Material change for
a better environment

Desktop study on new markets

New Markets for Digestate from Anaerobic Digestion

Expanding the market for liquid digestate beyond agricultural application is vital to generate increased opportunity for reuse of biodegradable waste and production of bioenergy

Project code: ISS001-001
Research date: Nov 2010-Mar 2011
ISBN: n/a
Date: Aug 2011

WRAP's vision is a world without waste, where resources are used sustainably.

We work with businesses and individuals to help them reap the benefits of reducing waste, develop sustainable products and use resources in an efficient way.

Find out more at www.wrap.org.uk

Written by: Dr Hannah Rigby and Professor Stephen R Smith, Department of Civil and Environmental Engineering, Imperial College London

Imperial College London

Front cover photography: Home garden products

Executive summary

Background:

Currently, the major outlet for liquid digestate is agricultural application and research is required to investigate the suitability of liquid digestate products for other purposes such as use as a soil conditioner or fertiliser in domestic gardens, growing media preparation and turf or roadside grass establishment. Technologies to further process digestate and utilise the by-products, such as extraction of nutrients to produce a high-quality fertiliser, also require investigation. Expanding the market for liquid digestates beyond agricultural application is important to generate increased opportunity for reuse of biodegradable waste and production of bioenergy. This is necessary to achieve government targets for reduction of biodegradable waste sent to landfill (CEC, 1999) and promote anaerobic digestion (AD) as a method to increase the proportion of energy generated from renewable sources (CEC, 2009).

Objectives and Approach:

This report presents the findings of a three month project to investigate new markets for digestate. The objectives of the project were: i) to identify uses for digestate (as a raw material and in a processed form); ii) identify competition in terms of currently available products, the physico-chemical requirements for the product and how well digestate properties match currently available products; iv) investigate processing technologies for novel uses of digestate and by-products (eg. P recovery) v) investigate technologies to process the digestate liquid into a suitable form for the potential uses identified in i; vi) to investigate market size and structure for each potential new use.

Data supplied by Waste Resources Action Programme (WRAP) from a separate project and additional information sourced suggested that the physico-chemical and microbiological properties of the digestate were generally within the specified levels stipulated in PAS 110. The exception to this was the microbiological properties of digestate derived from livestock slurry (DLS), which had presumably not undergone a pasteurisation step. Other differences between digestate from food waste feedstock (DFW) and DLS included a higher N and K concentration in DLS by approximately 1%.

Findings:

The physico-chemical and microbiological properties of digestate were generally below upper limit values defined in PAS 110, with the exception of the microbiological properties of digestate from DLS, which had presumably not undergone a pasteurisation step. Other differences between digestate from food waste feedstock and animal slurry feedstock included a higher N and K concentration in DLS by approximately 1%.

With the analysis of digestate available, the potential outlets for digestate considered in this report were: i) home garden fertiliser and soil amendment products; ii) landscaping; iii) commercial fruit and vegetable production; iv) compost tea production; v) mushroom growing media; vi) commercial nurseries; vii) forestry; viii) publically owned flower beds/green spaces; viii) fertiliser for organic crops and farms; x) nutrient extraction from digestate; xi) algal culture; xii) construction materials eg. Wood Plastic Composites (WPC) and Medium Density Fibreboards (MDF); xiii) fuel production and xiv) biopesticides production.

Digestate could not be used as a replacement to home garden fertiliser products without supplementing with additional nutrients, furthermore as a precautionary measure it is advisable not to use it for purposes where there is potential for ingestion such as fruit and vegetable fertilisers for home gardens. Digestate has potential for use in mushroom growing media, however, research to date has indicated that it may not be as suitable as other organic feedstocks.

The applications with the most potential for commercialisation were:

Underway (Technology developed and commercialised but further work is required to establish technology on a wider scale):

- extraction of nutrients and production of solid fuel using (for example) the 'GG Eco Solutions' process.

Promising (technology not yet developed for management of digestate on a commercial, economically viable scale):

- use of composted fibre as a bedding material for home gardens/landscaping/publically owned flower beds and urban forestry;

- use of separated liquor for turf fertiliser in home gardens/turf on publically owned sports grounds;
- algal growth for use as animal feed/fertiliser or feedstock for biofuels production;
- use as a construction material;
- cellulosic ethanol production.

Contents

Tables

Acknowledgements

The authors would like to thank WRAP for funding the project, especially Nina Sweet and David Tompkins for providing information and guidance. We would like to thank Chris Haley (Imperial Innovations) for advice on market research methods. Thanks to the Anaerobic Digestion plants which supplied the consultants with additional data for the study. Thanks to Andrew Chambers (Greenwich Council), Stefan Czeladzinski (Hammersmith & Fulham Council), Mrs K Ashani (Ealing Council), Alexander Piddington-Bishop (City of London) and Leslie Williams (Brent Council). Thanks to Jake Prior and Edgar Blanco (AnDigestion Ltd.) and Alexander Maddern (Agrivert Ltd.), who kindly provided advice. Goran Nylin (GG Eco Solutions) and Carl Aitken (Bidwells) for providing information on the GG Eco process. Laurant Mantuana (Michegan State University) kindly provided information on use of digestate fibres in construction materials. Ralph Noble (HRI Wellesbourne) for information on mushroom compost. Thanks to Stuart Booker (CHA) and John Adlam (HTA) for advice on fertiliser usage in the horticulture industry. Thanks to Andrew Moffat (Forestry Commission) for providing advice on fertiliser usage in forestry.

1.0 Background

The Coalition Government is committed to increasing energy from waste through AD (Defra, 2010), which will contribute towards the EU target of generating 20% of total energy use from renewable sources by 2020 (CEC, 2009). Anaerobic digestion decomposes biodegradable material using microorganisms in the absence of oxygen producing methane enriched biogas, which can be used to generate renewable energy, and a nutrient rich digestate which is a valuable fertiliser and source of organic matter. The UK produces over 100 million tonnes of organic material each year that could be used to produce biogas; 12-20 million tonnes of food waste (approximately half of which is municipal waste; collected by local authorities, the rest being hotel or food manufacturing waste); 90 million tonnes of agricultural material such as manure and slurry; and 1.73 million tonnes of sewage sludge (Defra, 2010). As more anaerobic digestion facilities become available there will be greater quantities of digestate produced and so there is a real need to develop markets for this digestate to ensure that this resource is used optimally.

If digestate meets the standards defined in the Quality Protocol PAS110 (BSI, 2010) then it is not considered a waste and can be marketed for beneficial use. Otherwise, it must comply with the Environmental Permitting Regulations (SI, 2010) and requires a waste management license or exemption from licensing. Agriculture is currently the major outlet for digestate, and is currently a major route for sewage sludge management in the UK as digestate is a stabilised and reliable fertiliser product, with a reduced odour and pathogen content (USEPA, 1993; Smith, 1996; Defra, 2007a; Smith, 2009). However, under the PAS110 standards, other uses such as forestry, commercial horticulture, land reclamation and restoration are permitted although currently digestate cannot be used for amateur gardening. Digestate may be used directly or separated into liquor (dry solids <6%) and fibre fractions which have differing nutrient compositions; the fibre can be used directly on soil or after composting (NNFCC, 2010). Research is required to review the potential for developing alternative markets to the agricultural outlet for liquid digestate. Further treatment may be required to reduce bulk, improve ease of handling and create digestate products which are fit-for-purpose for alternative and new market applications.

1.1. Objectives:

1. To identify potential new markets for digestate (as a raw material and as products that can use the nutrients in a purified form from the digestate) - this will include:

- use in the home and garden;
- use by local council contractors for fertilising publically owned flower beds/green spaces;
- land restoration;
- fertiliser for organic crops and farms;
- horticultural uses;
- turf establishment;
- additional uses.

2. For each potential use the following issues will be investigated:

- competition in terms of currently available products;
- the requirements for the product including nutrient levels, form (solid or liquid), concentration;
- how well the nutrient concentrations of digestate match currently available products and the requirements for
- the new markets identified;
- how well the physical properties of digestate match currently available products and the requirements for the new markets identified;
- any issues with the sale of this form of fertiliser such as odour and risks to health;

3. Processing technologies will be investigated:

- to process the digestate liquid into an acceptable form for the uses identified in 1 (eg. concentration, filtering);
- for novel uses of digestate and by-products (eg. nutrient recovery, enzyme production, cellulosic ethanol)

For each of the uses identified which has potential for commercialisation the size of the market, and how the supply chain works (eg. distribution outlets, the main companies selling products) will be investigated.

2.0 Approach

Physico-chemical and microbiological analyses of digestate from the WRAP project "AD & compost agricultural markets in Wales" reflected data from three AD plants, two of which digested mainly food waste feedstock and the main component of the feedstock for the third was animal slurry. The consultant requested additional analyses from two further plants to build on this, and the data was then converted to comparable units and the mean, maximum, minimum, range, percentiles and inter-quartile range was calculated for each parameter.

The nutrient content in separated liquor and fibre was estimated using separation efficiency values for three different dewatering methods (Belt press, Screw press, Centrifuge) (Lukehurst *et al.*, 2010).

Potential new uses for digestate included those listed under objective 1. Further uses were identified through internet searches and searches of online databases of scientific literature and trade journals.

For each potential use the following investigations were conducted:

1. Currently available products (this applied mainly to horticultural products) were identified through searches of available databases and online catalogues and direct contact with manufacturers/distributors.
2. The nutritional composition of a range of commercially available liquid fertilisers and mulches for home gardens and the nutrient requirements of other identified markets were assessed through: i) online searches for fertiliser specifications of commercially available products ii) direct contact with trade associations, manufacturers, retailers, researchers (telephone/visits/email).
3. The suitability of the nutritional composition of liquid digestate was assessed. This included consideration of the use of digestate from different feedstocks and digestate separated into liquor and fibre fractions. The nutrient concentrations of digestate (data supplied by WRAP) was compared with the nutrient requirements of each of the potential uses identified in Section 1, and the nutrient concentrations of currently available products. The data was presented in tables to enable clear comparisons to be made between digestate products and currently available products/product requirements. Where available, the mean and range of the data was calculated.
4. The suitability of the physical composition of liquid digestate was also assessed. This included consideration of the use of digestate separated into liquor and fibre fractions. The physical properties of the digestate (eg. dry solids content, suspended solids) were compared with the requirements of the potential use and the physical properties of currently available products.
5. Any issues with the sale of this form of fertiliser, or other end-use, of digestate were identified by examination of data supplied by WRAP. Contaminant concentrations, pH, electrical conductivity, pathogens and stability/odour were examined and parameters which may cause a concern in each of the potential new markets were identified.
6. Technologies required to further process digestate for new applications were investigated when digestate was not fit-for-purpose.

Processing technologies for novel uses of digestate and by-products (eg. P recovery, enzyme production, novel microbial groups) were investigated through an internet search including a review of the scientific literature and trade journals.

3.0 Digestate Properties

The physicochemical properties of digestate are presented in Appendix 1 and briefly discussed here in relation to the test parameters and upper limit values defined in PAS 110 Quality Protocol for digestate (BSI, 2010). The properties of digestate are discussed in further detail in relation to their suitability for various new markets in Section 4. Data from digestate produced mainly from food waste feedstock (DFW) and from livestock slurry feedstock (DLS) are presented separately. However, there were fewer examples of digestate produced from DFW, therefore direct comparisons of the data should be approached with caution.

3.1 General physicochemical properties

The dry solids (DS) content was between 2.7-9.3% of the fresh weight (Tables A1 and A2). The pH was similar, between pH 7.6-8.8, regardless of the feedstock source. The volatile solids (VS) content of digestate is equivalent to the organic matter content and was between 68.3-73.2%, indicating that digestate is a source of organic matter with potential for use to improve soil structural properties. The stability of digestate, as measured by the Residual Biogas Potential (RBP) test developed by (WRAP) (Walker *et al.*, 2010), was between 72-212 l kg^{-1}, and was below the upper limit value of 250 l kg^{-1} defined in PAS 110, thus demonstrating that digestate will not cause significant vector attraction problems.

3.2 Nutrient and heavy metal content

The nitrogen (N) contents of DFW and DLS are presented in Tables A3 and A4 respectively. The total N content was slightly lower for DFW, at 15%, compared to 16% in DLS. The majority of N was in mineral forms (62-65%) indicating that a large proportion of N is immediately bioavailable. The C:N ratio was greater for digestate produced from DLS compared to digestate produced from food waste only (4:1 compared to 1.5:1). The nutrient content (other than N) of digestate is presented in Tables A5 and A6. The total phosphorus (P) content was low and similar for digestate produced from DFW (0.7%) and DLS (0.9%); only a small proportion of this P was water soluble (0.1-0.3%). Total potassium (K) content was higher in DFW (4.7%) compared to DLS (3.2%). However the water soluble K was greater in DLS (3.3%) compared to DFW (1.9%). DLS was also a greater source of sulphur (S), 0.9% compared to 0.3%, and calcium (Ca), 2.6%, compared to 0.3% in DFW. Magnesium (Mg) concentrations were similar at 0.2-0.3%. The majority of heavy metal contents were below upper limit values specified in PAS110. However, for DLS in 3 of 40 samples the upper limit value of 400 mg kg^{-1} for Zn was exceeded by <231 mg kg^{-1}; in addition, for Cd the upper limit value of 1.5 mg kg^{-1} was exceeded by <0.8 mg kg^{-1} in 5/18 samples.

Estimated NPK content of separated liquor and fibre are presented in Table A13, nutrient separation is dependent on the dewatering method used and varies for separated liquor and fibre. However, no data is available on the bioavailability of nutrients in separated liquor and fibre, it is expected that the more soluble forms of nutrients are partitioned into the liquor and the recalcitrant forms are retained in the fibre. Further work is required to measure the nutritional composition of separated liquor and fibre.

3.3 Microbiological characteristics

Microbiological characteristics of DFW and DLS are presented in Table A9. Digestate from food waste passed the criteria specified in PAS 110. However, DLS did not pass the microbiological criteria: *Enterbacteriaceae* and *Salmonella* spp. were detected and *E.coli* exceeded the upper limit value of 1000 cfu g^{-1}. Under the PAS110 Specification (BSI, 2010) a pasteurisation step is not required if feedstocks are only manure, unprocessed crops, and/or used animal bedding that arise and are used entirely within the producer's premises or holding. This may explain the greater incidence of *Enterbacteriaceae*, *Salmonella* spp. and *E.coli*. However, these data were collected from one anaerobic digestion plant on one sampling date only. Plant pathogens are potentially a problem, if present; however there was no data available.

3.4 Organic contaminants

Organic contaminants in digestate are presented in Tables A11 and A12. No upper limits for organic contaminants are specified in PAS 110, as controls are placed on the feedstock materials in order to protect the quality of the digestate. However, for reference, organic contaminant concentrations are well below the European proposed limits for polyaromatic hydrocarbons (PAHs) in sewage sludge (6 mg kg^{-1}), polychlorinated biphenyls (PCBs) (0.8 mg kg^{-1}) and polychlorinated dibenzo-p-dioxins and dibenzo-p-furans PCDD/Fs (100 ng toxic equivalents (TEQ) kg^{-1} DS) (EC 2000; EC 2003).

4.0 New markets: requirements and potential barriers to use

4.1 Home garden products

4.1.1 Physico-chemical requirements

The nutritional content and descriptions of commercially available home garden fertilisers in comparison to nutritional properties of digestate are presented in Tables 1-8. The products are separated according to the purpose for which they are intended (eg. liquid tomato feed or granular general purpose fertiliser). The nutritional properties and physical requirements of the various home garden products are discussed here.

Multi-purpose garden compost:

A number of multi-purpose garden composts are available (Table 1). These are intended to be used in, for example, bedding, turfing or hanging baskets; composts are worked into the top soil to improve the soil structural properties such as bulk density, water holding capacity and cation exchange capacity (*CEC*). Currently available multi-purpose growing media are produced from materials such as peat and shredded straw. Peat is a finite resource and so composts produced from alternative sources are desirable. Nutritional characteristics of garden composts are not provided in product specifications as the products are sold mainly for their soil improving characteristics. The composting process tends to reduce the concentration of readily available nutrients; however, the compost must provide sufficient nutrition to sustain seeding growth before fertilisation. Composted biosolids from wastewater treatment have previously been successfully produced by TERRA ECOSYSTEMS at Thames Water Utilities and performed as well as the brand-leading peat-based media (Evans, 2009); plant tissue analysis showed that nutrient reserves in the biosolids/straw compost were adequate for seedling growth and comparable to peat-based media. Composts produced from separated digestate fibre would provide a similar source of stabilised organic matter suitable for improving soil properties. However, the reproducibility of the digestate compost properties may present a problem if feedstock sources were variable.

The relatively high N content of digestate would be useful in the composting process. However, if the N content is too high, it may be necessary to add bulking agents to increase the C:N ratio, such as woodchips, sawdust or straw. This is also required to increase air permeability during the composting process (Evans, 2009). Therefore, for the process to be viable there would need to a source of this type of biowaste in close proximity to the AD plant. Thames Water Utilities used straw as a bulking agent for their composted biosolids (Evans, 2009).

The composts are currently sold in bags of 50-100 l or bulk bags of $1m^3$, co-composted stabilised separated digestate fibre could also be packaged in the same manner.

Granular multi-purpose organic fertilisers:

Several granular multi-purpose garden fertilisers are commercially available; some of these are made from organic constituents such as "Miracle Gro Organic Choice" and "New Horizon organic poultry manure" (Table 2). General purpose granular fertilisers have a mean NPK content of 5.5 : 3.3 (1.5 soluble) : 4.4, compared to 15 (10.5 readily available) : 0.7 (0.1 soluble) : 4.7 in digestate from food waste feedstocks and 16 (10.9 readily available): 0.9 (0.3 soluble) : 3.2 in digestate containing livestock slurry. Estimated NPK values for dewatered slurry (mean for belt press and screw press) are 9.8 : 0.3 : 1.5. Therefore, the N content in digestate is greater than is generally found in granular multi-purpose fertilisers by 2-3 times and the P content is less than 3 times the amount in granular multi-purpose fertilisers. The K content of digestate is similar to granular multi-purpose fertilisers (although it may be lower in separated fibre).

Granular domestic fertilisers are currently available in boxes or bags of between 1-2 kg. To be marketed for use in home gardens to fulfil the same role as currently available granular multi-purpose fertilisers, digestate would need to be thermally dried to produce pellets or granules. This would also improve stability, reduce odour and make a more suitable product for packaging.

Granular slow release and organic vegetable fertilisers:

Manufacturers such as 'Vitax', 'Miracle Gro' and 'Burgon and Ball' produce granular slow-release and organic fertilisers designed as a slow release nutrient source for fruit and vegetables (Table 3). These products have a mean NPK content of 5.5 : 3.1 (0.5 soluble) : 7.5 compared to 15 (10.5 readily available) : 0.7 (0.1 soluble) : 4.7 in DFW and 16 (10.9 readily available): 0.9 (0.3 soluble) : 3.2 in DLS. Therefore, N is supplied in concentrations less than those typically found in digestate and P and K supplied in greater concentrations. Pelleted Vitax Q4 fertiliser for fruit, vegetables, flowers and roses also supplies Mg (0.012%), Mn (0.012%), Cu (0.017%) and Fe (0.2%). Magnesium and Mn were not amongst the parameters measured in digestate, but Cu and Fe were measured and were within the same range.

Table 1 Commercially available home garden composts

Company	Product name	Purpose	Constituents	Packaging
Murphy	Multi-Purpose Compost	Multi-purpose compost (pot, seed sowing, topping up beds and sowing)	Not specified	70 l bag
Levington	GRO-BAG	Gro-bag for vegetable crops		L950mm x W330mm x H50mm bag
J Arthur Bower	Multi-Purpose Compost with Sinero Boost	Peat compost for houseplants, seed-sowing, potting, hanging baskets (feeds for 4-6 weeks)	Peat compost	100l bag
Pro Grow	Peat free general purpose compost	Many different types of flowers, shrubs, fruit and vegetables (not suitable for acid loving plants e.g. rhododendrons or camellias), on own or raised beds & borders	Composted garden waste	$1m^3$ bulk bag
Miracle Gro	All purpose growing compost	Multi-purpose compost (enriched with 40% more nutrients to feed plants for <3 months) beds, borders, pots, hanging baskets	Compost enriched with Miracle Gro plant food & water retaining agent	50l bag
Pro Grow	Peat free soil conditioner	Tree, shrub, fruit, vegetables, turf	'completely natural'	60l bag
Rolawn	Soil Improver	General use (improves soil structure, WHC etc)	Shredded straw compost, iron minerals	1 m^3 bulk bag

To be marketed for use in home gardens to fulfil the same role as currently available granular vegetable fertilisers, digestate would need to be thermally dried to produce pellets or granules.

Ericaceous plant foods:
'Miracle Gro' are amongst the manufacturers which produce ericaceous plant foods, they produce both an organic-based and a slow release product. The mean NPK content is 7.8: 5.8 (3.5 soluble) : 3.5 (Table 4). Again, the N content of digestate is higher and the P is lower than the commercially available ericaceous plant foods, although the K content is similar (3.2-4.7%) The plant foods also state that they supply Mg (1.5%), which is higher than the Mg content of digestate (0.1-0.3%) and Fe (1%), within a similar range as the Fe content of digestate (1.4%). Furthermore, without adjusting the pH, digestate would be unsuitable for Ericaceous plants, which require a pH <7, whereas digestate has a pH of 7.5-8.5 (Tables A1 and A2). To be marketed for use in home gardens to fulfil the same role as currently available granular ericaceous plant food, digestate would need to be thermally dried to produce pellets or granules.

'Root booster' fertiliser:
'Miracle Gro' and 'Vitax' produce "root booster" fertilisers from sterilised ground bone, which are marketed as slow release sources of nutrients to encourage root development (Table 5). The organic nature of the nutrients in digestate would suggest there may be potential for use as "root booster" fertiliser, however, the balance of nutrients is not a good match; the mean NPK content is 3.8: 7.8 (0.9 soluble): 0. Therefore, the N content is over four times lower than in digestate, the P content is higher, although the soluble P content is similar, and the K content is lower. To be marketed for use in home gardens so that the physical characteristics are suitable for use as root-booster, digestate would need to be thermally dried to produce pellets or granules, or ground into a fine material.

Rose and shrub feed:
These commercially available feeds, some of which are organic ('Miracle Gro Organic Choice Bloom Booster') have a mean NPK content of 2.5 : 2.4: 17.5 (Table 6). The N content of digestate is higher and the P and K contents are lower.

To be marketed for use in home gardens so that the physical characteristics are suitable for use as a rose and shrub feed, digestate would need to be thermally dried to produce pellets or granules, or ground into a fine material.

Liquid tomato feed and other liquid plant feeds:
Of the available liquid tomato feeds, 'Miracle Gro' and 'New Horizon' produce organic plant feeds with NPK contents of 2 : 0.9 (0.65 soluble) : 5 and 3 : 0.9 (0.4 soluble) : 5 respectively. The mean NPK content for liquid tomato feeds is 3.8: 1.6 (1.5 soluble) : 4.6. The NPK contents of other liquid plant feeds are similar at 6 : 1.9 (1.9 soluble) : 5.4. The total N content of digestate relative to the PK content (15-16% DS) is three times greater than commercially available liquid feeds. However, the estimated N content of separated liquor is 7.3%, which is closer to the range of commercially available liquid plant feeds. The P content of digestate is similar to liquid tomato feeds at 0.7-0.9%, and 1.0% for separated liquor. The K content of whole digestate is similar at 3.2-4.7%; however the estimated K content of digestate liquor is 1.5%, lower than for liquid tomato feeds.

To be processed for use in home gardens so that the physical characteristics are suitable for use as a liquid plant feed, digestate would need to be separated into liquor to reduce the DS content from approximately 5% (Table A1) to 2-3% (Table A7). This would allow greater infiltration of the fertiliser into the soil and reduce residues on the soil surface, therefore more efficient use of nutrients. However, the nutrients in digestate are in a much more dilute form (<1% fresh weight) than the concentrated nutrients in liquid feed. Therefore, it would be necessary to apply the digestate liquor at 10-20 times the rate of commercially available liquid feeds (see further calculations below for turf fertiliser application). This would result in waterlogging and it is not practicable in terms of transport and packaging of the digestate liquor; it is therefore necessary to investigate methods of concentrating the nutrients before digestate liquor can be used as liquid tomato feed.

Turf fertilisers:
Commercially available solid turf fertilisers have a mean N content of 12% (range 6-20%); a mean P content of 5% (range 2-8%) with 1% soluble (range 0-5%) and a mean K content of 6 (range 0^{-1}2%) (Table 9). The available liquid turf fertilisers have a mean N content of 13% (range 3-25%); a mean P content of 1% (range 0-1.7%) and a mean K content of 4.4% (range 0-8.3%). The NPK contents of liquid digestate on a dry solids basis are therefore within the same range as turf fertiliser (Tables A3 and A4), and have similar NPK ratios. The high N

content of digestate (in relation to P and K), means digestate has a similar nutrient ratio to turf fertilisers designed for spring growth.

The majority of commercially available turf fertilisers are fine solids, although liquid turf fertilisers are also available, therefore whole digestate would not have suitable physical properties as it is and would require further processing. Separated liquor may be most suitable as a replacement for currently available turf fertilisers as it would infiltrate into the soil more easily due to the lower dry solids content. However, the comparatively low concentration of nutrients in liquid digestate (i.e. <1% fresh weight) means that transportation and packaging of separated liquor is unlikely to be viable without further concentration of the nutrient content.

Commercially available solid turf fertilisers are currently sold in 25 kg packs. The recommended application rate is generally 30-35 g m^{-2}; depending on the specific NPK content of the product, this is equivalent to N applications between 12-42 kg ha^{-1}, P applications between 0-17.5 kg ha^{-1} and K applications between 0-42 kg ha^{-1}. To apply approximately equivalent nutrient concentrations from separated liquor (with a DS content of 3% and NPK of 16:1:4) it would be necessary to apply 250-875 ml m^{-2}. A 25 kg pack of solid turf fertiliser is sufficient for approximately 800 m^2. It might be feasible, although bulky, to sell digestate in 25 l drums, which would be sufficient for a 28-100 m^2 area, however, it is likely that it would not be economically viable.

The available liquid fertilisers are sold in 10 and 200 l containers; the recommended application rate is between 40-120 l ha^{-1}. For a liquid turf fertiliser with an NPK content of 13:1:4, this would be equivalent to rates of N between 6.1-18.4 kg ha^{-1}; rates of P between 0.5-1.4 kg ha^{-1} and rates of K between 2.2-20.1 kg ha^{-1}. For equivalent applications of N from digestate liquor with a DS content of 3% (N:P:K, 16:1:4), the application rate would be 1076 l – 3249 l ha^{-1}, nearly thirty times the application rate of commercial fertiliser. A 10 l bottle of the commercial liquid turf fertiliser with NPK content of 833-2500 m^2, whereas to cover the same area separated 270 l of digestate liquor would be required.

The consistency of the nutrient concentration of separated liquor may also be problematic if it is to be marketed for use in domestic horticulture. However, the interquartile ranges for the major plant nutrients are relatively low (Table A3-A6). The variability may be further reduced if the digestate is sourced from plants receiving only certain feedstocks. Physico-chemical analyses of separated liquor are required to demonstrate the consistency of the nutritional composition.

The separated digestate liquor would need to be spread using a pedestrian sprayer or knapsack sprayer; as most of the commercially available products are fine solids it is likely that liquid digestate will not be appealing to the consumer. It is likely that transport costs for such a large volume of liquid would outweigh the value of the product; therefore, it is necessary to investigate methods of concentrating the nutrient content before use of digestate as turf fertiliser on home gardens is viable.

<u>Summary:</u>
A comparison of the physico-chemical properties of whole digestate, separated liquor and fibre and various commercially available home garden fertilisers has indicated that:

i) digestate fibre may be suitable for co-composting with other organic residuals and use in home gardens, however, consistency of the product may present a problem;
ii) separated liquor may be suitable for use as turf fertiliser in home gardens, but technologies for concentrating the nutrients are required;
iii) separated liquor may be suitable for use as liquid plant feed in home gardens but technologies for concentrating the nutrients are required;
iv) use of digestate for any other purpose in home gardens may require supplementing with P and K.

4.1.2 Potential risks to health and environment

The potential hazards of digestate are physical (glass, stones, plastic, metals), microbiological (risk to human health or plant health), organic contaminants (risk to human health or ecosystem damage), nutrients (contamination of water supplies), heavy metals (risk to human heath or soil health) and offensive odours. These risks are discussed here in relation to the data on heavy metals (Table A8 and A9), microbiological properties (Table A10 and A11), and organic contaminants (Table A12 and A13) presented in Appendix 1, and the three most promising end-uses in home gardens identified in Section 4.2.1. (composted fibre for bedding and potting and separated liquor for turf fertiliser or liquid fruit and vegetable feed).

The exposure assessment of anaerobic digestion products in various end uses conducted for WRAP by Cranfield University (Pollard *et al.* 2008) indicated that there was a relatively high likelihood of exposure to a range of potentially significant hazards from digestate residues when used in home gardens. The potential hazard was estimated by consideration for potential contaminants that would be introduced by each feedstock material, and the possible pathways to exposure to the hazard. According to the Cranfield exposure assessment, the pathways which presented the greatest risk were direct ingestion of digestate residues and ingestion of soil contaminated with digestate residues. Hence, use in domestic gardens is not currently permitted by the Anaerobic Digestate Quality Protocol (QP) (WRAP, 2010). Other highly available pathways were contamination of private water supplies by surface and subsurface routes and ingestion of contaminated crops. The end uses that presented the highest number of available exposure pathways were ready to eat crops, grazing and animal feed and non ready to eat crops as these are most closely linked to the human food chain. It is impossible to implement control methods to reduce exposure, such as code of practice, for domestic use of digestate, which is why this use presents a potentially significant risk and is currently excluded from the QP.

<u>Physical contaminants:</u>
Source segregation of organic wastes and control over input materials as specified in PAS110 means physical contaminants will pose minimal risk for use in domestic gardens. Further processing of digestate, such as separation of liquor and fibre, will further reduce the presence of physical contaminants.

<u>Nutrients:</u>
The three uses identified as most suitable for digestate in home gardens are use of composted fibre as a bedding material, use of separated liquor as turf fertiliser and use of separated liquor as a liquid vegetable feed.

Composting reduces the availability of nutrients, due to losses of ammonia through volatilisation and the conversion of soluble nutrients, such as P, to more recalcitrant forms during the composting process. Hence, there is a low risk of volatilisation of ammonia or leaching of nutrients from stable composted separated fibre.

Leaching or runoff of N and P, and subsequent contamination of water sources, or gaseous emissions of N are potential hazards from the use of separated liquor as a turf fertiliser. Nitrogen in digestate is present in both organic and mineral forms, the available N will be equivalent to the mineral N plus a fraction of organic N which will be mineralised over time; therefore, it is important to calculate availability of N accurately to calculate the correct application rate. In addition to ensuring there are adequate nutrients for plant growth, this will prevent over-application and potential losses to the environment. Leaching of N should not pose a greater risk than currently commercially available turf fertilisers or liquid vegetable feed if applied according to instructions. In addition, the slow release nature of the nitrogen will result in a lower risk of N loss during leaching events.

The slightly alkaline pH of digestate (Table A1) means that there may be a risk of ammonia losses by volatilisation. However, assuming that the separated liquor infiltrates into the soil rapidly leaving little residue there should be minimal risk of runoff of N or ammonia volatilisation. This is an area (soil infiltration) which may require investigation before separated liquor is used for this purpose.

<u>Microbiological characteristics:</u>
The data indicates that there is minimal microbiological risk from DFW (Table A10), although DLS (Table A11) may present a risk. However, if a pasteurisation step is included, which is required if digestate is to be used outside the holdings of the digestate producer, the microbiological risk will be minimal.

Furthermore, the two most suitable applications for digestate identified in Section 4.2.1 would introduce a further barrier to exposure. The composting process used to treat separated fibre for use in bedding and potting would further eliminate pathogens. The nature of the end-use of digestate on a non-edible crop, means that the use of separated liquor as turf fertiliser would not lead to potential exposure to hazardous organisms through ingestion in contaminated soil or crops.

<u>Heavy metals:</u>
Heavy metals measured in digestate (Tables A8 and A9) were below upper limits set in PAS110, with the exception of Cd and Zn in a limited number of cases. Further investigation may be required to identify sources of Cd and Zn in digestate. Concentrations of trace metals such as Cu, Mo, Fe and Zn were present in similar quantities to those in plant food such as "Miracle Gro Azelia, Camelia and Rhodedendron liquid plant food", indicating that these metals present a benefit rather than a barrier to use.

Two of the most suitable applications for digestate identified in Section 4.2.1 would introduce a further barrier to exposure. The composting process would further reduce the bioavailability of heavy metals. Use of separated liquor as turf fertiliser would prevent the risk of ingestion of PTEs in contaminated soil or crops. However, use of separated liquor as liquid vegetable feed presents the risk of ingestion of contaminants on soil or contaminated crops.

<u>Organic contaminants:</u>
Analysis of digestate indicated that concentrations of organic contaminants in digestate were low. As a reference point, they were below limits suggested by the EC for the use of biosolids in agriculture.

<u>Odour/Stability:</u>
Digestate must be digested to an extent to which it is stable and therefore does not digest further during storage and management and cause an offensive odour under the PAS 110 Specifications. Composting separated fibre for use as a bedding and potting product will further stabilise the material reducing odour. Separated liquor may have some odour and investigation may be required to determine whether this is considered unpleasant or offensive before it could be used as a domestic garden product.

<u>Salinity:</u>
The salinity of digestate is approximately 5500-7500 µS cm^{-1} ($20^{o}C$). This is similar to animal slurries and biosolids which have been demonstrated to cause an increase in soil salinity when used as a soil amendment. Composting fibre to use as bedding and potting material will prevent the risk of increased soil salinity, due to the reduction of salts in soluble forms. However, there is a risk from increasing soil salinity through use of separated liquor as a turf fertiliser or liquid vegetable feed. Therefore, the product instructions may need to recommend the use of fertiliser only 2-3 times during a growing season. There is no data available on the salinity of separated liquor; this would be useful to assess its suitability for use as a home garden turf fertiliser or liquid vegetable feed. Trials with garden plants would be required.

Table 2 Digestate nutrient and metal content compared to commercial multi-purpose home garden fertilisers (solid)

Product	**Whole digestate (food waste only:DFW)**	**Whole digestate (contains livestock slurry: DLS)**	**Digestate fibre (Belt press / Screw press)†**	**Miracle Gro Organic choice all purpose plant food**	**New Horizon Organic poultry manure**	**Vitax Growmore**	**Vitax Supagro with added lime**	**Mean general purpose fertiliser**
Description				100% organic granules, general purpose plant food	Poultry manure, general purpose plant food	General purpose (ideal before laying turf & sowing plant seed)	Odourless granules made from 'energy efficient process' from food processing for general purpose use	
Total N (%dm)	15.0 (11.9-20.5)	16.1 (6.7-24.9)	9.8	7.0	4.0	7.0	4.0	**5.5 (4-7)**
NO_3-N (%dm)	Trace	Trace	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
NH_4-N (%dm)	10.5 (5.5-16.0)	10.9 (5.3-19.3)	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Total P (%dm)	0.7 (0.3-2.0)	0.9 (0.2-5.0)	0.34	6	2.5	3.0	1.72	**3.3 (2.5-6)**
Soluble P (%dm)	0.1 (0-0.2)	0.3	n.d.	2.6	n.d.	n.d.	0.34	**1.47 (0.34-2.6)**
K (%dm)	4.7 (1.4-9.3)	3.2 (1.5-5.9)	1.5	5.8	2.5	5.8	3.3	**4.36 (2.5-5.81)**
Mg (%dm)	0.1 (0-0.48)	0.3 (0.0-3.7)	n.d	1.2	n.d.	n.d.	n.d.	**1.2**
Mn (%dm)	n.d.	n.d	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
B (%dm)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Cu (%dm)	0.0032 (0.0019-0.0043)	0.008 (0.002-0.018)	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Mo (%dm)	0.0029 (0.0027-0.003)	0.001	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Fe (%dm)	n.d.	1.4 (0.16-3.8)	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Zn (%dm)	0.011 (0.007-0.014)	0.024 (0.0004-0.063)	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**

†Estimated using separator efficiency values presented in Lukehurst *et al.* (2010)

Table 3 Digestate nutrient and metal content compared to commercial home garden 'vegetable' fertilisers (solid)

Product	Whole digestate (DFW)	Whole digestate (DLS)	Digestate fibre (Belt press/ Screw press)†	Pelleted Vitax Q4 The premier fertiliser for fruit, vegetables, flowers and roses	Miracle Gro fruit and vegetable plant food	Vitax Blood, fish and bone	Burgon & Ball 100% Organic potato fertiliser	Burgon & Ball	Mean vegetable fertiliser
Description				Slow release nutrients for fruit vegetables flowers and roses	100% organic granules for tomatoes fruit and veg	Dried and ground blood, fishmeal and bone with added potash for fruit and veg	Blood meal, feather meal, cocoa shells and vinasse	Blood meal, feather meal, cocoa shells, dried organic seaweed and vinasse: organic vegetable and salad fertiliser	
Total N (%dm)	15.0 (11.9-20.5)	16.1 (6.7-24.9)	9.8	5.3	5.0	5.0	6.0	6.0	**5.46 (5-6)**
NO_3-N (%dm)	Trace	Trace	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
NH_4-N (%dm)	10.5 (5.5-16.0)	10.9 (5.3-19.3)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Total P (%dm)	0.7 (0.3-2.0)	0.9 (0.2-5.0)	0.34	3.3	2.6	2.2	5.0	2.2	**3.10 (2.15-5.0)**
Soluble P (%dm)	0.1 (0-0.2)	0.3	n.d.	0.9	0	n.d.	n.d.	n.d.	**0.45 (0-0.9)**
K (%dm)	4.7 (1.4-9.3)	3.2 (1.5-5.9)	1.5	8.3	8.3	5.0	10.0	5.8	**7.48 (4.98-10)**
Mg (%dm)	0.1 (0-0.48)	0.3 (0.0-3.7)	n.d	1.8	1.8	n.d.	4.0	2.4	**2.5 (1.8-4)**
Mn (%dm)	n.d.	n.d	n.d.	0.0	n.d.	n.d.	n.d.	n.d.	**0.012**
B (%dm)	n.d.	n.d.	n.d.	0.0	n.d.	n.d.	n.d.	n.d.	**0.012**
Cu (%dm)	0.0032 (0.0019-0.0043)	0.008 (0.002-0.018)	n.d.	0.0	n.d.	n.d.	n.d.	n.d.	**0.017**
Mo (%dm)	0.0029 (0.0027-0.003)	0.001	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Fe (%dm)	n.d.	1.4 (0.16-3.8)	n.d.	0.2	n.d.	n.d.	n.d.	n.d.	**0.2**
Zn (%dm)	0.011 (0.007-0.014)	0.024 (0.0004-0.063)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**

†Estimated using separator efficiency values presented in Lukehurst *et al.* (2010)

Table 4 Digestate nutrient and metal contents compared to commercial Ericaceous plant food

Product	**Whole digestate (food waste only: DFW)**	**Whole digestate (contains livestock slurry: DLS)**	**Digestate fibre (Belt press/ Screw press)†**	**Miracle Gro Organic choice azelia, camelia and rhodedendron plant food**	**Miracle Gro Slow release azelia, camelia and rhodedendron plant food**	**Mean Ericaceous plant food**
Description				100% organic granules for all ericaceous plants (pH <7)	Slow release nutrients for Ericaceous plants (pH<7)	
Total N (%dm)	15.0 (11.9-20.5)	16.1 (6.7-24.9)	9.8	6.5	9	**7.8 (6.5-9)**
NO_3-N (%dm)	Trace	Trace	n.d.		3	**3.0**
NH_4-N (%dm)	10.5 (5.5-16.0)	10.9 (5.3-19.3)	n.d.		6	**6.0**
Total P (%dm)	0.7 (0.3-2.0)	0.9 (0.2-5.0)	0.34	5.5	6.1	**5.8 (5.5-6.1)**
Soluble P (%dm)	0.1 (0-0.2)	0.3	n.d.	2.4	4.6	**3.5 (2.4-4.6)**
K (%dm)	4.7 (1.4-9.3)	3.2 (1.5-5.9)	1.5	7.0	15.8	**11.5 (7-15.8)**
Mg (%dm)	0.1 (0-0.48)	0.3 (0.0-3.7)	n.d	1.2	1.8	**1.5 (1.2-1.8)**
Mn (%dm)	n.d.	n.d	n.d.			
B (%dm)	n.d.	n.d.	n.d.			
Cu (%dm)	0.0032 (0.0019-0.0043)	0.008 (0.002-0.018)	n.d.			
Mo (%dm)	0.0029 (0.0027-0.003)	0.001	n.d.			
Fe (%dm)	n.d.	1.4 (0.16-3.8)	n.d.		0.5	**1.0**
Zn (%dm)	0.011 (0.007-0.014)	0.024 (0.0004-0.063)	n.d.			

†Estimated using separator efficiency values presented in Lukehurst *et al.* (2010)

Table 5 Digestate nutrient and metal contents compared to commercial home garden 'root booster' fertiliser

Product	Whole digestate (food waste only: DFW)	Whole digestate (contains animal slurry: DLS)	Digestate fibre (Belt press/ Screw press)†	Miracle Gro organic choice Root booster	Vitax Sterilised Bonemeal	Mean 'Root Booster'
Description				Bonemeal granules Improved establishment for trees, shrubs, fruit & vegetables	Sterilised ground bone, slow release to encourage root development (roses, shrubs, border plants)	
Total N (%dm)	15.0 (11.9-20.5)	16.1 (6.7-24.9)	9.8	5.0	3.5	**3.8 (3.5-5.0)**
NO_3-N (%dm)	Trace	Trace	n.d.	n.d.	n.d.	**n.d.**
NH_4-N (%dm)	10.5 (5.5-16.0)	10.9 (5.3-19.3)	n.d.	n.d.	n.d.	**n.d.**
Total P (%dm)	0.7 (0.3-2.0)	0.9 (0.2-5.0)	0.34	7	8.6	**7.8 (7-8.6)**
Soluble P (%dm)	0.1 (0-0.2)	0.3	n.d.	0.9		**0.9**
K (%dm)	4.7 (1.4-9.3)	3.2 (1.5-5.9)	1.5	0.0	0.0	**0.0**
Mg (%dm)	0.1 (0-0.48)	0.3 (0.0-3.7)	n.d	0.0	0.0	**0.0**
Mn (%dm)	n.d.	n.d	n.d.	n.d.	n.d.	**n.d.**
B (%dm)	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Cu (%dm)	0.0032 (0.0019-0.0043)	0.008 (0.002-0.018)	n.d.	n.d.	n.d.	**n.d.**
Mo (%dm)	0.0029 (0.0027-0.003)	0.001	n.d.	n.d.	n.d.	**n.d.**
Fe (%dm)	n.d.	1.4 (0.16-3.8)	n.d.	n.d.	n.d.	**n.d.**
Zn (%dm)	0.011 (0.007-0.014)	0.024 (0.0004-0.063)	n.d.	n.d.	n.d.	**n.d.**

†Estimated using separator efficiency values presented in Lukehurst *et al.* (2010)

Table 6 Digestate nutrient and metal contents compared to commercially available rose and shrub feed (solid)

Product	**Whole digestate (food waste only: DFW)**	**Whole digestate (contains livestock slurry: DLS)**	**Digestate fibre (Belt press/ Screw press)†**	**Miracle Gro Organic choice bloom booster**	**Bayer Garden Toprose**	**Miracle Gro slow release rose and shrub feed**	**Mean (range) rose and shrub feed**
Description				100% Organic granules for flower beds & borders, roses & bushes, trees, including fruit trees & veg	Rose and shrub feed	Slow release rose and shrub feed	
Total N (%dm)	15.0 (11.9-20.5)	16.1 (6.7-24.9)	9.8	0.0	5.0	15	**2.5 (0-5)**
NO_3-N (%dm)	Trace	Trace	n.d.	n.d.	n.d.	6.4	**6.4**
NH_4-N (%dm)	10.5 (5.5-16.0)	10.9 (5.3-19.3)	n.d.	n.d.	n.d.	8.6	**8.6**
Total P (%dm)	0.7 (0.3-2.0)	0.9 (0.2-5.0)	0.34	0.0	2.6	4.6	**2.4 (0-4.6)**
Soluble P (%dm)	0.1 (0-0.2)	0.3	n.d.	n.d.	0.9	3.6	**2.9 (0.9-3.6)**
K (%dm)	4.7 (1.4-9.3)	3.2 (1.5-5.9)	1.5	30.0	10.0	12.4	**17.5 (10-30)**
Mg (%dm)	0.1 (0-0.48)	0.3 (0.0-3.7)	n.d	10.0	1.5	1.2	**4.2 (1.2-10)**
Mn (%dm)	n.d.	n.d	n.d.	n.d.	n.d.	n.d.	**n.d.**
B (%dm)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Cu (%dm)	0.0032 (0.0019-0.0043)	0.008 (0.002-0.018)	n.d.	n.d.	n.d.	n.d.	**n.d.**
Mo (%dm)	0.0029 (0.0027-0.003)	0.001	n.d.	n.d.	n.d.	n.d.	**n.d.**
Fe (%dm)	n.d.	1.4 (0.16-3.8)	n.d.	n.d.	0.6	n.d.	**0.6**
Zn (%dm)	0.011 (0.007-0.014)	0.024 (0.0004-0.063)	n.d.	n.d.	n.d.	n.d.	**n.d.**

†Estimated using separator efficiency values presented in Lukehurst *et al.* (2010)

Table 7 Digestate nutrient and metal contents compared to commercially available tomato feed (liquid)

Product	Whole digestate (food waste only: DFW)	Whole digestate (contains livestock slurry: DLS)	Digestate liquor (Belt press/ Screw press)†	Miracle-Gro fruit and vegetable concentrated plant food	New Horizon organic range Tomato Feed	Levington Tomorite	Maxicrop Extract of seaweed plus complete garden feed	Maxicrop extract of seaweed plus tomato fertiliser	Mean tomato feed
Description				100% organic liquid for Fruit and Veg (ideal for tomatoes)	Tomato feed	Tomato feed (also sweet peppers & aubergines)	Tomato feed (also sweet peppers & aubergines)	Fertiliser +seaweed extract for flowers, plants and veg	
Total N (%dm)	15.0 (11.9-20.5)	16.1 (6.7-24.9)	7.3	2.0	3.0	4	5.1	5.0	**3.8(2-5.1)**
NO_3-N (%dm)	Trace	Trace	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
NH_4-N (%dm)	10.5 (5.5-16.0)	10.9 (5.3-19.3)	n.d.	n.d.	n.d.	2.8	n.d.	n.d	**2.8**
Total P (%dm)	0.7 (0.3-2.0)	0.9 (0.2-5.0)	1.0	0.86	0.86	2	2.2	2.2	**1.6(0.86-2.2)**
Soluble P (%dm)	0.1 (0-0.2)	0.3	n.d.	0.65	0.43	2	2.2	2.2	**1.5(0.43-2.2)**
K (%dm)	4.7 (1.4-9.3)	3.2 1.5-5.9)	1.5	5.0	4.2	6.6	5.6	4.2	**4.6(4.2-6.6)**
Mg (%dm)	0.1 (0-0.48)	0.3 (0.0-3.7)	n.d	n.d	n.d	6.6	5.6	4.2	**5.5(4.2-6.6)**
Mn (%dm)	n.d.	n.d	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
B (%dm)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Cu (%dm)	0.0032 (0.0019-0.0043)	0.008 (0.002-0.018)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Mo (%dm)	0.0029 (0.0027-0.003)	0.001	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Fe (%dm)	n.d.	1.4 (0.16-3.8)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Zn (%dm)	0.011 (0.007-0.014)	0.024 (0.0004-0.063)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**

†Estimated using separator efficiency values presented in Lukehurst *et al.* (2010)

Table 8 Digestate nutrient and metal content compared to commercially available home garden liquid plant feed

Product	Whole digestate (food waste only: DFW)	Whole digestate (contains livestock slurry: DLS)	Digestate liquor (Belt press/ Screw press)†	Miracle Gro Azelia, camelia and rhodedendron liquid plant food	Maxicrop Extract of seaweed plus flower fertiliser
Description				All ericaceous plants (pH <7)	Fertiliser+seaweed extract for flowers
Total N (%dm)	15.0 (11.9-20.5)	16.1 (6.7-24.9)	7.3	6	5.9
NO_3-N (%dm)	Trace	Trace	n.d.	3.5	n.d
NH_4-N (%dm)	10.5 (5.5-16.0)	10.9 (5.3-19.3)	n.d.	2.5	n.d.
Total P (%dm)	0.7 (0.3-2.0)	0.9 (0.2-5.0)	1.0	1.72	2.1
Soluble P (%dm)	0.1 (0-0.2)	0.3	n.d.	1.72	2.1
K (%dm)	4.7 (1.4-9.3)	3.2 1.5-5.9)	1.5	5.0	5.7
Mg (%dm)	0.1 (0-0.48)	0.3 (0.0-3.7)	n.d	4.98	n.d.
Mn (%dm)	n.d.	n.d	n.d.	0.001 (soluble in water, chelated by EDTA)	n.d.
B (%dm)	n.d.	n.d.	n.d.		n.d.
Cu (%dm)	0.0032 (0.0019-0.0043)	0.008 (0.002-0.018)	n.d.	0.002 (soluble in water, chelated by EDTA)	n.d.
Mo (%dm)	0.0029 (0.0027-0.003)	0.001	n.d.	0.001 (soluble in water)	n.d.
Fe (%dm)	n.d.	1.4 (0.16-3.8)	n.d.	0.06 (soluble in water, chelated by DTPA)	n.d.
Zn (%dm)	0.011 (0.007-0.014)	0.024 (0.0004-0.063)	n.d.	0.002 (soluble in water, chelated by EDTA)	n.d.

†Estimated using separator efficiency values presented in Lukehurst *et al.* (2010)

Table 9 Digestate nutrient and metal contents compared to commercially available turf fertiliser (solid)

Product	**Whole digestate (food waste only: DFW)**	**Whole digestate (contains livestock slurry: DLS)**	**Digestate fibre (Belt press/ Screw press)†**	**Scotts Fairwaymaster**	**Scotts Greenmaster Pro-Lite Extra**	**Scotts Greenmaster Pro-Lite Mosskiller**	**Scotts Greenmaster Pro-Lite Autumn Mg**	**Scotts Greenmaster Pro-Lite Double K**	**Scotts Greenmaster Pro-Lite NK**	**Scotts Greenmaster Pro-Lite Spring & Summer**	**Mean (range) fine solid turf fertiliser**
Description				Granular NPK (solid)	Fine NPK & Zeolite & weed killer (fine solid)	Fine NPK & Zeolite & Mg +Fe & herbicide (fine solid)	Fine NPK & Zeolite + Mg: (fine solid)	Fine NK & Zeolite + Fe (fine solid)	Fine NK & Zeolite + Fe + Mg (fine solid)	Fine NPK & Zeolite +Mg: (fine solid)	
Total N (%dm)	15.0 (11.9-20.5)	16.1 (6.7-24.9)	9.8	20	14	14	6	7	12	14	**12 (6-20)**
Urea (%dm)	n.d.	n.d.	n.d.			8	4.2	4	4.3	8.9	**6 (4-9)**
NO_3-N (%dm)	Trace	Trace	n.d.		8						**8**
NH_4-N (%dm)	10.5 (5.5-16.0)	10.9 (5.3-19.3)	n.d.		6	6	1.8	3	7.7	5.1	**5 (2-8)**
Total P (%dm)	0.7 (0.3-2.0)	0.9 (0.2-5.0)	0.34	5	0.9	0	2.2	0	0	2.2	**1 (0-5)**
Soluble P (%dm)	0.1 (0-0.2)	0.3	n.d.				1.7			1.9	**2**
K (%dm)	4.7 (1.4-9.3)	3.2 (1.5-5.9)	1.5	8	3.3	0	0.091	11.6	10	8.3	**6 (0-12)**
Soluble K (%dm)	1.9 (0-5.7)	3.3	n.d.	n.d.				11.6		8.3	**10 (8-12)**
Mg (%dm)	0.1 (0-0.48)	0.3 (0.0-3.7)	n.d	n.d		8.9	0.5	4	2	0	**3 (0-9)**
Mn (%dm)	n.d.	n.d	n.d.	n.d.			1.8	0	1.8	1.8	**1 (0-2)**
B (%dm)	n.d.	n.d.	n.d.	n.d.	11.2	15.9	5.4	12.8	13	13	**12 (5-16)**
Cu (%dm)	0.0032 (0.0019-0.0043)	0.008 (0.002-0.018)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Mo (%dm)	0.0029 (0.0027-0.003)	0.001	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Fe (%dm)	n.d.	1.4 (0.16-3.8)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**
Zn (%dm)	0.011 (0.007-0.014)	0.024 (0.0004-0.063)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**n.d.**

†Estimated using separator efficiency values presented in Lukehurst *et al.* (2010)

Table 10 Digestate nutrient and metal content compared to commercially available turf fertiliser (liquid)

Product	Whole digestate (food waste only: DFW)	Whole digestate (contains livestock slurry: DLS)	Digestate liquor (Belt press/ Screw press)†	Scotts Greenmaster liquid High N	Scotts Greenmaster liquid Spring and Summer	Scotts Greenmaster liquid High K	Mean (range) liquid turf fertiliser
Description				Liquid	Liquid	Liquid	Liquid
Total N (%dm)	15.0 (11.9-20.5)	16.1 (6.7-24.9)	7.3	25	12	3.0	13.3
NO_3-N (%dm)	Trace	Trace	n.d.	7.3	0.8	0.3	2.8
NH_4-N (%dm)	10.5 (5.5-16.0)	10.9 (5.3-19.3)	n.d.	5.9	11.2	0.3	5.8
Total P (%dm)	0.7 (0.3-2.0)	0.9 (0.2-5.0)	1.0	0	1.7	1.3	1
Soluble P (%dm)	0.1 (0-0.2)	0.3	n.d.	0	1.7	1.3	1
K (%dm)	4.7 (1.4-9.3)	3.2 1.5-5.9)	1.5	0	5.0	8.3	4.4
Mg (%dm)	0.1 (0-0.48)	0.3 (0.0-3.7)	n.d	1.2	0	0	0.4
Mn (%dm)	n.d.	n.d	n.d.	0.01	0.01	0.01	0.01
B (%dm)	n.d.	n.d.	n.d.	0.01	0.01	0.01	0.01
Cu (%dm)	0.0032 (0.0019-0.0043)	0.008 (0.002-0.018)	n.d.	0.004	0.004	0.004	0.004
Mo (%dm)	0.0029 (0.0027-0.003)	0.001	n.d.	0.001	0.001	0.001	0.001
Fe (%dm)	n.d.	1.4 (0.16-3.8)	n.d.	0	0.0	0	0
Zn (%dm)	0.011 (0.007-0.014)	0.024 (0.0004-0.063)	n.d.	0.004	0.004	0.004	0.004

†Estimated using separator efficiency values presented in Lukehurst *et al.* (2010)

4.1.3 Further processing technologies

The major potential applications for digestate in home gardens were: i) use of co-composted digestate fibre as a multi-purpose growing media and ii) use of separated digestate liquor as a turf fertiliser.

However, the dilute concentration of nutrients in digestate liquor means it would be unsuitable for direct use as a home garden product due to the expense and difficulty in handling the product. To improve the product, it would be necessary to concentrate the nutrients; this would improve the economics of transporting digestate liquor. Various membrane filtration technologies, such as reverse osmosis (RO), can potentially be used to concentrate nutrients (Zhang *et al.*, 2004, Kumar *et al.* 2007, Masse *et al.*, 2007).

The state of research on the membrane treatment of manure, and concentration of nutrients was reviewed by Masse *et al.* (2007) at "Agriculture and Agri-Food Canada". Microfiltration (MF) and Ultrafiltration (UF) membranes act as efficient solid-liquid separators that can isolate nutrients such as P associated with particles. Technologies such as nanofiltration and RO are required for concentration of ammonia and potassium.

A laboratory-scale system to treat swine wastewater (15 000 mg l^{-1} volatile solids) with biological conversion, filtration and RO to produce reclaimed water and a concentrated liquid fertiliser was investigated by Zhang *et al.* (2004). The system consisted of an anaerobic sequencing batch reactor (ASBR), one or two aerobic sequencing batch reactors, a sludge settling tank, sand filter and RO unit. The oxidised N was increased to 53% of the total N content after it passed through both aerobic sequencing batch reactors. The sand filter further reduced the chemical oxygen demand (COD) and solids prior to RO treatment. The researchers found that RO was very effective in separating nutrient and salt elements from water; over 70% of NH_3-N, NO_2-N and NO_3-N and over 90% of other elements, such as P, K, Cl, Ca, Mg, Na, Zn, Fe and Cu were concentrated in a liquid effluent with 10% of the original volume. Preliminary analyses by the authors suggested that the biogas energy produced from swine manure was sufficient to meet the energy requirement for operating the wastewater treatment system; however, it was suggested that the system needs to be scaled up and evaluated at pilot and farm scale and costs and benefits analysed.

Masse *et al.* (2007) presented a summary of various commercial systems that have been established for manure concentration:
i) A pilot system in France (the Ecoliz system) that can treat 2 m^3 of swine manure day^{-1} which combines a flocculation step to remove large solids and membrane filtration to concentrate nutrients. The process concentrated manure in 10% of the initial volume; the cost of the system was evaluated at 12 Euros m^{-3} of manure in 2002 (Gérard, 2002 cited in Masse *et al.*, 2007).
ii) New Logic Research (http://www.vsep.com/) have developed the vibratory shear enhanced process (VSEP) for manure purification. The system has been demonstrated using pig manure (Johnson *et al.*, 2004); the effluent (1.9% TS) from an anaerobic digester treating pig manure was concentrated in about 20% of the initial volume. The Zn, Na, Mn, Mg, Fe and Cu were removed, whilst retention of potassium, phosphorus, Cl and Ca ranged between 98-99%. Ammonia and sulphate were retained at 94.5% and 93.4% respectively. The technology uses vibration to minimise membrane fouling, thereby minimising flux reduction. The technology has been installed on two commercial farms in Korea and the Netherlands (Johnson *et al.*, 2004).
iii) The company 'Purin Pur' installed a pilot membrane system was installed on a pig farm in Canada (Charlebois, 2000 cited in Masse *et al.*, 2007). The system used a screen for coarse SS and P retention and tubular RO membranes for final treatment. The cost of the system was evaluated at 5.97 Can$ m^{-3} manure. However the pilot plant was not extensively used as the membranes became rapidly fouled.
iv) The company Bioscan have designed and tested the Biorek® hybrid membrane bioreactor process for treatment of manure (Norddahl and Rohold, 2000, cited in Masse *et al.*, 2007; du Preez *et al.*, 2005). The system consistes of a mesophilic anaerobic digester coupled to ultrafiltration for biomass retention, ammonia and carbonate stripping and reverse osmosis (3.2 MPa, 35-40^{o}C) of the product from the stripper for concentration of P and K. Removal of ammonia and carbonate increase the permeate quality and prevent scaling on the membrane.

A further barrier to the use of digestate liquor as a turf fertiliser in public spaces is potential odour which may cause offence. A potential method for reducing odour may be stabilisation with iron or aluminium salts (eg. $Al_2(SO_4)_3$ or $FeCl_3$) (Novak *et al.*, 2007, Novak *et al.*, 2009). This is an area which may require further investigation if digestate liquor is judged to have an offensive odour.

4.1.4 Market information

The competing products for home garden use are both chemical fertilisers and products which are organic in origin such as sterilised bonemeal, fishmeal or bloodmeal (see Tables 2-10). Key players in the garden chemicals and growing media sector and their brand names are presented in Table 11. The total revenue of the garden products market in 2009 was £5.38m this increased to £5.48m in 2010, an increase of 5.8% (Mintel, 2010). Fertilisers and growing media represent 30% of the market, equivalent to £1.74m (Mintel, 2010).

Table 11 Key players in the garden chemicals and growing media sector, August 2007 (Mintel, 2007)

Companies	Brand names
Monro Group (Growing Success Organics Ltd)	Growing Success
The Scotts Miracle-Gro Company	Miracle-Gro, Levington, Evergreen, Roundup, Weedol, Pathclear, Clear, Nature's Answer, Scotts
Westland Horticulture	Garden Health
William Sinclair Horticulture Ltd	J Arthur Bowers, New Horizon
Bayer CropScience Ltd	Baby Bio, Bayer Garden, Phostrogen
Doff Portland Ltd	Doff, Green Fingers Organics
Joseph Metcalf Group	Gem, Cambark, Debco

Garden products are stocked by DIY multiples (33%), garden centres (30%), non-DIY multiples (15%), mail order/direct response (14%) and other sources (8%) (Mintel, 2010).

The leading product to the amateur market is multi-purpose compost (Evans, 2009) of which peat is frequently a major constituent. The UK government is committed to reducing peat use under the Biodiversity Action Programme (Defra, 2007b). In 2007, the total volume of peat and alternatives used in soil improvers and growing media was 6.61 million m^3 (~15.2 million tonnes). The overall proportion of peat in the products fell from 53% to 46% and the proportion of alternatives rose to 54%. The greatest consumption of peat was by amateur gardeners (69%) (Defra, 2007b), who use the greatest amount of growing media and soil improvers (60%), compared to landscape contractors and professional growers.

(TERRA ECO-SYSTEMS at Thames Water successfully produced a growing media from composted biosolids that sold at the same price as the brand-leading peat-based media (Evans, 2009). The product was sold nationwide and sales doubled year on year (Evans, 2009). Market research by TERRA ECO-SYSTEMS in 1995 revealed that gardeners looked favourable upon green products, but were concerned that they must perform as well as peat-based products, be good value for money and easy to use. However, Evans (2009) did not recommend composting biosolids for domestic use as a route forwards for wastewater treatment plant operators, one of the reasons being that any change in feedstock to the process may require re-formulation and further testing, which may take considerable time. Therefore, if digestate fibre was to be co-composted as a garden fertiliser it would be essential to have a consistent feedstock to ensure low variability in compost properties.

4.2 Horticulture: Landscaping

4.2.1 Physico-chemical requirements

Digestate has potential for use in commercial horticulture for landscaping purposes as the organic matter content may improve soil structure, water holding capacity and cation exchange capacity (*CEC*). Products are tailored to the clients' requirements and contain varying amounts of organic matter, frequently a 50/50 mix. Currently the organic materials used include composted green cuttings, spent mushroom compost or composted farmyard manure. Co-composted separated fibre would provide an excellent source of organic matter to use in manufactured soils for landscaping. The consistency of the co-composted fibre properties would be of less importance than compost used for the domestic garden market.

4.2.2 Barriers to use

Composted separated fibre presents minimal microbiological, chemical and physical risks and is likely to have an inoffensive odour as discussed in Section 4.2.2.

4.2.3 Market

Horticultural companies such as 'Monro Horticulture Ltd.' and 'CH Binder and Sons' produce engineered soils from loam combined with organic compost. There is potential for the market to expand; for example, extensive projects such as preparation of the site for the London Olympics require artificial soil for landscaping (John Adlam, HTA, *pers. comm.*).

4.3 Horticulture: Commercial fruit and vegetable production

4.3.1 Physico-chemical requirements

As discussed in Section 4.2.1 the nutritional composition of digestate may not be suitable for fruit and vegetable production without supplementing with additional nutrients. John Adlam, technical advisor to the horticultural trade association (HTA), advised that PAS100 green compost is currently be used for mulching of apple trees. Therefore, composted separated fibre from digestate could be used for a similar purpose.

4.3.2 Barriers to use

Composted separated fibre presents minimal microbiological, chemical and physical risks and is likely to have an inoffensive odour as discussed in Section 4.2.2.

4.4 Horticulture: Compost teas

4.4.1 Physico-chemical requirements

The use of compost teas in the production of a wide range crops has become popular in the UK (John Adlam, HTA, *pers. comm.*). This involves use of a 'broth' of microorganisms such as fungi, nematodes, bacteria and protozoa to improve soil ecology and hence soil health, productivity and plant health. Companies producing compost teas include the Dutch company 'Van Irsal', 'Martin Lischman Ltd.' and 'XL horticulture' who produce a product called "Revitealise". Digestate separated fibre could potentially be used as a feedstock for the composting process from which compost teas are produced.

4.4.2 Barriers to use

Composted separated fibre presents minimal microbiological, chemical and physical risks and is likely to have an inoffensive odour as discussed in Section 4.2.2.

4.5 Horticulture: mushroom growing media

4.5.1 Physico-chemical requirements

The use of waste materials in horticultural growing media has been investigated extensively at the Applied Crop Research Centre, Wellesbourne, Warwick. An investigation of straw types and N sources on compost productivity (Noble *et al.*, 2002) demonstrated that digestate did not compete with animal manures as the N and C were less available. However, the digestate used had a total N content of only 2.8% of which only 36% was present as ammonia-N. In comparison the data presented in Tables A3 and A4 demonstrate that digestate generally has a much greater total N content (15-16%) and an available N content >50%. Further research may be required to investigate composting digestate; reproducibility of the properties of the product may pose a problem as a consequence of feedstock variability.

4.5.2 Barriers to use

Composted separated fibre presents minimal microbiological, chemical and physical risks and is likely to have an inoffensive odour as discussed in Section 4.2.2.

4.5.3 Market

The mushroom industry may be the largest user of composted organics in the UK (John Adlam, HTA, *pers comm.*).

4.6 Horticulture: Commercial nurseries/herbaceous shrubs

4.6.1 Physico-chemical requirements

As discussed in Section 4.2.1 the nutritional composition of digestate may not be suitable for tree and shrub production without supplementing with additional nutrients. However, composted separated fibre from digestate could be used to improve soil structure, water holding capacity and *CEC*. Whole digestate or separated liquor could be used to irrigate the trees and shrubs with N. Separated liquor would be more suitable due to greater ease of infiltration into the soil and, therefore, more efficient use of nutrients. However, supplemental P and K would be required so digestate liquor is not ideally suited to this purpose.

4.6.2 Barriers to use

Composted separated fibre presents minimal microbiological, chemical and physical risks and is likely to have an inoffensive odour as discussed in Section 4.2.2. Leaching or runoff of N and P, and subsequent contamination of water sources, or gaseous emissions of N are potential hazards from the use of whole digestate or separated liquor. Leaching of N should not pose a greater risk than currently commercially available fertilisers. Nitrogen in digestate is present in both organic and mineral forms; hence, the slow release nature of the N will result in a lower risk of nitrate loss during leaching events. Use of separated liquor as opposed to whole digestate will improve infiltration into the soil and should reduce runoff or erosion of nutrients and gaseous emissions of ammonia.

The use of digestate on trees and shrubs eliminates the risk of ingestion of contaminants on crops or soil and thus provides a further barrier to exposure to contaminants.

4.7 Forestry

4.7.1 Physico-chemical requirements

Discussion with a Forestry Commission contact (Andrew Moffat, Forestry Commission, *pers. comm.*) suggested that there was little requirement for organic fertiliser materials in management of broadleaved woodland, although there may be some fertiliser use for commercial conifer woodland. Therefore, irrigation of woodland with separated liquor is a possibility, although supplementation with P and K may be required, so digestate liquor is not ideally suited to this purpose.

It was suggested that the majority of fertiliser use was in 'urban forestry'; therefore the amenity/landscape category has the greatest potential for use of digestate. There is likely to be use of fertilisers, compost and some mulch in 'urban forestry' or tree planting for landscape and amenity purposes, notably on brownfield land. The Forestry Commission guidance on use of biosolids and composts is found at http://www.forestry.gov.uk/PDF/fcin079.pdf/$FILE/fcin079.pdf and recommends PAS100 compost use. Therefore, composted, PAS 110 compliant, separated fibre has potential for use in 'urban forestry'.

4.7.2 Barriers to use

See 4.6.2.

4.8 Use on publically owned flower beds/green spaces

4.8.1 Physico-chemical requirements and Market information

A survey of 34 parks and gardens departments of London local authorities and their contractors was conducted; thus far 10 London Boroughs have provided information and the findings are presented in Appendix 2, Table A14. Currently, and without exception, local authorities aim to recycle green waste generated within the parks and gardens and from trees in the borough and the waste is composted or mulched and used as a bedding material. Hence, there is potential for composted separated digestate fibre to be used as a bedding material in publically owned parks and gardens and for mulching trees. The findings suggest that there is not currently a requirement for additional organic material for this purpose in London Boroughs as they have sufficient of their own material. However, there may be a requirement for this sort of material by other local governments.

Generally, within the London Borough Parks and Gardens the only areas on which mineral fertilisers are used are sports pitches and recreation grounds. The turf fertilisers used have a range of NPK contents, but generally have a high N:P or N:K ratio (See response from London Borough of Hammersmith and Fulham in Table A14, detailing nutrient specification of turf fertilisers). The NPK ratio of digestate is therefore within the range currently used as turf fertiliser and may act as a suitable replacement for mineral fertilisers as discussed in Section 4.1.1. in relation to fertiliser use in domestic gardens. Separated liquor would have the most appropriate physical properties as it would infiltrate the soil more readily due to the lower DS content. The nutrients are present in low concentrations as discussed in Section 4.1.1. This may not pose a problem as the dilute digestate liquor would represent a source of water for irrigation plus nutrients for fertilisation. Presumably the fine solid chemical fertilisers currently used on sports pitches are currently dissolved in water prior to application. However, economics of supplying digestate liquor for public green spaces mean that this practice may not be viable unless transport costs were low.

Replacement of the inorganic fertilisers currently used with separated liquor would allow London Boroughs to further achieve their aim of increasing the use of recycled materials.

4.8.2 Barriers to use

Use of composted fibre as a bedding material in parks and gardens presents a low risk. Composted separated fibre presents minimal microbiological, chemical and physical risks and is likely to have an inoffensive odour as discussed in Section 4.2.2.

Use of separated liquor as turf fertiliser would prevent the risk of ingestion of hazardous organisms in contaminated soil or crops. Appropriate codes of practice could be instigated for contractors if necessary.

Concentrations of organic contaminants and PTEs in digestate were low, and use of separated liquor as turf fertiliser would not present the risk of any potential ingestion of PTEs in contaminated soil or crops.

Separated liquor may have some odour and investigation may be required to determine whether this is considered unpleasant or offensive before it could be used in publically owned green spaces.

There is a risk from increasing soil salinity through use of separated liquor as a turf fertiliser. Therefore, the product instructions may need to recommend the use of fertiliser only 2-3 times during a growing season. There is no data available on the salinity of separated liquor; this would be useful to assess its suitability for use as a turf fertiliser.

4.9 Use as fertiliser for organic crops and farms

Certified inputs are products suitable for use in organic farming and growing systems, such as fertilisers or soil conditioners and must comply with the 'Soil Association organic standards for producers' and produced to the 'Soil Association organic standards for processors'. The producer and processor standards are available for download at www.soilassociation.org/organic standards.aspx. However, it is unlikely that fertilisers containing digestate could be certified as organic due to the requirement for non-GM ingredients. When digestates are produced from a mixture of food wastes it is would not be possible to exclude any wastes with GM ingredients.

4.10 Nutrient extraction

4.10.1 Struvite Recovery

A number of technologies exist to extract nutrients from digestate (eg. Struvite Recovery) which can be used directly as a high-value fertiliser. This recovers vital nutrients, such as P which is a limited resource, and provides added economic value to the digestion process. These processes are at various stages of development. For example, a struvite recovery system is in operation at Thames Water wastewater treatment plant in Slough (UK - Latest News - http://www.prlog.org/tag/uk/).

4.10.2 Nutrient extraction and fuel production

'GG Eco Solutions' is a Swedish technology developed to treat horse manure. It is a dewatering and nutrient extraction process, which produces biomass fuel pellets and biofertiliser pellets. The technology can also be applied to digestate of sewage sludge, food waste and energy crops and pilot plants have been established in Sweden. There are no constraints on the physico-chemical requirements of the digestate, and DS contents between 3-50% are suitable. The material should be free from contaminants (metal, plastic) and low in heavy metal content (Carl Aitken, Bidwells, *pers.comm*). An example, provided by Bidwells, suggested that 20,000 t of food waste with a dry solids content of 3.9%, produces an output of 913 tonnes of biomass fuel pellets and 645 tonnes of biofertiliser pellets. The NPK concentration of feedstock (17:1:6) given in GG Eco Solution's example is similar to the content measured in this study (15:1:5) and the DS content (3.9%) is also within the range measured in this study.

The first commercial installation is being undertaken at Helsingborg in Sweden. It will be commissioned at the end of December with full operation by mid January 2011. The plant will treat digestate of sewage sludge and the capacity will be 15 000 m^3 yr^{-1}. The fertiliser output is intended for use in agriculture and forestry in Sweden (Carl Aitken, Bidwells, *pers.comm.*).

The capital cost of the technology is dependent on the material to be treated. In the example provided by GG Eco Solutions for an energy crop digestate the capital cost is ~£400,000. The value of the output may vary but typical values for biomass fuel pellets are in the range £80-£120 t^{-1}, and for biofertiliser £80-£150 t^{-1} (Carl Aitken, Bidwells, *pers.comm.*).

4.10.3 Algal growth for nutrient removal

A potential method of nutrient extraction from organic wastes is the production of proteinaceous biomass by cultivating algae in engineered ponds (Baumgarten *et al.* 1999; Mulbry and Wilkie, 2001; Wilkie and Mulbry, 2002; Kebede-Westhead *et al.*, 2003). This increases the value and manageability of the nutrients. Harvested algal biomass is a high-grade protein which can be used as an animal feed; dairy cows fed a diet supplemented with algae may show an increase in omega-3-fatty acid content, which has the potential for improving consumer health (Wilkie and Mulbry, 2002). The algal biomass can also be used as a slow release fertiliser with reduced risk of losing nutrients to the environment by leaching or gaseous emissions of ammonia (Mulbry and Wilkie, 2001; Wilkie and Mulbry, 2002). The use of algal biomass as a feedstock for biofuel production also has major potential; The Carbon Trust is conducting research to investigate increasing oil yield from selected algal species and investigating methods to reduce costs for harvesting the oil (see http://www.carbontrust.co.uk/emerging-technologies/current-focus-areas/Algae-biofuels-challenge/pages/research-partners.aspx). The market for biofuels is discussed further in Section 4.12.

Research conducted by the 'Carbon Trust' and partners indicated that the most commercially viable and sustainable route to produce algae biofuels is to culture algae in mixed shallow salt/brackish water open ponds (or 'raceways') (Carbon Trust, 2010). Algal turf scrubbers (ATFTM) were designed by Water Adey and colleagues at the Smithsonian institute in the 1970s. They were developed as water quality control devices on coral reef, rocky shore, estuary and stream and pond microcosms and mesocosms (Craggs *et al.*, 1996; Adey and Loveland, 1998). They have also been used to remove nutrients from agricultural run-off (Craggs *et al.*, 1996). The wastewater treatment technology is a simple, low-cost system, which cultures attached or benthic bacteria, microalgae and filamentous algae on an inclined flow-way (Craggs *et al.*, 1996). The main components of the ATS system are a solid support for the growth and harvest of benthic algae, wave surge and optimal light (Mulbry and Wilkie, 2001). The advantages over planktonic algae ponds are that, if there is sufficient light, much higher rates of photosynthesis are achieved and it is easier to separate and remove the algal biomass. To harvest the algae, the flow of wastewater is stopped, the flow-way is drained for 1h and the biomass is vacuumed from the surface. This technology is already established commercially for wastewater treatment and water purification and is described in detail in "Dynamic Aquaria Building and Restoring Living Ecosystems. 3rd Edition" (Adey and Loveland, 2007).

Researchers at the USDA and Florida University have adopted Algal Turf Scrubber technology to recover nutrients from several types of dairy manure (Mulbry and Wilkie, 2001; Wilkie and Mulbry, 2002; Kebede-Westhead *et al.*, 2003). The technology is an effective solution for treating manure and recycling the nutrients on-farm; the combination of conventional cropping systems with an ATS could achieve more efficient crop production and farm nutrient management. Filamentous algae are capable of year-round growing in temperate climates and can be harvested on adapted farm-scale equipment. Mulbry and Wilkie (2001) conducted a study to investigate the adapted ATS system to remove N, P and other constituents from raw and anaerobically digested manure. Before digestion, the manure undergoes solids separation followed by anaerobic digestion of the separated liquids. A typical manure input contained 0.6-0.9 g total N day^{-1}, the dried algal yield was approximately 5 g m^{-2} day^{-1}. The dried algae contained approximately 5-7% N and 1.5-2% P. Algal N and P accounted for 33-42% of total N and 58-100% total input P. The technology was effective when anaerobically digested manure was used as a feedstock and the improved bioavailability of manure nutrients during anaerobic digestion was beneficial for algal production. Further research demonstrated that mean algal production increased with increased loading rate (0.8-3.7 g total N and 0.12 to 0.58 g total P m^{-2} day^{-1}) and irradiance (from 270-390 µmol photons m^{-2} s^{-1}) from approximately 8-19 g dry weight. The N and P content of the algal biomass and the recovery of nutrients by the algal biomass also increased with loading rate.

The N content of the manure used in these ATS studies was approximately three times less than the N content measured in DFW or DLS (Tables A3 and A4), and the P content was approximately half the P content measured in DFW or DLS (Tables A5 and A6). However, this should not pose a problem as ATS loading rates are based on the N and P content. The N:P ratio of the digested manure used by Mulby and Wilkie (2001) was between 9-10, whereas the N:P ratio of DFW and DLS is approximately 18-21. However, the N:P ratio of separated liquor, calculated from the estimated values in Table A7, is close to the values from Mulby and Wilkie's study at approximately 9.

The cost of drying and harvesting algae may present a barrier to implementing the technology; however, the researchers suggest that when the technology is used in conjunction with anaerobic digestion where energy is recovered from manure, the cost of drying harvested algae could be minimal. The N:P ratio of separated digestate liquor may need further investigation as it could impact the species composition of the algal turf. A further potential barrier would be if heavy metals or other contaminants from digestate are taken up or become more concentrated by the algae, this requires further investigation. An economic assessment of potential markets for the algae is required to determine if this technology could be adopted for beneficial use of digestate.

4.11 Construction material

Researchers at Michegan State University are developing construction materials from dried manure fibres of anaerobically digested animal manure (Jenner *et al.*, 2008; Spelter *et al.*, 2008; Winandy and Cai, 2008). They are working to develop medium density fibreboards (MDF) and wood-plastic composites (WPC). This technology has not been applied to anaerobically digestate food waste; however, it is likely that due to the similarity in composition this would be possible. The fibres are dried and blended with a 15% liquid UF resin and then pressed and formed into panels. This is the same as the process used to treat wood flour to produce panels; the researchers have demonstrated that the manure fibre panels have comparable bending strength, stiffness and internal strength (Caldwell, 2008). Further investigation is required to determine how well paint adheres to the fibreboards and expand the process to a larger scale.

The economic potential of using anaerobically digested bovine biofibre for construction materials has been investigated by the researchers (Spelter *et al.*, 2008); this indicated that it is a less economically favourable option than current uses for bovine biofibre (bedding). However, this could be overcome by larger scale and longer-term contractual arrangements with a secure long-term outlet for the digestate fibre.

4.12 Fuel

4.12.1 Cellulosic Ethanol Production

Bioethanol is the primary fuel used as a petrol replacement for road transport vehicles and is produced by sugar formation; the major source of sugar for bioethanol production is from energy crops. However, waste biomass is a source of cellulose, lignocellulose, polysaccharides, proteins and other organic materials that can be used as a low cost feedstock for enzymic hydrolysis to produce sugar for subsequent fermentation to bioethanol (Champagne and Li, 2009; Yue *et al.*, 2009).

The enzymic hydrolysis of cellulose is carried out by cellulase enzymes, such as the enzyme complex derived from the filamenous fungus Trichoderma Reesei (Champagne and Li, 2009). The rate and extent of cellulose hydrolysis by cellulase enzymes is influenced by substrate and enzyme factors and operational conditions. Pre-treatment processes may be used to improve sugar yield, minimise the loss of carbohydrates and minimise the formation of inhibitory by-products for hydrolysis and fermentation processes (Champagne and Li, 2009). These pre-treatment processes may include: i) physical pre-treatment to subdivide lignocellulose material into fine particles which are more susceptible to hydrolysis; ii) alkaline hydrolysis to increase internal surface area by separation of structural linkages between the lignins and carbohydrates and iii) acids, which act as catalysts for cellulose hydrolysis by increasing the rate of solubilisation resulting in higher conversion yields of cellulose to sugars.

The main components of digestate fibre are two carbohydrate polymers, cellulose and hemicellulose, which form the main structure of the biomass, and lignin, which binds the fibres together (Champagne and Li, 2009; Yue *et al.*, 2009). Previously, it has been assumed that digestate fibre is unsuitable for further conversion to other useful energy or chemical products because the more labile fractions of organic matter are degraded during digestate leaving a higher proportion of more recalcitrant molecules (Tambone *et al.*, 2009). However, recent research by Yue *et al.* (2009) demonstrated that, in fact, AD changes the composition of manure fibre and improves its suitability as a cellulosic feedstock for ethanol production. There was a lower concentration of hemicellulose in anaerobically digested manure fibre (12%) compared to raw manure (17%), and a greater concentration of cellulose (32% compared to 22%). Digestate was shown to have greater digestibility than switchgrass, commonly used as a feedstock for cellulosic ethanol production. The optimal pre-treatment process was dilute alkali (2% sodium hydroxide, 130^{o}C for 2 hours). Enzymatic hydrolysis of 10% (dry basis) pretreated digestate fibre produced 51 g l^{-1} glucose at a conversion rate of 90% (glucose conversion rate (%) = glucose content [g]/(1.1xcellulose in sample [g]) x 100). The fermentation of the hydrolysate had a yield of 72% ethanol.

The digestate fibre samples used by Yue *et al.* (2009) for the enzymatic hydrolysis process and subsequent ethanol fermentation were digested manure from a dairy farm with the following characteristics: dry matter content of 28.1%; 32.3% cellulose; 11.6% hemicellulose; 25.1% lignin; 7.5% crude protein; 48.4% C; 1.2% N; 0.36% ammonia; C:N ratio of 40.3; pH of 9.2% and total alkalinity of 400 mg $CaCO_3$ l^{-1}. The authors calculated that, for every dry tonne of cattle manure, 0.6 dry tonnes of digestate fibre could be produced, which could be used to produce 6.3 m3 of ethanol.

4.12.2 Biodiesel production

Biodiesel is a fuel produced by transesterification of fats with methanol, and has the potential to replace fossil diesel (Angerbauer *et al.*, 2004). An alternative to anaerobic conversion of organic wastes to methane and CO2 is to convert the C to lipids by aerobic microorganisms, lipid accumulating yeasts. The lipids can then be used as a raw material for the production of biodiesel. However, there is little potential to produce biodiesel from digestate as a basic requirement is a high C:N ratio of ~100, which is not met by digestate (Table A3 and A4). However, there may be potential for production of biodiesel from algae cultured from digestate.

4.12.3 Digestate as solid fuel

Researchers in Germany have investigated the potential of using dried, pelletised digestate as a solid fuel. Kratzeisen *et al.* (2010) used two different digestates as test fuel. The feedstock composition of digestate 1 was:

50% maize silage; 40% grass and grass silage and 10% potatoes, and digestate 2 was: 81% maize silage; 9% sugar sorghum/sudan grass silage; 7% poultry manure and 3% corn cob mix. The digestate was dewatered using a decanter to a dry matter of 25%, the digestate was then dried in a drum dryer using waste heat from biogas production to 80-85% dry matter. The calculated ratio between the total energy input for the production of digestate pellets and the net calorific value was 0.74 for digestate 1 and 0.78 for digestate 2.

Kratseisen *et al.* (2010) showed that the net calorific value of digestate 1 was 15.8 MJ kg^{-1} at a water content of 9.2% and for digestate 2, the calorific value was 15.0 MJ kg^{-1} at a water content of 9.9%. This is similar to the net calorific value of 16.3% from fuel pellets produced of pinewood with a water content of 12%. The N content of the pellets produced by Kratzeisen *et al.* (2010) was high in comparison to the German standards for solid fuels at 2.86% for digestate 1 and 1.54% for digestate 2. This is potentially a problem if the concentration of nitrogen oxide during combustion is increased. There is also a risk of noxious emissions of sulphur (S) and chlorine (Cl) if concentrations in the fuel are high. At concentrations of 0.3-0.9% S and 0.27-0.84% Cl, the concentrations measured by Kratzeisen *et al.* (2010) exceeded the threshold values of 0.08 and 0.03 in the German standards. Given the concentrations of 15-16.1% N, 0.33-0.9% S and 2.32-3.9% Cl measured in whole liquid digestate (Tables A2-A3), then there may be a risk of noxious N, S and Cl emissions if used as solid fuel, depending on partitioning of nutrients when digestate is dewatered and dried. In the study conducted by Kratzeisen *et al.* (2010), several of the heavy metals in the fuel pellets also exceeded threshold values for solid fuels given in German standards: As (threshold 0.8 mg kg^{-1}); Cr (threshold 8 mg kg^{-1}), Cu (threshold 5 mg kg^{-1}), Hg (threshold 0.05 mg kg^{-1}) and Zn (threshold 100 mg kg^{-1}), whereas Cd and Pb were below the thresholds of 0.5 mg kg^{-1} and 10 mg kg^{-1} respectively. By these standards, the heavy metal content of DFW and DLS presented in Tables A8 and A9 would also be high. However, in the experiment conducted by Kratzeisen *et al.* (2010), despite several elements in the solid fuel surpassing threshold values, the emissions of flue gas were within defined limits for biofuels. Following combustion of digestate fuel pellets, nutrients remain in the ash, which can be recycled as fertiliser. However, heavy metals such as cadmium, lead, zinc and mercury may also be found in the filter ash.

The authors concluded that the digestates investigated in the study could be recommended as a fuel for combustion due to their calorific value, ash properties and the emissions, which allow their use in the solid biomass combustion unit used for the study. However, they recommend that, as chemical composition and physical properties of digestate fuel pellets depend on the blend of feedstock used for biogas production, further investigations are required to cover a broader range of digestates and combustion techniques.

4.12.4 Market Information

The main biofuels likely to be supplied into the UK market over the next 5 years are bioethanol and biodiesel (AEA Technology Ltd, 2010). The government has initiated support mechanisms such as the Renewable Transport Fuels Obligation (RTFO) to promote production and utilisation of biofuels as they are not commercially competitive with fossil fuels.

A summary of UK biofuels production is presented in Table 12; the proportion of biodiesel and bioethanol from UK sources is 32% and 24% respectively, indicating there is potential for UK production to increase. Capacity for biodiesel production was reduced in 2010 due to adverse market conditions, uncertainty surrounding the value of RTFCs and potential changes to sustainability requirements when the EC Renewable Energy Directive is introduced (AEA, 2010). The production capacity for biodiesel in 2010 was estimated at 464 million litres. The bioethanol production capacity was estimated at 494 million litres for 2010, rising to 1100 million litres in 2012 and possibly to 1700 million litres after 2010 (AEA, 2010). The majority of biofuels are used in the UK road market, small quantities are exported and small quantities are going into the UK heat and power market (AEA, 2010).

Table 12 Summary of UK biofuels production (reproduced from AEA, 2010)

Biofuel	Estimated UK production 2009, million litres	Total biofuel supplied to UK road market in 2009, million litres	% of biofuels from UK sources	% of biofuels frojm UK sources in UK fossil equivalent supply
Biodiesel	223	1044	32	0.9
Bioethanol	76	317	24	0.4

Current forecasts predict that 70 billion litres per year of fossil fuels could be displaced by algae biofuels worldwide in road transport and aviation, by 2030; this is equivalent to a market value of over £15 billion (Carbon Trust, 2011).

4.13 Biopesticides production

Replacing chemical insecticides with biological agents for pest control is desirable to improve environmental quality, food safety, human and animal health (Yezza *et al.*, 2006). The most common bacteria used to produce biological insecticides is *Bacillus thuringiensis* (Saksinchai *et al.*, 2001; Yezza *et al.*, 2006). These biological pesticides consist of spore/crystal mixtures which are formed after vegetative growth (Saksinchai *et al.*, 2001). Biopesticides are produced commercially by batch fermentation on media such as soybean meal, fish mean of corn steep liquor plus glucose or soluble starch (Saksinchai *et al.*, 2001). However, the raw materials for production of *Bacillus thuringiensis* based biopesticides may not be locally available (Saksinchai *et al.*, 2001) and may represent a substantial proportion of the overall production cost (Yezza *et al.*, 2006). Therefore, several investigations have been undertaken to investigate the use of high yielding, low-cost and year round available raw materials for biopesticides production, such as spent brewer's yeast (Saksinchai *et al.*, 2001), starch industry wastewater, slaughterhouse wastewater (Yezza *et al.*, 2006), secondary sludges from wastewater treatment plants (Brar *et al.*, 2005, Verma *et al.*, 2005, Yezza *et al.*, 2006). It seems that there may, therefore, be potential to produce biopesticides from anaerobically digested food and farm waste. However, the medium composition has a significant impact on the insecticidal activity of biopesticides and different C and N sources and C:N ratios change the shape, composition and δ-endotoxin content of the toxin crystal affecting the entomotoxic activity (Yezza *et al.*, 2006). Therefore, detailed investigation into the suitability of digestate as a growth medium is required.

5.0 Summary

Currently, the major outlet for liquid digestate is agricultural application and research is required to investigate the suitability of liquid digestate products for other purposes such as use in home gardens, growing media preparation, turf establishment or roadside grass establishment. Expanding the market for liquid digestates beyond agricultural application is important to generate increased opportunity for reuse of biodegradable waste and production of bioenergy. This is necessary to achieve government targets for reduction of biodegradable waste sent to landfill (CEC, 1999) and increasing the proportion of energy generated from renewable sources (CEC, 2009).

This report presents the findings of a three month project to investigate new markets for digestate. The applications with the most potential for commercialisation were:

Underway (Technology developed and commercialised but further work is required to establish technology on a wider scale):

- Extraction of nutrients and production of solid fuel using (for example) the 'GG Eco Solutions' process. The extraction of nutrients in a concentrated form has the advantage of producing a reliable and marketable biofertiliser product. A commercial plant has been established in Sweden treating anaerobically digested sewage sludge, and a pilot plant is under development in the UK. Further work is required to demonstrate the process for a variety of AD feedstocks produced in the UK and to investigate the economics of the process/develop markets for the products.

Promising (technology not yet developed for management of digestate on a commercial, economically viable scale):

- Landscaping and urban forestry: digestate fibre, co-composted with straw or woodchips, has potential for use in landscaping, for example, production of artificial soils for the development of sites for major projects such as the Olympics site or roadside verge construction. Alternatively, it could be used as a bedding material for urban tree planting. These applications have the advantage that, unlike composts to be used as a multi-purpose growing media in domestic horticulture, there would not be such a great requirement for consistency in the compost properties. Instead, the co-composted fibre would be provided in large batches for individual projects.
- Turf fertiliser: separated liquor could be used for turf on publically owned sports grounds and other green spaces as the NPK ratio is equivalent to chemical fertilisers currently used for this purpose. In addition to nutrients digestate liquor would also supply water for irrigation. However, this may not be an economically viable solution if the transport costs for the large volumes of liquid outweigh the benefit from the nutrients. Further research is required to investigate methods of concentrating the nutrients such as use of membrane

technology. Any odour from the digestate liquor would present a barrier to application in public spaces; this is also an area requiring investigation.

- Algal culture: separated digestate liquor may represent a feedstock for culture of algal in engineered raceways; this improves the manageability of the nutrients from the digestate and may also produce some reclaimed water. The algae has potential for use as animal feed/fertiliser or a feedstock for biofuels production.
- Construction material: digestate fibre can be used to produce MDF or WPCs, however the economic potential of this technology is unknown.
- Fuel: there is potential to use digestate liquor or algae cultured from digestate liquor as a feedstock for biofuels production, cellulosic bioethanol in particular. Furthermore, depending on various legislative issues, there is market potential for an increase in bioethanol production.

References

Adey W, Loveland K, 1998. *Dynamic Aquaria: Building Living Ecosystems*, second ed. Academic Press, San Diego, CA, 498p.

AEA Technology plc. 2010. UK Production of Biofuels for Transport. Report to Department of Energy and Climate Change [online]. Available at https://restats.decc.gov.uk/cms/assets/Uploads/Results_2009/RestatsUKBiofuelsProduction2009Abstract27July10.pdf. Last consulted February 8, 2011.

Angerbauer C, Siebenhofer M, Mittelbach M, Guebitz GM, 2008. Conversion of sewage sludge into lipids by Lipomyces starkeyi for biodiesel production. *Bioresource Technology* 99, 3051–3056.

Barber WPF and Lancaster R, 2009. Quantifying the impacts of co-digestion of waste streams with sewage sludge. *Proceedings of the CIWEM/Aqua Enviro 14th European Biosolids and Organic Residuals Conference, Leeds, UK, 9-11 November 2009* [on pen drive].

Baumgarten E, Nagel M, Tischner R, 1999. Reduction of the nitrogen and carbon content in swine waste with algae and bacteria. *Applied Microbial Biotechnology* 52, 281-284.

BSI (British Standards Institution), 2010. PAS 110:2010 Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials, BSI [online]. Available at http://www.wrap.org.uk/farming_growing_and_landscaping/producing_quality_compost_and_digestate/bsi_pas_110_.html. Last consulted September 2010.

Caldwell E, 2008. From digester to backyard deck: turning manure fibers into construction material. Ag Nutrient Management [online]. Available at http://progressivedairy.com/anm/features/2008/0608/0608_caldwell.html.

Carbon Trust, 2011. Algal Biofuels Challenge [online]. Available at http://www.carbontrust.co.uk/emerging-technologies/current-focus-areas/algae-biofuels-challenge/pages/algae-biofuels-challenge.aspx. Last consulted February 8 2011.

Charlebois Y, 2000. Du lisier change en eau potable (Liquid manure changed into drinking water). La Terre de chez nous, 71, 1-2 cited in Masse L, Massé DI, Pellerin Y, 2007. The use of membranes for the treatment of manure: a critical literature review. *Biosystems Engineering* 98, 371-380.

Craggs RJ, Adey WH, Jessup BK and Oswald WJ, 1996. A controlled stream mesocosm for tertiary treatment of sewage. *Ecological Engineering* 6, 149-169.

CEC: Council of the European Communities, 2009. Directive 2009/28/EC of the European parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. *Official Journal of the European Communities*, No. L140/16-62.

Champagne P and Li C, 2009 Enzymatic hydrolysis of cellulosic municipal wastewater treatment process residuals as feedstocks for the recovery of simple sugars. *Bioresource Technology* 100, 5700-5706.

Defra, 2007a. Waste Strategy for England. Department of Environment, Food and Rural Affairs, London, UK [online]. Available at http://www.defra.gov.uk/environment/waste/strategy/index.htm. Last consulted March 24, 2009.

Defra, 2007b. Monitoring of peat and alternative products for growing media and soil improvers in the UK 2007. Second biennial report by ADAS UK Ltd and Enviros Consulting Ltd [online]. Available at http://www.defra.gov.uk/evidence/science/publications/documents/peatAlternatives2007.pdf. Last consulted February 8, 2011.

Defra, 2010a. Developing an anaerobic digestion (AD) framework document. Department of Environment, Food and Rural Affairs, London, UK [online]. Available at http://www.defra.gov.uk/environment/waste/ad/documents/anaerobic-digestion-framework-101130.pdf. Last consulted December 21, 2009.

Defra, 2010b. Accelerating the Uptake of Anaerobic Digestion in England: an Implementation Plan. Department of Environment, Food and Rural Affairs, London, UK [online]. Available at http://www.defra.gov.uk/environment/waste/ad/documents/implementation-plan2010.pdf. Last consulted December 21, 2009.

du Preez J, Norddahl B, Christensen K, 2005. The BIOREK® concept: a hybrid membrane bioreactor concept for very strong wastewater. *Desalination* 183, 407-415.

EC (European Commission), 2000. Working document on sludge. 3rd draft. 27 April. Brussels, Belgium: DG Environment, European Commission.

EC (European Commission), 2003. Report from the Commission to the Council and the European Parilament on the implementation of community waste legislation…for the period 1998-2000. COM(2003) 250 final/3. Brussels, Belgium: EC [online]. Available at http://eur-lex.europan.eu/en/index.htm.

Evans TD, 2009. Using composted biosolids as a peat replacement. *Proceedings of the CIWEM/Aqua Enviro 14th European Biosolids and Organic Resources Conference, Leeds, UK, 9-11 November 2009.*

Gérard C, 2002. Un pilote pour rejecter l'effluent en milieu naturel (A pilote to reject effluent in nature). Reússir Porcs, 85, 49-50 cited in Masse L, Massé DI, Pellerin Y, 2007. The use of membranes for the treatment of manure: a critical literature review. *Biosystems Engineering* 98, 371-380.

Jenner M, 2008. US Biofuels: a silver bullet or harbinger of death. *Biocycle*, May 2008.

Johnson G, Culkin B, Stowella L, 2004. Membrane filtration of manure wastewater [online]. Available at http://www.vsep.com/pdf/Membrane_filtration_of_manure.pdf. Last consulted 7 February 2011.

Jorgensen K, Magid J, Luxhoi J, Jensen LS, 2010. Phosphorus distribution in untreated and composted solid fractions from slurry separation. *Journal of Environmental Quality* 39 (1), 393-401.

Kebede-Westhea E, Pizarro C and Mulbry WW, 2003. Production and nutrient removal by periphyton grown under different loading rates of anaerobically digested flushed dairy manure. *Journal of Phycology* 39, 1275-1282.

Kumar M, Badruzzaman M, Adham S, Oppenheimer J, 2007. Beneficial phosphate recovery from reverse osmosis (RO) concentrate of an integrated membrane system using polymeric ligand exchanger (PLE). *Water Research* 41, 2211-1129.

Lukehurst C, Frost P and Al Saedi T, 2010. Utilisation of digestate from biogas plants as biofertiliser. IEA Bioenergy.

Mantuana L and Gould MC, 2006. Promoting the use of digestate from anaerobic digesters in composite materials. Final Report. Grant No. PLA-06-42. Community Energy Project Grant 2006. Michegan Biomass Energy Program.

Masse L, Massé DI, Pellerin Y, 2007. The use of membranes for the treatment of manure: a critical literature review. *Biosystems Engineering* 98, 371-380.

Mintel, 2007. Gardening Review-UK-September 2007 [online]. Available at http://academic.mintel.com/. Last consulted 8 February 2011.

Mintel, 2010. Garden Products Retailing-UK-July 2010. Available online: http://academic.mintel.com/. Last consulted 8 February 2011.

Mulbry WW and Wilkie AC, 2001. Growth of benthic freshwater algae on dairy manures. *Journal of Applied Phycology* 13, 301-306.

Norddahl B and Rohold L, 2000. The Biorek concept for the conversion of organic effluent to energy, concentrated fertiliser and potable water. cited in Masse L, Massé DI, Pellerin Y, 2007. The use of membranes for the treatment of manure: a critical literature review. *Biosystems Engineering* 98, 371-380.

Novak JT, Verma N, Muller CD, 2007. The role of iron and aluminium in digestion and odor formation. *Water Science and Technology* 26 (9), 59-65.

Novak JT, Park CM, 2009. The effect of iron and aluminium for phosphorus removal on anaerobic digestion and odor generation. *Proceedings of the 12th IWA-Sludge Conference-Sustainable Management of Water and Wastewater Sludges, 8-10 August 2009, Harbin, China [on pen drive]*

NNFCC (National Non-Food Crops Centre), 2010. The official information portal on anaerobic digestion [online]. Available at http://www.biogas-info.co.uk/. Last consulted 10 September 2010.

Noble R, Hobbs PJ, Mead A and Dobrovin-Pennington A, 2002. Influence of straw types and nitrogen sources on mushroom composting emissions and compost productivity. *Journal of Industrial Microbiology & Biotechnology*, 29, 99 –110.

Pollard S, Tyrrel S, Longhurst P and Villa R, 2010. A generalised exposure assessment of anaerobic digestion products in various end-use settings. WRAP and Environment Agency Project OFW002. Final Report to WRAP- March 2008.

Smith SR, 1996. *Agricultural recycling of sewage sludge and the environment*. Cab Intenational, Oxon, UK.

Smith SR, 2009. A critical review of the bioavailability and impacts of heavy metals in municipal solid waste composts compared to sewage sludge. *Environment International* 35, 142-156.

Spelter H, Winandy J and Zauche T, 2008. Anaerobically digested bovine biofiber as a source of fiber for particleboard manufacturing: an economic analysis. Bioresources 3(4), 1256-1266.

Tambone F, Genevini P, D'Imporzano G, Adani F, 2009. Assessing amendment properties of digestate by studying the organic matter composition and the degree of biological stability during the anaerobic digestion of the organic matter fraction of MSW. *Bioresource Technology* 100(12), 3140-3142.

USEPA (US Environmental Protection Agency), 1993. Part 503 standards for the use and disposal of sewage sludge. *Federal Register* 58, 9248-9415.

Walker M, Banks C, Heaven S and Frederickson J, 2010. Development and evaluation of a method for testing the residual biogas potential of digestates. Project number OFW004-005. Waste and Resources Action Programme, January 2010 [online]. Available at http://www.wrap.org.uk/downloads/Residual_Biogas_Potential_report_-_Final.f37df5ad.9581.pdf. Last consulted 10 December 2010.

Wilkie AC and Mulbry WW, 2002. Recovery of dairy manure nutrients by benthic freshwater algae. Bioresource Technology 84, 81-91.

Winandy J and Cai Z, 2008. Potential of using anaerobically digested bovine biofiber as a fiber source for wood composites. *BioResources* 3(4), 1244-1255.

WRAP: Waste and Resources Action Programme & Environment Agency, 2010. Quality Protocol. Digestate. End of waste criteria for the production and use of quality outputs from anaerobic digestion of source-segregated biodegradable waste [online]. Available at http://www.environment-agency.gov.uk/static/documents/Business/W524AnaerobicDigestatev4(1).pdf

Yue Z, Teater C, Liu Y, MacLellan J and Liao W, 2009. A sustainable pathway of cellulosic ethanol production integrating anaerobic digestion with biorefining. *Biotechnology and Bioengineering* 105, 1031^{-1}039.

Zhang RH, Yang P, Pan Z, Wolf TD and Turnball JH, 2004. Treatment of swine wastewater with biological conversion, filtration, and reverse osmosis: A laboratory study. *Transactions of the American Society of Agricultural Engineers* 47(1), 243-250.

6.0 Appendices

6.1 Physicochemical and microbiological properties of digestate

Table A1 Physicochemical properties of digestate produced from food waste feedstock (DFW)

	pH	DS (%)	Specific Gravity (g ml^{-1})	Volatile solids (%)	VFAs	Total neutralising value (%fw as CaO)	Conductivity (µS/cm 20°C)	BOD (mg l^{-1})	COD (mg l^{-1})	Stability (L kg^{-1} VS)
n	2	6	2	2	awaiting data	2	2	2	2	2
Mean	8.4	4.5	0.95	69.0		26.1	7490	8769	43887	142
Min	8.3	2.7	0.94	68.3		23.1	6940	6437	34067	72
Max	8.4	6.8	0.96	69.6		29.1	8040	11100	53707	212
SD	0.1	1.5	0.01	0.9		4.2	777.8	3297	13888	99
Percentile										
25	8.3	3.5	0.95	68.6		24.6	7215	7603	38977	107
50	8.4	4.7	0.95	69.0		26.1	7490	8769	43887	142
75	8.4	5.0	0.96	69.3		27.6	7765	9934	48797	177
Interquartile range	0.0	1.4	0.01	0.6		3.0	550	2332	9820	70.0

Data supplied by WRAP (each value from duplicate measurements) and anonymous AD plant

Table A2 Physicochemical properties of digestate produced livestock slurry feedstock (DLS)

	pH	DS (%)	Specific Gravity (g ml^{-1})	Volatile solids (%)	VFAs	Total neutralising value (%fw as CaO)	Conductivity (µS/cm 20°C)	BOD (mg l^{-1})	COD (mg l^{-1})	Stability (L kg^{-1} VS)
n	116	116	1	1	26	1	1	34	114	1
Mean	8	4.9	0.93	73.2	15.0	26.7	5477	10331	59106	89
Min	7.6	3.5	0.93	73.2	1.8	26.7	5477	1880	109	89
Max	8.8	9.3	0.93	73.2	41.7	26.7	5477	23600	170000	89
SD	0.2	1.0			9.5			4378	22177	
Percentile										
25	7.9	4.2	0.93	73.2	9.1	26.7	5477	7733	47789	89
50	8	4.8	0.93	73.2	13.8	26.7	5477	9145	56468	89
75	8.2	5.5	0.93	73.2	20.0	26.7	5477	12875	70125	89
Interquartile range	0.3	1.3	0	0.0	10.9	0.0	0	5143	22336	0.0

Data supplied by WRAP (each value from duplicate measurements) and anonymous AD plant (approximately monthly data over 5 years), raw data presented in Appendix 1

Table A3 Nitrogen content and C:N ratio of digestate produced from food waste feedstock (DFW)

		Total N (%)	Organic N (%)	NH_4-N (%)	Readily available N (%)[†]	Readily available N (% total N)	C:N ratio
n		6	6	4	6	6.0	2
Mean		15.0	5.7	10.5	9.3	61.9	1.5
Minimum		11.9	1.6	5.5	5.5	38.7	1.4
Maximum		20.5	10.0	16.0	16.0	86.8	1.6
Standard Deviation		3.19	3.14	4.33	3.87	3.87	0.10
Percentiles	25	12.7	3.6	9.0	6.6	45.0	1.5
	50	14.3	5.7	10.2	8.7	61.7	1.5
	75	16.0	7.7	11.8	10.3	77.5	1.5
Inter-quartile range		3.3	4.1	2.8	3.7	10.3	0.1

Data supplied by WRAP (each value from duplicate measurements) and Anonymous AD plant

[†]NH_4-N+NO_3-N by KCl extraction

Table A4 Nitrogen content of digestate produced from mainly livestock waste feedstock (DLS)

		Total N (%)	Organic N (%)	NH_4-N (%)	Readily available N (%)	Readily available N (% total N)	C:N ratio
n		116.0	116.0	115.0	116.0	115.0	4.0
Mean		16.1	5.4	10.9	10.8	65.4	4.1
Minimum		6.7	2.4	5.3	2.8	39.3	3.0
Maximum		24.9	8.7	19.3	19.3	85.6	5.0
Standard Deviation		4.2	1.1	4.0	4.1	9.1	1.1
Percentiles	25	13.0	4.7	7.8	7.6	59.0	3.2
	50	15.2	5.3	9.7	9.7	66.0	4.2
	75	19.3	5.9	13.5	13.5	71.7	5.0
Inter-quartile range		6.3	1.2	5.7	5.8	12.7	1.8

Data supplied by WRAP (each value from duplicate measurements) and anonymous AD plant (approximately monthly data over 5 years)

[†]NH_4-N+NO_3-N by KCl extraction

Table A5 Nutrient content (other than nitrogen) of digestate produced from food waste (DFW)

	Total P (%)	Water Soluble P (%)	Total K (%)	Water Soluble K (%)	Total Ca (%)	Water Soluble Ca (%)	Total Mg (%)	Water Soluble Mg (%)	Total S (%)	Water Soluble S (%)	Water Soluble Na (%)	Water Soluble Cl(%)
n	6	2	6	6	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Mean	0.7	0.1	4.7	1.9	0.34	0.10	0.19	0.01	0.33	0.07	3.09	2.32
Minimum	0.3	0.0	1.4	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	2.0	0.2	9.3	5.7	1.70	0.48	0.69	0.04	0.57	0.22	4.80	8.00
Standard Deviation	0.66	0.10	2.65	2.31	0.68	0.19	0.28	0.02	0.21	0.10	1.74	3.65
Percentiles												
25	0.3	0.0	3.5	0.0	0.00	0.00	0.02	0.00	0.23	0.00	2.78	0.00
50	0.5	0.1	4.7	1.3	0.00	0.00	0.05	0.00	0.37	0.00	3.16	0.00
75	0.6	0.1	5.1	2.8	0.24	0.11	0.28	0.01	0.47	0.14	4.35	4.43
Inter-quartile range	0.3	0.1	1.6	2.8	0.24	0.11	0.26	0.01	0.24	0.14	1.57	4.43

Data supplied by WRAP (each value from duplicate measurements) and anonymous AD plant

Table A6 Nutrient content (other than nitrogen) of digestate produced from mainly livestock waste (DLS)

	Total P (%)	Water Soluble P (%)	Total K (%)	Water Soluble K (%)	Total Ca (%)	Water Soluble Ca (%)	Total Mg (%)	Water Soluble Mg (%)	Total S (%)	Water Soluble S (%)	Water Soluble Na (%)	Water Soluble Cl (%)
n	116	1	116	1	19	1	116	1	116	1	11	4
Mean	0.9	0.3	3.2	3.3	2.6	0.4	0.3	0.1	0.9	0.3	3.0	3.9
Minimum	0.2	0.3	1.5	3.3	0.0	0.4	0.0	0.1	0.0	0.3	0.5	1.9
Maximum	5.0	0.3	5.9	3.3	4.8	0.4	3.7	0.1	1.7	0.3	4.0	5.2
Standard Deviation	0.5		1.1		1.3		0.4		0.3		1.0	1.4
Percentiles 25	0.6	0.3	2.3	3.3	2.0	0.4	0.1	0.1	0.8	0.3	2.9	3.5
50	0.8	0.3	2.9	3.3	2.6	0.4	0.2	0.1	1.0	0.3	3.2	4.2
75	1.1	0.3	4.2	3.3	3.3	0.4	0.3	0.1	1.2	0.3	3.5	4.6
Inter-quartile range	0.5	0.0	1.8	0.0	1.3	0.0	0.2	0.0	0.4	0.0	0.6	1.1

Data supplied by WRAP (each value from duplicate measurements) and anonymous AD plant (approximately monthly data over 5 years)

Table A7 Dry solids and NPK content of separated digested fibre and liquor estimated using separator efficiency values given by Lukehurst *et al.* (2010)

	DS in fibre (%)	Total N in fibre (%DS)	Total P in fibre (%DS)	Total K in fibre (%DS)	DS in liquor (%)	Total N in liquor (%DS)	Total P in liquor (%DS)	Total K in liquor (%DS)
Majority food waste								
Belt press	8.7	9.6	0.31	2.1	2.8	8.3	0.97	2.7
Screw press (median values)	12.9	9.8	0.28	1.2	3.0	6.8	0.84	0.9
Decanter centrifuge (mean)	22.3	19.0	0.82	0.9	2.4	3.7	0.36	1.0
Contains animal slurry								
Belt press	9.5	9.6	0.4	1.6	3.0	7.7	1.3	2.0
Screw press (median values)	14.0	9.9	0.4	0.9	3.3	6.3	1.1	0.7
Decanter centrifuge (mean)	24.3	19.1	1.1	0.7	2.6	3.4	0.5	0.7

Table A8 Heavy metal content of digestate produced from food waste (DFW)

	Total Cu (mg kg^{-1})	Total Zn (mg kg^{-1})	Total Pb (mg kg^{-1})	Total Cd (mg kg^{-1})	Total Hg (mg kg^{-1})	Total Ni (mg kg^{-1})	Total Cr (mg kg^{-1})	Total Mo (mg kg^{-1})	Total F (mg kg^{-1})	Total Se (mg kg^{-1})	Total As (mg kg^{-1})
n	6	6	6	6	2	6	6	2	2	2	2
Mean	31.5	105.1	46.3	1.2	1.1	43.2	50.2	2.9	209.5	0.59	1.7
Min	18.6	71.0	3.6	0.2	1	5.5	7.8	2.7	200.0	0.28	1.3
Max	42.6	142.3	114.7	2.2	1.1	137.3	157.5	3.0	219.0	0.89	2.1
SD	8.5	24.7	42.7	0.8	0.06	54.2	60.9	0.26	13.4	0.43	0.6
Percentiles											
25	27.7	92.8	11.8	0.5	1.1	7.9	10.0	2.8	204.8	0.43	1.5
50	31.2	104.5	43.7	1.2	1.1	14.5	19.0	2.9	209.5	0.59	1.7
75	36.7	115.6	64.2	1.7	1.1	64.7	73.1	2.9	214.3	0.74	1.9
Interquartile range	9.0	22.9	52.4	1.2	0.1	56.8	63.1	0.19	9.50	0.31	0.42

Data supplied by WRAP (each value from duplicate measurements) and anonymous AD plant

Table A9 Heavy metal content of digestate produced from mainly livestock slurry (DLS)

	Total Cu (mg kg^{-1})	Total Zn (mg kg^{-1})	Total Pb (mg kg^{-1})	Total Cd (mg kg^{-1})	Total Hg (mg kg^{-1})	Total Ni (mg kg^{-1})	Total Cr (mg kg^{-1})	Total Mo (mg kg^{-1})	Total F (mg kg^{-1})	Total Se (mg kg^{-1})	Total As (mg kg^{-1})	Total Al (mg kg^{-1})	Total Fe (mg kg^{-1})
n	40	40	40	18	14	42	40	1	1	1	1	45	51
Mean	82.1	240.0	1.0	1.5	0.1	8.6	12.4	10.4	118.0	1.1	2.2	4141	14059
Min	20.3	4.4	0.0	0.6	0.0	0.0	0.3	10.4	118.0	1.1	2.2	131	1551
Max	180.7	631.0	17.9	2.3	0.6	18.8	38.2	10.4	118.0	1.1	2.2	11812	37701
SD	47.8	115.7	3.4	0.5	0.2	4.5	7.0					2464	8377
Percentiles													
25	34.8	171.9	0.0	1.2	0.0	6.4	8.9	10.4	118.0	1.1	2.2	1847	7580
50	96.6	220.6	0.0	1.5	0.0	8.3	11.4	10.4	118.0	1.1	2.2	3556	15014
75	120.1	294.2	0.0	1.9	0.0	10.0	14.4	10.4	118.0	1.1	2.2	5942	17316
Interquartile range	85.3	122.4	0.0	0.7	0.0	3.6	5.5	0.0	0.0	0.0	0.0	4094	9736

Data supplied by WRAP (each value from duplicate measurements) and anonymous AD plant (approximately monthly data over 5 years)

Table A10 Microbiological characteristics of digestate produced from food waste

	Animal / human pathogens				**Plant pathogens**		
	Entero-bacteriaceae	*Salmonella spp* (MPN in 25g)	*Enterococci (CFU g^{-1})*	*E. Coli (CFU g^{-1})*	*Plasmodiophora brassicae*	*Phytophthora infestans*	*Microdochium nivale*
n	2	2	2	2	2	2	2
Mean	pass	n.d.	250	<10	a.d.	a.d.	a.d.
Min			70				
Max			430				
SD			254.6				
Percentiles							
25			160				
50			250				
75			340				
Interquartile range			180				

Data supplied by WRAP (each value from duplicate measurements)

Table A11 Microbiological characteristics of digestate produced from mainly livestock manure

	Animal/human pathogens				Plant pathogens		
	Entero-bacteriaceae	*Salmonella spp (MPN in 25g)*	*Enterococci (CFU g^{-1})*	*E. Coli (CFU g^{-1})*	*Plasmodiophora brassicae*	*Phytophthora infestans*	*Microdochium nivale*
n	1	1	1	1			
Mean	fail	detected	910000	5100			
Min			910000	5100			
Max			910000	5100			
SD							
Percentiles							
25			910000	5100			
50			910000	5100			
75			910000	5100			
Interquartile range			0	0			

Data supplied by WRAP (each value from duplicate measurements)

Table A12 Organic contaminants present in digestate produced from food waste

Polychlorinated biphenyls	n	Mean	Min	Max	SD	Percentile 25	50	75	Interquartile range
PCB - 18 (ng kg^{-1})	2	189.5	144	235	64.3	166.8	189.5	212.25	45.5
PCB - 28 (ng kg^{-1})	2	251.0	194	308	80.6	222.5	251	279.5	57
PCB – 31 (ng kg^{-1})	2	285.0	219	351	93.3	252	285	318	66
PCB - 47 (ng kg^{-1})	2	222.5	196	249	37.5	209.3	222.5	235.75	26.5
PCB - 49 (ng kg^{-1})	2	315.5	251	380	91.2	283.3	315.5	347.75	64.5
PCB - 51 (ng kg^{-1})	2	19.9	11.8	27.9	11.4	15.8	19.85	23.875	8.05
PCB - 52 (ng kg^{-1})	2	556.0	555	557	1.4	555.5	556	556.5	1
PCB - 77 (ng kg^{-1})	2	40.4	34.5	46.3	8.3	37.5	40.4	43.35	5.9
PCB - 81 (ng kg^{-1})	2	2.9	2.86	2.9	0.0	2.9	2.88	2.89	0.02
PCB - 99 (ng kg^{-1})	2	401.5	270	533	186.0	335.8	401.5	467.25	131.5
PCB - 101 (ng kg^{-1})	2	478.0	432	524	65.1	455	478	501	46
PCB - 105 (ng kg^{-1})	2	150.0	141	159	12.7	145.5	150	154.5	9
PCB - 114 (ng kg^{-1})	2	26.2	10.3	42.1	22.5	18.3	26.2	34.15	15.9
PCB - 118 (ng kg^{-1})	2	602.0	455	749	207.9	528.5	602	675.5	147
PCB - 123 (ng kg^{-1})	2	56.4	18.9	93.8	53.0	37.6	56.35	75.075	37.45
PCB - 126 (ng kg^{-1})	2	4.0	3.61	4.41	0.6	3.8	4.01	4.21	0.4
PCB - 128 (ng kg^{-1})	2	164.5	107	222	81.3	135.8	164.5	193.25	57.5
PCB - 138 (ng kg^{-1})	2	1036.5	710	1363	461.7	873.3	1036.5	1199.75	326.5
PCB - 153 (ng kg^{-1})	2	490.5	137	844	499.9	313.8	490.5	667.25	353.5
PCB - 156 (ng kg^{-1})	2	67.9	64.6	71.2	4.7	66.3	67.9	69.55	3.3
PCB - 157 (ng kg^{-1})	2	22.4	19.3	25.4	4.3	20.8	22.35	23.875	3.05
PCB - 167 (ng kg^{-1})	2	41.4	28.8	54.0	17.8	35.1	41.4	47.7	12.6
PCB - 169 (ng kg^{-1})	2	2.8	2.51	3.1	0.4	2.7	2.81	2.96	0.3
PCB - 170 (ng kg^{-1})	2	242.0	173	311	97.6	207.5	242	276.5	69
PCB - 180 (ng kg^{-1})	2	579.5	444	715	191.6	511.8	579.5	647.25	135.5
PCB - 189 (ng kg^{-1})	2	12.0	5.34	18.6	9.4	8.7	11.97	15.285	6.63
Total PCBs (ng kg^{-1})		**6260**							

7 primary PCBs+ (ng kg^{-1})	2	3993.5	3748	4239	347.2	3870.8	3993.5	4116.25	245.5
Dioxins and Furans (ng TEQ kg^{-1})	2	2.7	2.48	2.8	0.3	2.57	2.7	2.8	0.18
Polyaromatic hydrocarbons (PAHs)									
Acenaphthene (μg kg^{-1})	2	38.4	35.8	41	3.7	37.1	38.4	39.7	2.6
Acenaphthylene (μg kg^{-1})	2	15.7	9.17	22.3	9.3	12.5	15.7	19.0	6.6
Anthracene (μg kg^{-1})	2	66.7	50	83.3	23.5	58.3	66.7	75.0	16.7
Benzo(a)anthracene (μg kg^{-1})	2	66.7	50	83.3	23.5	58.3	66.7	75.0	16.7
Benzo(a)pyrene (μg kg^{-1})	2	66.7	50	83.3	23.5	58.3	66.7	75.0	16.7
Benzo(b)fluoranthene (μg kg^{-1})	2	66.7	50	83.3	23.5	58.3	66.7	75.0	16.7
Benzo(ghi)perylene (μg kg^{-1})	2	83.4	16.7	150	94.3	50.0	83.4	117.0	66.7
Benzo(k)fluoranthene (μg kg^{-1})	2	66.7	50	83.3	23.5	58.3	66.7	75.0	16.7
Chrysene (μg kg^{-1})	2	108.5	100	117	12.0	104.3	108.5	112.8	8.5
Coronene (μg kg^{-1})	2	34.2	26.7	41.7	10.6	30.5	34.2	38.0	7.5
Dibenzo(ah)anthracene (μg kg^{-1})	2	10.9	10	11.7	1.2	10.4	10.9	11.3	0.85
Fluoranthene (μg kg^{-1})	2	208.2	83.3	333	176.6	145.7	208.2	270.6	124.9
Fluorene (μg kg^{-1})	2	57.5	41.7	73.3	22.3	49.6	57.5	65.4	15.8
Indeno(1,2,3cd)pyrene (μg kg^{-1})	2	108.5	100	117	12.0	104.3	108.5	112.8	8.5
Naphthalene (μg kg^{-1})	2	34.2	26.7	41.7	10.6	30.5	34.2	38.0	7.5
Phenanthrene (μg kg^{-1})	2	283.5	167	400	164.8	225.3	283.5	341.8	116.5
Pyrene (μg kg^{-1})	2	150.0	100	200	70.7	125.0	150.0	175.0	50
Total PAHs		**1466**							

Data supplied by WRAP (each value from duplicate measurements)

Table A13 Organic contaminants present in digestate produced from mainly livestock slurry

Polychlorinated biphenyls	n	Mean
PCB - 18 (ng kg^{-1})	1	93.6
PCB - 28 (ng kg^{-1})	1	166
PCB – 31 (ng kg^{-1})	1	178
PCB - 47 (ng kg^{-1})	1	140
PCB - 49 (ng kg^{-1})	1	128
PCB - 51 (ng kg^{-1})	1	10.4
PCB - 52 (ng kg^{-1})	1	226
PCB - 77 (ng kg^{-1})	1	21.4
PCB - 81 (ng kg^{-1})	1	1.3
PCB - 99 (ng kg^{-1})	1	65.2
PCB - 101 (ng kg^{-1})	1	334
PCB - 105 (ng kg^{-1})	1	68.2
PCB - 114 (ng kg^{-1})	1	7.8
PCB - 118 (ng kg^{-1})	1	183
PCB - 123 (ng kg^{-1})	1	1.37
PCB - 126 (ng kg^{-1})	1	8
PCB - 128 (ng kg^{-1})	1	57.6
PCB - 138 (ng kg^{-1})	1	397
PCB - 153 (ng kg^{-1})	1	102
PCB - 156 (ng kg^{-1})	1	47.2
PCB - 157 (ng kg^{-1})	1	3.27
PCB - 167 (ng kg^{-1})	1	17
PCB - 169 (ng kg^{-1})	1	4.88
PCB - 170 (ng kg^{-1})	1	158
PCB - 180 (ng kg^{-1})	1	387
PCB - 189 (ng kg^{-1})	1	8.54
Total PCBs (ng kg^{-1})		**2815**
7 primary PCBs+ (ng kg^{-1})	1	1794

Dioxins and Furans (ng TEQ kg^{-1})	1	1.78
Polyaromatic hydrocarbons		
Acenaphthene (µg kg^{-1})	1	83.3
Acenaphthylene (µg kg^{-1})	1	9
Anthracene (µg kg^{-1})	1	66.7
Benzo(a)anthracene (µg kg^{-1})	1	66.7
Benzo(a)pyrene (µg kg^{-1})	1	66.7
Benzo(b)fluoranthene (µg kg^{-1})	1	66.7
Benzo(ghi)perylene (µg kg^{-1})	1	20
Benzo(k)fluoranthene (µg kg^{-1})	1	66.7
Chrysene (µg kg^{-1})	1	117
Coronene (µg kg^{-1})	1	33.3
Dibenzo(ah)anthracene (µg kg^{-1})	1	11.7
Fluoranthene (µg kg^{-1})	1	333
Fluorene (µg kg^{-1})	1	200
Indeno(1,2,3cd)pyrene (µg kg^{-1})	1	117
Naphthalene (µg kg^{-1})	1	33.3
Phenanthrene (µg kg^{-1})	1	433
Pyrene (µg kg^{-1})	1	233
Total PAHs		**1957**

6.2 Organic and mineral fertiliser use on parks and green spaces by London Boroughs and contractors

Table A14 Organic and inorganic fertiliser usage in London Boroughs

Borough	Contact	Current organic waste usage:	Fertilisers:
Brent	Leslie Williams (020 8937 5619)	Composting of materials (eg. London Plane leaves) in parks and use as a mulch to reduce weeds in flower beds. Brent council's sports pitch drainage and renovation project will include in the specification the incorporation of 10% organic material by volume into the top 15cm of topsoil. The largest Park, Freyent Country Park, has the Soil Association Organic Standard. All green waste is used on site, typically *in situ*. No artificial fertilisers are used for any of the crops, which include hay, timber and top fruit.	Brent council have reduced use of artificial fertilisers on sports pitches.
City of London	Alex.piddington-Bishop@cityoflondon.gov.uk	Purchase well rotted FYM from a local supplier to use for soil improvement on bedding displays and tend to undertake on a 3 year cycle due to the logistics inbolved. Use FYM for new permanent plantings as a final mulch. Proactive programme in mulching all permanent plantings with green wastre-leaves, prunings, grass cuttings, anything that can decompose. Source green waste from Royal Parks (very effective product to use)	**Elliot's**: Granular inorganic summer Turf fertiliser 10-4-4 (Turf); *Mascot*: Granular inorganic autumn turf fertiliser 5-5-10 (Turf); **Vitax**: Granular inorganic Q4HN (Feeding Buxus) 10-7.5-10.2 (Feeding box, hedging and reduces box wilt); **Phosmag**: Granular inroganic 5-19-10+7.5mg (Feeding trees and shrubs); **Growmore**: Granular inorganic 7-7-7 (Base dressing before summer bedding); **Elliot's**: Granular organic 5-18 (Base dressing before spring bedding)
Ealing	foirequests@ealing.gov.uk	compost derived from recycling of green waste generated from shrub works and leaf clearance carried out in Ealing parks (26t)	11-5-5 fine turf micro granular spring and summer fertiliser, 5-5-10 +4% Fe fine turf micro granular autumn and winter fertiliser, lawn sand 5.4% N + 1.5 % Fe and sulphate of potash (bowling greens (5.5t)and cricket squares(2t)); 20-10-10 Spring and summer outfield fertiliser, 3-12-12 autumn and winter outfield fertiliser (football and rugby pitches(2t)

Greenwich	Steve Roedel (stephen.roedel@greenwich.gov.uk)	All green waste processed to mulch on site from routine horticultural maintenance including tree pruning waste, used as mulch and bedding on beds.	30x25kg bags of fine granular fertiliser used annually on bowling green; 10x35 kg bags used on cricket table. High N in summer and high P in winter.
Hammersmith and Fulham	tony.potter@quandronservices.co.uk	Information not supplied	Fine turf fertilisers: SS2 mini-gran 14-2-7+1%Mg (35 g/m2); AW2 mini-gran 5-5-10+4% (35 g/m2); Mini-gran S/S 11-5-5 (35 - 70 g/per m2); Mini-gran A/W 3-10-5 (35 - 70 g/m2); Zero Phosphate 14-0-7+1%Fe+1% (35 g/m2); Turf Starter 6-0-12 +2%mg+2%fe (35 g/m2); Weed & Feed 12-5-3+MCPA+Dicamba (70 g/m2); Turf Hardener 3-0-3+4%fe+2%mg (70 - 105 g/m2); SS6 mini gran 12-0-9+1Mg+1Fe (35 g/m2); Lawn Sand 5.4%N+1.5%fe(powder) (70 - 140 g/m2); Duragran 15-5-15 (30 g/m2); Delta 12-4-8+0.5%fe (26% organic) (35-70 g/m2); Delta 8-6-6+0.5%fe (35-70 g/m2); Delta 6-3-9+0.5%fe (35-70 g/m2); Apex 7-0-14+2%fe (35 g/m2). Outfield Fertilizers: Granular 9-5-5 (35 - 70 g/m2); Granular 4-10-10 (35 - 70 g/m2); Granular 10-15-10 (35 g/m2); Granular 8-12-8 (35 - 70 g/m2); Granular 7-7-7 (35 - 70 g/m2); Granular 15-5-10 (35 - 70 g/m2); Granular 16-6-6 (35 - 70 g/m2); Granular 12-4-4 (35 - 70 g/m2). Amenity Fertilizer: Planting Plus (5-18-10+Mg) 70 - 140 g/m2. Rose Fertiliser: 4-3-13 + 1 Fe
Islington	Andrew.bedford@islington.gov.uk	The majority of material used to improve the quality and health of our plants actually comes from our own green waste which is produced as a result of our maintenance operations.We have an arrangement with the North London Waste Authority (NLWA) and our Grounds Maintenance Contractor (Enterprise) which sees the majority of our green waste transferred to the NLWA's recycling facility in Edmonton for the necessary treatment, once this process is completed we have access to the recycled material for use in our parks. We can use up to 14 tonnes of the material per	We do not generally use organic fertilisers at our sites, however, we may use a limited amount of fertiliser for use on our fine turf areas. Our Tree Service does not use compost or fertilizers, however, they do re-use the wood chips from Arboricultural operations as a mulch around tree bases in order to suppress weed growth. We also use woodchips in some of our parks.

		week and this is free of charge. This arrangement is also taken up by several other local authorities in London. You may wish to contact the NLWA direct via their website to secure more information about their operations.	
Kingston	Robert Waite environment@rbk.kingston.gov.uk	All mulches and composts used are natural sources. Horse manure from sources and woodchip from several sources are used. Manure was dug into most of the seasonal bedding in 2010. Seaweed extract is used to promote growth and grass health. Leaves are taken to Canbury Gardens and various allotment sites where it's turned into mulch by the various users. Some are taken to the recycling centre when there is no requirement atr other sites. Summer and winter bedding is composted at the same sites although some is given to organisations such as the Scouts.	No fertilisers used on flower beds. NPK fertilisers are used on sports surfaces.
Sutton	Mark.Dalzell@sutton.gov.uk	Sutton Parks Service currently uses recycled mulch and compost products only our parks borders both as a soil conditioner and mulch.	We do not use any other fertilisers on planted areas. We also use a seaweed based material on out bowling greens but no other fertilisers.
Wandsworth	Simon Cooper-Grundy (020 88718117)	Green waste processed on site from green arisings from routine horticultural maintenance operations: a) used mainly as a mulch on shrub beds to a depth of 75mm, borough wide inclusive of cemeteries; b) incoporated into soil for new shrub planting schemes and bedding once a year usually in spring; c) screened the mulch down to 10mm and used	Winter sports piches-Autumn 3:12:12; Spring 9:7:7; Bowling greens and cricket squares- Autumn 14:0:19:3-liquid seaweed extract feeds throughout the playing season as and when required all of which are slow release Nutralene and Poly PCU. Details of quanities unavailable restricted to fine turf areas.

		(as a trial) as top dressing on grass sports areas.	
Tower Hamlets	Raph O'Keeffe (02089851957)	Tower Hamlets Parks currently uses no Fertilisers on our beds or Planters. Well rotted F.Y.M. or Spent Mushroom Compost is dug into all our beds and planters prior to planting out with spring bedding in the Autumn. The leaves collected in Victoria Park are shredded and composted and used as mulch for the Shrub Borders in the park. Any surplus has been used to top up Street Planters and supplement the Autumn soil improvement in the Park. The Borough has recently started to produce recycled Green Waste in partnership with Veolia, who shred and compost the waste at a site in Essex. We have successfully used some of the coarser grade product as a mulch on Shrubberies in the south of the borough and are looking to expand use, including the use of a finer grade of recycled Green Waste as a soil improver for our seasonal beds and planters. I have spoken to our Arboriculture Officer regarding use of fertilisers. He said that they don't use any. They dig in some organic matter at planting to improve the soil. Most of the planting stock is rootballed, and the medium around the roots is of high quality.	No fertilisers used

Waste & Resources Action Programme

The Old Academy
21 Horse Fair
Banbury, Oxon
OX16 0AH

Tel: 01295 819 900
Fax: 01295 819 911
E-mail: info@wrap.org.uk

Helpline freephone
0808 100 2040

www.wrap.org.uk/ad

recycle