 13 (end of active phase, C:N 21.4) and 25 weeks (mature compost, C:N 16.7). There was also a soil-only treatment and a standard inorganic fertiliser treatment. Leaves were harvested three times at 28 day intervals. In the first harvest, the rye grass yield increased with increasing compost time, and the highest yield was the inorganic fertiliser treatment. Yields were less variable in the second and third cuts, with the 0 and 4 week old composts having yields comparable to the soil-only control, with slightly higher yields for the more mature composts. Fresh feedstock and immature composts (weeks 4 and 7) led to high microbial activity in the soil and initial N immobilisation. Re-mineralisation was then observed as there was an increase in leaf N content in the second and third cuts. Mature composts (13 and 25 weeks) promoted N mineralization, with 1.2-2.5% of the total N in the compost being taken up by the rye grass (Garcia-Gomez et al., 2003).

A one year incubation trial investigated N mineralisation of green and BMW composts on two soil types (sand and clay), at a rate of 600 kg N/ ha. The N mineralisation was 0.5-21% for fresh composts and 1-7% for mature composts (stability undefined) (Dreher, 2002).

In a pot study the effect of temperature on N mineralisation and the leaching of dissolved organic C (DOC) and dissolved organic N (DON) were investigated following application of fresh biowaste compost (C:N 15.4) and mature compost (C:N 9.2). A temperature dependent delay in N mobilisation was observed in fresh compost whilst there was no delay and no temperature effect on N mobilisation from mature compost. This suggested that application of fresh compost would be less likely to cause leaching during the cold winter months if applied in the autumn, yet mineral N would become available to crops in the following year as the weather warms up (Chodak, 2001).

Finally, in a German pot study (Scherer et al., 1996), the N mineralisation of a range of composts with input materials of three compositions (30% green waste:70% biowaste, 70% green waste:30% biowaste, and 100% green waste), and two stability levels (defined as Rottegrad fresh and Rottegrad very mature) was investigated. In each pot, a mixture of 10kg of soil (para-brown earth on loam, a type of sandy-loam soil) plus the quantity of compost to provide 1g total N was used. The 100% green waste composts had the lowest total and available N concentrations. As the proportion of biowaste in the compost increased

from 30% to 70%, so did the total and available N. This was observed for both the fresh and mature composts.

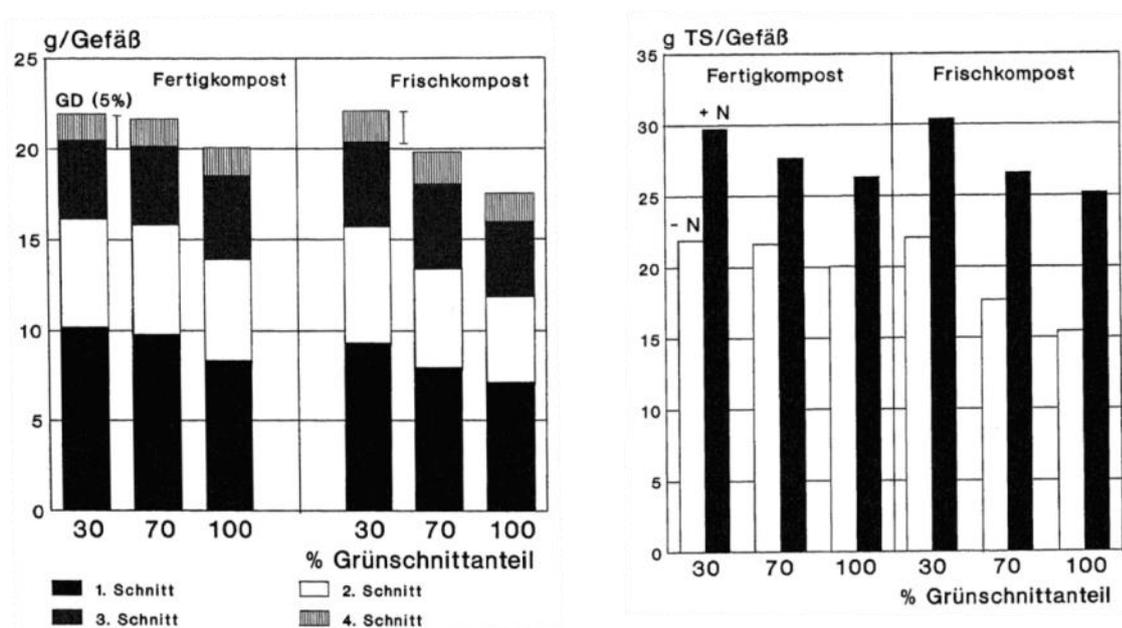
The ryegrass was cut four times during the study. For the mature composts, the % green waste in the feedstock had no significant influence on ryegrass yield, but there was a non-significant lower yield for 100% green compost during the first cut. For the fresh composts, there was a significant yield decrease with increasing % green waste for the first two cuts only (Figure 9a).

With the higher quantities of green waste in the fresh compost, initial lower N uptake was observed, but after the third ryegrass cut, the N uptake was no different to the other treatments. The compost with the 30% green waste:70% biowaste at both maturities resulted in the highest N uptake rate of 7%.

The authors attribute the decreased yield to increased N immobilisation for fresh composts with C:N ratios higher than 20:1. For mature composts, only a weak correlation of yield with C:N ratio was observed

In all cases, the addition of 250 mg N as  $(^{15}\text{NH}_4)_2\text{SO}_2$  at the start of the trial increased yield (Figure 9 b). This addition of inorganic N to the fresh composts resulted in a greater increased yield response than for the mature composts, with the 100% green waste mature compost having the lowest fertiliser response.

**Figure 9** Influence of feedstock type and compost maturity on dry matter yield of ryegrass (Scherer et al., 1996). Fertigkompost = mature compost, Frischkompost = fresh compost, g TS/Gefäß=dry matter yield in g per pot. % Grünschnittanteil = % green waste in the feedstock



a) Ryegrass yield for each of the four cuts (Schnitt)

b) Influence of additional N on the dry matter yield of ryegrass. White bars=no additional N, black bars = +N

### 6.3.2 Immature compost use as a mulch

The use of compost mulches to suppress weed growth has been investigated in a number of studies and summarised in a WRAP review (WRAP, 2006b). The review demonstrated that studies focussed on immature composts as mulches due to their phytotoxicity, at application rates of more than 50 tonnes/ha. Levels of weed control comparable with those obtained with herbicides were reported. This review also states that "There is a trend for composts that are intermediate in age (about 12 – 15 months after composting of feedstocks started) to be more suppressive than 'immature' (less than 6 months old) or 'very mature' (more than 2 years old) composts. Chronological age of compost may not be a reliable indicator of 'maturity', since this will also be influenced by the composting conditions and feedstocks."

A German fruit fertiliser guide recommended the use of mature composts (Rottegrad IV-V) in orchards, but stated that the use of fresh compost (Rottegrad II-III) as a fruit tree mulch was not recommended due to the likelihood of scorch as a result of the higher electrical conductivity (Immik and Baab, 2005). Some guidance states that even when using mature compost as a mulch for trees and shrubs, the compost should not touch the stem, to prevent scorching (WRAP, 2014; Anonymous, 2014).

In the USA, immature composts have been considered as alternatives to plastic mulches for fruit and vegetable production, to both aid moisture conservation and act as a herbicide (Composting Council, 2001). For example, in Florida immature compost was used as a mulch to prevent emergence of several common weeds (less was needed than with stable compost). Spatial separation of the compost and crops was recommended to prevent damage to the crops (Ozores-Hampton M, 2002). More details regarding pot trials investigating the use of mulches to suppress weeds can be found in Section 6.1.

### 6.3.3 Field trials: Nitrogen mineralisation

Highly matured composts have often been observed to increase crop yield, and a net inorganic-N accumulation may occur in the soil (Iglesias-Jimenez, 1993; Bernal et al., 1998). However, UK trials on compost use in wheat (WRAP, 2006a) showed that soil inorganic-N immobilisation may occur due to compost application, even when inorganic-N is also applied, but may only be measurable if the soil inorganic-N present from the previous crop was significant. Two fields were used reflecting a first and second cereal; the first being a cereal crop grown after a non-cereal crop (a break crop) with some residual N, and the second being a cereal crop grown after a cereal crop with little residual N. Inorganic fertiliser was applied in spring / summer at rates of 120, 150, 180, 210, 240 kg N/ha/year, with or without the incorporation of 30t/ha compost prior to autumn sowing. Soil N was assessed in spring (5 months after compost application) and after harvest. Where the soil started with some available N (in the first field) the mature compost reduced available N compared to the compost-free inorganic-N treatments. In the second year of wheat (field 2), the soil available N was low and so little lock-up could occur. As there was less residual N in the soil remaining after the first wheat crop for the second crop, some artificial N may need to be applied to compensate. In that case, year 1 wheat applications of around 220-240 kg inorganic-N/ha following compost incorporation achieved similar yields to crops grown in compost-free soil that received the field standard rate of fertiliser (180 kg N/ha). Whereas the year 2 wheat grown in compost treated soil required only 150 kg inorganic-N/ha to achieve a similar yield to the crop grown in compost-free soil requiring 180 kg inorganic-N/ha.

A series of UK trials at three sites investigated the N uptake of crops over a three year period with a range of late summer/early autumn and green/food waste compost (stability 6.3-11.5 mg CO<sub>2</sub>/g OM/day) application scenarios:

- Winter wheat. A single application of 250 kg N/ha compost applied in year 1.
- Winter wheat. 3 annual applications of compost at a rate of 250 kg N/ha with and without inorganic N at the recommended fertiliser rate for each crop.
- Oilseed rape / potatoes. Single compost application.
- All trials also had a zero fertiliser control and an inorganic fertiliser control at the recommended rate for each crop.

The authors concluded that approximately 5% (range 3-12%) of the total compost N was recovered by the crops in the year of compost application (ADAS, 2012). A further 3% N was recovered the following cropping year, and 2% in the third year. This equated to an N fertiliser replacement value of 12 kg/ha in year 1, 9 kg/ha in year 2 and 5 kg/ha in year 3. The evidence from these trials was used to inform the revision of RB209 which recommends that when farmers apply green/food waste compost they allow for 5% availability of the total N supplied via the compost (Defra, 2010).

In a UK study, a single spring application of five composts of different origins and ages, including one two week old CLO (produced from MSW) and two IVC composts was investigated (see section 6.2.1 for details). All five composts had a slight immobilising effect on existing soil mineral N in the year of application, as shown by a lower soil mineral N concentration than for the unfertilised control in May and August (Dimambro et al., 2006). However, in year 2, the control had the lowest concentration of soil mineral N in August (Lillywhite et al., 2009).

The previously discussed field trials by Buchanan (2002, see Section 6.2.2), observed that composts with a wide range of maturities made from poultry manure and green waste consistently released more N than green-waste only composts, and more often resulted in improved vegetable yield. This was attributed to poultry manure-green waste blend composts generally having greater organic matter, total N and inorganic N, water-soluble nutrients, and a finer particle size than green waste composts.

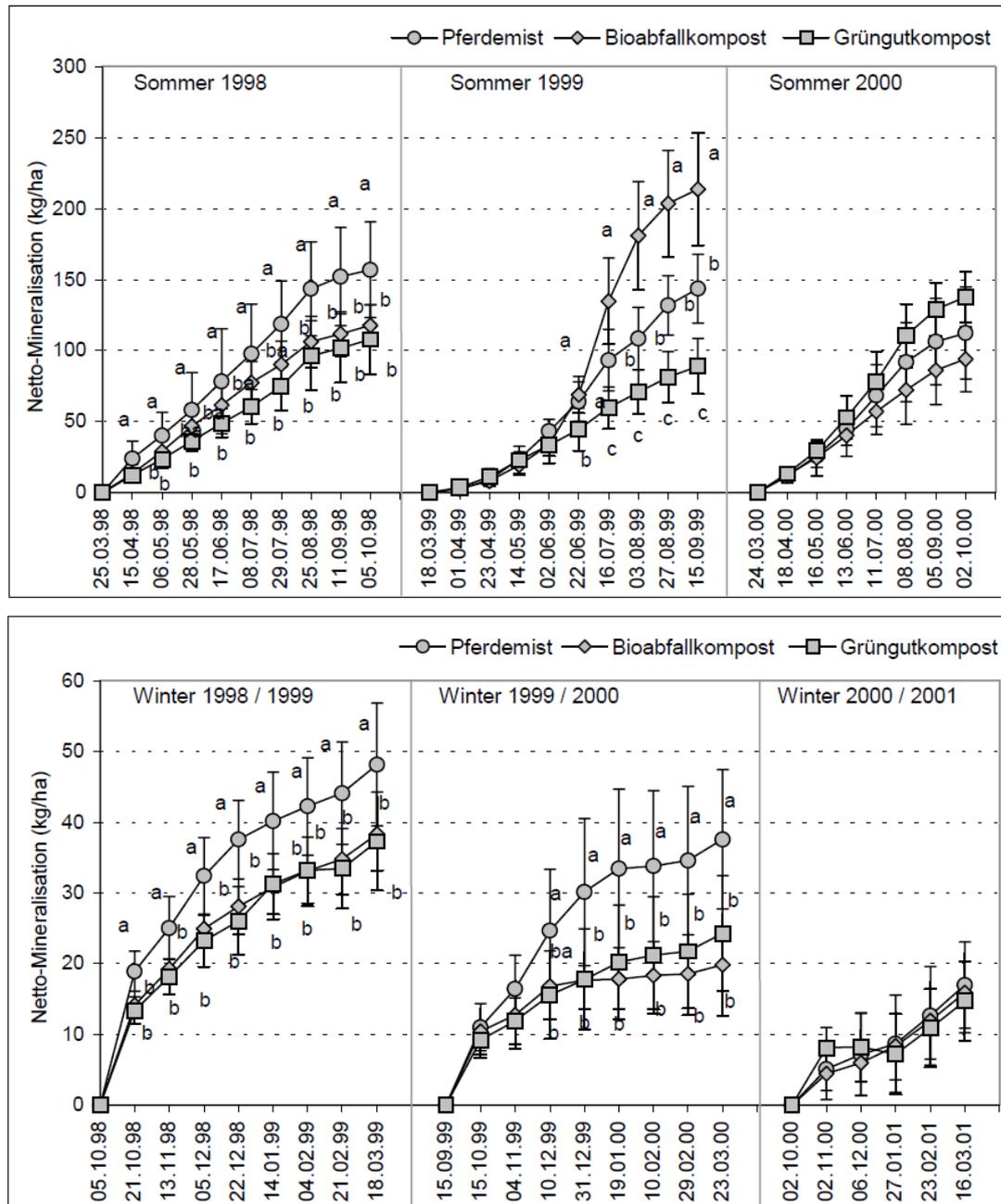
Two studies report on initial N immobilisation in the soil following application of fresh composts (stability undefined) (Ebertseder and Gutser, 2003; Husz, 1999). This immobilisation has been attributed to a specific C:N threshold in the compost. For example, if the C:N ratio of the compost is higher than 18-20, initial N immobilisation would be expected when applied to the soil (Amlinger et al., 2003).

The initial C:N ratio of the unamended soil itself has also been highlighted as influencing the tendency of mobilisation or immobilisation of N following compost application. On arable land, a C:N ratio of >14 was found to immobilise N, with < 8 releasing N, with these figures being >10.5 and <7.5 respectively for grassland (Husz, 1999). This highlights the importance of soil testing to determine readily available N levels, as part of normal good agronomic practice.

The previously discussed asparagus trial by Bloom (2003, see Section 6.2.2) involved a single spring application of horse manure, biowaste compost (Rottegrad IV, C:N 13) and fresh green waste compost (Rottegrad III, C:N 26) in 1997. The application rate of the three amendments was comparable to the quantity of carbon in the horse manure (600 dt/ha horse manure C equivalent). The soil was not cultivated again during the trial period, just annual harvesting of the asparagus shoots. An assessment of N mineralisation in the soil was made at regular intervals between 1998 and 2000, as shown in Figure 10. The N mineralisation was lower for all three amendments during the winter months, as compared to the growing season. During the summer and winter 1998, and winter 1999, the N mineralisation rate was higher for the horse manure. During the final winter, N mineralisation rate was low for all three amendments, being <18 kg N/ha. In summer 1999

the biowaste compost had the highest N mineralisation rate, and during the final summer there were no significant differences between the amendments.

**Figure 10** Cumulative net N mineralisation (kg/ha) over time. Summer (sommer) above, winter below. Error bars show standard deviation. Letters show significant difference ( $p < 0.05$ ) (Bloom, 2003). Pferdemist = horse manure, Bioabfallkompost = biowaste compost, Grüngutkompost = green waste compost



Generally, following initial N immobilisation caused by fresh composts (stability undefined), re-mineralization occurs in fertile soils, with the yield of crops with a longer growing period frequently not seriously affected. In addition, there are also fresh (stability undefined) composts, especially those that contain a large portion of N-rich biowaste, which have been observed to have a higher N release rate (>5% N release a year) than from average mature composts (Ebertseder and Gutser, 2003).

A six year trial investigated N mineralisation of green (fresh and mature) and BMW (fresh and mature) composts (stabilities not defined) on two soil types (sand and clay), at an application rate of 30 t DM/ ha every third year, with and without inorganic N. In year six, the N mineralisation with the fresh composts without additional N was 12 kg N/ha/year, being 7 kg N/ha/year for the mature composts (Dreher, 2002).

Field trials undertaken over 12 years on five sites in Germany concluded that, with an application of fresh compost (Rottegrad II) once every three years, up to 5% N is released each year from year four onwards (Kluge et al., 2008). In contrast, mature biowaste composts (stability undefined) had N release rates of 5-12% from year four onwards. The authors suggested that the lower long term N release of the fresh composts may be due to N-immobilisation.

Using 20 fresh biowaste composts over five years on one trial site, fresh composts (stability undefined) released 45 kg N /ha over a period of 98 days after application, which was significantly more N compared to a standard fertiliser control. The N mineralisation rate was observed to be significantly affected by the carbon fractions within the compost (organic, lignin and CaCl<sub>2</sub> extractable carbon fractions) (Pape and Steffens, 1998).

Due to the potential for initial N lock-up with immature compost, some authors recommend that the compost is applied well ahead of the next crop to allow field stabilisation (Composting Council, 2001). Moreover, a German report recommends applying fresh composts in the autumn (August-September) as the available N in the soil is bound by the compost and can reduce leaching during the winter, with N release occurring in the spring, supporting the growth of spring sown crops (Timmermann et al., 2003).

Although not specifically related to N lock-up, UK guidance recommends 'For crops with sensitive seeds, as with manures or NPK fertilizers, it is advisable to mix the compost with the soil at least two weeks prior to sowing in case the germination is affected by any temporary raised salt content of the soil' (WRAP, 2004b).

#### 6.4 Nitrate leaching

There are specific rules in the UK to safeguard the environment from ground and surface water pollution, such as nitrate leaching, following the application of composts, as discussed in Section 5. By tailoring compost and additional N fertiliser application rates to match the requirements of the crop (Defra, 2010), nitrate leaching should be minimised. Within NVZs the maximum compost application rate is 250 kg N/ha/year or 500 kg N/ha once every two years (Defra, 2013b), which equates to approximately 23 to 33 t FW/ha/year and 46 to 66 t FW/ha/once every two years for UK BMW and 'green' composts respectively (Defra, 2010).

Again, more information was found relating to nitrate leaching after mature compost application in field trial situations as opposed to immature composts. However, simulations using the Danish Nitrogen Simulation System showed that the effect of mature or non-mature compost on nitrate leaching was small compared to cropping, soil and other site specific effects (Gerke, 1999).

Nitrate leaching was assessed at one sandy loam site in England using porous cups over a three year period. Green/food waste compost (stability 6.3-11.5 mg CO<sub>2</sub>/g OM/day) was applied each year at a rate of 250 kg N/ha. There was no difference in nitrate leaching over winter following late summer/early autumn compost applications as compared to the control zero fertiliser treatment (ADAS, 2012).

UK trials conducted by HDRA/Garden Organic over a four year period included a range of treatments with mature green waste compost (C:N ratio of <20:1, a high proportion of carbon in the form of lignin and ammonium of <10mg/L):

- No application.
- Compost 250kg N annually, four years running.
- Compost 250kg N once.
- Compost 500kg N annually, four years running.
- Compost 500kg N once.
- Compost 750kg N annually, four years running.
- Compost 750kg N once.
- FYM 250 kg N annually.
- Poultry manure 250 kg N annually.

There was no increase in nitrate leaching (over a four year period) in any of the treatments, even at compost rates supplying 750 kgN/ha/year (HDRA, 2000).

In recent UK field trials, nitrate leaching losses were found to be low following the application of green/food waste PAS100 compost, which may be due to the low amount of readily available nitrogen in the compost (WRAP, 2013a). Moreover, this compost application did not influence the ammonium-N or phosphorus losses in the drainage water.

In a six year (1992-1997) organic farming trial in Austria, the effects of a mature (stability undefined, C:N 13-21 depending on year) biowaste and green waste compost on the yield of rye grass and soil N mineralisation were examined. The soil type was a molli-gleyic fluvisol. Compost was applied in the autumn before ploughing at the following rates (all FM):

- Treatment 1. 0 application.
- Treatment 2. 20 t/ha annually (except for 30 t/ha in year 3).
- Treatment 3. 40 t/ha in year 1, 50 t/ha in year 3 and 40 t/ha in year 5.
- Treatment 4. 60 t/ha in year 1 and 70 t/ha in year 3.
- Treatment 5. 60 t/ha in year 2 and 70 t/ha in year 3.
- Treatment 6. 70 t/ha in year 3.

With the exception of the one-off 70 t/ha treatment the total compost application over the five years was 130 t/ha. Rye yields were greater in all of the compost treatments except for the one-off 70 t/ha application which was comparable to the untreated control (Hartl et al., 2003).

Nitrate nitrogen was determined each year in the autumn 1-2 months after compost application, at 0-30, 30-60 and 60-90cm soil depths, and was observed to vary considerably due to temperature and precipitation. The control treatment ranged from 55-80 kg N/ha and the compost treatments from 60-140 kg N/ha. The lower more frequent application rates of 20 and 40 t/ha showed smaller increases in nitrate-N being comparable to the control. However at both of the 60+70 t/ha compost application rates (treatments 4 and 5), soil mineral N levels were raised on several occasions. At the 60-90cm soil depth, which is most of interest when considering ground water, the soil nitrate-N was significantly higher than the control only in treatment 4 in 1992 and 1996. The maximum increase in soil nitrate-N above the control for treatment 4 was 49 kg N/ha. The authors considered that this level was not of concern, given the greater economic efficiency of less frequent, larger applications (Hartl et al., 2003).

The effect of a mature biowaste compost (stability undefined) application compared with mineral fertilization on N leaching to the groundwater was investigated in a long-term field experiment in Austria. The plots investigated included two treatments with compost (16 and 23 t/ha/year), two treatments with inorganic N fertiliser (41 and 56 kg N/ha/year), and combined treatments (9 t compost + 56 kg N ha/year and 23 t compost + 22 kg N ha/year). N leaching to the groundwater as determined using ceramic suction cups was not increased

after 11 years of compost application, and the authors concluded that compost application does not represent a risk in terms of groundwater pollution in the short to medium term (Erhart, 2007).

A German field trial investigated the use of biowaste compost (75% kitchen and garden waste and 25% green waste including trees and shrubs) in two soil types (medium clay silt and light sandy clay) (Petersen and Stöppler-Zimmer, 1999). The two types of compost were fresh biowaste compost (Rottegrad I, composted for 12-25 days) and mature compost (Rottegrad IV-V, composted for 3 months). The control was a standard fertiliser (no details provided). The composts were applied at two rates in the spring in 1992, 1993 and 1995 (30 t/ha compost + inorganic fertiliser, and 100 t/ha compost (FM)). Crops grown were cauliflower, potatoes, beetroot and winter wheat. The composts were incorporated to 15 cm on the day or the day before sowing. Nitrate was measured at three soil depths: 0-30, 30-60 and 60-90cm.

No differences in the soil nitrate content and movement during the winter and spring were observed, for all three treatments. However, there was less total N in the fresh compost than the mature compost. When fresh compost was used, they observed higher soil N mobilisation and higher soil microbial metabolic rate than when the mature compost was used (more details on the soil microbiology of this study can be found in Section 6.6.1). The authors of the study attributed this to the higher activity of atmospheric-N-binding soil microorganisms making more N available to the soil for the fresh compost treatment.

When 300 t/ha compost in total was applied over the four year period, an increase in organic N in the clay silt soil was observed. In contrast, the inherently high permeability of the sandy soil facilitated nitrate movement down to the lower soil layers, which was seen as a reduction in nitrate in all three layers. This effect was seen for both the fresh and mature composts.

In a second trial, soils were amended once in the autumn with 100 and 250 t/ha (FM) of the same two composts in the autumn, for fuchsia production. The soil amended with mature compost at both application rates, had a higher nitrate content in the winter than soils amended with the fresh compost (Petersen and Stöppler-Zimmer, 1999).

Moreover, in the medium term (such as after one year), results from a number of trials have indicated that there is generally no difference between fresh and mature composts in terms of total N release in the soil in Germany, where standard application rates (8-10 t DM/ha) of compost are used (Amlinger et al., 2003). However, one-off high applications of 100 t DM/ha or more of mature compost, specifically on very light, sandy soils, were generally not recommended due to the potential risk of N leaching (assuming compost has a DM content of approximately 45%, this equates to 222 t FM/ha, which is much greater than permitted in NVZs in the UK – or considered acceptable within CoGAP).

## 6.5 Soil physical properties

The positive influence of long term mature compost application on soil physical properties such as bulk density, water holding capacity and aggregate stability are well documented (Diacono and Montemurro, 2010; Litterick et al., 2003; Wallace, 2009; Wallace and Carter, 2007). An Austrian review paper summarised the results from a wide range of studies on the impact of repeated compost applications on soil physical properties (Amlinger et al., 2007):

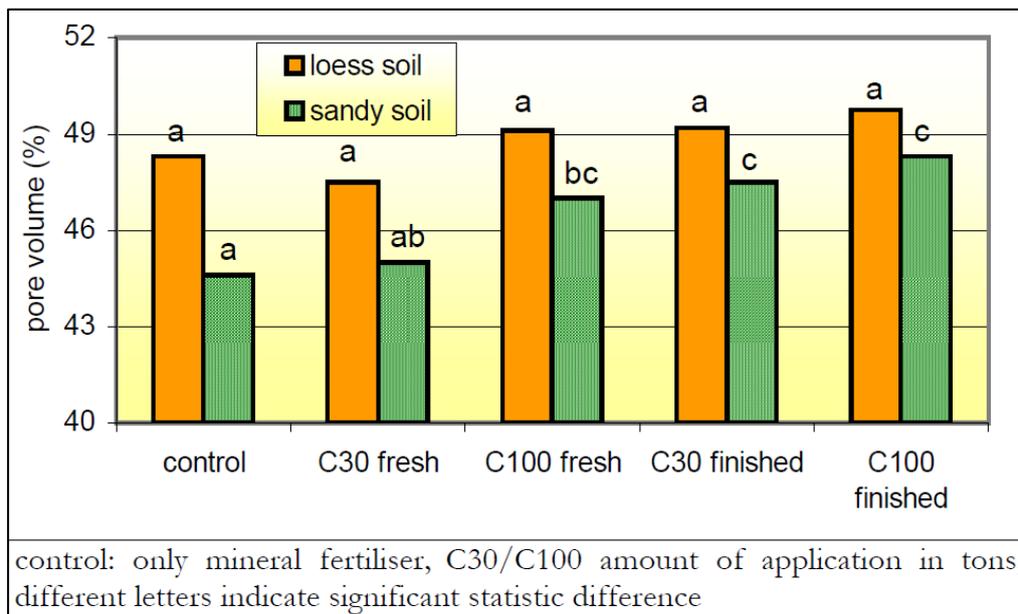
- Reduction of soil density.
- Increase of aggregate stability.
- Increase of pore volume and hydraulic conductivity.
- Increase of the proportion of macro-pores, predominantly at higher compost rates.

- Reduction of erosion processes due to higher stability of aggregates and improved infiltration.

A Defra project showed how organic matter additions, including green waste compost, livestock manures and paper crumble, affect soil properties (Bhogal et al., 2009). Green waste composts were observed to provide a very stable form of carbon to the soil, with 80% of the total organic carbon classed as stable, as compared to 30% for livestock manures and 20% for paper crumble. The composts used were very stable (all below the 16 mg CO<sub>2</sub>/g OM/d PAS100 threshold) and soil-like with an alkaline pH (7.8-8.1), low carbon content compared with farm manures and slurries and low C:N ratio (10-13:1) compared with paper crumble. The addition of 250 kg N/ha compost every year for two years on a number of sites increased soil water retention by 3-11% compared to the control. The authors provided a general observation on compost use in agriculture, that repeated rather than one-off applications of organic matter are needed to improve soil quality and resilience. This key observation that compost applications need to take place over a number of years to obtain maximum benefits for the soil and crop is highlighted by many (Lebensministerium, 2007).

German work has found that the influence of compost application on soil properties depends on the interval of application, the soil type and the maturity of the compost (Weinfurter, 2003). For example, in the aforementioned work by Petersen and Stöppler-Zimmer (1995, 1996 and 1999), soil structural properties were investigated after three applications of fresh (Rottegrad I, composted for 12-25 days) and mature (Rottegrad IV-V, composted for 3 months) biowaste compost over a four year period. In a loess soil, compost maturity and application rate did not influence aggregate stability and pore volume. However, for the sandy soil, there was an increase in these parameters compared to the standard inorganic fertiliser control with fresh compost applied at 100 t/ha, with an even greater increase for mature compost (Figure 11). However the fresh compost applied at 30t/ha was comparable to the control (Petersen, 1996; Petersen and Stöppler-Zimmer, 1999) .

**Figure 11** Pore volume at different quantities and types of compost in two soils (Petersen, 1996)



The aforementioned study by Hartmann (2002) using two biowaste composts (fresh 14 day old compost and mature 100 day old) on three soil types over two years also examined the effects of compost application on soil physical properties. The compost application rates were 40 t/ha FW (63-79 m<sup>3</sup>/ha) in year 1 and 33 t/ha FW (40-53 m<sup>3</sup>/ha) in year 2, with both

20mm and 40mm fractions of both composts used. There was also an unfertilised control and a standard NPK fertiliser treatment (nutrient concentrations not defined). The same trial was conducted at three sites with different soil types: Podsol, brown earth and para brown earth. On all three soil types, a significant increase in topsoil field capacity (assessed in terms of root accessible water content in the soil), aggregate stability and soil OM was observed after two years for all compost treatments relative to the fertilised and unfertilised controls. This increase was higher for the mature composts of both 20 and 40mm fractions than the fresh composts in all cases.

Soil organic matter was reported to be significantly increased when mature biowaste compost (Rottegrad IV, C:N 14), mature green waste compost (Rottegrad V, C:N 12) and fresh biowaste compost (Rottegrad II, C:N 14) were applied once every three years at two application rates of 20 and 40 t/ha over a 12 year period (Reinhold and Kluge, 2013).

## 6.6 Soil microorganism activity and diversity

Microorganisms (e.g. bacteria, fungi, actinomycetes and microalgae), play a key role in organic matter decomposition, nutrient cycling and other chemical transformations in soil (Murphy et al., 2007). Hence microbial activity in soil has long been used as an indicator of the quality or health of the soil and soil system, with microbial biomass and enzyme activity being the main methods of assessment (Nortcliff and Amlinger, 2001a). An increase in total microbial biomass usually occurs when soil is amended with compost or other organic amendments (Diacono and Montemurro, 2010; García-Gil et al., 2000; He et al., 2000).

The majority of publications regarding the effects of compost application on soil microorganisms focus on mature composts, with a summary of beneficial effects from a wide range of studies being (Amlinger et al., 2007):

- increase of biological activity.
- increase of microbial biomass.
- increase of dehydrogenase activity.
- in most cases increase of protease and  $\beta$ -glucosidase activity.
- in most cases increase of urease.
- Respiration: significantly enhanced.
- Mesofauna: higher numbers of species; and
- Increase of earth worm abundance.

As these amendments contain their own distinct microbial communities, the structure and metabolic diversity of the soil microbial community is affected by organic amendments, although there is a tendency for the soil microbial community to gradually revert to the original population structure over time (Litterick et al., 2003). Increasing soil microbial activity improves soil biological characteristics and overall soil health, and has been highlighted as being a beneficial key feature in soil restoration and reclamation schemes (Nortcliff and Amlinger, 2001a).

The suppressive activity of certain types of compost towards plant pathogens is now well documented (Litterick et al., 2003; WRAP, 2006b). Although there is no one specific mechanism for disease suppression following compost application, the presence of beneficial micro-organisms within the compost have been highlighted as providing competition for nutrients, producing antibodies and by parasitising pathogens (WRAP, 2006b).

The effects of fresh compost application on soil microorganisms are considered in the following section.

### 6.6.1 Fresh compost: Soil microorganism activity and diversity

In a laboratory study, the effects of composts on the activity of nine enzymes concerned with C and N cycling were determined over a period of 189 days. The two French municipal composts used were termed immature (three months old, C:N 9.7) and mature (seven months old, C:N 11.3). Mixtures of 10% and 30% (w/w) compost were combined with clay-loam soil and then incubated in 500 ml jars. Enzyme activities in all cases were higher in the compost than in the soil only controls. Enzyme activities were generally higher in the immature compost than the mature compost. Both the mature and immature composts increased the N cycling enzymes. However, at the 30% application rate, the immature compost increased both N and C groups of enzymes (Serra-Wittling, 1995).

In an 18 month laboratory study, biowaste composts were mixed with two types of soil and placed in 13 L microcosms (Leifeld, 1999). The soil types were a sandy dystric cambisol and a loamy orthic luvisol. Each microcosm was filled with soil in the lower 200 mm and a compost-soil mixture in the upper 100 mm, corresponding to an application volume (DM) of 70t/ha of immature and 65t/ha of mature compost, with the control being a soil only treatment. Carbon mineralisation and microbial biomass were assessed after 0, 2, 6, 12 and 18 months.

The carbon mineralisation rates were initially up to 100 fold higher due to compost application. Even after 18 months of incubation the rates of carbon mineralisation per day of the compost amended soils were 5 to 15 fold higher than the soil-only controls. Thus the effect of a single compost application on the carbon turnover of soils can be assumed to be effective not only in the short term, but also for prolonged time periods. A much lower carbon mineralisation rate was observed in the orthic luvisol compared to the dystric cambisol.

Moreover, the application of both composts initially increased microbial biomass significantly, being highest in the immature compost where a 14-fold increase was observed in month 0. Higher activity for both composts was observed in the sandy soil. This increase in microbial biomass was followed by a gradual decrease, and by the end of the trial the microbial biomass was the same with or without compost. The author concluded that "in soils with low biological activity such as the dystric cambisol, compost amendment significantly enhances the turnover of organic matter and thus contributes to soil fertility. Therefore, the application of compost should be aligned not only to the compost quality but also to soil characteristics like pH and texture".

A significant increase of microbial biomass was observed after field application with fresh composts (high portion of easily degradable organic matter). After approximately two months the microbial mass decreased by 60-85 % and after one year reached the level of soils without compost application (Kögel-Knabner, 1996).

In the aforementioned Petersen and Stöppler-Zimmer (1999) study, the effects of extremely fresh (Rottegrad I, composted for 12-25 days) and mature (Rottegrad IV-V, composted for four months) biowaste composts (75% kitchen and garden waste, 25% green waste) were compared with inorganic fertiliser on a range of crops. The composts were applied in years 1, 2 and 4 at two rates; 30t/ha with inorganic N, and 100t/ha with no added N. In the fourth year of the trial, the soil was sampled twice; at the end of end of July and September. The soil from the 100 t/ha fresh compost treatment had higher microbial activity (i.e. bacteria, fungi, algae, protozoa) at both sampling times than the other treatments, being statistically significant in July. In September, both the fresh and mature composts had statistically higher microbial activity than the other treatments.

As highlighted above, increasing soil microbial activity improves soil biological characteristics and overall soil health (Nortcliff and Amlinger, 2001a), and so with repeated applications of compost an improvement in soil biological functions should be observed (Diacono and Montemurro, 2010).

## 6.7 Greenhouse gas emissions during and after compost application

Many references found were concerned with compost and GHG emissions when used to cover landfill sites and so are not included here. Few references mention GHG emission measurements being undertaken following application of food waste compost of different ages, although GHG emissions during composting are considered in section 0.

In a review of the life cycle assessment of GHGs during compost application, it was observed that as well as directly adding to soil carbon, the use of compost can reduce emissions from agriculture by reducing the need for chemical fertilisers, minimising cultivations and the need for irrigation (Favoino and Hogg, 2008).

Fresh green waste was compared with green waste compost (12 weeks old, produced in windrows) in an Australian study (Queensland) (Vaughan et al., 2011). The organic wastes were mixed with a tropical Black vertisol soil (clay loam) at a rate of 3 t C/ha. For each amendment there was a 0 N and a 231 kg N/ha equivalent treatment using  $\text{NH}_4\text{NO}_3$ . There were also two control treatments with soil with or without the same quantity of N. In 28 day laboratory incubations both organic wastes reduced the mineral N levels in a subtropical soil that was high in available N, but only the mature compost significantly reduced nitrous oxide emissions compared to the controls. Compost application was suggested post-harvest to reduce leaching and gaseous N losses in subtropical horticulture in the risk period (heavy rainfall and humid conditions) between rotations.

In a further example from Queensland (Australia), a 12 month old green waste compost was compared to cattle manure and urea in a field trial growing sorghum (*Sorghum bicolor*) on a Vertisol. The amendments were spread and immediately cultivated to 10 cm depth, with the sorghum planted 16 days later. Sorghum grain yields showed no significant response to the organic amendments except for a small response to fertiliser N. The compost treatment had a lower emission of  $\text{N}_2\text{O}$  than all of the other treatments, including the untreated control. Moreover, combining the compost with the manure resulted in lower emission of  $\text{N}_2\text{O}$  than manure alone (Dalal et al., 2010).

Laboratory studies showed that 2 to 7 times more  $\text{CO}_2$  was released from immature than mature olive mill waste compost after addition to soil, but only because in the mature compost the  $\text{CO}_2$  had already been lost during the composting process (Mondini et al., 2007). Maturity was assessed by the ratios of total organic C: total organic N and humic-like acid carbon: total alkali extracted organic carbon.

In a German laboratory study there was a large variability in  $\text{CO}_2$  emission when impacts of mature (assumed to be Rottegrad IV-V) compost were compared to fresh compost (assumed to be Rottegrad II-III) following application to two soil types: high C brown earth soil and low C Kippenboden soil (Kögel-Knabner, 1996). The  $\text{CO}_2$  released was quantified by measuring the % organic C which has been mineralised to  $\text{CO}_2$  over 18 months. At 14°C and on low C Kippenboden soil the fresh compost had double the  $\text{CO}_2$  release rate (17.2%) compared to mature compost (8.7%). However, when mature compost was applied to brown earth soil,  $\text{CO}_2$  release was higher (20%), and comparable to the fresh compost (18.8%) which suggests that  $\text{CO}_2$  release is strongly affected by soil type.

## 6.8 Odour during and after compost application

As part of the considerations for the use of immature composts in agriculture and field horticulture, odour released during and after application is deemed to be of interest. However, very little information concerning odour from compost application (as opposed to manure application or the composting process itself) was found. No comparative studies regarding odour emitted during the application of composts of different maturities were obtained, although the issue was raised in passing in reviews of the need to assess maturity (Wichuk and McCartney, 2010). Further information regarding odour during composting and storage can be found in Section 2.6.

## 6.9 Weeds

Weed seeds are a potential contaminant of composts, as a potential component of green waste feedstocks, and also as contaminants being deposited onto open windrows by wind dissemination (Grundy et al., 1998). The complete composting process is generally considered sufficient to kill weed seeds, and PAS100-compliant composts must contain no viable weed seeds or other propagules (such as root fragments) (BSI, 2011). Fresh composts containing food wastes will have undertaken the required ABPR pasteurisation stage, although may not have undergone such an extensive maturation phase as PAS100 composts. Evidence regarding the time taken for neutralisation during composting is discussed below.

A German report discussed that when composting temperatures do not achieve pasteurisation then there is a risk of viable weed seeds being present, with this being observed occasionally in fresh composts (Rottegrad II-III), but never in mature composts (Rottegrad IV-V) (Deutschen Bundesstiftung Umwelt, 2003).

In a UK study, mesh bags containing seeds of eight weed species were buried in 80 l of mature BMW compost and subject to three temperatures (35, 45 and 55°C) to simulate the composting process. Seed germination and viability was assessed after 3, 21 and 84 days in the compost. Some seeds were still recoverable after 84 days at 35 and 45°C, whereas others had disintegrated. Three days at 55°C was found to be sufficient to destroy all eight weed species. The authors stated that had the weed seeds been added to immature compost the germination observed at the lower temperatures may have been lower. Thus weed growth following compost application was considered to be associated with seed contamination during compost storage rather than a lack of seed destruction during the composting process itself (Grundy et al., 1998).

The viability of 12 weed species was assessed after two and four weeks of open windrow composting of a mixture of cattle manure, wood chip and straw in a Canadian study (Tompkins et al., 1998). Weed seeds were placed in muslin bags and buried within the windrows at the start of the study. Weed seed viability was evaluated chemically using the tetrazolium test. Two weeks of composting with temperatures of at least 55°C was sufficient to kill six of the weed species, with the remaining six species having a much reduced viability of 3.5% or less compared to 100% for the uncomposted control seeds. All 12 species had 0% viability after four weeks of composting.

A German study investigated the presence of weed seeds in 41 compost samples of a range of maturities (Kluge et al., 2008). Overall, there was an average of 0.5-0.6 weed seeds / l compost. This relatively high value was caused by the inclusion of some fresh composts, which had up to 2-3 weed seeds / l. However, the incidence (viability) of weeds in trial areas where these fresh (Rottegrad II) and mature biowaste composts (stability undefined) were applied was not significantly different to the control trial areas where no compost was applied. Additional research with farmers who use compost regularly confirmed these

findings, with no evidence of compost use increasing the frequency of arable weeds found. The authors concluded that the pasteurisation phase of composting is sufficient to kill weed seeds, and hence the weed seeds observed in the composts prior to application must have been rendered unviable during the composting process.

## 7.0 Compost stability tests in the UK and further afield

A large number of tests of compost stability/maturity have been investigated over the past 25 years. They have been used for garden waste, food waste, manure, sewage sludge and various industrial wastes. Some papers deal with only one method but many are comparisons of methods. Often the focus is on the methods and only a limited number of composts are tested. Several papers review the methods (see Table 9) and such studies have formed the basis of quality standards in some countries. Much more attention has been paid to some methods than others.

In recent years WRAP has commissioned two studies focussing on stability tests which use measurements of respiration (ADAS, 2005; Wood et al., 2009) and so alternatives to respiration have mainly been examined herein. This section highlights the stability tests currently used in the EU and also other stability which have been considered by academic researchers as potential alternatives.

**Table 9** Literature assessing / reviewing stability tests

Summary	Country	Reference
Review of compost stability methods	UK	(ADAS, 2005)
Review of compost stability methods	UK	(Wood et al., 2009)
Laboratory comparison of stability methods	UK	(Cabañas-Vargas, 2005)
Review including a discussion of the relative merits of various indices of compost maturity	Spain	(Bernal M.P. et al., 1998)
Review of compost stability methods focussing on city refuse waste	Spain (Tenerife)	(Iglesias-Jimenez, 1989)
Maturity assessments by the California Compost Quality Council	USA (California)	(TMECC, 2002)
Review of compost stability methods	Canada	(Mathur et al., 1993)
Review of compost stability methods	Canada	(Wichuk and McCartney, 2010)
A review of chemical, physical and biological methods to evaluate maturity	Nigeria	(Iwegbu et al., 2006)
Laboratory comparison of stability methods on IVC composts	Iran	(Mokhtari et al., 2011)

There are few reports on compost maturity analyses using solid waste composts in developing countries and there are no standard procedures for determining compost maturity in these countries (Mokhtari et al., 2011).

Compost analyses such as C:N ratio, EC, pH, cation exchange capacity, NH<sub>4</sub> and NO<sub>3</sub> have been mentioned in many papers and often quoted as preliminary characterisation steps to other tests such as respirometry or spectrometry. They are discussed particularly in a recent review (Wichuk and McCartney, 2010), where compost C:N was highlighted as not being a suitable indicator of compost stability, with some studies observing a decrease in C:N during composting, whereas others finding fluctuations during the composting process, such as an increase during the thermophilic phase prior to a final reduction.

Cooper (2004) describes four methods commonly used to measure the rate of aerobic biological activity: The evolution of heat, oxygen uptake, carbon dioxide release, and the Solvita test kit. These methods were reviewed extensively by ADAS (ADAS, 2005) and are summarized in a recent WRAP report (Wood et al., 2009). The latter also discussed the advantages and disadvantages of a range of compost stability methods in a UK context, and provides data of the stability of a range of UK composts using a number of these methods.

## 7.1 Germination/ plant growth

A number of publications consider plant germination tests and bioassays as a method for assessing compost stability and maturity. Seed germination tests often use an extract of compost to test inhibition of seed germination, but sometimes seeds are sown in the compost itself. For plant bioassays the compost is mixed with soil or other materials (such as peat) and plants are grown for a number of weeks. Many different ways of undertaking bioassays have been examined.

Seed germination tests have been trialled on a range of plant species including cress (Cabañas-Vargas, 2005) (Brinton, 1999), radish (Makni et al., 2010), wheat (Brinton, 1999), mung bean (Gopinathan M, 2012), pakchoi (Miaomiao, 2009), lettuce and cabbage (Lee B, 2002). In some cases, researchers have found seed germination tests to be unsuitable for use as an indicator of compost maturity (Brinton, 2002). For example, in a Spanish study seed germination of cress seeds was used to assess the stability and maturity of compost tested regularly 1-18 weeks from the start of the composting process, and compared to other stability tests (SOUR and Solvita) indicated that the compost was immature, the cress bioassay did not show any phytotoxic effects, with a high percentage of germination in all ages of compost.

Ko et al (2008) developed a maturity index based on the percentage germination and the root length of radish using a compost made from 90:10 (v/v) animal manures and saw dust. This was developed alongside testing of the humic acid/fulvic acid (HA/FA) ratio and the  $\text{NH}_4/\text{NO}_3$  ratio.

A tomato bioassay, using the PAS100 method, compared three UK food and green waste composts, with two being mature (4.8 and 1.2 mg  $\text{CO}_2/\text{g VS/d}$ ) and a third immature (21.4 mg  $\text{CO}_2/\text{g VS/d}$ ). An increase in tomato plant fresh weights compared to the peat control was observed with all three composts (Tompkins, 2006).

In a tomato bioassay where a range of ratios of UK CLO and peat were trialled, a two week old CLO increased plant growth at a rate of 25% inclusion, but delayed germination and reduced plant growth when grown in 50, 75 or 100% CLO, compared to the peat control (Dimambro et al 2006). This could be due to a combination of high EC ( $2.20 \text{ mS cm}^{-1}$ ) and C:N ratio (34) in the 100% CLO, with the latter potentially causing N immobilisation.

In a bioassay using wheat and cress, a mixing ratio of compost / peat / washed sand (2:1:1) was used. An immature (21 days old, Rottegrad II,  $0.2 \text{ CO}_2 - \text{C}\% \text{ dm}$ ) IVC biosolids compost suppressed root growth as compared to mature compost (250 days old, Rottegrad V,  $0.04 \text{ CO}_2 - \text{C}\% \text{ dm}$ ) (Brinton, 2002).

Seven types and maturities of compost were used to evaluate the sensitivity of various bioassays to determine maturity (Warman, 1999). Test species were cress, radish and Chinese cabbage, exposed to compost extracts or sown in pure compost or compost with soil. Immature composts in this study were sampled from the thermophilic phase of composting whilst raw feedstock components could be clearly identified. They concluded that the bioassay tests used were not able to detect differences in maturity.

Bioassay approaches would appear to offer benefits by providing an overall estimation of any phytotoxicity problems with a compost, but there are often drawbacks. Plant bioassays are time consuming, expensive to conduct, need to be rigorously controlled and may fail to distinguish the actual cause of the toxicity – only some of which may be related to maturity (salinity, extreme pH, nitrogen availability, herbicide residues, organic acids, heavy metals etc).

## 7.2 Respiration methods

Variations on respiration methods are probably the most widely used approach to determining compost stability in many countries, by measuring oxygen uptake and/or carbon dioxide production. This can be expressed in various ways relative to fresh or dry matter, organic matter etc., in an attempt to improve standardisation. False indications of stability can result from excessively dry or wet samples, lack of inoculum, low pH, presence of toxic compounds and inadequate preparation/conditioning of the samples. Respiration methods form the basis of the current PAS 100 stability test although they have drawbacks, and WRAP has commissioned a number of recent projects to evaluate the current tests (ADAS, 2005; Wood et al., 2009). The literature has therefore not been extensively investigated again here.

Over 400 papers can be found with an academic search for 'compost maturity respiration', including review papers of respiration techniques (Gómez et al., 2006; Komilis et al., 2004; Lasaridi, 1998). Some examples of respiration methods are highlighted below. Sometimes 'pre-incubation' is used to allow microbial activity to stabilise after adjustment of MC. There is no agreement concerning the optimal temperature for respirometric assays but mostly they are performed between 30 and 40°C.

### 7.2.1 *Dynamic respiration test*

Dynamic respiration tests use a continuous supply of air throughout the assay. The difference in oxygen or carbon dioxide content is measured at the inlet and outlet of the vessel, usually over a period of several days. The dynamic respiration test (DR4) was developed as a UK requirement of mechanical biological treatment (MBT) outputs to test for biodegradability (Environment Agency, 2009) and the method is now used extensively to assess MBT bio-treatment performance. The DR4 test is similar to the current ORG 0020 (PAS100) method except with the addition of an inoculum and nutrients. For both tests a controlled air flow is passed through the sample.

### 7.2.2 *Static respiration tests – measuring oxygen uptake*

OUR (oxygen uptake rate) and SOUR (specific oxygen uptake rate) are respirometric methods based on O<sub>2</sub> consumption by microorganisms degrading a liquid suspension of the organic matter, expressed in terms of the organic matter (volatile solids) fraction of the compost. There is an EN standard for OUR (EN 16087-1). For OUR the decline in oxygen concentration in the headspace of a sealed flask containing compost is measured (Iannotti et al, 1993).

#### **OUR**

The OUR is used as a measure of compost stability in voluntary standards in a number of EU countries, with specific threshold values shown in Table 13. The British Standard BS16087-1 specifies the range of the OUR test as reaching a pressure between -2 and -5 kPa after three days, with a linear pressure decrease.

The OxiTop system is a commercial system available for carrying out the OUR test (WTW, 2006). This test is normally carried out using fresh samples equivalent to 3g or less of volatile solids over a seven day period (Cooper, 2004). This small volume of compost may result in issues of variability.

An OxiTop OUR study from the Netherlands included an in-depth assessment of a range of composts of different ages and maturities, both resulting from standard composting systems and also from a controlled laboratory system (Veeken et al., 2007). From this, a stability index was proposed, as shown in Table 10. The index is comparable with the OUR data on Table 1, where the OUR is compared to the Rottegrad stability index.

**Table 10** Proposed compost stability index using the OUR method, with actual measured data in the right hand column, both from controlled laboratory composting of biowaste (lab) and organic materials from a range of sources (s) (Veeken et al., 2007)

Stability class	Respiration rate (mmol O <sub>2</sub> kg <sup>-1</sup> OM h <sup>-1</sup> )	Respiration rate (mg O <sub>2</sub> g <sup>-1</sup> OM d <sup>-1</sup> )	Actual data Respiration rate (mmol O <sub>2</sub> kg <sup>-1</sup> OM h <sup>-1</sup> )
Very stable	<5	<4	Dark peat (s): 0.6±0.1 Fresh compost stored aerobically for 5 months (s): 3±1
Stable	5-15	4-11	Composted for 4 weeks (lab): 7±3 Composted for 2 weeks (lab): 7-15 Fresh biowaste compost (s): 10±3
Unstable	15-30	11-23	Fresh green waste compost (s): 17±3 Composted for 1 week (lab): 15-25
Very unstable	>30	>23	Fresh biowaste (s): 50-300

## SOUR

Cabañas-Vargas et al (2005) compared several methods to assess the maturity of English green waste compost. They found that SOUR reduced rapidly from an initial value of 5.89 to 0.51 mg/g O<sub>2</sub> VS/hour during the first three weeks of composting (whilst the windrow temperature was still high); there was a further gradual decline over the following 14 weeks to 0.39 mg/g O<sub>2</sub> VS/hour. The test was thus better for monitoring progress in the early stages of composting than for determining when maturity had been reached (Cabañas-Vargas, 2005).

A recent study evaluated a range of stability parameters in in-vessel composting of MSW in Iran every two days over a forty day composting period. This study deemed the compost to be mature when the SOUR had a value of less than 2 mg O<sub>2</sub>/g VS/hour (Mokhtari et al., 2011).

### 7.2.3 Static respiration tests – measuring carbon dioxide production

Equipment to measure CO<sub>2</sub> production is generally simpler and more readily available than that needed for OUR (Gómez et al., 2006).

The Solvita® test is a commercial maturity index (developed by Woods End Research Laboratory in the USA) based on measuring carbon dioxide production (ammonia emission can be measured simultaneously). It is very simple to use – plastic ‘paddles’ are pre coated with reagents that change colour.

The Solvita® test is routinely used by some growing media manufacturers and their suppliers to spot check batches of compost, as it is faster and cheaper than ORG0020. This

is a semi-quantitative method suitable for a quick field check, but not as the basis for a nationwide standard.

Some compost producers have indicated that, in addition to the routine PAS100:2011 stability measurements, they also use Solvita test kits to gain additional information to assist in management of their composting operations and to identify batches of compost that are suitable for higher value markets such as growing media (Wood et al., 2009). Training is recommended for ensuring correct usage of the equipment and interpreting the results (Zerkoune et al., 2002).

A WRAP study in 2004 tested a range of composts using the Solvita method at three independent laboratories, and observed the results to be comparable between laboratories (WRAP, 2005). The Solvita test was found to be more subtle than SOUR to indicate the degree of maturity of an English green waste compost at the later stages of composting; SOUR suggested that maturity was reached earlier in the process (Cabañas-Vargas, 2005). Further information regarding comparison studies including Solvita is summarised in a WRAP report (Wood et al., 2009).

### 7.3 Self-heating test

This is often called the Dewar self-heating test because of the name given to the vacuum flasks used. There is an EN standard method for self-heating (EN 16087-2). The test itself is simple to conduct but does take time, with maximum temperature generally recorded after 4-7 days. The method measures the temperature increase due to the heat released from the biological and chemical activity of the compost sample and so should be closely related to the results of respiration measurements. Accuracy of the method depends on the presence of suitable microorganisms and on appropriate water content – failure to heat up can give a false positive result (Brinton, 2000a).

Germany adopted self-heating as a national standard in 1984. The German Rottegrad classification of compost maturity is based on the temperature increase in compost under standardised conditions (Tontti et al., 2011). Further details regarding the Rottegrad system can be found in **Figure 1**.

### 7.4 Spectroscopy

Near infrared reflectance spectroscopy (NIRS) is a useful technique for probing bulk samples with little need for preparation. It is widely used for determining the quality of forage and food. Rather than detecting specific chemical parameters, a profile of the sample is compared with a standard 'library' with known characteristics.

Samples of sewage sludge compost were analysed by 14 conventional methods and NIRS (Albrecht et al., 2009). Although some parameters were better correlated than others, NIRS allowed rapid estimation of the maturity of the compost.

Fluorescence excitation–emission matrix (EEM) spectroscopy is extensively utilized to determine protein-like, fulvic acid-like and humic acid-like substances. Fluorescence regional integration (FRI) and parallel factor analysis (PARAFAC) can be used to analyse quantitatively data from EEM spectra.

In China, extracts of compost of various ages were scanned using a fluorescence spectrophotometer (Tang et al., 2011). Various mathematical transformations of the results were compared with temperature, germination inhibition, nitrate/ammonium ratios. They concluded that FRI is suitable to assess maturity.

A study of organic matter dynamics during in-vessel composting of an aged coal–tar contaminated soil using fluorescence excitation–emission spectroscopy showed that the fluorescence index can be applied to investigate the humification or maturation of compost (Antizar-Ladislao et al., 2006).

Fourier transform infrared spectroscopy (FT-IR) spectroscopy was used to monitor the composting process (of sewage sludge with wood chips), evaluate the degradation rate and thus determine the maturity (Grube et al., 2006). FT-IR spectroscopy is a quick and useful method to monitor the composting process; however any particular composting mixture needs preliminary studies of the spectra.

EEM and FT-IR techniques were used on composts from domestic solid wastes with a range of maturities, and seemed to produce spectra that correlated with the degree of maturity of the compost (Provenzano et al., 2001).

The detection of long wavelength emitting fluorophores (humic-like acids) was found to be linked to the progression of the composting process using fluorescence analysis (Richard et al., 2009). Using sophisticated mathematics (eg PARAFAC analysis) it is possible to interpret fluorescence EEMs to identify specific chemical components, which could be used a tool to rapidly assess compost maturity Yu et al. (2010).

In a Chinese study, fluorescence EEM spectra were used to monitor the component changes in the dissolved organic carbon (DOC) of swine manure and straw compost (Wang et al., 2013). The EEM spectra produced distinct peaks at specific wavelengths which were correlated to DOC groups, with some peaks (corresponding to protein-like substances and soluble microbial byproduct-like materials) being greater in the initial stages of composting. Other peaks increased at later composting stages, correlating to humic acid compounds followed by fulvic acid compounds. The authors suggested that fluorescence EEM with data interpretation could be used as a tool for assessing compost maturity.

A Tunisian study focussing on composting olive mill waste and manure attempted to define the parameters for product maturity by adapting chemical and spectroscopic methods during composting (Makni et al., 2010). FT-IR spectroscopy results revealed enrichment in aromatic structures and a degradation of the aliphatic and alcoholic structures, indicating stabilization of the final compost. The phytotoxic effects of olive mill wastes and animal manures was assessed by germination index (*Raphanus sativus*) indicating the absence of phytotoxicity in the majority of mature composts.

In summary, many authors have evaluated the use of various spectroscopic methods to assess compost maturity. Some of the methods are relatively new (and have been developed for other areas of environmental biology) and require much more expensive capital equipment than the chemical or biological assessments described in other sections of this review. However, they can be rapid to conduct. More work is needed to evaluate such approaches, especially under UK conditions and to relate the results to current standards for stability.

By comparing fluorescence characteristics of mature and immature composts, some of the studies discussed above suggest that the appearance of specific peaks may be an indication of the degree of humification, and hence determine compost stability. However, most of the above studies were undertaken with specific types of waste, MC, composting system etc. More work is needed to determine if these factors (and others) interfere with maturity assessment using spectroscopy.

#### 7.4.1 Humic acid fractionation

Readily available organic matter in the feedstock is converted to stable, humic compounds by the formation of fulvic acids (FA), later converted to humic acids (HA) during the composting process.

A range of tests were used to assess the maturity of ten different composts (including green waste composts) in Italy (Tomati et al., 2002). As well as all the normal chemical method and FT-IR spectra and Solid State  $^{13}\text{C}$  CP-MAS Nuclear Magnetic Resonance and genotoxicity tests on bean root cells, Sephadex gel filtration elution profiles were used to characterize the molecular weight of HA. The authors considered that this gave a better index of maturity than just the total amount of HA present.

A Dutch study on biowaste composts trialled extracting HA with NaOH, showing that total HA levels fluctuated during composting. They found that this method was not suitable as an assessment of compost maturity, and suggested that more sophisticated characterisation and quantification of available (rather than total) HA is necessary to determine the progress of composting (Veeken et al., 2000).

#### 7.5 Chemical methods: Ammonium and nitrate

Generally mature compost is associated with more nitrate and less ammonium. Levels of these forms of nitrogen can either be considered on their own or as ratio but there is little agreement as to the values that a stable compost may have.

High concentrations of  $\text{NH}_4\text{-N}$  (in the region  $1.2\text{-}2.3\text{ g kg}^{-1}$ ) in composts have been found to inhibit grass seed germination (O'Brien and Barker, 1996). Although such high concentrations of  $\text{NH}_4$  were found to decline 7-10 days after compost application, the initial phytotoxic effects can damage seeds, and plants may not recover. This may be less of an issue in the field after dilution with soil – and would be true whether ammonium were sourced from compost or inorganic fertiliser.

In an Iranian study (Mokhtari et al., 2011) it was concluded that the  $\text{NH}_4/\text{NO}_3$  ratio fluctuated too much during composting to be a good indicator of maturity; after an initial steep decline from 1.4 to 0.1 it rose again to 0.4. In contrast, a Korean study (Ko, 2008) considered that, in conjunction with a number of other parameters, a  $\text{NH}_4/\text{NO}_3$  ratio  $< 1.0$  indicated maturity in composts made from animal manure. The authors recommended that compost maturity should be assessed using two or more parameters, which could include  $\text{NH}_4/\text{NO}_3$  ratio, HA/FA ratio (humic acid/fulvic acid) and germination index (bioassay).

#### 7.6 Biochemical enzyme activity and DNA analysis

Used as a microbial activity index in soil, dehydrogenase enzyme activity has been suggested as another potential indicator of compost stability, since dehydrogenases are involved in the oxidation or fermentation of carbon sources such as glucose (Barrena et al., 2008). A study on MSW compost stability observed fluctuations of dehydrogenase activity over time, with stabilised compost having the lowest dehydrogenase activity (Mokhtari et al., 2011). However, the authors felt that dehydrogenase activity was not an ideal index of maturity, due to several peaks and troughs being observed during the composting process.

In a Greek study, the fluorescein di-acetate (FDA) enzymatic assay, which originates from soil studies, was examined as a potential compost stability test, by comparison with microbial respiration and phytotoxicity in 13 composts (Komilis et al., 2011). The net fluorescein rate

was found to correlate with all stability indices measured except for the germination index (bioassay).

Various hydrolase enzymes (protease, urease, cellulase,  $\beta$ -glucosidase) and water-soluble carbon and nitrogen (carbohydrates and phenols) have also been observed at fluctuating levels during composting (Castaldi et al., 2008). These could be used to assess maturity but they do vary depending on feedstock and other factors, so it is unlikely that they will be universally useful.

An Austrian study looked at a range of 25 composts (age 7-53 weeks), mainly composted in windrows, produced from a range of feedstocks and combinations including biowaste, tree clippings, wood bark, anaerobically digested biowaste, sewage sludge and loam. DNA analysis (PCR-DGGE) profiled the microbial community in these composts. The results showed distinctions between the bacterial communities of the composts produced from the different main inputs: biowaste and sewage sludge. There were no differences between composts of the same feedstock type but different ages. For example, in the biowaste composts, no significant difference was detectable between samples composted for 10, 35 or 52 weeks. The composition of the microbial communities was therefore attributed to the input material (Klammer et al., 2008). The authors state: "we could not produce a standard DGGE pattern that could serve for inter-laboratory comparisons. As long as there is no certainty about key indicator organisms, microbial communities can only serve as an additional parameter indicating the status of the degradation process, but cannot replace chemical parameters". Hence DNA analysis of microbial communities is not deemed suitable as a stand-alone tool to assess compost stability or feedstock materials.

### 7.7 Dissolved organic carbon

Stable compost tends to have lower levels of water-soluble organic compounds, including dissolved organic carbon (DOC), because readily available sources of nutrients (particularly those that are water-soluble) have been used up. Using a variety of composted materials (including sewage sludge and municipal waste) in Israel, DOC concentration decreased to less than 10g/kg after 14-28 days, and reached a stable level of < 4g/kg within less than 50 days of composting (Zmora-Nahum et al., 2005). As this is simple to measure, it was recommended as an indicator of compost stability, with the potential to use a simple spectrophotometric technique to measure concentration in solution (based on absorbance at 465 nm).

For a range of 'biosolids' composts in Florida (including food waste), various tests to assess compost stability were undertaken including pH, electrical conductivity, CO<sub>2</sub> evolution rate, seed germination rate and DOC (Wu et al., 2000). DOC (determined using absorbance at 420 nm) was observed to be promising as a simple but comprehensive index for compost stability and maturity.

### 7.8 Other chemical stability methods

A Spanish study recommended using chemical stability degree (SD) to assess compost stability (López et al., 2010). Determination of SD consists of two consecutive sulphuric hydrolyses applied to dry and ground samples. The first, in cold and concentrated sulphuric acid, destroys celluloses and more labile carbonaceous compounds, while the second, in hot and diluted sulphuric acid, hydrolyses the remaining polysaccharides as well as hemicelluloses and proteins. The remaining residue includes resistant organic matter and non-hydrolysable N, which are then determined via loss on ignition (for organic matter) and the Kjeldahl method (for N). This method may overcome some of the disadvantages of self-

heating or respirometric methods, as SD is not affected by certain sample conditions such as temperature, water content and particle size.

## 7.9 Summary of stability test methods

The advantages and disadvantages of the various methods described in the previous sections are summarised in Table 8. Many authors suggest that more than one type of test is necessary to draw firm conclusions regarding the stability/maturity of a particular sample. For all methods, some degree of training and quality assurance are prerequisites for accurate results.

**Table 11** Summary of key stability test methods

<b>Test type</b>	<b>Advantages</b>	<b>Disadvantages</b>
Germination/plant growth in either extracts or whole compost	Analytical equipment not needed A 'holistic' test	Takes days to weeks depending on plant species – may require glasshouse facilities Plants may be inhibited by factors (e.g. high salts, PTEs) unrelated to stability Different species may give different results
Respiration – O <sub>2</sub> uptake	UK standards relate to this method Testing kits are available	Specialised equipment may be needed Time consuming – takes a number of days depending on method Sensitivity depends on water content etc. Many variations with methods make comparisons difficult
Respiration – CO <sub>2</sub> production	Simple equipment can be used – kits also available	Time consuming – takes hours to days depending on method Sensitivity depends on water content (CO <sub>2</sub> highly water soluble) CO <sub>2</sub> can be produced by anaerobic respiration Abiotic sources and sinks of CO <sub>2</sub>
Self heating	Straightforward to set up	Long incubation, with maximum temperature usually reached within 4-5 days, with the standard suggesting up to 10 days Sensitivity depends on water content etc.
Spectroscopy	Analysis quick – multiple samples can be tested to give a more representative result	Specialised capital equipment required Calibration of results needed to relate them to standards defined using other more established methods Influence of feedstock, MC etc. on results not fully understood

Chemical methods including pH, C:N ratio, cation exchange, conductivity, nitrate:ammonium	Chemical test. No prolonged monitoring	Individual parameters may not be enough on their own
Enzyme activity e.g. dehydrogenase	Theoretical link to degradation of organic matter	Less commonly used in this context than other methods
Humic acid fractionation	Theoretical link to degradation of organic matter	Results may differ between feedstocks Specialised equipment needed
Dissolved organic carbon	Theoretical link to degradation of organic matter	Not widely used

## 8.0 EU stability tests

In this section, stability tests currently employed and recommended by compost quality assurance schemes in Europe are described. In order to identify the most commonly used compost stability test methods and country specific requirements, the most recent updates published by the European Commission (Anonymous, 2013b) (Anonymous, 2013c) were reviewed, as well as fairly recent systematic country-by-country reviews produced on behalf of the European Commission (Barth et al., 2008) and the Irish Environmental Protection Agency (Prasad and Foster, 2009).

In a parallel effort, members of the European Compost Network (ECN) as well as experts from the European Framework for Compost in Agriculture were contacted by email and/or phone. The information obtained through this method did not highlight substantial changes to the recent systematic reviews, but did provide some further details regarding limits for specific end uses.

While there are not a large number of test methods enshrined in EU regulation or compost quality assurance schemes, suggestions of compost producers (Carlsbaek and Broegger, 1999) and current method proposals (Prasad and Foster, 2009) are also described below.

For each stability test identified, the baseline stability limit for composts, and any differentiation on limit according to a range of factors was investigated. For example, any differences in baseline limit for compost use in different markets were identified, such as in agriculture, land restoration or horticulture (including field horticulture and growing media).

### 8.1 Proposed EU-wide compost stability criteria

Recently there have been in-depth discussions regarding the inclusion of a stability criterion for proposed EU-wide End-of-Waste (EoW) criteria for compost. The opinions from the Technical Working Group experts remained divided and an extensive list of pros and cons was generated (Anonymous, 2013b). In 2013 the suggestion by the Joint Research Committee (JRC) was to introduce the following EU wide stability criteria (Anonymous, 2013c):

- Oxygen update rate (OUR) of maximum 15 mmol O<sub>2</sub>/kg OM/h, measured according to method EN 16087-1, or
- Minimum Rottegrad IV measured with the self-heating test method EN 16087-2

However, in 2013 the ECN suggested that the stability limit values be changed (ECN, 2013), to the values which were finally agreed in the 2014 proposal by the JRC (JRC, 2014):

- OUR 25 mmol O<sub>2</sub>/kg organic matter/h (instead of 15 mmol O<sub>2</sub>/kg OM/h), or
- Rottegrad III (self-heating test) (instead of IV)

## 8.2 UK compost stability criteria

The current PAS100 compost stability method is the ORG 0020 test based on CO<sub>2</sub> evolution, which was first incorporated into PAS100 in 2005. The rationale and details of the development of this test are included in a WRAP report (Llewelyn, 2005). The stability limit has always been 16 mg CO<sub>2</sub>/g OM/day as a baseline for all markets. Markets can set more stringent limits, but not more relaxed limits compared with the baseline (if the compost is to continue to be accredited to the PAS100 specification). For example, an upper limit of 10 mg is recommended for compost used in growing media (WRAP, 2011c).

A WRAP review considering the PAS100 stability limit in 2009 (Wood et al., 2009) concluded that they could find no justification for reducing or increasing the baseline PAS 100:2005 stability limit of 16 mg CO<sub>2</sub>/g OM/day for compost going to any market.

## 8.3 EU country-specific stability requirements

The JRC workshop report from February 2013 (Anonymous, 2013c) contains the most up-to-date list of compost stability limits and test methods for the majority of EU members. It is noted that AT and ES do not require measurement of compost stability levels (within either regulation or quality assurance schemes), while BG, EE, FI, MT, RO and SI are listed as "N/A" (indicating that there are currently no requirements with regards to compost stability in those states). For BE, DE, DK, FR, IE, IT, LU, NL, SE and the UK, current, proposed or recommended methods are listed in the JRC report (and in the table below). Responses to emails and/or phone calls (as described in section 8.0) were obtained from the following countries: AT, BE, CZ, DE, DK, EE, GR, IE, IT, LU, NL and SE.

Below are compost stability analysis methods listed by country. It must be noted that DE, BE (Flanders only), UK and IE are the only countries in which stability limits are defined (either through regulation or quality assurance schemes). In all other countries stability levels must/can simply be declared.

Regulations for analytical methods required for composted waste (CLO) from MBT plants that is destined to be landfilled have been excluded from this review.

The Greek expert, in common with the experts from EE and CZ, replied that stability requirements did not apply in their countries.

In Denmark, the compost producer Solum recommends a combination of 2 out of 4 stability test methods. The list of recommended test methods include a self-heating test, Solvita, Oxygen uptake and C/N ratio (Carlsbaek and Broegger, 1999). Recent certificates display total oxygen uptake over four days as well as the results of a self-heating test (Solum, 2013).

For Ireland, in parallel to a voluntary upper limit defined by I.S. 441, composting plants conform to waste license conditions that permit them to carry out their activities. The licensing conditions of 14 sites are published. Licensing conditions regarding compost maturity are typically as follows (Anonymous, 2010b):

“Compost shall be deemed to be mature if it meets two of the following groups of requirements or other maturity tests as may be agreed with the Agency:

1. Respiration activity is 10mg O<sub>2</sub>/g dry matter or Dynamic Respiration Index is 1000mg O<sub>2</sub>/kg VS/h.
2. Germination of cress (*Lepidium sativum*) seeds and of radish (*Raphanus sativus*) seeds in compost must be greater than 90 percent of the germination rate of the control sample, and the growth rate of plants grown in a mixture of compost and soil must not differ more than 50 percent in comparison with the control sample.
3. Compost must be cured for at least 21 days; and  
Compost will not reheat upon standing to greater than 20°C above ambient temperature.  
Or  
Compost must be cured for a six month period and offensive odours from the compost shall be minimal for the compost to be deemed mature”.

**Table 12** Compost stability test methods listed by country

Listed here are methods defined within regulations, voluntary compost quality assurance schemes as well as optional stability test methods suggested by compost producers.

	Reference	Principle
<b>JRC-IPTS</b>	EN 16087-1:2011	Oxygen Uptake Rate
<b>JRC-IPTS</b>	EN 16087-2:2011	Self-heating test
<b>BE</b>	FPS (2013a)	Self-heating test
<b>BE</b>	FPS (2013b)	Oxygen Uptake Rate
<b>DE</b>	Kehres and Thelen-Jüngling (2006)	Self-heating test
<b>DE</b>	Kehres and Thelen-Jüngling (2006)	Respiration activity (AT4)
<b>DK</b>	Carlsbaek and Broegger (1999)	Org C/N ratio in water extract
<b>DK</b>	Carlsbaek and Broegger (1999)	Oxygen demand in 96h
<b>DK</b>	Carlsbaek and Broegger (1999)	Self-heating test
<b>DK</b>	Carlsbaek and Broegger (1999)	Solvita compost test
<b>FR</b>	Anonymous (2013c)	Biochemical fractionation of organic material (prXP U 44-162)
<b>IE</b>	IS 441	Oxygen Uptake Rate
<b>IE</b>	Anonymous (2010b)	Respiration activity (e.g. AT4)
<b>IE</b>	Anonymous (2010b)	Dynamic Respiration Index
<b>IE</b>	Anonymous (2010b)	Self-heating test
<b>IT</b>	pers. comm. 2013	Dynamic Respiration Index
<b>LU</b>	Kehres and Thelen-Jüngling (2006)	Self-heating test
<b>NL</b>	Stichting (2009)	Oxygen Uptake Rate
<b>NL</b>	Anonymous (2013c)	Self-heating test
<b>SE</b>	Anonymous (2007)	Self-heating test
<b>SE</b>	(Anonymous, 2007)	Solvita compost test
<b>UK</b>	Llewelyn (2005)	Microbial respiration rate (as CO <sub>2</sub> evolution)
<b>AT, IT, ES, SI, RO, MT, BG, FI, EE, PL, PT, CY, LV, LT, GR, SK, HU, CZ</b>		No compost stability test method requirements identified.

## 8.4 Current compost stability limits and corresponding end uses

In this section, definitions of compost stability limits are listed, together with the end use to which these limits apply.

The most stringent compost regulatory stability limits were found in BE, where OUR limits of <10 mmol O<sub>2</sub>/kg OS/h are required for all end uses. IE has a voluntary limit of <13mmol O<sub>2</sub>/kg OS/h. Most other countries do not have any stability limits defined by the regulator, however appropriate labelling (Tables 13-16) is required as part of voluntary quality assurance schemes.

Most EU countries do not distinguish between end uses in terms of compost stability. Exceptions are DE and LU, where the quality assurance scheme BGK stipulates that fresh compost is used in agriculture, mature compost in horticulture, and substrate compost is used in growing media (Table 15).

In NL, the RHP quality assurance scheme for growing media produced from composts requires a minimum stability level of <15 mmol O<sub>2</sub>/kg OS/h. (Table 13). In SE, the end use influences labelling requirements. Compost for agriculture does not require a stability statement on the compost documentation, as opposed to compost for direct or indirect use in soil mixtures in the “green area sector” (gardening and hobby cultivation), which does.

### 8.4.1 Oxygen uptake rate

**Table 13** Compost stability limits measured using oxygen uptake rate

	Uses	Stability limits
<b>BE</b>	All end uses	Federal Public Service, Health, Food chain safety and Environment (Flanders only) (FPS, 2013b):  Oxitop®: <10 mmol O <sub>2</sub> /kg OS/h (in combination with required self-heating test, maximum temperature 30°C - 50°C )
<b>IE</b>	All end uses	Voluntary standard I.S. 441: <13mmol O <sub>2</sub> /kg OS/h
<b>IE</b>	Compost as soil improver	Dynamic Respiration Index: As part of waste license condition for some composting sites (Anonymous, 2010b): ≤1000 mg O <sub>2</sub> /kg VS/h (equivalent to ≤31.25 mmol O <sub>2</sub> /kg VS/h)
<b>NL</b>	All end uses	No regulatory requirements.
<b>NL</b>	Growing media	Quality assurance scheme RHP (Stichting, 2009): Oxitop test: < 15 mmol O <sub>2</sub> /kg OS/h

### 8.4.2 Solvita Test

**Table 14** Compost stability limits measured using Solvita test

	Uses	Stability limits
<b>DK</b>	All end uses	No regulatory requirements. Producer labelling (Solum) (Solum, 2013). The stability is correlated to a colour code on the Solvita chart: Not ready: 1 Fresh: 2-3 Stable: 4-5 Very stable: 6-8

<b>SE</b>	Farming	No regulatory requirements.
<b>SE</b>	Direct or indirect use in soil mixtures in the green area sector, gardening, and hobby cultivation	Voluntary certification SPCR 152 (Anonymous, 2007): Labelling requirements: Not ready / Fresh / Stable /Very stable

### 8.4.3 Self-heating test

**Table 15** Compost stability limits measured using the self-heating test

	<b>Uses</b>	<b>Stability limits</b>
<b>BE</b>	All end uses	Federal Public Service, Health, Food chain safety and Environment (Flanders only) (FPS, 2013b): Either: Maximum temperature reached <30°C Or both of the following conditions are met: Maximum temperature reached 30°C - 50°C (in combination with Oxitop®: <10 mmol O <sub>2</sub> /kg OS/h)
<b>DE</b>	Agriculture "Fresh compost"	Voluntary scheme by BGK (Kehres and Thelen-Jüngling, 2006): Rottegrad II or III Maximum temperature reached 40.1°C - 60°C
<b>DE</b>	Horticulture "mature compost"	Voluntary scheme by BGK (Kehres and Thelen-Jüngling, 2006): Rottegrad: IV or V Maximum temperature reached ≤30°C - 40°C
<b>DE</b>	Growing media "substrate compost"	Voluntary scheme by BGK (Kehres and Thelen-Jüngling, 2006): Rottegrad: V Maximum temperature reached ≤30°C
<b>DK</b>	All end uses	No regulatory requirements.  Producer labelling (Solum) (Solum, 2013) of maximum temperature reached: Not ready: >60°C Fresh: 40.1°C - 60°C Stable: 30.1°C - 40°C Very stable: ≤30°C
<b>IE</b>	Compost as soil improver	As part of waste license condition for some composting sites (Anonymous, 2010b): Compost will not reheat upon standing to greater than 20°C above ambient temperature; and compost must be cured for at least 21 days.
<b>LU</b>	Same as DE	Same as DE, in practice composts are Rottegrad IV or better.
<b>SE</b>	Farming	No regulatory requirements.
<b>SE</b>	Direct or indirect use in soil mixtures in the green area sector, gardening, and hobby cultivation	Voluntary certification SPCR 152 (Anonymous, 2007): Method described in bgk II :10 98:4 (Rottegrad) Labelling requirements: Not ready / Fresh / Stable /Very stable

**Table 16** Compost stability limits measured using respiratory activity

	<b>Uses</b>	<b>Stability limits</b>
<b>DE</b>	Agriculture. "Fresh compost"	Voluntary scheme by BGK (Kehres and Thelen-Jüngling, 2006):  Rottegrad II or III  30.1 – 80.0 mg O <sub>2</sub> /g organic dry matter
<b>DE</b>	Horticulture. "mature compost"	Voluntary scheme by BGK (Kehres and Thelen-Jüngling, 2006):  Rottegrad: IV or V  ≤ 30.0 mg O <sub>2</sub> /g organic dry matter
<b>DE</b>	Growing media. "substrate compost"	Voluntary scheme by BGK (Kehres and Thelen-Jüngling, 2006):  Rottegrad: V  ≤ 20.0 mg O <sub>2</sub> /g organic dry matter
<b>DK</b>	All end uses.	No regulatory requirements.  Producer labelling (Solum) (Solum, 2013): Total oxygen demand in 96 hours :  Not ready: >40.0 mg O <sub>2</sub> /g OM Fresh: 40.0-16.1 mg O <sub>2</sub> /g OM Stable: 16.0-6.1 mg O <sub>2</sub> /g OM Very stable: ≤6.0 mg O <sub>2</sub> /g OM
<b>IE</b>	Compost as soil improver.	Respiration activity: As part of waste license condition for some composting sites (Anonymous, 2010b):  ≤10 mg O <sub>2</sub> /g dry matter

## 9.0 Conclusions

The project was initiated due to questions about the PAS100 stability test, which were prompted by structural changes in the composting industry since its introduction. Over the last 10 years, an increasing amount of food waste has been collected and composted through in-vessel systems, and economic pressure has resulted in shorter processing times followed by the field storage and spreading of younger, less mature composts either within or outside the PAS100 scheme.

It was therefore important to understand how processing factors and operating conditions of IVC systems may influence compost stability, whether compost stability has an impact on compost storage, and to also understand which stability tests are used in other EU countries. The main conclusions of the literature review, which concentrated on composts produced in IVC systems are summarised below, focussing on the four key research objectives.

### **Objective 1. The influence of the various processing factors and operational conditions of in-vessel systems on the stability of the resulting composts**

The majority of the literature obtained in this area used bench scale composting systems with one or two feedstocks. Hence drawing specific conclusions on the resultant compost stability for the range of UK feedstock types and composition, and operational conditions is not possible. However, where one or more processing factors are not creating the ideal composting conditions, the potential for a delay in the composting process can occur.

Wastes containing animal by-products (ABP), such as source-separated kitchen waste, must be treated according to the ABP Regulations and achieve one of the required time/temperature regimes. Managed aeration is one of the important processing factors, alongside C:N ratio, porosity, structure, moisture, etc. During the early phase of composting, volatile organic acids are produced and the pH of the waste falls. With adequate aeration, these acids are either broken down as a food source by the adaptive microorganisms or volatilised. However, with poor aeration and the development of anaerobic conditions in part or most of the waste, these acids may persist, delay composting and cause offensive smells (odours) when the material is moved and spread on fields. An excessive initial rate of increase in temperature may not encourage the establishment of the correct thermophilic microorganisms required to degrade these acids and, unless suitable aeration is provided to moderate temperatures and allow mesophilic organisms to degrade them, the composting process itself can be inhibited. In addition, in acid conditions, while ammonia is not volatilised, it may be released at a later time – such as when pH rises or when temperatures enter the thermophilic range during subsequent windrowing or storage. Feedstocks containing greater amounts of food wastes are likely to present these problems to a greater extent than feedstocks containing green waste only, since they contain greater proportions of water and readily-degradable organic matter.

Phase two of this project (site and laboratory work) therefore considered aeration (to provide oxygen and contribute to cooling the compost) in conjunction with characteristics such as feedstock type, C:N ratio, pH, ammonium (and other nutrients), microbial activity and diversity, and stability over time.

### **Objective 2. The impact of compost stability on compost storage, with an emphasis on agriculture and growing media**

No direct evidence was found in the literature to suggest the potential for run-off during in-field storage of immature composts, or pollution incidences resulting from this scenario.

### **Objective 3. The impact of compost stability on compost end use, with an emphasis on agriculture and growing media**

Across the EU, composts with a similar range of stabilities are applied to land. Agricultural and field horticultural trials have not shown significant agronomic problems when less mature composts have been used. Yield effects may be linked to changes in soil available nitrogen relating to microbial activity and the C:N ratio of the compost, or the particular soil it is applied to. Some nitrogen lock-up has been experienced but this is considered to be temporary, and effects on crop yield can be avoided by applying the compost well in advance of sowing the crop, such as in the autumn before a spring sown crop. This timing strategy would also reduce any salt induced effects on plant establishment, as can also be found from artificial fertilisers. In a field, little compost is applied in relation to the amount of soil present due to loading-rate restrictions, but in growing media compost may be used at a third or even more as part of a mixture and nitrogen lock-up effects are more readily seen unless corrective nitrogen is applied. In the field situation, composts supply both carbon, as a source of energy for soil microorganisms, and nutrients leading to increased soil microbial activity. When adequate quantities of compost are applied over time, this in turn improves soil conditions and plant growth and yield when conditions are otherwise limiting.

For the UK regulator, there is a need for a definition of 'treatment' within the Standard Rules relating to composting permits. This relates to the distinction between the soil utilising applied organic materials such as compost as energy (carbon) and for nutrients versus the soil 'treating' the materials. This is linked to the purpose of adding organic matter to soil and whether the compost has been sufficiently treated so as to be 'fit' for this purpose. A simple pH or stability test of the material might indicate its condition and likelihood of causing a pollution incident either in storage or after spreading, although lime addition may mask this.

Ground water pollution and GHG emissions are not considered to be a cause for concern if compost is used in accordance with the Standard Rules, NVZ Regulations, CoGAP and RB209.

#### **Objective 4. The range of compost stability tests in use in the UK and elsewhere – with particular reference to those required by compost specifications other than PAS100 in Europe**

A large number of tests of compost stability/maturity have been investigated over the past 25 years. They have been used for composts derived from garden waste, food waste, manure, sewage sludge and various industrial wastes. The most commonly cited tests have been highlighted, but not extensively reviewed here as this has already been undertaken in earlier WRAP reports (2005 and 2009). The two tests found to be used most often in the EU, and also proposed for EU-wide End-of-Waste stability criteria for compost are self-heating and oxygen uptake rate. Thus these two stability tests were included in Phase 2 of this project, for comparative purposes.

For the majority of EU countries, there are no legal requirements with regards to compost stability testing, except for Flanders. Specific voluntary stability limits are defined in Germany, Flanders, Ireland and the UK. The UK's PAS100 stability limit is 16 mg CO<sub>2</sub>/g OM / day, with an upper limit of 10 mg and a target of 8 CO<sub>2</sub>/g OM / day recommended for compost used in growing media (WRAP, 2011c). The only other countries which have a distinction between compost end use and stability are for a specific quality assurance scheme (BGK) in Germany and Luxembourg, with fresh compost used in agriculture, mature compost in horticulture, and substrate (very mature) compost used in growing media. This is not a legal requirement.

## 10.0 References

- ADAS 2005. Assessment of options and requirements for stability and maturity testing of composts (Issue 2). *WRAP report*. Banbury.
- ADAS 2012. The ADAS composting research project.
- AHLVA 2012. Guidance on composting and biogas (anaerobic digestion) of animal by-products in approved plants for industry Third Edition ed.: Animal Health and Veterinary Laboratories Agency.
- ALBRECHT, R., JOFFRE, R., LE PETIT, J., TERROM, G. & PERISSOL, C. 2009. Calibration of chemical and biological changes in cocomposting of biowastes using nearinfrared spectroscopy. *Environment & Science Technology*, 43, 804-811.
- AMLINGER, F., PEYR, S. & CUHLS, C. 2008. Green house gas emissions from composting and mechanical biological treatment. *Waste Management & Research*, 26, 47-60.
- AMLINGER, F., PEYR, S. & DREHER, P. 2003. Kenntnisstand zur Frage der Stickstoffaustrags in Kompostdüngungssystemen. *ZL. 34 2500/48-III/4/99*. Lebensministerium.
- AMLINGER, F., PEYR, S., GESZTI, J., DREHER, P., WEINFURTNER, K. & NORTCLIFF, S. 2007. Beneficial effects of compost application on fertility and productivity of soils. Federal Ministry for Agriculture and Forestry, Environment and Water Management.
- AN, C. J., HUANG, G. H., YAO, Y., SUN, W. & AN, K. 2012. Performance of in-vessel composting of food waste in the presence of coal ash and uric acid. *J Hazard Mater*, 203-204, 38-45.
- ANONYMOUS 2004. Landwirtschaftlicher Anwendungsversuch mit Kompost (Versuchsfeld Everlange). *Administration de l'Environnement, Division des Déchets*, Luxembourg.
- ANONYMOUS 2007. Avfall Sverige Utveckling B2009. In: AVFALL SVERIGE AB (ed.). Malmö.
- ANONYMOUS 2010a. The Environmental Permitting (England and Wales) Regulations. HM Government, The Stationery Office Limited,.
- ANONYMOUS 2010b. Waste License. Environmental Protection Agency, County Wexford, Ireland.
- ANONYMOUS 2011. The Animal By-Products (Enforcement) (England) Regulations 2011. Animal Health,.
- ANONYMOUS. 2013a. <http://www.greenmountaincompost.com/2011/03/buying-compost/>, <http://organicgrowersschool.org/1147/ask-ruth-smelly-bagged-compost-home-composting-tips/> [Online].
- ANONYMOUS 2013b. The JRC fourth and final draft EoW for composts and digestates report - Draft Final Report. IPTS: European Commission.
- ANONYMOUS 2013c. Third Workshop on End-of-Waste (EoW) criteria for Biodegradable waste subject to biological treatment (compost and digestate). Seville: EUROPEAN COMMISSION.
- ANONYMOUS. 2014. *How to use quality compost* [Online]. Available: <http://www.cgas.ie/compost/>.
- ANTÍZAR-LADISLAO, B., LOPEZ-REAL, J. & BECK, A. J. 2006. Investigation of organic matter dynamics during in-vessel composting of an aged coal-tar contaminated soil using fluorescence excitation-emission spectroscopy. *Chemosphere*, 64, 839-847.
- ASCHE, E. & STEFFENS, D. 1995. Einfluß von Bioabfallkomposten unterschiedlicher Reifegrade auf Ertrag, N-Dynamik und Bodenstruktur im Feldversuch auf neun Standorten in Hessen. *Kolloquium über die Verwertung von Komposten im Pflanzenbau*. Kassel: HLRL/HLVA.
- ASSOCIATION FOR ORGANICS RECYCLING 2010. Survey of the UK organics recycling industry 2008/09. The Association for Organics Recycling, Wellingborough.
- BARRENA, R., VÁZQUEZ, F. & SÁNCHEZ, A. 2008. Dehydrogenase activity as a method for monitoring the composting process. *Bioresource Technology*, 99, 905-908.
- BARTH, J., AMLINGER, F., FAVOINO, E., SIEBERT, S., KEHRES, B., GOTTSCHALL, R., BIEKER, M., LÖBIG, A. & BIDLINGMAIER, W. 2008. Compost production and use in the EU. Orbit ECN.

- BECK-FRIIS, B., SMÅRS, S., JÖNSSON, H. & KIRCHMANN, H. 2001. Gaseous Emissions of Carbon Dioxide, Ammonia and Nitrous Oxide from Organic Household Waste in a Compost Reactor under Different Temperature Regimes. *Journal of Agricultural Engineering Research*, 78, 423-430.
- BERNAL M.P., PAREDES, C., SÁNCHEZ-MONEDERO, M. A. & CEGARRA, J. 1998. Maturity and stability parameters of composts prepared with a wide range of organic wastes. *Bioresource Technology*, 63.
- BERNAL, M. P., NAVARRO, A. F., SANCHEZ-MONEDERO, M. A., ROIG, A. & CEGARRA, J. 1998. Influence of sewage sludge compost stability and maturity on carbon and nitrogen mineralization in soil. *Soil Biology & Biochemistry*, 30, 305-313.
- BHOGAL, A., CHAMBERS, B. J., WHITMORE, A. P. & YOUNG, I. 2009. Organic manure and crop organic carbon returns – effects on soil quality: SOIL-QC. Final report for Defra Project SP0530.
- BLANCO, M. J., ALMENDROS, G. 1997. Chemical transformation, phytotoxicity and nutrient availability in progressive composting stages of wheat straw. *Plant and Soil* 196, 15-25.
- BLOOM, P. 2003. *Einfluss von Komposten auf Stickstoffdynamik und -haushalt, Wachstum und Ertrag von Spargel (Asparagus officinalis L.)*. Universität Hannover.
- BOLDRIN, A., ANDERSEN, J. K., MØLLER, J., CHRISTENSEN, T. H. & FAVOINO, E. 2009. Composting and compost utilization: accounting of greenhouse gases and global warming contributions. *Waste Management & Research*, 27, 800-812.
- BORDER, D. 2002. Processes and plant for waste composting and other aerobic treatment. R&D technical report P1-311/TR. Environment Agency.
- BRINTON, W. F. 1998. Volatile organic acids in compost: production and odorant aspects. *Compost Science & Utilization*, 6, 75-82.
- BRINTON, W. F. 2000a. Compost quality standards and guidelines: an international view. *Final Report to the New York State Association of Recyclers, Woods End Laboratory*.
- BRINTON, W. F. 2000b. How compost maturity affects plant and root performance in container grown media. *Journal of Biodynamics*, 1-10.
- BRINTON, W. F., EVANS, E. 2002. Plant Performance in Relation to Oxygen Depletion, CO<sub>2</sub>-Rate and Volatile Fatty Acids in Container Media Composts of Varying Maturity. *Microbiology of Composting*, 335-345.
- BRINTON, W. F., TRÄNKNER, A. 1999. Compost Maturity as Expressed by Phytotoxicity and Volatile Organic Acids. *Orbit-99 Conf Proceedings, University Bauhaus Weimar*.
- BROWN, S., KRUGER, C. & SUBLER, S. 2008. Greenhouse Gas Balance for Composting Operations. *Journal of Environmental Quality*, 37, 1396–1410.
- BSI 2010. PAS 110:2010. Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials. *British Standards Institution (BSI)*. First Edition ed. London.
- BSI 2011. PAS 100:2011. Specification for composted materials. *British Standards Institution (BSI)*. Third Edition ed. London.
- BUCHANAN, M. 2002. Compost Maturity and Nitrogen Release Characteristics in Central Coast Vegetable Production. *California Integrated Waste Management Board*, 62.
- CABAÑAS-VARGAS, D. D., SÁNCHEZ-MONEDERO, M.A., URPILAINEN, S.T. , KAMILAKI, A., STENTIFORD, E.I. 2005. Assessing the stability and maturity of compost at large-scale plants. *Ingeniería*, 9, 25-30.
- CARLSBAEK, M. & BROEGGER, M. 1999. New standardised product sheet for compost in Denmark. Danish Soil Improvement / SOLUM Ltd.,
- CASTALDI, P., GARAU, G. & MELIS, P. 2008. Maturity assessment of compost from municipal solid waste through the study of enzyme activities and water-soluble fractions. *Waste Manag*, 28, 534-40.
- CHATTERJEE, N., FLURY, M., HINMAN, C. & COGGER, C. G. 2013. Chemical and physical characteristics of compost leachates. A review. Washington State University.

- CHIANG, K. Y., HUANG, H. J. & CHANG, C. N. 2007. Enhancement of heavy metal stabilization by different amendments during sewage sludge composting process. *Journal of Environmental Management*, 17, 249-256.
- CHODAK, M., BORKEN, W., LUDWIG, B., BEESE, F. 2001. Effect of temperature on the mineralization of C and N of fresh and mature compost in sandy material. *Journal of Plant Nutrition and Soil Science*, 164, 289-294.
- COMPOSTING COUNCIL 2001. Field Guide to Compost Use.
- COOPER, B. J. 2004. Stability (Biodegradability) HORIZONTAL -7 WP4.
- COOPERBAND, L. 2002. The Art and Science of Composting. A resource for farmers and compost producers. Center for Integrated Agricultural Systems: University of Wisconsin-Madison.
- CROUCH, E. 2014. Process Control in Windrow Composting: the importance of oxygen, carbon dioxide, temperature, moisture, pile configuration, and turning in minimising emissions.
- D'IMPORZANO, G., CRIVELLI, F. & ADANI, F. 2008. Biological compost stability influences odor molecules production measured by electronic nose during food-waste high-rate composting. *Science of the Total Environment*, 402, 278-284.
- DALAL, R. C., GIBSON, I., ALLEN, D. E. & MENZIES, N. W. 2010. Green waste compost reduces nitrous oxide emissions from feedlot manure applied to soil. *Agriculture, Ecosystems & Environment*, 136, 273-281.
- DAS, K. & KEENER, H. M. 1997. Numerical model for the dynamic simulation of a large scale composting system. *Transactions of the ASAE*, 40, 1179-1189.
- DAY, M., KRZYMIEN, M., SHAW, K., ZAREMBA, L., WILSON, W. R., BOTDEN, C., & THOMAS, B. 1998. An investigation of the chemical and physical changes occurring during commercial composting. *Compost Science & Utilization*, 6, 44-66.
- DEFRA 2008. Guidance on the treatment in approved composting or biogas plants of animal by-products and catering waste. London.
- DEFRA 2009a. Agronomic and Environmental Impacts of Organic Materials Applied to Agricultural Land. WQ0206. London.
- DEFRA 2009b. Protecting our Water, Soil and Air: A Code of Good Agricultural Practice for farmers, growers and land managers.
- DEFRA 2010. Fertiliser Manual (RB209). The Stationary Office.
- DEFRA 2013a. Derogations from the Animal By-Product controls under Regulation (EC) 1069/2009 and Commission Regulation (EU) 142/2011.
- DEFRA 2013b. Guidance on complying with the rules for Nitrate Vulnerable Zones in England for 2013 to 2016.
- DEFRA & AHLVA. 2014a. *Guidance: Using animal by-products at compost and biogas sites* [Online]. Available: <https://www.gov.uk/using-animal-by-products-at-compost-and-biogas-sites>.
- DEFRA & AHLVA 2014b. Using fertilisers made from processed animal by-products on farms.
- DELGADO-RODRÍGUEZ, M., RUIZ-MONTOYA, M., GIRALDEZ, I., CABEZA, I. O., LÓPEZ, R. & DÍAZ, M. J. 2010. Effect of control parameters on emitted volatile compounds in municipal solid waste and pine trimmings composting. *J Environ Sci Health A Tox Hazard Subst Environ Eng*, 45, 855-862.
- DEUTSCHEN BUNDESSTIFTUNG UMWELT 2003. Verbund-Forschungsprojekt, Abschlussbericht. Nachhaltige Kompostverwertung in der Landwirtschaft.
- DIACONO, M. & MONTEMURRO, F. 2010. Long-term effects of organic amendments on soil fertility. A review. *Agronomy for Sustainable Development*, 30, 401-422.
- DIMAMBRO, M. E., LILLYWHITE, R. D. & RAHN, C. R. 2006. Biodegradable municipal waste composts: analysis and application to agriculture. University of Warwick.
- DREHER, P. G., S., WEINFURTNER, K 2002. Auswirkungen der Anwendung von Klärschlämmen und anderen organischen Abfällen auf die Nährstoffbilanz landwirtschaftlich genutzter Böden. Abschlussbericht. FKZ.

- EBERTSEDER, T. & GUTSER, R. Nutrition potential of biowaste composts. *In: AMLINGER, F., DREHER, P., NORTCLIFF, S. & WEINFURTNER, K., eds. Applying compost - benefits and needs, 2003. Federal Ministry of Agriculture, Forestry, Environment and Water Management, Austria, and European Communities, 117-128.*
- ECN 2013. Cautious Welcome to End-of-Waste Proposals. *ECN News*, 03.
- EKLIND, Y., SUNDBERG, C., SMARS, S., STEGER, K., SUNDH, I., KIRCHMANN, H. & JONSSON, H. 2007. Carbon turnover and ammonia emissions during composting of biowaste at different temperatures. *J Environ Qual*, 36, 1512-20.
- ENVAR LTD 2010. Defra New Technologies Demonstrator Programme. Demonstration of a double-ended in-vessel composting system. Report prepared by Fowles M, Mohabuth N, Starnawska A, Webb A, Whiteley J and Border D: Waste Implementation Programme, Defra, London, UK.
- ENVIRONMENT AGENCY 2009. Guidance on monitoring of MBT and other treatment processes for the landfill allowances schemes (LATS and LAS) for England and Wales.
- ENVIRONMENT AGENCY 2010a. Chapter 4, The Environmental Permitting (England and Wales) Regulations 2010. Standard rules SR2011No1\_500t. Composting in open and closed systems.
- ENVIRONMENT AGENCY 2010b. Chapter 4, The Environmental Permitting (England and Wales) Regulations 2010. Standard rules SR2012No3. Composting in closed systems. Waste operation - capacity no more than 75 tonnes per day. 11.
- ENVIRONMENT AGENCY 2010c. Regulatory Guidance Series, No EPR 13. Defining Waste Recovery: Permanent deposit of waste on land.
- ENVIRONMENT AGENCY 2011. Guidance notes – Application for deployment (LPD1).
- ENVIRONMENT AGENCY 2012a. Chapter 4, The Environmental Permitting (England and Wales) Regulations 2010. Standard rules SR2012No7. Composting in open systems. Waste operation - no more than 75 tonnes per day.
- ENVIRONMENT AGENCY 2012b. Oxygen solubility in compost. Odour Technical Guide 3. Version 1.0.
- ENVIRONMENT AGENCY 2012c. Quality protocol. Compost. Banbury: WRAP.
- ENVIRONMENT AGENCY 2013a. Biofilter performance and operation as related to commercial composting. *Written by Frederickson, J., Boardman, C. P., Gladding, T. L., Simpson, A. E., Howell, G., Sgouridis, F.* Bristol: Environment Agency.
- ENVIRONMENT AGENCY 2013b. Chapter 4, The Environmental Permitting (England and Wales) Regulations 2010. Standard rules SR2008No16\_\_25kte. Composting in open systems.
- ENVIRONMENT AGENCY 2013c. Chapter 4, The Environmental Permitting (England and Wales) Regulations 2010. Standard rules SR2008No17\_75kte. Composting in closed systems.
- ENVIRONMENT AGENCY 2013d. Chapter 4, The Environmental Permitting (England and Wales) Regulations 2010. Standard rules SR2010No4 Mobile plant for landspreading (land treatment resulting in benefit to agriculture or ecological improvement).
- ENVIRONMENT AGENCY 2013e. Chapter 4, The Environmental Permitting (England and Wales) Regulations 2010. Standard rules SR2010No14\_500t. Composting in open and closed systems.
- ENVIRONMENT AGENCY 2013f. How to comply with your landspreading permit. TGN EPR 8.01. Version 2
- ENVIRONMENT AGENCY. 2014a. *Guidance. Waste exemption: U10 spreading waste to benefit agricultural land* [Online]. Available: <https://www.gov.uk/waste-exemption-u10-spreading-waste-to-benefit-agricultural-land> [Accessed 2/6/14].
- ENVIRONMENT AGENCY. 2014b. *Waste exemption: T23 aerobic composting and associated prior treatment. Published 28 April 2014* [Online]. Available: <https://www.gov.uk/waste-exemption-t23-aerobic-composting-and-associated-prior-treatment> [Accessed 29/05/2014].

- ENVIRONMENT AGENCY. 2014c. *Waste exemption: U10 spreading waste to benefit agricultural land* [Online]. Available: <https://www.gov.uk/waste-exemption-u10-spreading-waste-to-benefit-agricultural-land> [Accessed 29/05/2014].
- ENVIRONMENT AGENCY. 2014d. *Waste exemption: U11 spreading waste to benefit non-agricultural land* [Online]. Available: <https://www.gov.uk/waste-exemption-u11-spreading-waste-to-benefit-non-agricultural-land> [Accessed 29/05/2014].
- ENVIRONMENT AGENCY & FMA. 2012. Protecting the environment. The essentials for storing solid and liquid fertilisers.
- ERHART, E., FEICHTINGER, F., & HARTL, W. 2007. Nitrogen leaching losses under crops fertilized with biowaste compost compared with mineral fertilization. *Journal of Plant Nutrition and Soil Science*, 170, 608-614.
- EUROPEAN UNION 2009. Regulation (EC) No 1069/2009 of the European Parliament and of the Council of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 (Animal by-products Regulation).
- FAVOINO, E. & HOGG, D. 2008. The potential role of compost in reducing greenhouse gases. *Waste Management and Research*, 26, 61-69.
- FISCHER, K. & SAKRABANI, R. 2011. Greenhouse Gas Impacts of Biowaste Management. WR0210. London: Defra.
- FMA 1998. Code of practice for the prevention of water pollution from the storage and handling of solid fertilisers.
- FMA. 1998. Code of practice for the prevention of water pollution from the storage and handling of solid fertilisers.
- FONT, X., ARTOLA, A. & SÁNCHEZ, A. 2011. Detection, Composition and Treatment of Volatile Organic Compounds from Waste Treatment Plants. *Sensors (Basel)*.
- FOWLES, M., MOHABUTH, N., STARNAWSKA, N., WEBB, A., WHITELEY, J., BORDER, D. 2010. Demonstration of a double-ended in-vessel composting system. *Defra New Technologies Demonstrator Programme*. .
- FPS 2013a. CMA/2/IV/22 - Rijpheidsgraad (zelfverhittingstest). Compendium voor monsterneming en analyse in uitvoering van het Materialendecreet en het Bodemsaneringsdecreet.
- FPS 2013b. CMA/2/IV/25 - Stabiliteit met gesloten respirometer.
- FUCHS, J. G., BAIER, U., BERNER, A., MAYER, J., SCHLEISS, K. ., Effects of digestate on the environment and on plant production - results of a research project. ECN/ORBIT e.V. Workshop. The future for Anaerobic Digestion of Organic Waste in Europe, 2008a FiBL-Nürnberg. 11.
- FUCHS, J. G., BERNER, A., MAYER, J., SCHLEISS, K. , 2008b. Einfluss von Komposten und Gärgut auf die Bodenfruchtbarkeit. *Forschungsinstitut für biologischen Landbau (FiBL), AgrarForschung*, 15, 276-281.
- GAJALAKSHMI, S. & ABBASI, S. A. 2008. Solid Waste Management by Composting: State of the Art. *Critical Reviews in Environmental Science and Technology*, 38, 311-400.
- GARCÍA-GIL, J. C., PLAZA, C., SOLER-ROVIRA, P. & POLO, A. 2000. Long-term effects of municipal solid waste compost application on soil enzyme activities and microbial biomass. *Soil Biology and Biochemistry*, 32, 1907-1913.
- GARCIA-GOMEZ, A., BERNAL, M. P. & ROIG, A. 2003. Carbon mineralisation and plant growth in soil amended with compost samples at different degrees of maturity. *Waste Management & Research*, 21, 161-171.
- GERKE, H., H., ARNING, M., STÖPPLER-ZIMMER, H. 1999. Modeling long-term compost application effects on nitrate leaching. *Plant and Soil* 213, 75-92.
- GÓMEZ, R. B., FELICITAS, L. V. & SANCHEZ, F. A. 2006. The use of respiration indices in the composting process: a review. *Waste Management and Research*, 24, 37-48.
- GOPINATHAN M, T. M. 2012. Evaluation of Phytotoxicity for Compost from Organic Fraction of Municipal Solid Waste and Paper & Pulp Mill Sludge. *Environmental Research, Engineering and Management*, 1, 47-51.

- GRÖLL, K. 2007. Application Trials with Biowaste Compost in Grand Duchy Luxembourg. Ingenieurgemeinschaft Luxemburg.
- GRUBE, M., LIN, J. G., LEE, P. H. & KOKOREVICH, S. 2006. Evaluation of sewage sludge-based compost by FT-IR spectroscopy. *Geoderma*, 130, 324-333.
- GRUNDY, A. C., GREEN, J. M. & LENNARTSSON, M. 1998. The Effect of Temperature on the Viability Of Weed Seeds in Compost. *Compost Science & Utilization* 6, 26-33.
- GUO, R., LI, G., JIANG, T., SCHUCHARDT, F., CHEN, T., ZHAO, Y. & SHEN, Y. 2012. Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost. *Bioresource Technology*, 112, 171-8.
- HARTL, W., PUTZ, B. & ERHART, E. 2003. Influence of rates and timing of biowaste compost application on rye yield and soil nitrate levels. *European Journal of Soil Biology*, 39, 129-139.
- HARTMANN, R. 2002. *Studien zur standortgerechten Kompostanwendung auf drei pedologisch unterschiedlichen, landwirtschaftlich genutzten Flächen der Weshäuser Geest, Niedersachsen*. Universität Bremen.
- HAUG, R. T. 1993. *The Practical Handbook of Compost Engineering*, Florida, Lewis Publishers.
- HDRA 2000. Final report: Researching the use of compost in agriculture *Environmental Body Project 948082.001*.
- HE, Z. L., ALVA, A. K., CALVERT, D. V., LI, Y. C., STOFELLA, P. J. & BANKS, D. J. 2000. Nutrient availability and changes in microbial biomass of organic amendments during field incubation. *Compost Science and Utilization* 8, 293-302.
- HUSZ, G.-S. 1999. Stickstoffdynamik in Abhängigkeit von ökologischen Rahmenbedingungen insbesondere Humushaushalt. In: AMLINGER, F. & GÖTZ, B. (eds.) *Runder Tisch Kompost - RTK*. Wien.
- IGD. 2012. *Composting* [Online]. Available: [www.igd.com/our-expertise/Supply-chain/WastePrevention/15923/Composting/](http://www.igd.com/our-expertise/Supply-chain/WastePrevention/15923/Composting/) 2014].
- IGLESIAS-JIMENEZ, E., ALVAREZ, C.E. 1993. Apparent availability of nitrogen in composted municipal refuse. *Biology and Fertility of Soils*, 16, 313-318.
- IGLESIAS-JIMENEZ, E., GARCIA, V.P. 1989. Evaluation of city refuse compost maturity: A review. *Biological Wastes* 27, 115-142.
- IMMIK, E. & BAAB, G. 2005. Kompost - Kompostausbringung. In: IMMIK, E. (ed.) *Einsatz von Bioabfallkomposten im Obstbau*. Oppenheim: DLR Rheinpfalz.
- IWEGBU, C. M. A., EGUN, A. C., EMUH, F. N. & ISIRIMAH, N. O. 2006. Compost Maturity Evaluation and its Significance to Agriculture. *Pakistan Journal of Biological Sciences*, 9, 2933.
- JACOBS, J., SAUER, N. & GILBERT, J. 2007. An industry guide for the prevention and control of odours at biowaste processing facilities. Wallingborough: The Composting Association and the Environment Agency.
- JRC 2014. End-of-waste criteria for biodegradable waste subjected to biological treatment (compost & digestate): Technical proposals. European Commission Joint Research Centre.
- KASTEN, J. 1999. *Ökonomische Aspekte der dezentralen Dreiecksmietenkompostierung von Bioabfällen aus Haushalten in landwirtschaftlichen Low-Tech-Anlagen und der landbaulichen Kompostverwertung*. Georg-August-Universität
- KEHRES, B. & THELEN-JÜNGLING, M. 2006. Methodenbuch zur Analyse organischer Düngemittel, Bodenverbesserungsmittel und Substrate. Köln: Bundesgütegemeinschaft Kompost e.V.
- KLAMMER, S., KNAPP, B., INSAM, H., DELL'ABATE, M. T. & ROS, M. 2008. Bacterial community patterns and thermal analyses of composts of various origins. *Waste Management & Research*, 26, 173-187.
- KLUGE, R., DELLER, B., FLAIG, H., SCHULZ, E., REINHOLD, J. & HABER, N. 2008. Nachhaltige Kompostanwendung in der Landwirtschaft. In: LTZ, L. T. A. (ed.) *Thema*

*des Abschlussprojektes Kompost-Anwendungsversuche Baden-Württemberg, Abschlussbericht April 2008.*

- KO, H. J., KIM, K. Y., KIM, H. T., KIM, C. N., UMEDA, M. 2008. Evaluation of maturity parameters and heavy metal contents in composts made from animal manure. *Waste Management*, 28, 813-821.
- KÖGEL-KNABNER, I., LEIFELD, J., SIEBERT, S., 1996. Humifizierungsprozesse von Kompost nach Ausbringung auf den Boden. In: STEGMANN, R. (ed.) *Neue Techniken der Kompostierung*. Economica Verlag, Bonn, Hamburger Berichte.
- KOKKORA, M. I. 2008. *Biowaste and vegetable waste compost application to agriculture*. PhD, Cranfield University.
- KOMILIS, D., KONTOU, I. & NTOUGIAS, S. 2011. A modified static respiration assay and its relationship with an enzymatic test to assess compost stability and maturity. *Bioresource Technology*, 102, 5863–5872.
- KOMILIS, D. P., HAM, R. K. & PARK, J. K. 2004. Emission of volatile organic compounds during composting of municipal solid wastes. *Water Research*, 38, 1707-1714.
- KÖRNER, I. 2009. *Stickstoffhaushalt bei der Kompostierung*. PhD, Technische Universität Hamburg-Harburg.
- KUMAR, M., OU, Y.-L. & LIN, J.-G. 2010. Co-composting of green waste and food waste at low C/N ratio. *Waste Management*, 30, 602-609.
- LASARIDI, K. E. 1998. *Compost stability: a comparative evaluation of respirometric techniques*. PhD Thesis, University of Leeds. UK.
- LEBENSMINISTERIUM 2007. Beneficial Effects of Compost Application on Fertility and Productivity of Soils.
- LEE B, K. P. J., CHANG K W 2002. Evaluation of stability of compost prepared with Korean food wastes. *Soil Science and Plant Nutrition*, 48, 1-8.
- LEIFELD, J., SIEBERT, S., KÖGEL-KNABNER, I., 1999. Effects of biowaste compost amendment on soil microbial biomass and specific carbon turnover in agricultural soils. In: BILDINGMAIER, W., DE BERTOLDI, M., DIAZ, L.F., PAPADIMITRIOU, E.K. (ed.) *ORBIT - Organic Recovery and Biological Treatment. Proceedings of the International Conference ORBIT 99 on Biological Treatment of Waste and the Environment. Part II: Perspectives on Legislation and Policy, Product Quality and Use, Biodegradable Polymers, and Environmental and Health Impacts*. Weimar.
- LI, S., HUANG, G.H., AN, C.J., YU, H. 2013. Effect of different buffer agents on in-vessel composting of food waste: performance analysis and comparative study. *Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering*, 48, 772-780.
- LILLYWHITE, R. D., DIMAMBRO, M. E. & RAHN, C. R. 2009. Effect of Five Municipal Waste Derived Composts on a Cereal Crop. *Compost Science & Utilization*, 17, 173-179.
- LITTERICK, A., HARRIER, L., WALLACE, P., WATSON, C. A. & WOOD, M. 2003. Effects of composting manures and other organic wastes on soil processes and pest and disease interactions. Defra Report.
- LLEWELYN, R. H. 2005. Development of standard laboratory based test to measure compost stability. *The Waste & Resources Action Programme Project ORG0020*.
- LÓPEZ, M., HUERTA-PUJOL, O., MARTÍNEZ-FARRÉ, F. X. & SOLIVA, M. 2010. Approaching compost stability from Klason lignin modified method: Chemical stability degree for OM and N quality assessment. *Resources, Conservation and Recycling*, 55, 171-181.
- LU, S. G., IMAI, T., LI, H. F., UKITA, M., SEKINE, M. & HIGUCHI, T. 2001. Effect of enforced aeration on in-vessel food waste composting. *Environmental technology*, 22, 1177-1182.
- MAFF 1999. The environmental implication of manure use in organic farming systems, OF0161.
- MAKAN, A., ASSOBEI, O. & MOUNTADAR, M. 2013. Effect of initial moisture content on the in-vessel composting under air pressure of organic fraction of municipal solid waste in Morocco. *Iranian Journal of Environmental Health Science & Engineering*, 10, 3.

- MAKNI, H., AYED, L., BEN KHEDHER, M. & BAKHROUF, A. 2010. Evaluation of the maturity of organic waste composts. *Waste Manag Res*, 28, 489-95.
- MARTINS, O. 1992. Loss of nitrogenous compounds during composting of animal wastes. *Bioresource Technology*, 42, 103-111.
- MATHUR, S. P., OWEN, G., DINEL, H. & SCHNITZER, M. 1993. Determination of Compost Biomaturity. I. Literature Review. *Biological Agriculture & Horticulture* 10.
- MEYER, D. 2009. *Optimale Nutzung heizwertreicher Fraktionen in der Kompostierung - Eine Betrachtung nach energetischen und ökologischen Gesichtspunkten*. Bauhaus-Universität.
- MIAOMIAO, H., WENHONG, L., XINQIANG, L., DONGLEI, W., GUANGMING, T. 2009. Effect of composting process on phytotoxicity and speciation of copper, zinc and lead in sewage sludge and swine manure. *Waste Management*, 29, 590-597.
- MICHEL, F. C., FORNEY, L. J., HUANG, A. J.-F., DREW, S., CZUPRENSKI, M., LINDEBERG, J. D. & REDDY, C. A. 1996. Effects of Turning Frequency, Leaves to Grass Mix Ratio, and Windrow vs. Pile Configuration on the Composting of Yard Trimmings. *Compost Science & Utilization*, 4, 126-143.
- MICHEL, F. C. & REDDY, C. A. 1998. Effect of Oxygenation Level on Yard Trimmings Composting Rate, Odor Production, and Compost Quality in Bench-Scale Reactors. *Compost Science & Utilization*, 6, 6-14.
- MILLER, J. H. & JONES, N. 1995. Organic and compost-based growing media for tree seedling nurseries. *World Bank Technical Paper*. Washington D. C.: The World Bank.
- MOHEE, R. & MUDHOO, A. 2005. Analysis of the physical properties of an in-vessel composting matrix. *Powder Technology*, 155, 92-99.
- MOKHTARI, M., NIKAEEN, M., AMIN, M. M., BINA, B. & HASANZADEH, A. 2011. Evaluation of stability parameters in in-vessel composting of municipal solid waste. *Iran. J. Environ. Health. Sci. Eng* 8, 325-332.
- MONDINI, C., CAYUELA, M. L., SINICCO, T., CORDARO, F., ROIG, A. & SÁNCHEZ-MONEDERO, M. A. 2007. Greenhouse gas emissions and carbon sink capacity of amended soils evaluated under laboratory conditions. *Soil Biology and Biochemistry*, 39, 1366-1374.
- MURPHY, D. V., STOCKDALE, E. A., BROOKES, P. C. & GOULDING, K. W. T. 2007. Impact of microorganisms on chemical transformation in soil. *Soil Biological Fertility*. Netherlands: Springer
- MURPHY, J. D. & POWER, N. M. 2006. A technical, economic and environmental comparison of composting and anaerobic digestion of biodegradable municipal waste. *J Environ Sci Health A Tox Hazard Subst Environ Eng*, 41, 865-79.
- NICOLETTI, R. & TAYLOR, J. 2005. Comparing positive and negative aeration at in-vessel facility. *Bicycle*.
- NORTCLIFF, S. & AMLINGER, F. Compost impacts on soil biology and anti-phytopathogenic potential. Applying composts. Benefits and needs, 2001a Brussels. 147-152.
- NORTCLIFF, S. & AMLINGER, F. 2001b. Session 1. N and C pools - what is their fate in compost amended systems? *Applying composts. Benefits and needs*. Brussels.
- O'BRIEN, T. A. & BARKER, A. V. 1996. Evaluation of ammonium and soluble salts on grass sod production in compost 1. Addition of ammonium or nitrate salts. *Communications in Soil Science and Plant Analysis*, 27, 57-76.
- OHIO EPA 1999. Odor management practices for composting facilities. State of Ohio Environmental Protection Agency.
- OZORES-HAMPTON M, O. T. A., STOFFELLA P J, FITZPATRICK G 2002. Immature Compost Suppresses Weed Growth Under Greenhouse Conditions. *Compost Science & Utilization* 10, 105-113.
- PAGANS, E., BARRENA, R., FONT, X. & SANCHEZ, A. 2006. Ammonia emissions from the composting of different organic wastes. Dependency on process temperature. *Chemosphere*, 62, 1534-42.
- PAIN, B. & BUSS, J. 2002. Silage decisions factsheet. Applying manure. BGS and EBLEX.

- PAPE, H. & STEFFENS, D. 1998. Schätzung der N-Nachlieferung von Bioabfallkomposten im Labor- und Feldversuch. *VDLUFA Kongressband, Schriftenreihe*, 49, 147-150.
- PETERSEN, U. & STÖPPLER-ZIMMER, H. 1999. Orientierende Felversuche zur Anwendung von Biokomposten unterschiedlichen Rottegrades. *In: AMLINGER, F. & GÖTZ, B. (eds.) Runder Tisch Kompost - RTK*. Wien.
- PETERSEN, U., STÖPPLER-ZIMMER, H., 1995. Frisch- oder Fertigungskompost - Pflanzenbauliche Vor- und Nachteile. Was hat die Praxis zu erwarten? *In: K. WIEMER, M. K. (ed.) Biologische Abfallbehandlung III, M.I.C. . Baeza-Verlag, Witzenhausen, Germany.*
- PETERSEN, U., STÖPPLER-ZIMMER, H., 1996. Anwendungsversuche mit Komposten unterschiedlichen Rottegrades. *Technische Universität Hamburg-Harburg, Abfallwirtschaft, Neue Techniken der Kompostierung, Dokumentation des 2. BMBF-Statusseminars "Neue Techniken der Kompostierung"*. Hamburg: Economica Verlag, Bonn, Hamburger Berichte
- PRASAD, M. & FOSTER, P. 2009. Development of an Industry-Led Quality Standard for Source-Separated Biodegradable Material Derived Compost. *EPA STRIVE Programme 2007–2013*. Wexford, Ireland: The Environmental Protection Agency (EPA).
- PROVENZANO, M. R., DE OLIVEIRA, S. C., SANTIAGO-SILVA, M. R. & SENESI, N. 2001. Assessment of maturity degree of composts from domestic solid wastes by fluorescence and fourier transform infrared spectroscopies. *Journal of Agricultural Food Chemistry*, 49, 5874-5879.
- RECYCLED ORGANICS UNIT 2007. Greenhouse Gas Emissions from Composting Facilities. Second edition ed.: Recycled Organics Unit and NSW Department of Environment and Conservation.
- RICHARD, C., GUYOT, G., TRUBETSKAYA, O., TRUBETSKOJ, O., GRIGATTI, M. & CAVANI, L. 2009. Fluorescence analysis of humic-like substances extracted from composts: influence of composting time and fractionation. *Environ. Chem. Lett.*, 7, 61-65.
- RICHARDSON, S. & RAINBOW, A. 2005. Storage trials of retail growing media products containing composted green materials. WRAP report ORG0019.
- ROGASIK, J. & REINHOLD, J. 2006. Organische Düngung. Grundlagen der guten fachlichen praxis. *Kompost für die Landwirtschaft*. Köln: Bundesgütegemeinschaft Kompost e.V.
- RPA & DEFRA 2013. The guide to cross compliance in England 2014. Version 1.
- RYCKEBOER, J., MERGAERT, J., VAES, K., KLAMMER, S., DE CLERCQ, D., COOSEMANS, J., SWINGS, J. 2003. A survey of bacteria and fungi occurring during composting and self-heating processes. *Annals of Microbiology*, 53, 349-410.
- SAUER, N. & CROUCH, E. 2013. Measuring oxygen in compost. *Biocycle*, 12, 23-26.
- SAVEYN, H. & EDER, P. 2014. End-of-waste criteria for biodegradable waste subjected to biological treatment (compost & digestate): Technical proposals. European Commission Joint Research Centre.
- SCAGLIA, B., ORZI, V., ARTOLA, A., FONT, X., DAVOLI, E., SANCHEZ, A. & ADANI, F. 2011. Odours and volatile organic compounds emitted from municipal solid waste at different stage of decomposition and relationship with biological stability. *Bioresour Technol*, 102, 4638-45.
- SCHERER, H. W., WERNER, W. & NEUMAN, A. 1996. N-Nachlieferung und N-Immobilisierung von Komposten mit unterschiedlichem Ausgangsmaterial, Rottegrad und C/N-Verhältnis.
- SERRA-WITTLING, C., HOUOT, S., BARRIUSO, E. 1995. Soil enzymatic response to addition of municipal solid-waste compost. *Biology and Fertility of Soils* 20, 226-236.
- SHORT, J. & WALLACE, P. 2004. Comparison of Enclosed Composting Systems. *For The Norlands Foundation*. Enviro.
- SMÅRS, S., GUSTAFSSON, L., BECK-FRIIS, B. & JÖNSSON, H. 2002. Improvement of the composting time for household waste during an initial low pH phase by mesophilic temperature control. *Bioresource Technology*, 84, 237-241.

- SMET, E., VAN LANGENHOVE, H. & DE BO, I. 1999. The emission of volatile compounds during the aerobic and the combined anaerobic/aerobic composting of biowaste. *Atmospheric Environment* 33, 1295–1303.
- SOLUM 2013. D-Gro A Kompostdeklaration for vinteren 2012/2013. Solum Roskilde A/S.
- STEGER, K., EKLIND, Y., OLSSON, J. & SUNDH, I. 2005. Microbial community growth and utilization of carbon constituents during thermophilic composting at different oxygen levels. *Microb Ecol*, 50, 163-71.
- STEINER, C., DAS, K. C., MELEAR, N., & LAKLY, D. 2010. Reducing Nitrogen Loss during Poultry Litter Composting Using Biochar *Journal of Environmental Quality*, 39, 1236-1242.
- STICHTING 2009. Productblad MOD 430 RHP Compost. *In: RHP (ed.)*.
- STROM, P. F. 1985. Effect of temperature on bacterial species diversity in thermophilic solid waste composting. *Applied Environmental Microbiology*, 50, 899-905.
- SUNDBERG, C., FRANKE-WHITTLE, I. H., KAUPPI, S., YU, D., ROMANTSCHUK, M., INSAM, H., & JÖNSSON, H. 2011. Characterisation of source-separated household waste intended for composting. *Bioresource technology*, 102, 2859-2867.
- SUNDBERG, C., SMARS, S. & JONSSON, H. 2004. Low pH as an inhibiting factor in the transition from mesophilic to thermophilic phase in composting. *Bioresour Technol*, 95, 145-50.
- SUNDBERG, C., YU, D., FRANKE-WHITTLE, I., KAUPPI, S., SMARS, S., INSAM, H., ROMANTSCHUK, M. & JONSSON, H. 2013. Effects of pH and microbial composition on odour in food waste composting. *Waste Manag*, 33, 204-11.
- TANG, Z., YU, G., LIU, D., XU, D. & SHEN, Q. 2011. Different analysis techniques for fluorescence excitation-emission matrix spectroscopy to assess compost maturity. *Chemosphere*, 82, 1202-8.
- THE COMPOSTING ASSOCIATION 2004. A Guide to In-Vessel Composting: Plus a Directory of System. (2nd Edition) Wellingborough, Northamptonshire, UK.
- THE COMPOSTING ASSOCIATION 2007. An industry guide for the prevention and control of odours at biowaste processing facilities. Wellingborough.
- THOMPSON, A. G., WAGNER-RIDDLE, C. & FLEMING, R. 2004. Emissions of N<sub>2</sub>O and CH<sub>4</sub> during the Composting of Liquid Swine Manure. *Environmental Monitoring and Assessment*, 91, 87-104.
- TIMMERMANN, F., KLUGE, R., BOLDUAN, G. R., MOKRY, M., JANNING, S., GROSSKOPF, W., SCHREIBER, A., ZIEGLER, W. & KOSCIELNIAK, N. 2003. Nachhaltige Kompostverwertung in der Landwirtschaft. *Praxisbezogene Anwendungsrichtlinien sowie Vermarktungskonzepte für den nachhaltigen Einsatz von gütegesicherten Komposten im landwirtschaftlichen Pflanzenbau*. Gütegemeinschaft Kompost Region Süd e.V, Leonberg.
- TMECC 2002. Test Methods for the Examination of Composting and Compost. US Composting Council, Bethesda, MD.
- TOMATI, U., BELARDINELLI, M., ANDREU, M., GALLI, E., CAPITANI, D., PROIETTI, N. & DE SIMONE, C. 2002. Evaluation of commercial compost quality. *Waste Management & Research*, 20, 389-397.
- TOMPKINS, D. 2005. Composting food wastes. 1. Scientific aspects. *Available from: <http://www.research.plymouth.ac.uk/pass/Research/Scientific%20aspects%20of%20food%20waste%20composting.pdf>*. University of Plymouth.
- TOMPKINS, D. 2006. Organic waste treatment using novel composting technologies. University of Plymouth.
- TOMPKINS, D. K., CHAW, D. & ABIOLA, A. T. 1998. Effect of windrow composting on weed seed germination and viability. *Compost Science & Utilization*, 30-34.
- TONTTI, T., HEINONEN-TANSKI, H., KARINEN, P., REINIKAINEN, O. & HALINEN, A. 2011. Maturity and hygiene quality of composts and hygiene indicators in agricultural soil fertilised with municipal waste or manure compost. *Waste Manag Res*, 29, 197-207.
- TRAUTMANN, N. M. & KRASNY, M. E. 1997. *Composting in the classroom*, Cornell Univeristy.

- TUITERT, G., BOLLEN, G.J., 1996. The Effect of Composted Vegetable, Fruit and Garden Waste on the Incidence of Soilborne Plant Diseases. *In: DE BERTOLDI, M., SEQUI, P., LEMMES, B., PAPI, T. (ed.) The Science of Composting., European Commission, International Symposium.* London: Chapman & Hall.
- VAUGHAN, S. M., DALAL, R. C., HARPER, S. M. & MENZIES, N. W. 2011. Effect of fresh green waste and green waste compost on mineral nitrogen, nitrous oxide and carbon dioxide from a Vertisol. *Waste Manag*, 31, 1720-8.
- VEEKEN, A., BLOK, W., MOOLENAAR, S. & GRIGATTI, M. 2007. Standardized determination and classification of compost organic matter stability. *2nd BOKU Waste Conference.* Vienna, Austria.
- VEEKEN, A., NIEROP, K., DE WILDE, V. & HAMELERS, B. 2000. Characterisation of NaOH-extracted humic acids during composting of a biowaste. *Bioresource Technology*, 72, 33-41.
- WALLACE, P. 2008. Trials Review. WRAP report WA1000119.
- WALLACE, P. 2009. Soil health following medium-term green compost additions at two arable sites in East Anglia OAV023-010. Banbury: WRAP report OAV023-010.
- WALLACE, P., BROWN, S. & MCEWAN, M. J. 2004. To support the development of standards for compost by investigating the benefits and efficacy of compost use in different applications. WRAP Project STA0015.
- WALLACE, P. & CARTER, C. 2007. Effects of compost on yields of winter wheat and barley, sugar beet, onion and swede in the fourth and fifth years of a rotation. *Project Report No. 422.*
- WANG, L., LV, D., YAN, B. & ZHANG, Y. 2013. Fluorescence characteristics of dissolved organic matter during composting at low carbon/nitrogen ratios. *Waste Manag Res*, 31, 203-11.
- WARMAN, P. R. 1999. Evaluation of seed germination and growth tests for assessing compost maturity. *Compost Science & Utilization*, 7, 33-37.
- WEINFURTNER, K. Session V: Meliorating physical properties - Introduction. *In: AMLINGER, F., DREHER, P., NORTCLIFF, S. & WEINFURTNER, K., eds. Applying compost - benefits and needs, 2003.* Federal Ministry of Agriculture, Forestry, Environment and Water Management, Austria, and European Communities, 213-218.
- WICHUK, K., M., & MCCARTNEY, D. 2010. Compost stability and maturity evaluation — a literature review. *Canadian Journal of Civil Engineering*, 37, 1505-1523.
- WOOD, M., WALLACE, P., BECVAR, A. & WALLER, P. 2009. BSI PAS 100 Update – Review of Stability Testing. WRAP.
- WRAP 2004a. Guidelines for the specification of composted green materials used as a growing medium component.
- WRAP 2004b. Using compost in agriculture and field horticulture. Compost information package 1.
- WRAP 2005. Statistical comparison of the laboratory stability test with the Commercial SOLVITA rapid test for stability and maturity. Interim report – statistical analysis. Banbury: Written by: Wallace, P.
- WRAP 2006a. Commercial Benefits of Municipal Organic Waste in Winter Wheat Production WRAP report ORG033-017 written by: Norman, K., Cartwright, P., Wallace, P.
- WRAP 2006b. Scoping study of research conducted on the disease suppression capability of composted materials in horticulture, agriculture and turf grass applications. *WRAP report ORG0034.* Written by: Noble, R., Pereira, N., Coventry E., Whipps, J.
- WRAP 2011a. Compost & Anaerobic Digestate Quality for Welsh Agriculture. *WRAP.* Banbury: Written by: Taylor, M., Rollett, A., Chambers, B.
- WRAP 2011b. Compost Production for use in Growing Media – a Good Practice Guide.
- WRAP 2011c. Guidelines for Specification of Quality Compost for Use in Growing Media. Banbury.
- WRAP 2013a. Digestate & Compost in Agriculture, Bulletin 5.

- WRAP 2013b. Evidence for digestate use in different UK markets: an annotated bibliography. Banbury: Written by: King, C., Bardos, P.
- WRAP 2013c. A survey of the UK organics recycling industry in 2012. *WRAP Project RAK-005-002*. Written by Horne J, Scholes P, Areikin E, Brown B.
- WRAP. 2014. *Mulch - why compost is good for mulch* [Online]. Available: <http://www.wrap.org.uk/content/mulch-why-compost-good-mulch> [Accessed 30/05/2014].
- WRAP 2015. Compost stability: Impact and assessment. Written by Dimambro M, Frederickson J, Aspray T, Wallace P.
- WTW 2006. System OxiTop® Control. Weilheim, Germany: Wissenschaftlich-Technische Werkstätten GmbH.
- WU, L., MA, L. Q. & MARTINEZ, G. A. 2000. Comparison of Methods for Evaluating Stability and Maturity of Biosolids Compost. *Journal of Environmental Quality*, 29, 110-112.
- WU, T., WANG, X., LI, D., YI, Z. 2010. Emission of volatile organic sulfur compounds (VOSCs) during aerobic decomposition of food wastes. *Atmospheric environment*, 44, 5065-5071.
- YU, G. H., LUO, Y. H., WU, M. J., TANG, Z., LIU, D. Y., YANG, X. M. & SHEN, Q. R. 2010. PARAFAC modeling of fluorescence excitation–emission spectra for rapid assessment of compost maturity. *Bioresource Technology*, 101, 8244-8251.
- YU, H. & HUANG, G. H. 2009. Effects of sodium acetate as a pH control amendment on the composting of food waste. *Bioresource Technology*, 100, 2005–2011.
- ZERKOUNE, M., BEQUETTE, B. & GIBSON, R. 2002. On site compost maturity testing. The University of Arizona.
- ZMORA-NAHUM, S., MARKOVITCH, O., TARCHITZKY, J. & CHEN, Y. 2005. Dissolved organic carbon (DOC) as a parameter of compost maturity. *Soil Biology & Biochemistry*, 37, 2109-2116.

---

[www.wrap.org.uk](http://www.wrap.org.uk)

