Quality management of digestate from biogas plants used as fertiliser

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IEA Bioenergy

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Task 37 – Energy from Biogas

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Foreword

The increasing global demands for food dictate higher yields per hectare which can be achieved, *inter alia*, through an increase in the use of fertilisers. The traditional use of mineral fertilisers has important limits and requires new, sustainable alternatives. The main limits concern the decreasing worldwide natural reserves of mineral fertilisers and the negative environmental impact caused by the use of fossil fuels for their production. Digestate from biogas plants is rich in plant nutrients and has excellent fertiliser qualities and has great potential worldwide as a sustainable alternative to mineral fertilisers. Despite its potential, the use of digestate as fertiliser is limited in many countries due to unfamiliarity of the product and insufficient confidence in its quality and safety. Quality assurance is therefore an important condition for increased market confidence in digestate and for its enhanced use as fertiliser. Digestate quality management is implemented through various means: standards of digestate quality, digestate certification systems, nutrient regulations and legislative frameworks, and most important through on-going quality control practices along the whole digestate production cycle.

This brochure is focused on quality management of liquid digestate from biogas plants where animal manures and slurries, crop residues, organic wastes and residues from agri-food processing industries and from other industrial processes are the principal feedstocks. The aim is to provide guidance on best practices for the production of high quality digestate, which is suitable for application as a crop fertiliser and with a positive environmental impact and a high degree of safety for human and animal health. The information contained in this brochure should be of interest to biogas and digestate producers, to farmers who use digestate as fertiliser, to industries which supply organic wastes to biogas plants as well as to policy makers, regulators and consumers.

Introduction

The biogas process, usually called anaerobic digestion (AD), occurs naturally in different environments (Figure 1): the stomach of ruminants, landfills, volcanic hot springs, submerse rice fields, etc. The main difference between naturally occurring AD and biogas plants is that in a biogas plant the AD process is deliberately controlled to achieve maximum methane production. In controlled AD processes organic matter breaks down in the same way as in nature, in the absence of molecular oxygen. This results in two valuable products: renewable methane and digestate.

The biogas that is produced this way is a very useful source of renewable energy, whilst digestate is a highly valuable biofertiliser. IEA Bioenergy Task 37 has a number of publications on different aspects of biogas production and on utilisation of digestate as biofertiliser. These can be accessed and downloaded at: www.iea-biogas.net/publications.

Use of digestate as fertiliser requires that rigorous attention is paid to the quality of digestate and the feedstock supplied to biogas plants where digestate is intended for use as fertiliser. This is the only way to achieve maximum ecological and economic benefits, while at the same time ensuring sustainability and environmental safety. Quality management of digestate used as fertiliser should be integrated into overall national environmental protection and nutrient management policies. Good examples of this can be found in countries like Austria, Canada (Ontario), Denmark, Germany, Netherlands, Sweden, Switzerland and the United Kingdom. National regulatory frameworks for digestate quality management and certification for use enhance its use as fertiliser in a safe and sustainable way.

Figure 1: Ruminants, landfills, volcanic hot springs and rice fields are all active methane producers. Sources of photos: Lemvigbiogas.com; Newterra.com; WordPress.com; C. Lukehurst.

1 Applications of AD

Anaerobic digestion technologies and processes are widely used throughout the world for various purposes. There is renewed interest in AD nowadays as a sustainable technology for reducing the rate of climate change and global warming. An overview of some applications of AD in society follows.

1.1 Manure treatment

Animal manure has one of the world's largest potentials for biogas production. AD of animal manure and animal slurry is carried out in many areas with intensive animal production and high density of manure per hectare as a sustainable option for manure treatment and manure management. The nutrients that are contained in the manure are also present in the resulting digestate, although their availability compared with raw manure is improved due to higher rates of mineralisation (ADAS UK *et al.*, 2007, Jørgensen, 2004, Lukehurst *et al.*, 2010, Smith *et al*, 2010). Digestate has therefore an improved fertiliser quality compared with the undigested manure. As the methane yield of manure is relatively low, manure is frequently mixed and co-digested with other feedstocks in order to enhance the methane production.

Manure based biogas plants can be single farm units, processing manure from one farm only (Figure 2, A and B), or they can be centralised biogas plants, processing manure from several farms (Figure 3).

There are thousands of technologically advanced manure based biogas plants in Europe and North America, producing biogas for renewable heat and power generation and as vehicle fuel and digestate for use as biofertiliser. In addition, there are several million low technology installations in Asia (Figure 4) that digest manure and human waste as well as farming residues to produce biogas for family cooking and lighting and digestate for use as biofertiliser for the family crops.

Figure 2: Single farm biogas plants, in Thuringia, Germany/www.pigprogress.net [A] On-farm anaerobic digester in Northern Ireland. Source Agri-Food and Biosciences Institute (www.afbini.gov.uk) [B].

Figure 3: Lemvig centralised co-digestion plant in Denmark. Source: Lemvig Biogas (www.lemvigbiogas.com)

Figure 4: An award winning development of a typical family biogas plant in Kerala, India used to convert animal and human waste, crop residues etc into biogas for cooking and digestate to return to land as biofertiliser. Further details at www.biotech-india.org: Photo: David Fulford, Ashden Awards

1.2 Co-digestion

Co-digestion[1] of animal manure with organic materials with high methane potential such as oily residues and by-products, alcohol residues, digestible organic wastes from agri-processing and food industry or food waste, produces more gas from the digester than manure only. Co-digestion can therefore improve the profitability of biogas plants. In addition, co-digestion of animal manure and slurry with suitable organic wastes from food industries utilise the huge amounts of organic wastes that are produced annually and in many places otherwise dumped into landfills. In some countries, subject to approved lists of feedstocks, such residues are allowed to be spread to land without any further treatment. Examples of direct land spreading of organic residues from sugar refining, drinks manufacture, fruit and vegetable processing etc. are given by Davis and Rudd (1999), Gendebien, *et al.* (2001) and Tompkins (in press). However, when these residues are digested in a biogas plant they will yield not only their fertiliser value but also renewable energy. The share of mineral nitrogen is enhanced and the nutrient content in the digested material is analysed and declared. This allows its efficient integration in the fertiliser plan of the farm. This is not possible in the case of land spreading of untreated organic residues. Furthermore, anaerobic digestion will provide safety for land application through sanitation and effective inactivation of animal and plant pathogens and weed seeds.

1.3 Waste water treatment

AD has been used for decades in waste water systems, for the treatment of a wide range of waste and process waters from the public sewerage system. The technology is widely utilised in the industrialised world as part of advanced treatment systems for municipal and industrial waste waters, usually as a sludge stabilisation treatment.

The stabilisation of sludge

Anaerobic digestion is used to treat primary sludge and secondary sludge produced by the aerobic treatment of municipal waste water. The use of the resulting digestate as fertiliser is controversial because of high risks of chemical contamination. For this reason, digested sewage sludge is allowed to be used as a fertiliser in some European countries, with the condition that its quality meets with the national limit values set for chemical pollutants (heavy metals and for organic pollutants) and for the pathogen content, prescribed by regulations concerning such products. There are other countries like the Netherlands, Switzerland and Austria where land application of sewage sludge and of any sludge derived products, including digested sewage sludge, is banned.

Industrial waste water treatment

Industrial waste water treatment usually involves on-site treatment of the organic content of industrial waste waters produced by the food-processing and the agri-industries (beverages, food, meat, pulp and paper, milk industries etc.). The biogas produced is normally used to provide energy for the main processes. Because of the energy and environmental benefits involved, as well as the higher costs of other treatment and disposal methods, it is estimated that the use of this application will increase in the future. Digestate utilisation from industrial waste water treatment must be considered on a case-by-case basis and is not discussed further in this publication.

1.4 Organic waste treatment

More recently, AD is used to process "beyond sell-by date" food and source separated biodegradable wastes from households. The increasing world population will likely result in increased quantities of household wastes in spite of overall waste reduction efforts. It is therefore expected that the organic wastes generated in society will continue to have large potentials as AD feedstock throughout the world. The AD treatment produces renewable methane and reduces the flow of organic material to incineration and to landfills. In a number of countries separately collected food wastes are co-digested with animal manure in manure-based biogas plants. Utilisation of the digestate as biofertiliser is dictated by its content of heavy metals and organic pollutants and must therefore be subjected to strict quality control. Specialised plants running on food waste only are in operation in countries like the United Kingdom. These specialised plants are subjected to the same quality

[1] In some contexts, outside the scope of this publication, co-digestion can also refer to sewage sludge digesters accepting additional inputs.

control as co-digestion plants in order to deliver the same benefits and safety advantages as those found in long established manure co-digestion plants. A list of the 44 pioneering AD plants in the UK, based on food waste, can be found at www.biogas-info.co.uk

2 Quality management of digestate used as fertiliser

This brochure focuses on the quality of digestate produced in biogas plants and its suitability for use as biofertiliser. The underlying principles that define the 'quality' of digestate as a biofertiliser, suitable to replace mineral fertilisers in crop production, are the same irrespective of the size and location of the biogas plant. High quality digestate fit for use as fertiliser is defined by essential features such as: declared content of nutrients, pH, dry matter and organic dry matter content, homogeneity, purity (free of inorganic impurities such as plastic, stones, glass etc), sanitised and safe for living organisms and the environment with respect to its content of biological (pathogenic) material and of chemical pollutants (organic and inorganic).

The digestion process cannot degrade all potential chemical contaminants which are supplied with the feedstock. This means that the only way to produce high quality digestate is to use feedstocks for AD which do not contain unwanted impurities. For this reason, countries with developed biogas sectors and with policies of environment and human and animal health protection have introduced "positive lists" of feedstock materials for AD. These are part of the quality assurance schemes in these countries. Three examples of national quality assurance schemes for digestate from Sweden, Switzerland and the United Kingdom are outlined in Appendix 2. Although the quality criteria and the parameters used for digestate certification vary between the three examples, the certified digestate is suitable for use in agriculture, in conformity with the legal frameworks and policies of the respective country.

The use of quality standards for organic materials that are applied to agricultural land is not new. In Europe, the European Parliament Directive 86/278 was adopted two decades ago in order to regulate the application of waste products as fertilisers and to prevent any potential negative effects on soil, vegetation and on animal and human health. Later, in 2002, the regulation governing the treatment of animal by-products, including the requirements for their safe application to land was introduced, following the European outbreaks of Bovine Spongiform Encephalopathy (BSE). The Regulation 1774/2002, known as the Animal By-Products (ABP) Regulation and superseded by the current Council Regulation 1069/2009, stipulates *inter alia* the categories of animal by-products and the condition in which these can be used as feedstock for AD (European Parliament, 2009). Such regulations are regularly up-dated.

2.1 Importance of digestate quality

Digestate quality assurance means not only that digestate is safe for use but that it is also perceived as a safe product by farmers, food wholesalers, food retailers, politicians, decision makers and the general public. Improved confidence in the quality and safety of digestate is expected to lead to its more widespread use as biofertiliser. This should contribute to the development of a market for the quality certified product and support the further deployment of biogas technologies which provide important associated benefits to society (Tafdrup, 1994 and Berglund, 2006):

- Production of renewable methane, to displace use of fossil fuels
- Displacement of mineral fertilisers, lowering their negative impact on the environment
- Increased recycling of organic matter and nutrients and conservation of natural resources
- Sanitation of organic wastes and animal manures, breaking the chain of pathogen transmission
- Cost savings to farmers through enhanced use of own resources, reduced purchases of mineral fertiliser and higher nutrient efficiency
- Potential for reduced air pollution from emissions of methane and ammonia through application of "good practices"
- Contribution to food safety

This brochure gives general guidance on production of high quality digestate, suitable for use as biofertiliser, and provides references and indicates sources for further information.

2.2 Digestate production and the management of quality

The production and recycling of digestate as fertiliser requires quality management and quality control throughout the whole closed cycle of AD, from the production of the AD feedstock until the final utilisation of digestate as fertiliser.

Quality management implies the use of high quality feedstock, pre-processing of specific feedstock types, close control of the AD process and of process parameters affecting digestate quality, digestate processing, declaration and optimal storage and application as fertiliser, as shown in Figure 5.

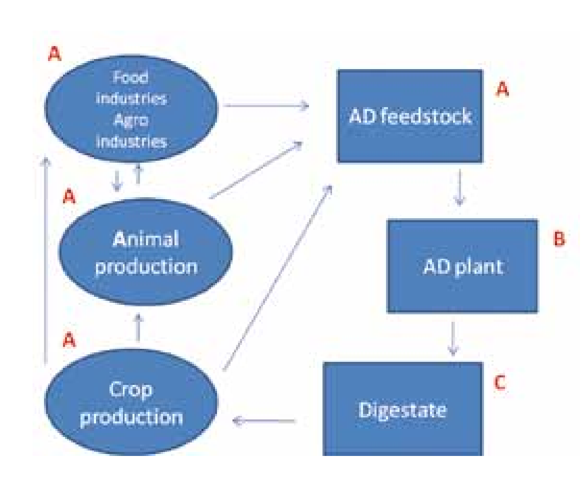

Figure 5: The closed cycle of digestate production and utilisation and the critical check points of digestate quality management: A) The AD feedstock; B) The AD process; C) Digestate processing, storage and application as fertiliser. (Adapted after Al Seadi, 2001)

3 Control of feedstock quality

The composition and quality of the digestate is determined by the composition and quality of the feedstock combined with the effectiveness of the AD process. These are the two most critical factors that underpin the quality of digestate as a fertiliser. Therefore, the main measure in digestate quality management is to ensure high feedstock quality. The materials used as feedstock should not only be easily digestible, but they must not be polluted by unwanted materials and compounds of chemical (organic and inorganic), physical or biological nature. "Positive lists" (See example in Annex 1 of positive list in use in The Netherlands) of materials considered suitable as AD feedstock are adopted in many countries and regularly reviewed and up-dated. Nevertheless, a positive list is only a guide, not a guarantee that a certain material, although "listed", has a suitable quality. Thus, positive lists cannot supersede the necessity for ongoing control of the actual quality of the feedstocks supplied to the biogas plant.

3.1 Feedstock categories

A comprehensive list of biowastes, suitable for biological treatment, including AD, was published in the European Waste Catalogue in 2002 (Table 1).

Compared with Table 1, the "Positive lists" which are part of the digestate certification schemes are more restrictive since they contain only digestible materials and define the quality and safety criteria for their selection. Such positive lists are published as part of quality protocols for digestate in a number of countries like Sweden, Germany, United Kingdom, Switzerland, Netherlands, Belgium and Canada. The materials commonly supplied to biogas plants using digestate as fertiliser mainly belong to the categories listed below:

- Animal manure
- Crops
- Vegetable by-products and residues as well as wastes from agriculture, horticulture, forestry, etc

Table 1: Codes for "biowastes" suitable for biological treatment according to the European Waste Catalogue

Waste Code	Waste description	
02 00 00[1]	Waste from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing	Waste from agriculture, horticulture, aquaculture, forestry, hunting and fishing
		Waste from the preparation and processing of meat, fish and other foods of animal origin
		Wastes from the fruit, vegetables, cereals, edible oils, cocoa, tea and tobacco preparation and processing: conserve production; yeast and yeast extract production, molasses preparation and fermentation
		Wastes from sugar processing
		Wastes from the dairy products industry
		Wastes from the baking and confectionery industry
		Wastes from the production of alcoholic and non-alcoholic beverages (except coffee, tea and cocoa)
03 00 00	Wastes form wood processing and the production of panels and furniture, pulp, paper and cardboard	Wastes from wood processing and the production of panels and furniture
		Wastes from pulp, paper and cardboard production and processing
04 00 00	Waste from the leather, fur and textile industries	Wastes from the leather and fur industry
		Wastes from the textile industry
15 00 00	Waste packing; absorbents, wiping cloths, filter materials and protective clothing not otherwise specified	Packaging (including separately collected municipal packaging waste)
19 00 00	Waste from waste management facilities, off-site wastewater treatment plants and the preparation of water intended for human consumption and water for industrial use	Wastes from anaerobic treatment of waste
		Wastes from wastewater treatment plants not otherwise specified
		Wastes from the preparation of water intended for human consumption or water for industrial use
20 00 00	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Separately collected fractions (except 15 01)
		Garden and park wastes (including cemetery waste)
		Other municipal wastes

[1)] The 6-digit code refers to the corresponding entry in the European Waste Catalogue (elaborated by Environmental Protection Agency, Wexford, Ireland 2002)

- Digestible organic residues and waste waters from human and animal feed industries (of vegetable and animal origin)
- Organic fraction of household waste and food remains (of vegetable and animal origin)
- Animal by-products, as defined by the EC-Regulation 1069/2009, except for category 1 (Appendix 4)
- Other industrial residues (tannins, bleaching clay from paper and textile industry, glycerol, etc.)

Along with these, sewage sludge can be used as feedstock (co-digested) in biogas plants where the national legislation permits it. In Europe, this practice is subject to the conditions of the EU Sewage Sludge Directive (86/278/WWC 1986) and to national quality standards for waste products used as fertilisers (See section 4.2 and 4.3). As indicated earlier, co-digestion of sewage sludge in biogas plants using digestate as fertiliser is controversial because of its high risk of chemical contamination and the variable public acceptance of this practice. Land application of sewage sludge or of sludge derived products (including digested sewage sludge) is banned in countries like Austria, The Netherlands and Switzerland.

3.2 Feedstock description

A detailed description of the feedstock supplied to a biogas plant is a very important part of the feedstock quality control. The description must comply with the appropriate national regulations in order to allow the plant operator to assess suitability as feedstock, conform with the existing protocols and quality standards for digestate destined for agricultural and horticultural use. The feedstock producer is responsible for providing complete and accurate feedstock description and for ensuring that the feedstock quality is as declared in the description. The biogas plant operator must verify not only the documentation sent by the producer, but regularly evaluate the quality of the feedstock supplied.

The feedstock description which accompanies the feedstock material supplied to the biogas plant must be archived at the plant and available to digestate customers. The basic information which must be provided by feedstock description includes:

- Origin: the name and the address of the feedstock producer/supplying company; from which process the feedstock originates; the raw materials or processed materials used
- For household waste: the area of collection; if source-separated or not; the type of collection containers (plastic bags, paper bags, bins, other)
- Methane potential
- Description: colour, texture, consistency, smell, etc.
- Chemical description: pH value, content of dry matter, organic dry matter, and of macro-and micro- elements;
- Content of chemical pollutants (organic and inorganic)
- Pathogen contamination
- Recommendations for safe handling and storage; precautions and potential hazards related to handling and storage
- Availability: the amount and the period of time when material of the same quality can be regularly supplied to the biogas plant
- Any other relevant information

4 Unwanted impurities

The quality of the digestate produced in a biogas plant is dependent on the composition of the AD feedstock supplied. To ensure that quality and safety are preserved the presence in the digestate of unwanted materials and contaminants of biological, chemical or physical nature must be avoided. Digestate from agricultural, agro-industrial and food processing feedstock materials is normally a high quality product which is used safely and beneficially as fertiliser.

A robust and stable AD process has a positive effect on digestate quality, to a certain extent able to degrade many of the unwanted compounds and pollutants supplied with the feedstock (see Appendix 3). Specific feedstock types can be pre-treated by mechanical, chemical and thermal methods in order to remove, decompose or inactivate such unwanted impurities. The rule of thumb is that *if efficient pollutant removal cannot be guaranteed either by pre-treatment or through the AD process, the respective material must not be used as feedstock in biogas plants where digestate is used as fertiliser or for other agricultural purposes.*

This section highlights the unwanted impurities, often referred to as contaminants that influence the quality and safety of digestate used as fertiliser.

4.1 Physical impurities

A range of materials are considered physical impurities when present in AD feedstock material. These include undigestible materials as well as very large particle sizes of digestible materials. For example, in manure there can be clumps of straw, animal identification tags, bailer twine, sand, stones, rubber, glass and wood. Organic household waste and food waste may also contain a multitude of unwanted physical impurities including cutlery, plastics, packaging materials, bulky garden waste, etc. Such impurities can be removed most effectively by source separation and separate collection of the digestible fraction of the waste (Figure 6).

When source separation is not possible, the physical impurities can be removed at the biogas plant by physical barriers such as screens, sieves, stone traps, protection grills etc. prior to digestion. This practice appears to be a preferred option for supermarket food waste. If particle sizes of the digestible material are too large, they can be reduced by chopping, maceration or treatment by other means prior to entering the AD system.

4.2 Chemical impurities

Feedstocks from agriculture and the human food chains are in most cases low in chemical impurities (Govasmark *et al* 2011). Nevertheless, stringent quality requirements for digestate also imply strict control of these materials. Two categories of chemicals are of particular concern for the quality of digestate used as fertiliser, heavy metals and organic pollutants.

4.2.1 Heavy metals

Heavy metals (HM), sometimes referred to as potentially toxic elements, are chemical elements that are present in the environment, soil and in food products (Davis and Rudd, 1999; Lukehurst, *et al* 2010; Smith 2009). They are also found in animal feed as well as in crops (Institut für Energetik und Umwelt GmbH (2006)). In small quantities, some HM (also referred to as the trace elements) like iron, copper, manganese and zinc are essential nutrients for healthy life. Trace elements are naturally

Figure 6: Example of source separated, high quality vegetable waste. Source: BiogenGreenfinch Ltd (www.biogen.co.uk)

present in foodstuffs, fruits and vegetables and are included in food supplements and multivitamin products. However, these elements become toxic when they are not metabolized by the body and accumulate in the soft tissues. The toxic levels can be just above the background concentrations naturally occurring in the environment. HM such as lead, cadmium, zinc, copper or mercury are present in waste streams, as part of discarded items such as batteries, lighting fixtures, colorants and inks, and are normally found only at very low levels in food and food waste.

HM present in digestate originate from the feedstock used and they pass through the AD process unchanged into the digestate and eventually into the soil when the digestate is used as fertiliser. Copper is sometimes used to compensate for deficiencies in some soils. Where a high accumulation of HM occurs in the soil it is associated with contamination and potential toxicity and ecotoxicity. Accordingly, most countries have strict limits on concentrations of heavy metals in any material that is to be applied to land, whilst others place limits on the soil content of such pollutants. The quality of digestate used as biofertiliser must therefore comply with such limit values set by each country, as illustrated in Table 2.

Table 2: Limits of heavy metals (mg/kg DM) in 'waste' products that can be applied to land in the IEA Bioenergy Task 37 member countries

Country/Region	Cd	Pb	Hg	Ni	Zn	Cu	Cr
EU, recommendations [1]	20	750	16	300	2500	1000	1000
EU, recommendations starting 2015 [1]	5	500	5	200	2000	800	600
EU, recommendations starting 2025 [1]	2	300	2	100	1500	600	600
Austria [2]	3 (10)	100 (600)	1 (10)	100 (400)	- (3000)	- (700)	100 (600)
Canada [3]	3	150	0,6	62	500	100	210
Denmark [4]	0.8	120	0.8	30	4000	1000	100
Finland [5]	1.5	100	1	100	1500	600	300
France [6]	3	180	2	60	600	300	120
Germany	10	900	8	200	2500	800	900
Ireland	20	750	16	300	2500	1000	1000
Norway [7]	2	80	3	50	800	650	100
Sweden [8]	1	100	1	50	800	600	100
Switzerland [9]	1/0.7	120/45	1/0.4	30/25	400/200	100/70	70/na
The Netherlands	1.25	100	0,75	30	300	75	75
United Kingdom [10]	1.5	200	1	50	400	200	100

[1] Source EU (2000) 3rd Working Document of the EU Commission on Sludge management; (Sludge defined by EWC Codes covering agri-food processing, animal by-products, fruit and vegetables, dairy, baking and drinks residues); ENV.E3/LM, 27 April. Available from: <www.ec.europa.eu/environmeny/waste/sludge/pdf_en.pdf>

[2] The values in the brackets express g/ha limited nutrient loads for a two years period, Düngemittelverordnung, 2004

[3] Ontario Regulation 267/03 under the (Ontario) Nutrient Management Act 2002. Available from: www.e-laws.gov.ca/html/2007/elaws_src_regs_07394-e_htm

[4] Danish Ministry of the Environment (2006), Bekendtgørelse om anvendelse af affald til jordbrugsformål. BEK nr. 1650 af 13. december 2006 (Slambekendtgørelsen) Available from: https://www.retsinformation.dk/Forms/R0710.aspx?id=13056

[5] The Decree of the Ministry of Agriculture and Forestry on Fertiliser Products 24/11. Available at: http://www.mmm.fi/attachments/elo/newfolder/lannoiteaineet/61fAI8BFZ/MMMMa_24_11_lannoitevalmisteista_FI.PDF

[6] French norm for compost and digestate, NF U 44-051. Available at: http://www.boutique.afnor.org/norme/nf-u44-051/amendements-organiques-denominations-specifications-et-marquage/article/686933/fa125064

[7] According to quality class 3which is the maximum concentration for use in agricultural production

[8] Swedish digestate certification standards

[9] Swiss guidelines for utilisation of compost and digestate in conventional/organic farming

[10] Publicly Available Standard (PAS) 110

The content of HM in digestates from AD plants processing feedstock materials from agriculture, food waste and residues from food processing are normally within the limits of suitability as agricultural fertilisers. As a practical example, monthly analyses over a twelve month period undertaken on digestate from three Norwegian biogas plants (Govasmark *et al* 2011) processing food, household and garden waste as well as residues from the food industry showed that concentrations of Ni, Cr, Pb and Hg did not exceed the quality criteria for the best Norwegian classification (class 0). Consequently, the digestate could be used without restriction as fertiliser, also in organic farming. However, use of the digestate in organic farming where the Cd, Pb, Hg, Ni, Zn, Cu, and Cr levels in the soil are above 1, 50, 30, 150, 50 and 100 mg/kg/DM respectively would be restricted. Even though levels fluctuated on a monthly basis over the 12 month period the average heavy metal content was so low that the digestate from these biogas plants was acceptable to qualify for use in organic farming. In the UK, samples of digestate taken in 2009 and 2010 from 3 biogas plants processing food waste, crop residue and livestock manure showed that the levels of heavy metals, in mg/kg DM, were all below the levels set by the PAS 110 standards (Tompkins, in press).

4.2.2 Organic pollutants

Organic pollutants are unwanted chemical compounds supplied to the AD process in various amounts via digestible materials like sewage sludge, mixed waste (bulk collected waste), domestic wastewaters, industrial organic wastes and even food waste and other agriculturally derived materials. Some organic pollutants are known as persistent organic pollutants (POPs), as they do not biodegrade in the environment. POPs are recognized as being directly toxic to biota (UNEP 2012), and because of their environmental persistence they can progressively accumulate higher up in the food chain, so that chronic exposure of lower organisms even to low concentrations can expose predatory organisms, including humans, domestic animals and wildlife to potentially harmful concentrations (European Environment Agency, 2011).

POPs can be industrial chemicals like polychlorinated biphenyls (PCBs), unintentional products from industrial processes like dioxins and furans, products of incomplete combustion such as polycyclic aromatic hydrocarbons (PAHs), plasticizers (e.g. phthalates), flame retardants (e.g. polybrominated diphenyl ethers - PBDE) and medicines as well as personal care products (e.g. triclosan) (Tompkins, in press). A major proportion of these substances ultimately make their way into wastewater and into sewage sludge, hence, the special attention that is paid to co-digestion with sewage sludge. For more details see also Appendix 3 and Appendix 5.

The occurrence, types and concentrations of organic pollutants in AD feedstock will vary geographically, depending to a large extent of how strict the legislation controlling the use of chemicals is in different parts of the world and how consistently such legislation is implemented. As an example, strict legislation banning the use of the persistent pesticides DTT and HCH, eliminated such pollutants from the agricultural AD feedstock in most European countries, although trace amounts of other pesticides, antibiotics and chemicals used in agriculture can be found. In most developing countries, DTT and HCH are often still used in agricultural practices. In those countries their occurrence in agricultural products and wastes is therefore likely to be much higher (United Nations Environment Programme, 2010; Stockholm Convention, 2011).

Crop derived AD feedstock may contain traces of herbicides and fungicides. The probability of transfer of herbicides through digestate application back to land is estimated by Tompkins (in press) to be relatively low in the UK. Govasmark, *et al* (2011) reported that eleven fungicides and one pesticide were detected in the digestate from the three Norwegian biogas plants. However, the European Food Standards Agency (EFSA 2007) noted that the risk of transfer of the very low levels of some specific pesticide residues found in the digestate to rotational crops and to feed stuffs for livestock is very low and does not result in detectable or quantifiable levels in the eventual food for human consumption.

As in the case of HM, there are regulations which prescribe limit values of organic pollutants, including POPs. Such regulations show wide variations worldwide according to Teglia *et al*, (2010). The national limit values as well as the range of organic pollutants which are regulated vary according to the priorities in the legislation of different countries. These are determined by the types, frequency and concentrations of specific pollutants found in waste products in respective countries, as illustrated in the examples shown in Table 3 below.

Analyses of digestate from Norwegian (Govasmark, *et al* 2011) and UK biogas plants (Tompkins, in press) found very low levels of PCBs, PAHs, DEPH and PBDEs. In the United Kingdom samples, dioxin (PCDD) and furans (PCDF), and DEPHs were 1.89% and 2%, of the European Union limits of 100 ng-TEQ/kg and 100 µg/kg dry solids, respectively. It should be noted that the EU limit values for both heavy metals and organic pollutants are considered only as minimum guidelines, likely to become more restrictive in the future. The national legislations in most European countries are therefore more restrictive, compared to the prescribed EU limits.

A recent EU report (European Commission JRC-IPTS (2011)) emphasizes the need for further toxicological and eco-toxicological risk assessments and for a revision of the scientific base for setting the limit values for chemical pollutants (organic and inorganic) in waste derived fertilisers. As new chemicals are regularly produced and used by all the sectors of society, Clarke and Smith (2011) emphasize the need for continued vigilance in assessing the significance and implications for the environment and for the human and animal health of the already known and the "emerging" organic contaminants.

4.2.3 Feedstock selection and ongoing quality control

In practice it is difficult to perform screening of a broad spectrum of chemical pollutants at reasonable cost. For the biogas plant operator, the cheapest and safest way to avoid chemical impurities in digestate is therefore the rigorous selection and quality control of the AD feedstock. Positive lists and feedstock declaration/description are therefore helpful tools, but may only be used only as a guide, and must never eliminate the ongoing quality control of feedstock materials. Quality control has the determinant role in achieving the required standards of quality for digestate applied as fertiliser and in ensuring the long-term sustainability and safety of this practice.

Table 3 Example of limit values for organic pollutants in waste and waste products applied as fertiliser in Austria, Denmark and Switzerland.

OP (Organic pollutant)	**Country**		
	Austria (Düngemittel-verordnung, 2004)	**Denmark** (Slambekendtgørelsen, 2006); Danish Ministry of Environment	**Switzerland** (Guidelines for utilisation of compost and digestate, 2010)
PAHs (Polycyclic aromatic hydrocarbons)	6 mg/kg DM	3 mg/kg DM	4 mg/kg DM
PCDD/F (Dioxins and furans)	20 ng TE/kg DM		20 ng I-TEC*/kg DM
HCH, DDT, DDE etc. (Chlorinated pesticides)	0.5 mg/kg Product		
PCB (Polychlorinated biphenyls)	0.2 mg/kg DM		
AOX (Absorbable organic halogens)	500 mg/kg DM		
LAS (Linear alkylbenzene sulphonates)		1300 mg/kg DM	
NPE (Nonylphenol and nonylphenolethoxylates		10 mg/kg DM	
DEPH Di (2-ethylhexyl) phthalate)		50 mg/kg DM	

* I-TEC: International Toxicity Equivalents

4.3 Pathogens and other unwanted biological matter

Digestate used as fertiliser must pose minimal risk of transmitting bacteria, viruses, intestinal parasites, weed and crop seeds and crop diseases. Feedstock selection and exclusion of materials with high risk of biological contamination are vitally important measures in digestate quality control (hence, positive lists in some countries and the "animal by-product regulation" in Europe – see section 4.3.1 and Appendix 4). Exclusion of specific biologically contaminated feedstock applies to all feedstock types, including animal manure and other feedstock materials which originate from farms having serious animal health problems.

The AD process has a sanitation effect whereby it is able to inactivate most of the pathogens present in the feedstock mixture inside the digester. Depending on the materials involved, additional sanitation measures like pasteurisation or pressure sterilisation can be necessary and are therefore required for specific materials supplied as feedstocks to European biogas plants. The strict sanitation requirements have the aim to break the chain of pathogens and animal and plant diseases transmission. Denmark was a pioneer country in this area, implementing sanitation measures and veterinary safety regulations as long ago as 1989. Later on, other countries including Sweden, Germany and the United Kingdom have introduced similar regulations.

4.3.1 Control of animal pathogens

The sanitation effect of AD is illustrated in Table 4, which compares pathogen reduction in untreated animal manure storage with the effect of the AD at mesophilic and thermophilic temperatures.

A graphic comparison of the efficiency of pathogen reduction under thermophilic and mesophilic conditions, compared with untreated slurry is illustrated by Figure 7.

Pathogen inactivation/destruction is mainly the result of the combined effect of process temperatures (thermophilic or mesophilic) and the retention times of feedstock inside the digester. In countries like Denmark and Germany, methods to measure the sanitation efficiency of AD based on "indicator organisms" were developed. A commonly used indicator organism is *Streptococcus faecalis* (FS) (Bendixen, 1994, 1995, 1999) was chosen because it takes longer to be destroyed during the AD process compared with other pathogenic bacteria, viruses and parasite eggs (see Section 5.2 for more information).

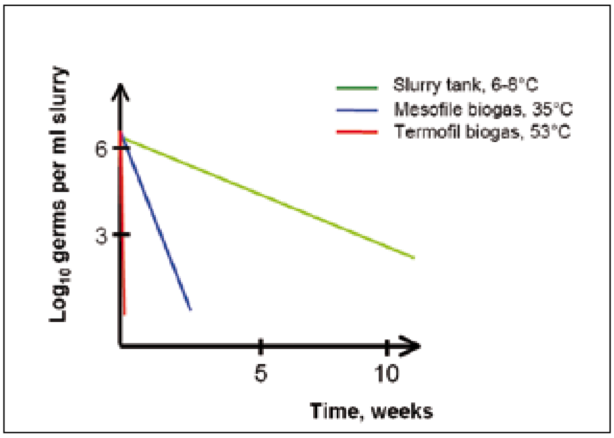

Figure 7: Comparative rates of pathogen reduction in digestate and undigested slurry measured by the log 10 FS (Streptococcus faecalis) method (Source: Al Seadi, 1999, from the Danish Veterinary Research Programme)

Table 4: Comparison between the decimation time (T-90)* of some pathogenic bacteria in the AD system and in untreated slurry system. (Bendixen, 1994)

Bacteria	AD system		Untreated slurry system	
	53°C hours	35°C days	18-21°C weeks	6-15°C weeks
Salmonella typhimurium	0.7	2.4	2.0	5.9
Salmonella dublin	0.6	2.1	–	–
Escherichiacoli	0.4	1.8	2.0	8.8
Staphylococcus aureus	0.5	0.9	0.9	7.1
Mycobacterium paratuberculosis	0.7	6.0	–	–
Coliform bacteria	–	3.1	2.1	9.3
Group D Streptococci	–	7.1	5.7	21.4
Streptococcus faecalis	1.0	2.0	–	–

* Destruction of 90% of the pathogens

4.3.2 The Animal By-Product Regulation (ABP)

Use of animal by-products not suitable for human consumption is regulated in many regions, particularly Europe, where the Animal By-Product Regulation EC1069/2009 is in force (see www.eur-lex.europa.eu. for the most recent updates). The occurrence of bovine

Figure 8: Pasteurisation tanks in foreground, at Blaabjerg AD plant in Denmark. Source Blaabjerg Biogas (www.blaabjergbiogas.dk)

spongiform encephalopathy (BSE) and of foot and mouth disease (mononucleosis) have led to the enforcement of strict rules on treatment and further use of animal by-products, in order to prevent transmission of these diseases. The ABP regulation stipulates, *inter alia*, which categories of animal by-products and in which conditions they are allowed to be treated in biogas plants. For specific animal by-products the ABP Regulation requires batch sanitation by pressure sterilisation or by pasteurisation at 70°C for 1 hour (Figure 8), and also sets limits for particle size and count for indicator organisms such as Escherichia coli, Enterococcaceae and Salmonella. More information is available at www.iea-biogas.net and in Appendix 4 of this brochure.

4.3.3 Control of plant pathogens

Plant pathogens present in AD feedstock materials are efficiently inactivated by the AD processes. It has been demonstrated that even mesophilic AD offers significant or total destruction of most crop disease spreading spores (Zetterstrom, 2008; Lukehurst *et al.*, 2010). Scientific literature (Harraldsson, 2008; Zetterstrom, 2008; Van Overbeek & Runia, 2011) confirms effective destruction by mesophilic digestion of plant pathogens like potato nematodes, *Globodera rostochiensis* and *G.pallida*, none of which survived after 4 and 5 days respectively, at 35°C. Tests showed that *Fusarium oxysporum*, which affects maize and cereal crops, declined rapidly in just one day in a digester, and no spores were present in the final digestate from a mesophilic reactor (Van Overbeek & Runia, 2011). Engeli (1993) indicates that brassica club root (*Plasmodiophora brassicae*), considered more difficult to inactivate, did not survive the hydrolysis stage after 14 days at 55°C. *Plasmidiophora brassicae* is therefore used in Germany as an indicator organism, according to the German Waste Ordinance, to prove that effective sanitation of plant pathogens in digestate has occurred.

4.3.4 Inactivation of weed seeds

Recent research results from Denmark show that AD effectively reduces the germination power of plant seeds present in feedstock (Johansen *et al*, 2011). Table 5 illustrates how effectively mesophilic digestion reduces the germination of seeds from common weeds present in feedstock.

In Germany, the “phyto-hygenic safety” of digestate is defined by the absence of more than two viable tomato seeds (*Lycopersicon lycopersicum*) capable of germination, and/or less than two reproducible parts of plants per litre of digestate.

In summary, high quality digestate has minimal biological contamination from plant pathogens and viable seeds, which is much lower than in the case of undigested animal manure and slurries. Application of digestate as fertiliser breaks the chain of transmission of plant diseases and weeds seeds on farmland and lowers the need for subsequent use of herbicides and pesticides on respective crops.

Table 5 Survival of weed seeds (% germination) after mesophilic AD, expressed in number of days (d) at 37°C

Plant species	2d	4d	7d	11d	22d
Brassica Napus (Oil Seed Rape)	1	0	0	0	0
Avena fatua (Wild Oat)	0	0	0	0	0
Sinapsis arvensis (Charlock)	0	0	0	0	0
Fallopia convolvulus (Bindweed)	7	2	2	0	0
Amzinckia micranta (Common Fiddleneck	1	0	1	0	0
Chenopodium album (Common lambs quarter)	78	56	28	0	0
Solidago Canadensis (Golden Rod)	0	0	0	0	0

Source: Derived from Johansen, et.al (2011)

5 The effect of the AD-process on digestate quality

5.1 Pre-treatment of feedstock

5.1.1 Pre-sanitation

As indicated in Section 4.3, the AD process has a sanitation effect on the feedstock digested. Although most of the common pathogens and common viruses are killed during mesophilic and thermophilic digestion (Bendixen, 1994, 1995, 1999; Lund *et al.*, 1996), supplementary sanitation as a pre-sanitation step can be required for some specific feedstock types, prior to being added to the digester and mixed with the rest of the biomass. Pre-sanitation of only specified feedstocks avoids contamination of the entire feedstock mixture and saves the extra costs of having to pasteurise the entire digester volume.

For specific feedstock types (see ABP regulation in Appendix 4), pre-sanitation takes place at the site of the feedstock producer, thereby minimising any possible biological hazard associated with transport of un-sanitised material. In other situations, pre-sanitation is carried out in special installations at the biogas plant. In European biogas plants pre-sanitation usually involves pre-heating of specific feedstocks (dependent upon the category of material in the ABP regulation) by batch pasteurisation at 70°C for 1 hour, or pressure sterilisation at 133°C and 2.4 bar (absolute) for 20 minutes.

Danish experience shows that sanitation equivalent to pasteurisation can be achieved at thermophilic or mesophilic AD temperatures if the feedstock resides inside the digester for a specifically required amount of time (minimum guaranteed retention time (MGRT)), as indicated in Section 5.2.1, Table 6.

The residual heat in the sanitised material can be recovered through heat exchangers and used to raise the temperature of the incoming feedstock.

In other cases, the sanitization can be carried out after digestion.

5.1.2 Digestibility enhancement

A number of pre-treatments can be applied to feedstock in order to improve AD performance by increasing the concentration or the availability of readily degradable organic material. The pre-treatments include basic operations like the removal of physical impurities, mashing and homogenization. Others pre-treatments are more complex and include maceration, thermal and chemical hydrolysis, ultra sound treatments etc. Their aim is to open the structures which are not available to AD microorganisms (Mata-Alvarez *et al*, 2000; Hendriks and Zeeman, 2009; Bruni *et al*, 2010) thereby enhancing digestibility of the material. These types of treatment are usually undertaken at the AD plant and are usually applied to materials that contain high proportions of lignocellulose and hemicellulose (Triolo *et al*, 2011; Hjorth *et al*, 2011).

5.1.3 Solid-liquid separation

Feedstocks with low dry matter content like pig slurry can be pre-separated before digestion into a liquid and a solid fraction. Solid-liquid separation is used to reduce the volumes and the costs of the feedstock transport. The solid fraction can be supplied to the biogas plant (Moeller, 2001; Moeller *et al*, 2007; Hansen *et al*, 2004) and the liquid fraction can be applied as liquid fertiliser. Mobile separators (e.g. decanter centrifuges or screw presses) servicing several farms can be used (Soerensen and Moeller, 2006). Sharing separators will lower the costs of separation. More information on solid-liquid separation is given in Section 8 *Digestate processing* of this brochure.

5.1.4 Centralised pre-treatment – the HUB

Many farms with small scale AD plants could benefit from the chance to co-digest manure with high gas yielding feedstock such as food waste or animal by-products. As such situations will require pasteurisation or its equivalent, the cost of which usually cannot be justified for the relatively small quantities of material involved, Banks *et al* (2011) propose the establishment of centralised pre-treatment facilities (HUBs) to serve clusters of biogas plants. Each HUB would receive the materials to be pasteurized and, after appropriate pre-treatment, would supply digester-ready feedstock as required by the individual on-farm biogas plants, referred to as Point of Digestion (PoD). Each load provided by the HUB would be fully ABPR (animal by-products regulation) compliant and in accordance with any other national standards and regulations. This system would enable the individual farmers to avoid the capital expenditure for similar technology on the farm.

5.2 Process temperature and retention time

The time of residence of the feedstock inside the digester (retention time), at constant process temperature, influences the digestate quality. Retention times are quoted as hydraulic retention time (HRT) and as minimum guaranteed retention time (MGRT).

HRT is the nominal time that feedstock remains inside the digester at the process temperature. HRT is usually expressed in days and depends to a large extent on the digestibility of the feedstock mixture.

HRT [h or days] = Digester volume [m^3] / the influent flow rate [m^3/h or days]

MGRT is the minimum time (usually measured in hours) that any portion of the feedstock resides inside the digester. In continuous flow, stirred digesters, it is possible that fractions of feedstock (and the impurities contained in them) find a short cut through the digester. The MGRT in this type of digester is shorter than the HRT.

Short circuiting is avoided in batch digesters and where feedstock is held in a batch prior to digestion at the required temperature for the required time.

5.2.1 The sanitation effect of combined process temperature and retention time (controlled sanitation)

Combinations of thermophilic or mesophilic process temperatures and MGRT can provide pathogen reduction in animal manure and animal slurries equivalent to the EU sanitation standard of 70°C for 1 hour and are thus allowed, depending on the feedstock mixtures. The treatment should be carried out in a thermophilic digester, or in a sanitation tank combined with thermophilic or mesophilic digestion and the indicated combinations of temperatures and MGRT (Table 6) must be respected (Bendixen, 1999).

In Europe, combinations of temperature and retention time are sufficient and permitted only for feedstock types where other specific pathogen reduction measures are not required by other regulations, as is the case of the Animal By-product Regulation 1069/2009.

Biogas plant operators must select process temperatures and retention times which are appropriate for the kind of feedstock that is to be digested. In the case of existing biogas plants, the choice of allowable feedstock depends to a large extent on the type of process applied (e.g. mesophilic or thermophilic) and the existing pretreatment facilities at the plant.

Although the combination of process temperatures and retention time is the most important sanitation/pathogen inactivation factor, research results (Martens *et al.*, 1998; Engeli, 1993: Carrington 2001) indicate that the pathogen inactivation is more complex and occurs from the combined effect of these with other process parameters such as pH, redox potential and NH_3 concentration inside the digester. For this reason, it is important to optimise and monitor closely the AD process and the process parameters.

Table 6: Controlled sanitation through combinations of temperatures and minimum guaranteed retention time (MGRTs), equivalent to 70°C for 1 hour – Adapted from Bendixen, 1999

Temperature	Retention time (MGRT) in a thermophilic AD reactor [a]	Retention time (MGRT) by treatment in a separate sanitation tank [b]	
		before or after digestion in a thermophilic digestion tank [c]	before or after digestion in a mesophilic digestion tank [d]
52.0°C	10 hours		
53.5°C	8 hours		
55.0°C	6 hours	5.5 hours	7.5 hours
60.0°C		2.5 hours	3.5 hours
65.00°C		1.0 hours	1.5 hours

[a] The thermophilic digestion is defined as 52°C or greater. The hydraulic retention time (HRT) in the digester must be at least 7 days.
[b] Digestion may take place either before or after sanitation
[c] See point a)
[d] The mesophilic digestion temperature must be between 20°C and 52°C. The hydraulic retention time must be at least 14 days.

6 Preserving digestate quality

Unlike raw animal manure and other AD feedstock, sanitised digestate poses minimal risk of pathogen transfer through handling and application. Therefore, it is important to avoid re-contamination from raw manure and slurries as well as from other un-sanitised materials and sources. Bagge *et al.* (2005) reported recontamination and re-growth of bacteria in biowaste after pasteurisation and digestion. Precautions therefore need to be taken both at the biogas plant and at other digestate storage areas in order to preserve the high quality of digestate until its final utilisation as biofertiliser.

The following hygiene measures are recommended at all biogas plants, for general veterinary and human health safety and in order to prevent re-contamination of the sanitised digestate:

- At each AD plant there should be a strictly defined "dirty area" for fresh feedstock/un-sanitised materials and a "clean area" dedicated to sanitised materials, digestate and other "clean" activities and materials
- Any movement of vehicles and people between "dirty" and "clean" areas must be treated appropriately, e.g. disinfection of vehicles and for people changing shoes and clothing
- Feedstock must not be supplied from farms where there are livestock with serious health problems
- For AD plants that involve transport of biomass to and from farms, it is vital that there is no contamination between farms. This can be achieved by ensuring that only one farm is serviced at a time and drivers take appropriate precautions (remain in the delivery vehicle at the farms during biomass loading/unloading) to avoid contaminant transfer.
- Transport efficiency can be improved if tankers travel with full loads, so the delivery of digestate for use as a biofertiliser is followed by collection of fresh slurry for AD. Cross-contamination between fresh feedstock and digestate must always be avoided through strict hygiene measures. Therefore, after delivery of fresh feedstock to a biogas plant, all tankers should be cleaned before loading with digestate for subsequent delivery. For this reason there should be *standard procedures for cleaning vehicles* at biogas plants

Example of the standard procedure for cleaning biomass transport vehicles, as implemented at Ribe Biogas A/S in Denmark:

At the biogas plant:

1. After the vehicle tank has been completely emptied of feedstock all the inner surfaces are flushed out with tap water.
2. The interior of the vehicle tank is then disinfected by rinsing with 0.2% sodium hydroxide (NaOH) solution for 2 minutes, at least 200 litres for a 30 m^3 vacuum tanker and at least 150 litres for a 15 m^3 tanker.
3. All the exterior parts of the vehicle are rinsed and disinfected, in particular the wheels (Figure 9).

Figure 9: Exterior disinfection of slurry transport vehicle.
Source: Ribe Biogas A/S (www.ribebiogas.dk)

7 Digestate declaration and characteristics

The content of nutrients in digestate depends on the content of the incoming feedstock. For this reason, the content and availability of plant nutrients in digestate varies between biogas plants and will vary over time at the same biogas plant according to the feedstock digested.

Before digestate is used as a fertiliser, in line with best farming practices, its composition should be analysed and declared. This applies also to digestate produced and used on a single farm. Declaration of macro and micro nutrients and dry matter content is part of the quality assurance schemes for digestate in many countries.

Biogas plants in Denmark, particularly large scale centralised plants, include small laboratories on site for measuring the dry matter content, the organic dry matter and the pH of samples from all loads of digestate (Figure 10). More complex nutrient content analyses are carried out by accredited laboratories. To avoid any uncertainty, the frequency and the procedure for sampling and analysis should be stipulated by specific protocols.

Figure 10: Mini laboratory at Lemvig Biogas Plant in Denmark
Source: Lemvig Biogas (www.lemvigbiogas.com)

8 Digestate processing

Digestate can be used as fertiliser without any further treatment after its removal from the digester and after the necessary cooling. As digestate usually has low dry matter content, its storage, transport and application are expensive. This makes digestate processing and volume reduction an attractive option.

Digestate processing can involve a number of different treatments and technologies. They are comparable to those used for manure processing or for wastewater treatment. Processing of digestate can have different aims, depending on local needs. If the aim is to enhance quality and marketability of the digestate and to produce standardised biofertilisers (solid or liquid), this is called *digestate conditioning*. If the aim is to remove nutrients and organic matter from the digested effluent, digestate can be processed by practices similar to *wastewater treatment*. From a technical point of view, digestate processing can be *partial*, usually targeting simple volume reduction, or it can be *complete*, separating the digestate into solid fibers, concentrates of mineral nutrients and clean water.

8.1 Partial processing

Partial processing uses relatively simple and cheap technologies. The first step in any digestate processing is separation of the solid phase from the liquid. Flocculation or precipitation can be used in order to improve solid-liquid separation. A range of separation methods can be used, for example, mechanical means such as screw press separators or decanter centrifuges. Decanter centrifuges, for example, can be used to separate the majority of the phosphorus in the digestate into the fibre fraction (Møller, 2001, Gilkinson and Frost, 2007). Phosphorus separation improves management of macro nutrients because it enables separate application of phosphorus and nitrogen. It also allows the distribution and application of the phosphorus rich fibre to other geographical areas with a phosphate deficit or the mixing of fibre with the AD feedstock for re-digestion.

The solid fraction can subsequently be applied directly as fertiliser in agriculture or it can be composted or dried for intermediate storage and enhanced transportability. The solid fraction can also be sold as a phosphorus–rich fertilizer, without any further treatment or it can be pelletized as shown in Figure 11. Other options are use for industrial purposes, such as production of composite materials, or incineration for energy production.

The liquid fraction, containing the main part of nitrogen (N) and potassium (K), can be applied as liquid fertilizer or mixed with high solids feedstock and re-fed to the digester.

8.2 Complete processing

Complete processing applies different methods and technologies, each at different stages of technical maturity (Braun *et al.* 2010). Membrane technologies such as nano- and ultra-filtration, followed by reverse osmosis are used for nutrient recovery (Fakhru'l-Razi 1994, Diltz *et al.* 2007). Membrane filtration gives two products, a nutrient concentrate and purified process water (Castelblanque and Salimbeni 1999, Klink *et al.* 2007). The liquid digestate can alternatively be purified by aerobic biological wastewater treatment (Camarero *et al.* 1996). Addition of an external carbon source may be necessary to achieve appropriate denitrification because of the high nitrogen content and low biological oxygen demand (BOD). A further possibility for concentrating digestate is evaporation using surplus heat from the biogas plant. Stripping (Siegrist *et al.* 2005), ion exchange (Sánchez *et al.* 1995) and struvite precipitation (Uludag-Demirer *et al.* 2005, Marti *et al.* 2008) can be used to reduce the nitrogen content in the digestate. Independent of the technologies used, complete processing requires high chemical and energy inputs. Treatment costs are usually high and there will be higher investment costs for appropriate machinery.

Figure 11: Fertilizer pellets produced from decanter separated fibre fraction, through application of the patented VALPURENTM-process at the AD plant in Spain. Source: www.actiweb.es

9 Storage and application of digestate

Correct storage, handling and application of digestate preserve its value and qualities as biofertiliser and helps prevent losses of ammonia and methane to the atmosphere, nutrient leakage and run off as well as emissions of unpleasant odours and aerosols.

9.1 Storage of digestate

Digestate must be applied during the growing season when it is best utilised by crops. Application outside the growing season has serious water and air pollution consequences. National regulations which govern nutrient management and manure application also prescribe the periods of digestate application as well as the necessary storage capacity. These are compulsory in many countries, and integrated in the agricultural and environmental protection legislation.

Production of digestate is a continuous process, and therefore requires storage capacity until digestate can be applied to crops during the growing season. The necessary storage capacity and the length of the storage period depend on geographical location, soil type, winter rainfall, crop rotation etc. In the temperate climate of parts of Europe for example, the storage capacity must accommodate 4–9 month of digestate production.

Digestate can be stored at the biogas plant, or even better at a convenient location close to the fields where it will be applied as biofertiliser. Independent of location, digestate stores are normally above ground storage tanks. Lagoons and storage bags can also be used. In all cases, it is very important to cover the storage facilities as this prevents nutrient losses and pollution through ammonia emissions and from residual methane production, as well as digestate dilution by rainwater.

A range of gas tight storage covers are in use (Al Seadi and Holm Nielsen, 1999). There are membranes that can be fastened to the side of the tank and supported by a central mast or float on the surface of the digestate. Membrane covers are commonly used on farm-scale biogas plants (Figure 12) and for storage tanks located close to the agricultural fields. On large scale co-digestion plants, storage tanks for digestate can also be covered with concrete roofs (Figure 13) or steel covers, which are usually more expensive than membrane covers.

If the use of membrane covers is not possible, storage tanks should at least have a surface crust or a floating layer of chopped straw (Figure 14), clay granules or plastic pieces. The floating crust must be artificially created because digestate, unlike raw slurry, does not produce a surface crust naturally.

The crust must be kept intact until the digestate is ready for transport or application, prior to which it is stirred. Stirring ensures the homogeneity of the fertilizer during utilisation and must *only* take place when digestate is to be used, in order to avoid unnecessary emissions and odour release. The stirring of the digestate in storage tanks can be carried out by fixed or mobile stirrers.

9.2 Application of digestate as biofertiliser

Like any other fertiliser, digestate must be applied during the growing season in order to ensure the optimum uptake of the plant nutrients and to avoid pollution of ground water. Digestate must be integrated in the fertilisation plan of the farm in the same way as mineral fertilisers and it must be applied at accurate rates, with equipment that ensures even applications throughout the whole fertilised area.

Figure 12: Digestate storage tank, covered with gas tight membrane (soft cover) fastened on the edges of the tank. Source: Lundsby Industry A/S (www.lundsby.dk)

Figure 13: Storage tanks for digestate, covered with concrete tops, at Lemvig AD plant in Denmark. Source: Lemvig Biogas (www.lemvigbiogas.com)

Figure 14: Open storage tank for digestate with freshly chopped straw spread on the liquid surface. Source T. Al Seadi

Figure 15: Digestate is applied as fertilizer with the same equipment which is normally used for application of liquid manure and slurry. 15A: Band application of digestate on freshly cultivated soil; Source: Collyer Services Ltd, (http://www.ihampshire.co.uk/profile/10449/Waterlooville/Collyers-Services-Ltd/); 15B Injection of digestate into the top soil, for minimization of nitrogen losses through ammonia volatilization. Source: Rækkeborg Maskinstation (www.raekkeborgmaskinstation.dk).

The suitable methods of application are the same as those used to apply raw, untreated slurry, with the exception of splash plate spreading which causes pollution and losses of valuable nutrients. Because of the significant pollution caused by splash plate spreading, this method is banned in countries with modern agriculture and environmental protection legislation (Lukehurst *et al*, 2010). The equipment used to apply digestate should minimise the surface area exposed to air and ensure rapid incorporation of digestate into the soil. For these reasons, digestate is best applied with trailing hoses, trailing shoes or by direct injection into the topsoil (Figure 15). These methods of application will also minimise ammonia volatilisation.

Final comments

Digestate from biogas plants which follow the examples of good practices described in this brochure is a high quality product, suitable and safe for use as fertiliser in agriculture, horticulture and forestry.

Utilisation of digestate as biofertiliser recycles the nutrients and the organic matter, and saves costs to the farmers while enhancing the utilisation of own resources. The significant reduction of animal and plant pathogens and of weed seeds through AD treatment breaks the chain of their transmission and improves veterinary safety and phyto-hygenic safety on farms. This gives digestate a significant advantage over the raw feedstock. Its use as biofertiliser contributes to preservation of the natural reserves of fossil phosphorus, a highly valuable but rapidly depleting resource on our planet. As digestate is often utilised as fertiliser for crops dedicated to human food and animal feed production, its high quality has direct impact on food quality and food safety.

Despite its potential, utilisation of digestate as biofertiliser is limited in many countries due to lack of information about its qualities and fear of potential risks related to its use. Product quality, food safety and risk management are currently important focus areas in all the aspects of life and productive activities. The quality management of digestate not only guarantees that digestate is safe for use, but also contributes to the perception of digestate as a safe and healthy product. The ultimate aim is to enhance digestate utilisation as biofertiliser and consequently to provide incentives for the further development of biogas technologies, which are not only able to provide renewable energy and CO_2 neutral fuel, but are also environmentally sound and veterinary safe treatment options for animal manures and suitable organic wastes.

The quality management of digestate is part of the overall demand for quality products in today's society. The requirement for quality necessarily implies adoption of a unified approach herewith and of a system of quality parameters to measure and guarantee quality. The increasingly strict environmental legislations introduced in most countries aim to address pollution of all kinds and losses of biodiversity and to minimise any current and future hazards for living organisms. Legal frameworks and quality standards for digestate used as biofertiliser provide confidence in digestate quality and safety and contribute to a sound and stable market for digestate. Such regulations, introduced by an increasing number of countries, include standards of digestate quality, digestate certification schemes, guidelines for recommended practices for digestate utilisation and positive lists of materials suitable for use as AD feedstock. The rigorous selection and strict quality control of the materials used as feedstock for AD is the first and most important step of digestate quality management ensuring maximum ecological and economic benefits from use of digestate as a biofertiliser.

The guidance offered by this brochure will help set the basis for quality standards for digestate in places where digestate utilisation as fertiliser is an established practice and in those places where such practices are just emerging.

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11.2 Web sources

http://www.avfallsverige.se/fileadmin/uploads/Rapporter/Biologisk/English_summaryof_SPCR_120.pdf The English version of the Swedish certification system for digestate, including the positive list of materials considered suitable as AD feedstock.

http://www.biogas-info.co.uk – The UK Official Information Portal on Anaerobic Digestion

http://www.bmu.de/english/waste_management/acts_and_ordinances/acts_and_ordinances_in_germany/doc/20203.php – English versions of German acts and ordinances.

www.bmu.de/english/renewable.../5433.php/ – The German Biomass Ordinance, stipulates which substances are recognised as biomass under the tariff provisions of the Renewable Energy Sources Act (EEG)

http://www.defra.gov.uk/food-farm/byproducts/ – Helpful interpretation of the European Animal By-Product Regulation and guidelines on how to apply it.

http://eur-lex.europa.eu/ – The Animal By-Product Directive, and other EC laws can be downloaded in full text, in all languages of the European Union.

http://www.lemvigbiogas.com/download.htm – The website contains valuable biogas information, available in several languages. The Big East "Biogas Handbook" is also available in several languages for free download from this website.

http://www.mst.dk/ – Danish Ministry of the Environmemt. The Environmental Protection Agency. The Danish Ministry of Environment is the advisor of the Danish Government on environmental initiatives. The web page contains, *inter allia*, Danish and international environmental legislation, rules and measures, working documents, publications for free download, collation and dissemination of knowledge about the environment and other information designated to the general public, the companies and to other national authorities.

www.wrap.org.uk/farming/ – A wide array of technical and scientific literature on the safety of using digestate and any risks this might have, effectiveness of mesophilic and thermophilic digestion and/or pasteurisation, along with reviews and summary of this kind of information is provided by the United Kingdom government.

Appendix 1

Example of positive list of materials suitable as AD feedstock in biogas plants using digestate as fertiliser in the Netherlands (summary translation from the original language)

I. MATERIALS THAT CAN BE TRADED AS FERTILISER

1. *Residue from the factory production* of sugar from beet and that mainly consists of calcium carbonate, organic matter from sugar and water (lime).

2. *Residue, consisting solely of calcium carbonate* in the form of egg shells crushed into granules from the industrial processing of eggs (calcium carbonate processed egg shells).

3. *Residue from the manufacture of drinking water* from groundwater or surface water, which mainly consists of calcium carbonate (lime sludge from drinking water).

4. *Residue from the production by fermentation* of the antibiotic 7-amino-acetoxy-cephalosporinic which mainly consists of sulphur, potassium and nitrogen (residue at 7-ADCA production).

5. *Residue from the purification* of rock salt in the manufacturing of pure sodium chloride, which is composed of calcium carbonate, water, magnesium and trace salt and gypsum (calcareous residue of salt),

6. *Residue from the production of urean* from urea and calcium ammonium nitrate, which is composed of calcium carbonate (lime), water filtering and adjuvant amorphous aluminosilicate (lime cake released during the production of inorganic fertilizers).

7. *Residue from the industrial production* of baker's yeast by fermentation of dilute molasses from beet and that consists of dark brown viscous slurry of crystals of potassium sulphate (potassium sulphate suspension).

8. *Residue from the manufacture of alcohol* by fermentation of molasses, which was from the factory processing of sugar beet and consists of a dark brown viscous liquid (vinassekali) or consists of a thickened dark brown viscous liquid (condensed vinassekali).

9. *Residue from the chemical purification of air* from an enclosed industrial building, where (composted) sludge with wood chips are composted through washing with a dilute aqueous solution of sulphuric acid and comprising a pH-neutral solution of ammonium sulphate in water (ammonium sulphate water of chemical air scrubbers of composting hall).

10. *Residue from the production of hydrocyanic acid* (hydrogen cyanide) of methane and ammonia according to the BMA process and consists of a solution of ammonium sulphate in water with a maximum hydrocyanic acid content of 0.00027% (ammonium sulphate aqueous solution of hydrogen cyanide production by BMA process).

11. *Residue from the factory processing of potatoes* into starch, which consists of concentrated deproteinized potato juice (un-concentrated de-proteinized potato juice).

12. *Residue from the production of alcohol* by fermentation of glucose derived from the processing from wheat to wheat gluten and wheat starch after addition of yeast, where the alcohol by distillation is removed and that propionic and stabilised butyric acid can consist of aqueous sludge residues of fermented yeast and wheat ingredients (wheat yeast concentrate)

13. *Residue after removing potassium* from glycerine from biodiesel production from rapeseed by precipitation and consisting mainly of dried potassium sulphate (Potassium Sulphate biodiesel production).

14. *Residue from the factory removal* of peel with steam pre-washed and made up of water chilling in roots (roots shells litter).

II. MATERIALS THAT CAN BE TRADED AS FERTILISER

(Categories of waste or residue)

III. MATERIALS USED IN THE PRODUCTION OF FERTILISERS

1. *Residue from the production of burnt out magnesium* calcium hydroxide dolomite (calcium magnesium oxide formed from calcium magnesium carbonate) and grey-white granules consisting of calcium oxide and magnesium magnesium calcium hydroxide (granulates magnesium calcium hydroxide)

IV. END PRODUCTS OF PROCESSING PROCEDURES THAT CAN BE TRADED AS FERTILISER

1. *Product obtained by fermentation* of at least 50 percent by weight animal excrement, as a side item only one or more of the substances listed in the list below under the respective categories or subcategories (cover digested manure):

A Materials of plant origin from a farm

A1 Crop (products) for human consumption or animal feed

1. *Meadow grass (fescue),* pasture silage, maize, silage maize/silage, grain corn, corn cob mix (CCM), barley, oats, rye grain, wheat grain, potatoes, sugar beet, fodder beet, onions, chicory, seeds of peas, seeds of lupins, beans / pods of beans , sunflower seed, rape seed, flax seed oil, flax seed, fruits and vegetables belonging to the Annex A leafy vegetables, brassica crops, herbs, fruit crops, fruit crops and plant stems/ roots.

A2 Crop (products) for biogas production

1. *Energy Maize*

B Materials of plant origin from nature reserves as defined in Article 1, first paragraph, section e, of the Decree fertiliser use

B1 Prairie grass from pasture as defined in Article 1, first paragraph; subsection C of the fertiliser use decision.

C Materials from the food and beverage industries

C1 Materials of vegetable origin

1. *Residue from the factory processing of potatoes* into starch, fibre and protein, which consists of concentrated deproteinized potato juice with a dry matter content of at least 50% (protamylasse).

2. *Residue from the factory processing of potatoes* into starch, fibre and protein and starch residues comprising a settling agent that is separated from the released wastewater (primarily potato sludge).

3. *Residue from the production of alcohol* by fermentation of glucose into product of processing from wheat to wheat gluten and wheat starch after addition of yeast, where the alcohol by distillation is removed and that propionic and stabilized butyric acid can consist of aqueous sludge residues of fermented yeast and wheat ingredients (wheat yeast concentrate).

4. *Residue from the factory removal of peel* with steam prewashed potatoes and potato peels in water consists of (potato peelings).

5. *Residue from the factory removal of peel* with steam prewashed and made up of water chilling in roots (roots shells litter).

6. *Residue from the factory manufacture of starch,* protein, germ and fibre from corn and composed of evaporated (concentrated) water with a dry matter content of at least 50% (concentrated corn steep water).

7. *Residue from the factory unpacking* by an specialized company exclusively packaged soft drinks and light alcoholic beverages from retail, wholesale and manufacturers, and only because they exceeded their expiry date, packing errors and preservation have become unfit for human consumption. The mixture consists of unpacked or light soft drinks, alcoholic beverages and is free of packaging (liquid mixture of soft and light alcoholic beverages).

8. *The residue with water and physical processes* either as a concentrated residual liquid from the factory separation of wheat flour in wheat starch and wheat protein (gluten) for use in the food industry (wheat).

9. *Residue from the manufacture of canned products* comprising a mixture of selected dry white beans or broken selected soaked blanched beans unfit for human consumption (mixture of white beans).

10. *Residue from the factory processing* of wheat gluten to flour, bran and starch for the food industry which consists of a concentrated sugar-rich side stream (wheat gluten concentrate).

11. *Residue from the factory mechanical peeling* of oranges intended for human consumption of orange juice (orange peel residues).

12. *Residue from the factory cleaning processes* of raw vegetable oil - exclusively from seeds of rape, soybean or sunflower - by physical separation and wherein the hydrophilic portion of the oil dissolves in water or a weak acidic solution and is composed of phospholipids, water soluble fats, oils and any residual acid in water (aqueous lecithin-oil mixture).

13. *Residue from filtering by mechanical separation* of pure vegetable oil, pre-cut and blanched potato chips with pre-made batter, batter or spices and baked comprising residues/batter with starch and oil.

14. *Residue from soy beverage processing* of soybeans comprising a mixture of liquid and the separated poorly soluble fraction (mixture of soy pulp and cooking liquid).

15. *Residue from the factory processing* of pre-washed potatoes, yellow turnips, white turnips, white beets and celery air dried with a steam, brushed and rinsed with water and then dried with air. (Peels of tuber crops).

16. *Residue from the factory processing* of sugar beet and cleaned debris consisting of beet, especially the thin ends, and parts of beet leaves, with or without silage. (Beet points).

C2 Materials of animal origin, whether or not combined with substances of plant origin

1. *Residue from an extraction company specializing* exclusively in packaged fluid milk products from retail, wholesale and manufacturers, and only because they exceeded their expiry date, packing errors and preservation have become unfit for human consumption. The residue consists of unpacked fluid milk products or mixtures thereof and is free from pakkaging and cleaning water (extracted LDP and mixtures thereof).

2. *Residue from the factory manufacture* of ice cream and raw material consisting of debris, and rejected ice cream residues and free of packing and cleaning water.

3. *Residue as a mixture released from a factory* unpacking only pre-packaged foods that come from retail, wholesale and manufacturers, and only because they exceeded their expiry date, packing errors and preservation have become unfit for human consumption. The mixture is extracted from foods that were originally intended for human consumption and is free of packaging and cleaning water (extracted foods for human consumption).

4. *Residue from the factory removal* of lactose by separation from the permeate obtained by ultra-filtration of sweet cheese whey (liquid permeate delactosed).

D Materials from the feed industry

E Materials from other industries

1. *Residue from the factory production of biodiesel,* from rapeseed oil or rapeseed oil by transesterification with methanol and separation under the influence of gravity (glycerin).

F Excipients or additives

1. *Sludges or semi-solid sludges, r*eleased during the production of drinking water from groundwater or surface water and composed of iron (III) hydroxide and water (water iron).

Appendix 2

Examples of national quality standards for digestate

Many aspects of digestate quality management presented in this brochure have already been adopted by a number of countries. Uses of certification systems, positive lists, quality standards and guidelines of recommended practices for use of digestate as biofertiliser give confidence in digestate quality and contribute to development of healthy markets for this valuable product. Three examples of schemes adopted in Sweden, United Kingdom and Switzerland are summarised in this section. It is essential that regulations and schemes of this kind are regularly up-dated, to stay in line with changing market demands, technical development and new legislation. References and links to similar regulations and schemes in other countries can be found in “Recommended sources of further information” in this brochure.

Extract from the Swedish Certification Rules for digestate

The Certification Rules for digestate lay down requirements for certification, technical requirements and

requirements for continuous control and self-control of the certified digestate. Table A 2.1 lists the materials which are suitable for production of certified digestate.

The certification is based on prevailing standards and on the requirements of Swedish Waste Management, which are documented in the RVP report 99:2 (AFR report 257) “Sjösättning av certifieringssystem för kompost och rötrest”.

The certification principles are based on the European regulation 1069/2009, and the guidelines and advice about storage, digestion and composting of organic waste of the Swedish Environmental Protection Agency. The certification rules are regularly up-dated through decisions taken by the management committee.

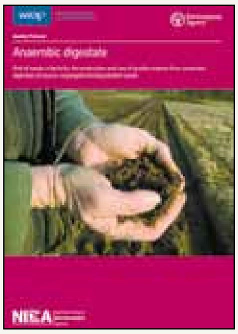
In all cases when the feedstock contains animal by-products, the prescription of the European “animal by-products” Regulation should be followed.

The full text of the newest version of the Swedish certification rules is published at: http://www.sp.se

Table A2.1: Types of AD feedstock permitted for certificated digestate

Source	Example
Parks, gardens etc.	Leaves, grass, branches, fruit, flowers, plants and parts of plants
Greenhouses, etc.	Tops, soil, peat products.
Households, kitchens, restaurants	Residues from fruit and vegetables residues, coffee and tea, food, egg shells, cardboard, paper, paper bags, biodegradable bags, plants and flower soil. Bags for source separated house hold waste should fulfil EN 13432 from 1/1 2005.
Food related shops	Fruits, vegetables, potatoes, dairy waste, paper towels, paper napkins, bread, meat, meat remnants, charcuterie remnants, flowers, plants, soil and peat. Food containing additives allowed for food production are also allowed in the substrates.
Food industry	Remains from food industry that contain additives allowed in food production are allowed as substrates
Agriculture	Manure, straw, harvesting by-products, silage, energy crops
Forrest	Bark, wood chips, fibre, sludge from the cellulosic industry
Animal by-products, category 2	Only manure, stomach and intestine content (separated from the tissue of stomach and intestine), milk and raw milk
Animal by-products, category 3	In accordance with ABPR (1069/2009)

Extract from the Quality Protocol for anaerobic digestate in the United Kingdom



Uncertainty over the point at which waste has been fully recovered and ceases to be waste within the meaning of Article 6(1) of the EU Waste Framework Directive (WFD) (2008/98/EC) has inhibited the development and marketing of materials produced from waste which could be used beneficially without damaging human health and the environment. For this reason, a Quality Protocol applicable in England, Wales and Northern Ireland was developed by the Environment Agency and WRAP (Waste & Resources Action Programme) in consultation with DEFRA, industry and other regulatory stakeholders (Environment Agency 2010). The standards in table A.2.2 below form the basis of The Quality Protocol for anaerobic digestate in the United Kingdom.

The Quality Protocol aims to provide increased market confidence in the quality of products made from waste and so to encourage greater recovery and recycling. The protocol sets out criteria for the production and use of quality outputs from anaerobic digestion, indicating how compliance may be demonstrated and points to best practice for the use of the fully recovered product.

The full text of the protocol is available for free download from:

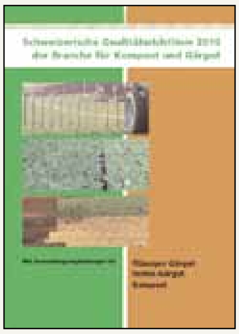
http://www.environment-agency.gov.uk/business/topics/waste/114395.aspx

PAS110 is also available for free download from the WRAP and BCS websites:

http://www.biofertiliser.org.uk/certification/england-wales/pas110

http://www.wrap.org.uk/farming_growing_and_landscaping/producing_quality_compost_and_digestate/bsi_pas_110_.html

Extract from the Swiss Quality Guidelines for compost and digestate



The purpose of the Swiss Quality Guidelines is to clarify the required properties of digestate and compost, to stipulate their standards of quality (Table A2.3) as well as to recommend good practices for application in agriculture, horticulture and greenhouses/protected cultures.

The document specifies that the “minimum quality requirements” formulated by the Research Institute of Agrochemistry and Environmental Hygiene in 1995 are still valid. The present guidelines published in 2010 complement them with practical knowledge, defining the products compost and digestate and providing criteria for demarcation between the two. The stated aim is to ensure that only high quality products reach the market. The high quality refers to control of xenobiotic contaminants and other potentially harmful compounds as well as the stability and maturity of these products. The importance of using only feedstock of high quality with as low as possible content of potentially harmful compounds is emphasised.

The guidelines also contain a positive list of feedstock which is allowed to be used for digestate and compost, as well as instructions for sample taking methodology and frequency of analysis by accredited laboratories. The guidelines are addressed to the processing companies, feedstock producers and the users of compost and digestate.

The newest version of the Swiss quality guidelines is available for free download at: http://www.kompost.ch/anlagen/xmedia/2010_Qualitaetsrichtlinie_Kompost_Gaergut.pdf

Table A2.2: Test parameters and upper limit values for digestates derived from source-segregated wastes in the UK (PAS 110, 2010). The same parameters apply to whole digestates (WD), separated liquor digestates (SL) and separated fibre digestates (SF).

Parameter	Upper limit and unit
Pathogens (human and animal indicator species)	
ABP digestate: human and animal pathogen indicator species	As specified by the competent authority/Animal Health vet/Veterinary Service vet in the 'approval in principal' or 'full approval'
Non-ABP digestate: *E. coli*	1000 CFU / g fresh matter
Non-ABP digestate: *Salmonella* spp	Absent in 25 g fresh matter
Non-ABP digestate: *Salmonella* spp	Absent in 25 g fresh matter
Potentially Toxic Elements	
Cadmium (Cd)	1.5 mg/kg dry matter
Chromium (Cr)	100 mg/kg dry matter
Copper (Cu)	200 mg/kg dry matter
Lead (Pb)	200 mg/kg dry matter
Mercury (Hg)	1.0 mg/kg dry matter
Nickel (Ni)	50 mg/kg dry matter
Zinc (Zn)	400 mg/kg dry matter
Stability	
Volatile Fatty Acids	Screening value: 0.43 g COD/g VS
Residual Biogas Potential	0.25 l/g VS
Physical contaminants	
Total glass, metal, plastic and any 'other' non-stone, man-made fragments > 2mm	0.5% m/m dry matter, of which none are 'sharps'
Stones > 5mm	8% m/m dry matter
Characteristics of digestate for declaration, without limit values, that influence application rates	
pH	Declare as part of typical or actual Characteristics
Total nitrogen (N)	Declare as part of typical or actual characteristics, units as appropriate (e.g. $kg.m^{-3}$ fresh matter and nutrient units per 1000 gallons (4500 litres) fresh matter
Total phosphorus (P)	
Total potassium (K)	
Ammoniacal nitrogen (NH_4-N) extractable in potassium chloride	
Water soluble chloride (Cl^-)	
Water soluble sodium (Na)	
Dry matter (also referred to as total solids)	Declare as part of typical or actual characteristics, % m/m of fresh sample
Loss on ignition (also referred to as volatile solids and a measure of organic matter)	Declare as part of typical or actual characteristics, units as appropriate

Note 1: This Table is a brief summary and can only be used in conjunction with the full protocol.

Note 2: The protocol does not apply to digestate derived from manures and purpose grown crops as these are not considered waste and do not need to comply with PAS 110.

Table A2.3: Criteria for certification of digestate and compost in Switzerland

Criteria	Agriculture			Horticulture	
	Liquid digestate	Solid digestate	Compost	Compost for field horticulture	Compost for protected horticulture (greenhouse)
Minimum quality	Fulfilled according to "minimum quality" (FAC 1995)				
Heavy metals	Limit values ChemRRV				
Xenobiotic compounds	Fulfilled according to ChemRRV				
Hygiene	Fulfilled		Fulfilled according to "minimum quality", with temperature protocol		
Nutrients P_2O_5, K_2O, Mg, Ca	x	x	x	x	x
Decomposition			Raw material no longer recognizably, except wood		
Dry matter	x	x	x	>50%	>50%
Organic dry matter	x	x	x	<50%	<40%
pH	x	x	x	<7,8	<7,5
Screen size		x	x	<25mm	<15mm
Specific weight	x	x	x	x	x
Colour of extract					
(Extinction 1cm cell 550 nm)		(x)	<1.1(~HZ 37)	<0.5 (~HZ 37)	<0.2 (~HZ 37)
Salts content	x	x	x	<20gKCleg/kg TS	<10gKCleg/kg TS
Total N	x	x	x	>10g/kg TS	>12g/kg TS
C/N ratio	x	x	x	x	x
Ammonium-N	>3g/kgTS	>600mg/kgTS	<600mg/kgTS	<200mg/kgTS	<40mg/kgTS
Nitrate-N			x	>80mg/kgTS	>160mg/kgTS
Nitrite-N			(x)	<20mg/kgTS	<10mg/kgTS
N_{min}	>3g/kgTS	>600mg/kgTS	>60mg/kgTS	>100mg/kgTS	>160mg/kgTS
Nitrate-N/N_{min}-ratio			(x)	>0.4	>0.8
Plant tolerance:					
Open cress				>50% of ref.	>75% of ref.
Closed cress			(x)	>25% of ref.	>50% of ref.
Salad test				>50% of ref.	>70% of ref.
Beans test					>70% of ref.
Ryegrass test					>70% of ref.
Diseases suppression test					(x)

Must fulfil minimum/maximum rate
Recomended minimum/maximum rate
x: Must be indicated
(x): To indicate recommended

Appendix 3

Managing digestate quality

Separate collection of digestible household waste

The digestible fraction of household waste must have high purity for problem-free use as AD feedstock. High purity of household waste can be achieved through source separation and separate collection in paper bags or in bio-degradable plastic bags. Source separation and separate collection has other important advantages:

- Provides higher purity materials, compared with bulk collection and "on-site" separation
- Prevents contamination of the digestible fraction from other materials
- Eliminates the cost and consumption of work hours, energy and materials, necessary for on-site separation and purification operations
- Prevents losses of organic matter attached to the inorganic fraction
- Reduces the amounts of residual municipal solid waste (MSW), and by this the overall capital and operating costs for waste treatment
- Enhances waste recycling, resource preservation and energy savings
- Improves quality of biological waste treatment
- Reduces wear and tear of AD equipment

Bulk collection followed by "on-site" separation of the digestible fraction is less beneficial, compared with source separation. The major disadvantages of bulk collection are: high risk of inclusion of contaminants of all kinds from other waste materials, losses of organic matter attached to the inorganic material and increased overall costs of waste treatment.

Management of feedstock containing sand

Feedstock materials from agriculture (cow and pig slurry, poultry manure, plant residues etc.) may contain sand or small stones. The presence of sand inside the digester is undesirable as it increases the load on the stirring system, pumps and heat exchangers, causing fouling, obstructions and potentially severe wear. Accumulation of sand on the bottom of digesters and storage tanks reduces their active volume. It is therefore worth implementing specific practices to avoid problems caused by the presence of sand in the AD system:

- Avoidance of feedstock with very high sand content
- Strategic placement of the feeding pipe inlets in order to avoid sand circulation
- Building reactor tanks with conical bottom, to permit easy sand extraction
- Adequate stirring capacity in tanks and digesters, capable of handling sand containing biomass
- Sufficient pre-storage capacity, as sand reduces the active tank volume
- Regularly empting pre-storage and storage tanks, to prevent formation of hard sediments of sand
- Regularly removal of sand from digesters, using methods specially developed for this purpose

Two-stage AD for removal of heavy metals

As indicated in Section 4.2.1, there are usually low levels of heavy metals in digestate. Metals can be removed from digestate through a two-stage AD process (Evans, 2001). The 1st stage includes hydrolysis/acidification and liquefaction of the substrate and the 2nd stage includes methanogenesis. Research results show that up to 70% of the Ni, 40% of the Zn and 25% of the Cd were removed when the leachate from hydrolysis was circulated over a macroporous polyacrylamide column for 6 days (Lehtomäki and Björnsson, 2006). For Cu and Pb, mobilization in the hydrolytic stage was lower resulting in less effective removal (Selling *et al*, 2008). The two-stage AD technology is under development and has therefore only few commercial applications. One of them is the Borås biogas plant in Sweden, digesting high purity source separated household waste.

Degradation of organic pollutants during AD

Organic pollutants in feedstock and in the resulting digestate must be avoided because of their potential toxic effect on living organisms. Persistent organic pollutants (POPs) are compounds which are not biodegraded in the environment. They are proven toxic to biota and their long term effects due bioaccumulation is not known. Laboratory research showed that robust AD processes are able to degrade to some extent some organic pollutants, especially at the hydrolysis stage (Mogensen *et al*, 1999, Selling *et al*, 2008; Kupper, *et al*; Smith, 2009). Parker (1994) also indicate that a range of toxic compounds can be degraded to non toxic combinations during one and two stage AD processes. There is on-going research concerning degradation of organic pollutants through the AD process.

Appendix 4

The European Animal By-Product Regulation

The European Animal By-Product Regulation (ABP) 1069/2009 controls the use, recycling, disposal and destruction of animal by-products which are declared not suitable for human consumption. The initial version of the regulation, enforced in Europe in 2002 (1774/2002), was a measure of preventing transmission of bovine spongiform encephalopathy (BSE) and of foot and mouth disease (mononucleosis). The renewed ABP Regulation 1069/2009 stipulates also which categories of animal by-products and in which conditions these are allowed to be treated in biogas plants, as shown in Table A4.1.

Appendix 5

Glossary of terms

Anaerobic micro-organisms: Micro-organisms that live and reproduce in an environment containing no "free" or dissolved oxygen.

Anaerobic digestion (Synonym: digestion, anaerobic fermentation): A microbiological process of decomposition of organic matter, in the absence of oxygen, carried out by the concerted action of a wide range of micro-organisms.

Animal manures: Animal manures are animal faeces (usually >10% DM).

Animal slurries are a mixture of faeces and urine (2–10% DM depending on dilution).

AOX (Absorbable organic halogens): AOX is a standard parameter for organohalogen compounds. It is defined as the amount of chlorine chemically bound to soluble organic matter in effluent.

Biogas: A combustible gas typically containing 50–70% methane and 30 – 50% carbon dioxide produced through anaerobic digestion of organic matter.

Biogas plant (Synonym: anaerobic digester, anaerobic digestion plant, AD plant, AD and Biogas Reactor): Technical device for optimization of anaerobic digestion process and extraction of biogas.

Table A4.1: Conditions and pre-treatments required under Regulation (EC) number 1069/2009 for animal by-products allowed to be supplied to biogas plants.

Examples of animal by-products suitable for AD	Required pre-treatment conform to ABP	ABP category
Manure and digestive tract content from slaughterhouse	No pre-treatment	Category 2
Milk and colostrums	No pre-treatment	Category 2
Perished animals	Pressure sterilisation	Category 2
Slaughtered animal, not intended for human consumption	Pressure sterilisation	Category 2
Meat-containing wastes from foodstuff-industry	Pasteurisation	Category 3
Slaughterhouse wastes from animals fit for human consumption	Pasteurisation	Category 3
Catering waste, except for waste from international transports (flights and trains etc)	In accordance with national regulation	Category 3

Centralised biogas plants (Synonym: Joint biogas plants): Manure based AD plants, receiving and co-digesting animal manure and slurries from several animal farms.

DDT, DDE & HCH (Chlorinated Pesticides, including Lindane etc): DDT is today restricted to malaria vector control and was banned for agricultural use in 2001. Contamination of feedstock can occur from insecticides used in domestic gardens (Lindane, Pyrethroide, Thiabendazole etc.) and from agricultural run-off. Human exposure occurs mainly through contaminated high fat foods, contaminated leafy and root vegetables, dust and soil contaminated with these pesticides. The toxins are fat-soluble and they bio-accumulate in the fat tissues of humans and animals and are thus passed to the next generations. Acute toxicity from chlorinated pesticides is rarely seen since they have been banned but their persistence in the environment and human bodies can still cause a variety of health problems in the neurological, immunological, and endocrine systems, although they can also affect the cardiovascular, respiratory, and gastrointestinal systems.

DEPH (Di (2-ethylhexyl) phthalate): These compounds are primarily used as plastic fillers/softeners, such as PVC (e.g. tarpaulins, toys, cars and vinyl flooring). By washing, the substance end up in the sewage system. DEHP is reported to give reproductive and developmental toxicity in rodents.

Digestate (Synonym: AD residues, digested biomass, digested slurry): The digested effluent from the AD process.

Effluent: The liquid discharged from a process or chemical reactor.

Emissions: Fumes or gases that come out of smokestacks and tailpipes, escape from inside factories or enter the atmosphere directly from oil well flares, garbage dumps, rotting vegetation and decaying trees and other sources. They include carbon dioxide, methane and nitrous oxide, all of which contribute to the global greenhouse effect.

Feedstock: Any material which is fed to a process and converted to another form or product.

Inactivation of pathogens: the annihilation of pathogenic microorganisms by the action of heat or another agent.

LAS (Linear alkylbenzene sulphonates): These substances are primarily used as surfactants in detergents and cleaning agents. Accumulation of LAS has ecotoxic effect for soil invertebrates and plants.

Mesophilic digestion: anaerobic digestion in the temperature range between about 30 and 42°C.

Micro-organisms (Syn. Microbes): Are mainly unicellular organisms or living in a colony of cellular organisms. Microorganisms include bacteria, fungi, archaea, protists, microscopic plants (green algae) and animals such as plankton and the planarian. Some microbiologists also include viruses, while others consider these as non-living. Most microorganisms are unicellular (single-celled), but some multicellular organisms are microscopic, while some unicellular protists and bacteria, like *Thiomargarita namibiensis*, are macroscopic and visible to the naked eye.

Municipal solid waste (MSW): All types of solid waste generated by a community (households and commercial establishments), usually collected by local government bodies.

NPE (Nonylphenol and nonylphenolethoxylates with 1-2 etoxy groups): These compounds are used as surfactants in detergents, cleaning agents, cosmetic products and vehicle care products. They find their way into the sewage system via waste water from laundries and vehicle workshops and from cosmetics in household waste and sewage. Alkylphenols are known to have estrogenic effects. For example nonylphenol induces both cell proliferation and progesterone receptor in human estrogen-sensitive MCF7 breast tumor cells.

PAH (Polycyclic aromatic hydrocarbons): These substances are used in colouring agents, mothballs, wood treatment, refrigerating material, fungicide (paper industry), and are products of incomplete combustion. PAHs occur during combustion of carbon-containing fuel such as wood, coal and diesel and are a part of fossil fuels. They deposit on roofs and road surfaces, from where they are flushed into the sewage systems by rain water. PAHs are absorbed by plants and some are reported to be carcinogenic, mutagenic and teratogenic.

PCB (Polychlorinated biphenyls): PCB was used until 1977 as electrical insulators, heat transfer medium, hydraulic fluids and lubricants and today are prohibited in many countries. The contamination is mainly airborne. PCB accumulates in adipose tissues and is considered neurotoxic, hepatotoxic, immunotoxic and toxic to reproduction.

PCDD/F (Polychlorinated Dibenzodioxins & Dibenzofurans): Compounds used by chemical industries, (chlorinated compound processes), manufacture of insecticides, herbicides, antiseptics, disinfectants, wood preservatives. Contamination of AD feedstock can occur from treated wood products, chipboard and leaves/grass from contaminated areas. It is through intake of food but also drinking water and air, that the general population currently receives its major exposure to PCDD. The compounds are known to be carcinogenic, mutagenic and to have critical effects on organs and tissues.

Pasteurisation: partial sterilization of biomass by exposure to a temperature that destroys pathogenic microorganisms, without causing major changes in the chemistry of the pasteurised material.

Pathogen (Synonym. Infectious agent, Germ): Is a biological agent such as a virus, bacteria, prion, or fungus that causes disease to its host.

pH: An expression of the intensity of the alkaline or acidic strength of water. Values range from 0–14, where 0 is the most acidic, 14 is the most alkaline and 7 is neutral.

Sanitation of organic wastes and animal manures: application of thermal treatments and hygienic measures designed to protect animal and human health

Thermophilic digestion: anaerobic digestion in the temperature range between about 50 and 57°C.

IEA Bioenergy