Utilisation of digestate from biogas plants as biofertiliser

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Introduction

Anaerobic digestion (AD) in a biogas plant is a well proven process in which organic matter breaks down naturally in the absence of oxygen to produce two valuable products - biogas and digestate. Biogas is an extremely useful source of renewable energy, whilst digestate is a highly valuable biofertiliser. AD can also offer a range of other benefits.

During anaerobic digestion all of the nitrogen, phosphate and potash that were present in the feedstock are retained and this as a very useful organic fertiliser.. Over the last 50 or so years increasing use of inorganic fertilisers throughout the world has been central to increased farm production. However, the volatility of world oil prices has a major effect on the use of oil-based fertilisers with high oil prices leading to increased costs to farmers and to reduced fertiliser consumption. The use of digestate as a fertiliser to offset inorganic fertiliser is thus of major economic and ecological importance.

Current issues such as global warming, demand for renewable energy, landfill tax on organic waste, demand for organic fertiliser, high fossil fuel prices, pollution of the environment and legislation relating to the treatment and disposal of organic wastes have resulted in renewed worldwide interest in AD.

AD benefits

- Lowers fossil fuel use
- Lowers mineral fertilisers use - up to 2kg/t less CO_2 emissions from manufacturing
- Lowers GHG emissions from open manure stores
- Provides highly efficient method for resource recycling
- Closes the production cycle

Photo 1: Anaerobic digestion plant in Germany

1 Understanding AD

AD is a natural process in which microbes decompose a wide range of organic matter (feedstock) in airtight tanks (digesters) to produce biogas and digestate. Feedstock can include the organic fractions of industrial wastes and by-products, sewage sludge, municipal solid waste and most commonly other organic materials such as animal manures, agricultural crops, agri-food processing residues, unsold food, the organic fraction of household waste etc (see section 2). The feedstock for AD can be a single input (e.g. animal manure) or can be a mixture of two or more feedstock types (co-digestion). Most biogas plants use more than one substrate. When the dry matter content of inputs is below 15% the AD process is called 'wet' digestion (or 'wet' fermentation) and when feedstock is above this level it is referred to as 'dry' digestion. Figure 1 summarises the AD process.

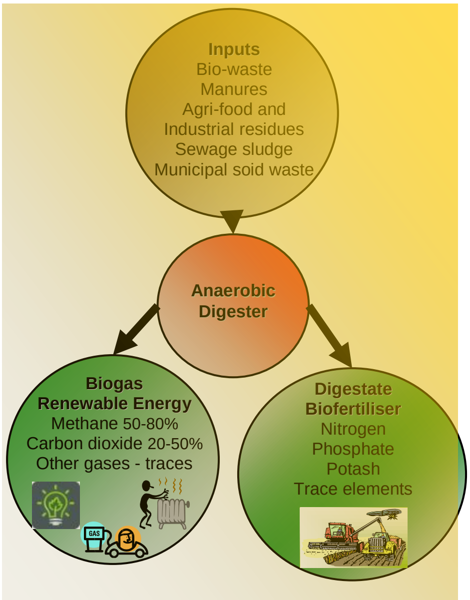

Figure 1: The anaerobic digestion process

Table 1 Estimated quantities of feedstock arising in the European Union (million tonnes fresh weight) (Gendebien, *et al*., 2001)

	Produced
Animal manure	1,200
Sugar beet processing	25
Olive oil production	7
Other fruit and vegetable processing	30
Other food and drink (including dairy, breweries, distilleries, soft drinks, abattoirs, etc)	40
Leather processing and tanning	900
Textiles (from organic fibres)	5
Estimated total	2,207

2 Feedstock

2.1 Feedstock types amounts and availability

Photo 2: Grass harvesting with a self-loading forage wagon and whole crop wheat harvesting with a self-propelled forage harvester

All organic materials, apart from lignin, are bio-degradable and therefore, AD feedstock are many and varied (see IEA Bioenergy, 2005 for more detail) and many billions of tonnes are available worldwide. Within the EU, for example, there are over 2 billion tonnes of potential feedstock (Table 1).

The data in Table 1 exclude left over and out of date food from supermarkets, households and catering establishments as well as sewage sludge. Even within the UK food and drink supply chain there is an estimated 11.3 million tonnes per year of food waste (WRAP, 2010).

2.2 Nutrient content of feedstock

AD feedstock contain plant nutrients (macro and micro) and, occasionally, they can also heavy metals and

Table 2 Nutrients present in plant and animal products

Macro nutrients	Nitrogen (N), Phosphorous (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Sulphur (S)
Micro nutrients/trace elements	Boron (B), Cobalt (Co), Copper (Cu), Chlorine (Cl), Iron (Fe), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Selenium (Se), Zinc (Zn)
Heavy metals	Lead (Pb), Chromium (Cr), Cadmium (Cd), Mercury (Hg)

persistent organic compounds (Table 2).

The macro-nutrients are essential for all forms of plant, animal and bacterial life. However, animals do not use these nutrients efficiently and high proportions are excreted. Recent research results indicate that 55-95% of the N in animal diets is excreted through faeces and urine (Oenema & Tamminoa, 2005). High proportions of P and K in animal diets are also excreted. Animal manures and slurries as well as many other types of AD feedstock are rich in plant nutrients. Digestate is therefore a valuable biofertiliser.

The composition of manure feedstock depends: primarily on the digestive system of the animal (ruminant, omnivore, etc.) and on the diet; and secondarily, on the species, sex and age of the animals. In addition, geographical and climatic conditions, diet and the efficiency of digestion by the animal are also important. An example of the average composition of manure in the UK is given in Table 3.

Table 3 Approximate nutrient concentration of selected manure sources (kg/m^3 or kg/t fresh weight) (MAFF, 2000)

Feedstock	**TS %**	**Total N**	**NH_4–N**	**P**	**K**	**S**	**Mg**
Dairy cow slurry	6	3.0	2.0	0.5	2.9	0.4	0.4
Pig slurry	4	4.0	2.5	0.9	2.1	0.4	0.2
Poultry:							
Layer manure	30	16.0	3.2	5.7	7.5	1.5	1.3
Broiler/turkey litter	60	30.0	12	10.9	15.0	3.3	2.5
Farmyard manure							
Cattle	25	6.0	0.6	1.5	6.7	0.7	0.4
Pig	25	7.0	0.7	3.1	4.2	0.7	0.4

Manure alone as feedstock substrate for AD gives relatively low biogas yields per unit of fresh weight and as a result it is frequently mixed and co-digested with other feedstock types which have higher biogas yields (Braun and Wellinger, 2003). Commonly used co-substrates include residues from food processing industries, vegetable residues from crop production and even specially grown crops (energy crops). In practice the selection of AD feedstock usually depend on what is available

locally as well as aiming to optimise biogas output. Use of animal by-products as AD feedstock in the EU is governed by EC Regulation No 1774 /2002. In countries such as Austria, Switzerland and the UK AD is the preferred technology for processing food waste from supermarkets, catering establishments and households.

The macro-nutrient concentrations of some feedstock commonly used in co-digestion are shown in Table 4.

Apart from macro-nutrients, the feedstock (and thus the digestate) can contain micro-nutrients that are present as very small amounts of trace elements as well as heavy metals (Table 2) and persistent organic compounds (not biodegradable) (Table 5). Most of the micro-elements are essential for plant and microbial growth but heavy metals and other contaminants can have a toxic effect and thus can represent a hazard for humans, animals and the environment. For this reason, the content of contaminants in the feedstock, as well as in the digestate, must be carefully monitored. Concentrations must not exceed the legal limits that are set in each country. Most of the heavy metals in manure are introduced through the diet in often unnecessarily high concentrations. Part 6 of this brochure contains further information about quality management of digestate with respect to management of contaminants.

Table 4 Nutrient content (kg/m^3 fresh weight) of some feedstock commonly used in co-digestion. (Institute fuer Energetik und Umwelt gGmbH, 2006; Davis and Rudd, 1999; Kuhn *et al*., 1995)

Feedstock	**% TS**	**Total N**	**NH_4-N**	**Total P**	**Total K**
Grass silage	25-28	3.5-6.9	6.9-19.8	0.4-0.8	-
Maize silage	20-35	1.1-2	0.15 – 0.3	0.2-0.3	4.2
Dairy waste	3.7	1.0	0.1	0.4	0.2
Stomach content	10.1	3.1	0.3	0.7	0.5
Blood	10.9	11.7	1.0	0.4	0.6
Food leftovers	9-18	0.8-3	2-4	0.7	NA*

* Value not available

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Table 5 Approximate trace elements and heavy metals concentrations (mg kg^{-1} dry matter) in some feedstock types (**Davis and Rudd, 1999; *Institut fuer Energetik und Umwelt gGmbH, 2006)

Feedstock	Zn	Cu	Ni	Pb	Cr	Cd	Hg
Animals*							
Dairy slurry	176	51.0	5.5	4.79	5.13	0.20	
Pig slurry	403	364	7.8	<1.0	2.44	0/30	
Poultry (egg layers	423	65.6	6.1	9.77	4.79	1.03	
Crops*							
Crops: Grass silage	38-53	8.1-9.5	2.1	3.0		0.2	
Maize silage	35-56	4.5-5.0	5.0	2.0	0.5	0.2	
Agri-food products**							
Dairy waste	3.7	1.4	<1.0	<1.0	<1.0	<0.25	<0.01
Stomach contents	4.1	1.2	<1.0	<1.0	<0.15	<0.25	<0.01
Blood	6.1	1.6	<1.0	<1.0	<1.0	<0.25	<0.o1
Brewing wastes	3.8	3.7	<1.0	0.25	<1.0	<0.25	<0.01

2.3 Impact of AD on nutrient value and availability

The fertiliser value of digestate depends on the nutrients present in the feedstock while its value as a mineral fertiliser replacement is determined by the effect of AD on nitrogen availability; the effect of co-digestion on nutrient content; and the implication of these issues for fertiliser planning. However, digestate characteristics are specific to each digester tank and can vary even between batches from the same digester and within the same batch of digestate during storage.

2.3.1 Effect of AD on nitrogen availability

The quantities of nutrients that are supplied to a digester in the feedstock are the same as those in the digestate. However, during AD chemical changes take place that can alter the chemical structures in which the nutrients are present and enhance their availability to crops. For example, during AD some of the organic nitrogen is converted to ammonium (Table 6). Therefore, whilst the total nitrogen content in digestate is the same as in the feedstock, the proportion of nitrogen in the form of ammonium is greater.

Table 6	Average nutrient composition of feedstock (dairy cow slurry) and digestate for a mesophilic digester at the Agri-Food and Biosciences Institute in Northern Ireland (Frost, 2009 personal communication)

	Dry matter (g/kg)	Total N (g/kg fresh)	NH_4-N (g/kg fresh)	NH_4-N (% Total N)	pH
Feedstock	81.6	4.2	2.8	67.0	7.7
Digestate	64.4	4.1	3.3	80.5	8.0
Change	-21.1%	-2.4%	+ 15.5%		
Standard deviation feedstock	3.46	0.23	2.5		7.4
Standard deviation digestate	3.08	0.17	0.64		0.1
Number of observations	15	15	15	15	13

In the case of co-digestion it is very important that the dry matter and nutrient concentrations of each feedstock are known beforehand. If feedstock are brought in from agri–food processors, or other sources, they should be accompanied by appropriate quality assurance declarations that are required by law in the respective countries (see Regulations and quality controls for the use of digestate as a fertiliser below). Many biogas plant operators wish to use combinations of feedstock that give high biogas outputs along with high nutrient content in digestate.

2.3.2 The fertiliser value of nitrogen in digestate

The fertiliser value of nitrogen in digestate can be expressed as the “utilisation percentage”. This is defined as the relative quantity of mineral fertiliser nitrogen necessary to obtain the same yield of crop as the quantity of total nitrogen supplied in digestate. The fertiliser value of the digestate increases with increasing nutrient utilisation percentage. Table 7 shows an example from Denmark.

Table 7: Measured utilisation percentage and ammonium share from selected field trials in spring barley and winter wheat at the Danish Agricultural Advisory Service. Source: Danish Agricultural Advisory Service.

Manure type	Crop and application time	NH_4-N share of total-N (%)	N utilisation (% of total N)
Deep litter, cattle	Spring barley, spring	22	32
Deep litter, pigs	Winter wheat, autumn	23	27
Cattle slurry	Winter wheat, spring	52	45
Pig slurry	Winter wheat, spring	74	63
Digestate *)	*Winter wheat, spring*	*83*	*80*
Liquid fraction of digestate	*Winter wheat, spring*	*82*	*78*

*) Average of 20 samples of digestate from co-digested slurry (with what?) used in field trials

It is mainly the mineral nitrogen component of digestate that is available to crops immediately after application. There is therefore a strong correlation between the share of ammonium and the utilisation percentage.

In theory, the utilisation percentage of N in manure and digestate should be equivalent to the share of ammonium. However, when digestate is applied to a field surface, some ammonia volatilization will take place after application. As a result the utilisation percentage will decrease. The expected utilisation percentage of nitrogen is different between raw slurry and digestate and varies with crop type, application method and time of the year. Table 8 shows an example from Denmark.

Table 8: Comparative utilisation % of N between slurry and digestate for winter oil seed rape and grass (Birkmose, 2008)

	Spring		Summer	
	Injection	Trailing-shoe	Injection	Trailing-shoe
Winter oil seed rape				
Pig slurry		65		
Cattle slurry		45		
Digestate		75		
Grass				
Pig slurry	60	60	55	45
Cattle slurry	50	45	45	35
Digestate	70	65	60	45

Photo 3: Trailing hose application of digestate to cereal

3 Nutrient management in digestate and fertiliser management plans

The application of digestate or any crop fertiliser at times of the year when there is little plant uptake e.g. autumn and winter can result in nutrient leaching and runoff into ground and surface waters (e.g. nitrogen and phosphorus). Field trials undertaken over two years as part of the Canadian Government's Technology Assessment Programme showed no significant increase in N leaching from digestate (compared with that from raw cow slurry) following spring application. In contrast, after autumn application, almost double the amount of N from the digestate leached into the drainage waters compared with that from raw slurry. The potential for nutrient leaching is higher on sandy soils with poor water retention capacity, but in all cases it can be minimised by avoiding application of digestate, raw slurry or chemical fertilisers in periods with low plant uptake or high rainfall.

At the outset, therefore, it is essential to know not only the fertiliser composition of digestate–but also how to apply it accurately during crop growth. These issues are essential irrespective of whether digestate is produced from a farm's own digester or is received from other farms or from centralised biogas plants. Digestate supplied by the latter must also be accompanied by a delivery note (see example in Appendix 3) and be certified in compliance with the respective national bio-security regulations (see Section 6).

Photo 4: Photo required of digestate being taken from a digestate tank by a tractor and slurry tanker

Fertiliser applications should match crop requirements (see Appendix 2 for links to further information) to minimise any unintended negative impact to the environment and

Table 9: Examples of national regulations of the nutrient loading on farmland (amended from Nordberg, 1992 and citation in Al Seadi, 2009)

	Maximum nutrient load	Required storage capacity	Compulsory season for spreading
Austria	170 kg N/ha/year	6 months	28/2-2 5/10
Denmark	170 kg N/ha /year (cattle) 140 kg N/ha/year (pig)	9 months	1/2-harvest
Italy	170-500 kg N/ha /year	90-180 days	1/2- 1/12
Sweden	170 kg N/ha /year (calculated from livestock units per ha)	6-10 months	1/2- 1/12
Northern Ireland	170 kg N/ha/year	4 months	1/02- 14/10
Norway			
Canada			
Brazil			
Germany	170 kg N/ha/year	6 month	1.02.-31.10 Arable land 1.02.-14.11 Grassland

maximise farmers' profits. Applications must also comply with national limits which in the EU, for example, must not exceed 170 kg N/ha in designated Nitrogen Vulnerable Zones (Table 9).

A fertiliser management plan, therefore, for an individual field should take account of:

- Crop to be grown and previous crop grown
- Soil type and existing reserves of nutrients in the soil (carried out by periodic soil sampling, agrochemical analysis and mapping of soils)
- Expected crop yield
- Recommended nutrient requirements of crop to be grown (nitrogen, phosphorus, potassium and sulphur)
- Nutrient content of manure/digestate to be applied

- Expected utilisation percentage of nitrogen in manure/digestate (Table 9)
- Time and method of digestate application
- Requirements for mineral fertilisers - types, amounts and times of application

Switzerland, for example, has established an action plan that has well defined application rates depending on type of digestate/raw waste, season of application, type of crop and time of seeding (Grudaf, 2009).

In areas where phosphate overload leads to diffuse pollution and eutrophication of coastal and inland waters (e.g. Denmark, south west Sweden and Northern Ireland) it is best practice to apply the digestate to meet the phosphorus needs of the crop and to complete the nitrogen requirement by making up any shortfall with mineral fertiliser. A further strategy to assist in precise fertiliser application is to separate digestate into liquid/solid fractions where up to 90% of the phosphorus that was contained in the original digestate is separated into the fibrous fraction.(See Section 4) Advice on crop requirements for fertiliser is provided in many countries (see Appendix 2 for useful links).

3.1 Storage of digestate

Digestate is usually produced throughout the year and therefore it will need to be stored until the appropriate time for application as a fertiliser during the growing season. The length of storage period will depend on geographical area, soil type, winter rainfall, crop rotation and national regulations governing manure applications. In many cases 6-9 month storage capacity is recommended and in some countries is obligatory (see Table 9).

During storage, digestate, unlike whole slurry especially from dairy cows, does not usually form a crust because the solid material that would have formed the crust is broken down during digestion to produce the biogas. When digestate, as indeed manure, is stored in open tanks, ammonia and methane gases are given off. Natural crusts (provided that they are 10-20cm thick) and floating layer of plastic pieces, clay pebbles or chopped straw etc minimise ammonia losses,. Another approach that minimises both methane and ammonia losses is to cover storage tanks with air tight membranes or use flexible storage bags. After digestion with energy crop up to 100 days of (covered) storage is necessary to reduce the emission of methane to less than 1% (Figure 2). In some European countries with a developed biogas sector (e.g. Germany, Denmark and Austria) there are financial incentives to cover digestate stores with the main objective of reducing methane emissions. At the same time ammonia losses will also be avoided.

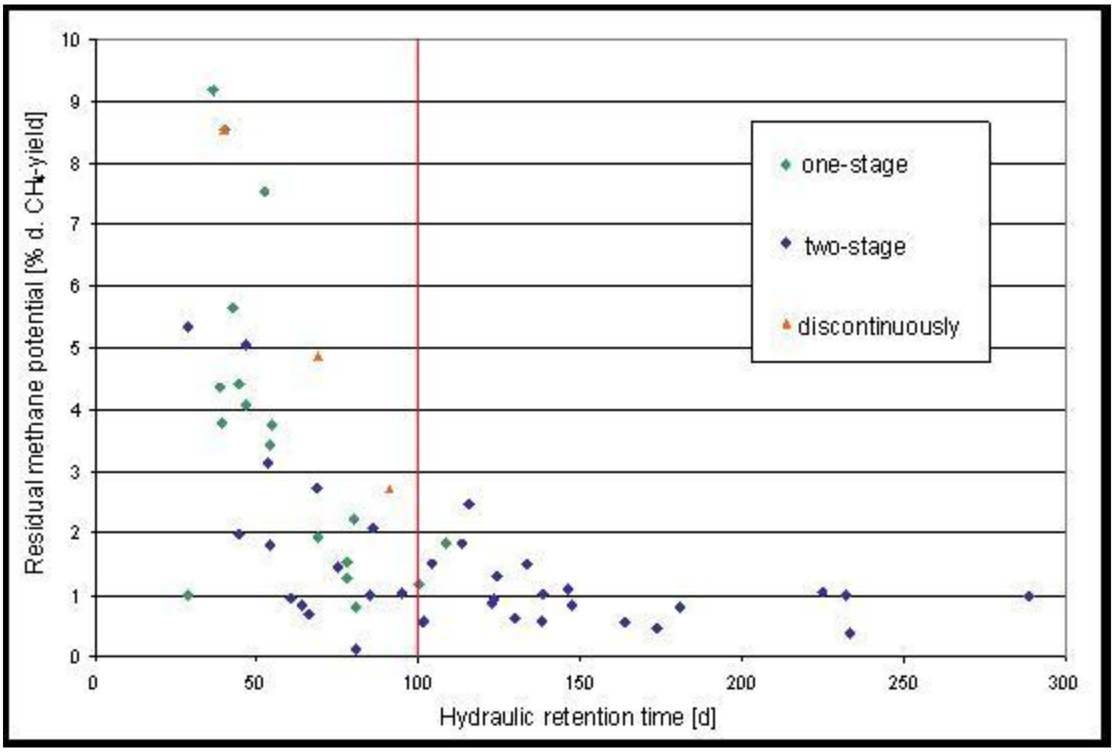


Figure 2: Losses of methane from digestate stores (Weiland, 2009)

Photo 4: Bag tank (copyright required www.albersalligator.com)
Photo of Flexible storage bag.

Photo: Torben Skøt

Photo 6: Covered digestate storage tank
Photo of Digestate/slurry storage tank with tent cover.*Photo: Torben Skøt*

3.2 Methods of digestate application

It is important that application methods provide even applications across the whole field, correct application rates and minimise ammonia volatilisation in order to ensure optimum use of digestate as a fertiliser. Digestate can be spread with the same equipment that is used to spread raw slurry.

Table 10 summarises some of the characteristics of the main application methods used for raw slurry.

Compared with raw slurry, digestate has fewer odours, percolates more quickly into the soil and has a much lower risk of air pollution during and after spreading. Nevertheless, ammonia volatilisation can occur after digestate has been spread and therefore, from a fertilisation and an environmental viewpoint the most attractive methods for spreading digestate are trailing hoses, trailing-shoes and injection (Table 11).

Table 10: Summary of characteristics of four raw slurry application methods (adapted from Birkmose, 2009)

	splash plate *	Trailing hose	Trailing-shoe	Injection
Distribution of slurry	Very uneven	Even	Even	Even
Risk of ammonia volatilization	High	Medium	Low	Low or none
Risk of contamination of crop	High	Low	Low	Very low
Risk of wind drift	High	Minimal after application	Minimal after application	No risk
Risk of smell	High	Medium	Low	Very low
Spreading capacity	High	High	Low	Low
Working width	6-10 meters	12-28 meters	6-12 meters	6-12 meters
Mechanical damage of crop	None	None	None	High
Cost of application	Low	Medium	Medium	High
Amount of slurry visible	Most	Some	Some	Very little

*The splash plate method is commonly used though is not recommended and is banned in some countries

Table 11: Separator efficiency[1] of common manure separators for dry matter (DM), nitrogen (N), phosphorus (P), potassium (K) and volume reduction (VR). Without polymer addition unless otherwise stated. (Derived from *Burton and Turner, 2003; +Frost and Gilkinson, 2007)

	Separator efficiency[1] (%)				
	DM	N	P	K	VR (%)
Belt press*	56	32	29	27	29
Sieve drum*	20-62	10-25	10-26	17	10-25
Screw press*	20-65	5-28	7-33	5-18	5-25
Sieve centrifuge*	13-52	6-30	6-24	6-36	7-26
Decanter centrifuge*	54-68	20-40	52-78	5-20	13-29
Brushed screen+ (cattle slurry)	36	18	26	15	14
Decanter centrifuge+ (cattle slurry)					
no polymer	51	25	64	13	13
with polymer	65	41	82	15	increased
Brushed screen+ (pig slurry)	19	6	7	5	5
Decanter centrifuge+ (pig slurry)					
no polymer	53	21	79	8	8
with polymer	71	34	93	11	increased

[1] Percentage of component in total slurry input that was partitioned to solid fraction

Photo 7: Shallow injector places digestate just below the soil surface

Photo 8: Trailing-shoe application places digestate on the soil surface beneath any foliage

Photo 9: Trailing hose application places slurry on the surface

The higher costs of these methods compared with splash plate spreading are offset by a higher utilisation of the nutrients in the digestate. In Germany, researchers found that on arable land, trailing hose application of co-digestate followed by immediate shallow incorporation resulted in the lowest greenhouse gas emissions (combined carbon dioxide equivalents for nitrous oxide, methane and ammonia) (Wulf *et al.*, 2002). When measured on the same basis on grassland it was found that found trailing-shoe applications gave the lowest greenhouse gas emissions.

A further strategy to assist in precise fertiliser application is to separate digestate into liquid/solid fractions. However, dependant on the type of feedstock and the separation technology used, separation can partition up to 90% of the phosphorus that was contained in the original digestate into a fibrous fraction.

4 Digestate separation

Digestate can be mechanically separated in the same manner as animal manure to:

- Produce a pumpable liquid fraction from the digestate produced from some of the dry AD processes
- Lower the volume of liquid requiring storage
- Create potential to export separated fibre
- Improve efficiency in nitrogen uptake from the liquid
- Provide a greater window of opportunity for application of the liquid
- Minimise the requirement for mixing of the liquid prior to spreading.

Note: it is recommendable that the solid fraction should be stored without disturbance or even composted in order to avoid methane emission.

Some commonly used mechanical separators and their efficiencies are shown in Table 11 below. Chemicals can be used to improve separator efficiency and help to partition plant nutrients differentially (particularly phosphorous) to the separated fibrous fraction. Note that separation creates two outputs, a liquid and a fibrous material, that need to be stored and handled separately.

Photo 10: Rotary screen separator (copyright required www.lintonsolutions.com)
Photo of screw press separator

Separation may also be by non-mechanical methods such as sedimentation or filtration through geo-textile tubes. Whatever the method, separators are being used increasingly in combination with biogas production either after digestion to help in nutrient management or pre-digestion to help with transport efficiency. When used post digestion the partitioning of the nutrients between liquid and solid fractions (Table 12) can help in management and efficient redistribution of digestate as a biofertiliser. Separation pre-digestion as for example in Denmark, allows for separated fibre transport to centralised biogas plants. This is particularly appropriate for feedstock with low volatile solid content such as pig slurry and flushed dairy manure systems. Moller *et al*. (2007) found that 60% inclusion on a fresh weight basis of separated pig manure solids along with whole pig manure more than doubled the yield of biogas per digester volume compared to whole manure alone. Pre-separation of slurry and digestion of the separated solid fraction may be an option for dilute feedstock that would not otherwise be considered for anaerobic digestion, because of the low biogas yield relative to the energy requirement for digester heat.

In a comparison between screw press and rotary screen separation of digestate in Austria, Bauer *et al.* (2009) found the screw press to give higher separation efficiency and to be more reliable. The screw press differentially partitioned more dry matter, volatile solids, carbon, ash and phosphorus to the solid phase than to the liquid phase. In contrast, nitrogen, ammonia and potassium were not differentially partitioned between liquid and solid. However, it is generally recognised that decanter centrifuges give good differential partitioning of nutrients, particularly phosphorous into the separated fibrous fraction (Table 11). The use of chemicals to coagulate and/or flocculate the liquid prior to centrifuging can improve partitioning. Decanter centrifuges have high capital and operating costs and as a result their use tends to be limited to high volume systems such as large pig farms and centralised biogas plants (e.g. in Denmark).

Photo 11: Decanter centrifuge and separated liquid and fibre

Complete conditioning of digestate is a stage beyond mechanical separation. Ultimately complete conditioning produces three refined end products: pure water, concentrated nutrients and organic fibres. Purified water could be discharged into the surface water system (with appropriate approval), used for irrigation or as process water. Complete conditioning is particularly suitable for agricultural areas with excess manure, where the nutrients need to be exported to areas of nutrient deficiency. The two main technologies used are membrane separation and evaporation. Both are complex and require significant energy consumption and for these reasons, they are currently considered economically feasible for the large scale biogas plants such as those in the waste water treatment industry.

5 Environmental effects of using digestate as a fertiliser

Direct environmental benefits from using digestate as a fertiliser result from adopting the best management practices outlined previously. These practices result in lower gaseous emission to the atmosphere and in less diffuse pollution from surface run off and leaching. As a result, direct benefits help governments meet targets for reducing GHGs along with the requirements of, for example, the EU Nitrates Directive and Water Framework Directive. Four major environmental benefits from AD are: reduced odours, veterinary safety, plant pathogen reduction, and reduction of weed seeds.

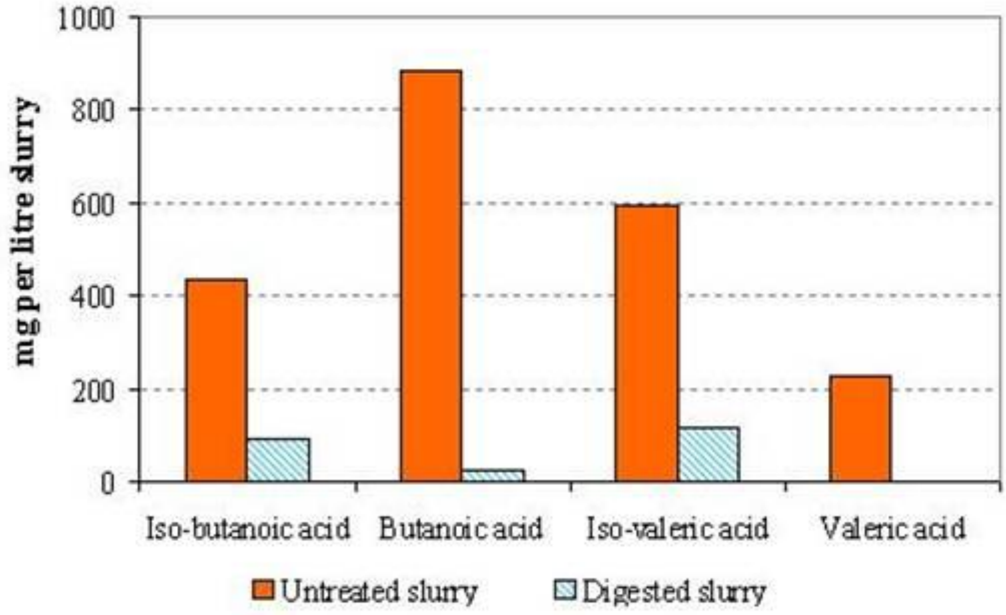
5.1 Odours

Animal manures and many organic wastes contain volatile organic compounds (e.g. iso-butonic acid, butonic acid, iso-valeric acid and valeric acid along with at least 80 other compounds) that can produce unpleasant odours. Hanson *et al*. (2004) showed that digestion significantly reduced concentrations of many of these compounds such that their potential for giving rise to offensive and lingering odours during storage and spreading are significantly reduced (Figure 2). Use of appropriate spreading methods can prevent release of any residual odour. For example, injection of digestate (or slurry) into soil largely eliminates odour and loss of ammonia (Table 10). It is important however, to minimise the disturbance of the digestate during its transfer from the storage tank to the spreaders as this can result in release of odour.

5.2 Animal and human health issues

The use of digestate as fertiliser is usually governed by regulations and standards that protect animal and human health as well as the quality of crops. Each country has its own standards, such as EC Regulation No 1774/2002 which applies to all EU member countries when digestate contains industrial residues and animal by-products.

Anaerobic digestion is very effective at lowering the pathogen load in the digestate. Table 12 below summarises results from an extensive and detailed research programme carried out in Denmark along with results from tests carried out in Germany and the United Kingdom. The EU standard where animal by-products are present in the feedstock is pasteurisation at 70^0 C for 1 hour or its equivalent with thermophilic digestion with a guaranteed retention of 5 hours at 53^0 C (in Germany: 24 hours at 55 °C). These treatments result in minimal risk (if any) of transferring pathogens *via* digestate. (See Kirchmayr *et al*., 2003 for further information on animal by-products regulations).



Figures 2: Concentration of volatile fatty acids in untreated slurry and in digested slurry (Hansen *et al.*, 2004)

Table 12: Comparison of pathogen and nematode survival times in digestate and raw slurry (T90) ([1]Bendixen, 1995; [2]Test carried out by ADAS; [3]Neil, 2007; [4]Bohm *et al.*, 1999)

	Biogas system			**Raw slurry**[3]	
Pathogen	**70^0 C (Seconds)**	**53^0 C (hours)**	**35^0 C (days)**	**18-21 ^{0} C (weeks)**	**6-16^0 C (weeks)**
Salmonella T.	6	0.7	2.4	2.0	5.9
Salmonella D.	6	0.6	2.1	?	?
Coliform bacteria	20	0.6	3.1	2.1	9.3
Staphilococcus Aura	8	0.5	0.9	0.9	7.1
Mycobacterium Para TB	8	0.7	6.0	? ND	?ND
Strep. faecalis	3.92 mins	1.0	2.0	?	?
Group D streptococci	20	?	7.1	5.7	21.4
M.Bovis (TB) [2]	90	nt	nt	22.0	nt
Larvae of nemotodes [4]	< 0.6	<0.7	<2.4	<2.0	<5.9

The eggs of common gastrointestinal worms and larvae of lungworm are inactivated in less than 4 hours at 53^0C and after 8 days at 35^0C. Mesophilic digesters are the most common on-farm type in Europe and are very effective at lowering pathogen numbers (Table 12).

Many common viruses are also killed during mesophilic and thermophilic digestion. For example, bovine viral diarrhoea (5 minutes at 55^0C; 3 hours at 35^0C) (Bendixen 1995) and Aujesky's disease in pigs (10 minutes at 55^0C; 5 hours at 35^0C) (Botner, 1991) and Johne's disease (M.Para tuberculosis) (0.7 hours at 55^0 C, 6 days at 35^0 C) In summary, anaerobic digestion (particularly thermophilic) can offer a useful means of lowering numbers of pathogens that can otherwise lower the productivity of livestock farms or present a risk to human health.

5.3 Plant health

There are relatively few studies that have tested the effect of AD on the survival rate of pathogens that affect plants. While plant pathogens can be treated by fungicides, many farmers try to avoid their use due to expense and environmental concerns.

Two recent studies in Sweden (Haraldsson, 2008 and Zetterstrom, 2008) showed that common fungal diseases of plants are irreversibly inhibited or killed during mesophilic digestion with a hydraulic retention time of between 25-30 days.

Both Haraldsson (2008) and Zetterstrom (2008) highlighted the fact that the digester temperature alone is not responsible for the destruction of the spores. The evidence suggested that it is the combination of the conditions in the digester – pH level, quantities of volatile fatty acids, the negative effect of ammonium and hydrogen sulphide together with time and temperature that combine to create the hostile environment in which the spore are unable to survive. This in itself demonstrates the need for caution in making generalisations as the conditions inside the digester can vary between digesters and between feedstock.

Nevertheless, it is reasonable to conclude from the Swedish work that farms with a mesophilic digester would benefit from a significant or total destruction of many disease spreading spores that can affect the crops. Most notably this would exclude *Plasmodiophera brassicae* (cabbage club root) that can survive 14 days of mesophilic digestion but are killed in thermophilic conditions within 14 days (Engeli *et al*., 1993). AD thus has the potential to offer real benefit to organic farmers and those wishing to reduce the use of fungicides.

5.4 Weed seeds

Lowering the number of viable weed seeds in digestate will lower their dispersal by land spreading and as a consequence there will be less need for herbicide. There appears to be very little evidence available in the literature on the destruction of weed seeds by AD. However, there is some information to indicate that mesophilic anaerobic digestion can reduce the viability of weed seeds and some crop seeds (Table 13). Inactivation time is even shorter at higher process temperatures (thermophilic digestion (Engeli *et al*, .1993).

Table 13: The survival of weed seeds in cattle slurry (% of untreated control) after mesophilic digestion (35^0C) with a 21.5-day retention time (derived from Hansen and Hansen, 1983; Engeli *et al.,* 1993).

Species	
Wild oat *(Avena fatua)*	0
Black nightshade *(Solanum nigrum)*	0
Stinging nettle (*Urtica urens)*	0
Common lambsquarter (*Chenopodium album)*	5[1]
Oilseed rape *(Brassica napus)*	0
Broad leafed dock *(Rumex obtusifolius)*	0
Tomato *(Lycopersicon lycopersicum)*	48[2]

1. Reduced to zero at 38^0C
2. Reduced to zero at 55^0 C at 14 days

The new German biowaste ordinance requires proof that hygienisation has occurred by determining inactivation of *Salmonella senftenberg*, tomato seeds and *Plasmidiophora brassicae* after digestion.

6 Regulations and quality controls for the use of digestate as a fertiliser

Quality management of digestate involves a range of permits and quality standards to ensure the safety and value of digestate as a fertiliser, soil conditioner or growing medium.

Farmers who use their own on-farm produced feedstock (such as manure, crops or sweepings from grain stores) should carry out their own quality controls. These should include periodic sampling and analysis of feedstock to determine their biogas potential (e.g. dry matter, nutrients and volatile solid content plus pH levels). Similarly–digestate should be analysed before spreading to aid accurate fertiliser planning.

When off-farm material (e.g. industrial residues, biodegradable fractions of municipal solid waste, sewage sludge etc) is co-digested, the digestate can contain various amounts of hazardous matter – biological, chemical and physical that could pose risks for animal and human health or cause environmental pollution (Al Seadi and Holm Nielsen, 2004). These contaminants can include residues of pesticides and antibiotics, heavy metals and plant and animal pathogens. The latter may result in new routes of pathogen and disease transmission between plants and animals if appropriate and stringent controls are not enforced. In the EU, for example, the trans-national EC Regulation 1774/2002 stipulates a range of precautions against the spreading of communicable diseases, such as spongiform encephalopathy and foot and mouth disease. Whilst this regulation deals with the use of animal by-products generally it also presents co-digestion for consideration (see Kirchmayr, *et al.,* 2003 for discussion in relation to biogas plants). This regulation is reinforced in many countries by further stringent regulations governing the admissible feedstocks for AD and uses of the digestate as an organic fertiliser. Annex 4 summarises examples of tests that are commonly undertaken for determining the specifications for the use of digestate whether used unseparated or separated into a liquid fertiliser and fibre. The regulations and quality controls applied in each country should be included in the specification/certification (delivery note) that would accompany every load of organic or trademarked biofertiliser supplied by the biogas plant. Storage and application of the digestate would then comply with the codes of good agricultural practice and be in accordance with national guidance or legislation.

As indicated above, feedstock for AD can contain contaminants that can be classified as chemical, biological and physical.

6.1 Chemical contaminants

If there are any chemical contaminants in the feedstock they will also be present in the digestate. Agricultural wastes, for example, can contain persistent organic compounds such as pesticide residues, antibiotics and other medications. Industrial organic waste, sewage sludge and household waste can contain aromatic, aliphatic and halogenated hydrocarbons, organo-chlorine pesticides, PCBs, PAHs etc. Thus it is important at the outset to ensure high quality feedstock. This can be achieved by eliminating feedstock with levels of contamination that are above the permitted limits. Some countries such as Germany and Switzerland provide lists of substrates that are recommended for digestion.

6.2 Biological contaminants

The presence of biological contaminants in digestate such as various pathogens, prions, seeds and propagules[1] may result in new routes of pathogen and disease transmission between animals, humans and the environment. For this reason strict control of specific feedstock types and of digestate must be carried out.

[1] any plant material used for plant propagation

Animal by-products used as AD feedstock require specific attention regarding their utilisation as substrate for anaerobic digestion, with reference to safe utilisation of digestate as fertiliser and soil conditioner. In EU countries, Regulation 1774/2002 stipulates a range of precautions against the spreading of transmissible spongiforme encephalopathy and regulates the sanitary measures for utilisation of animal by-products as feedstock for biogas production.

Table 14: Category of animal by-products not intended for human consumption according to EC Regulation no 1774/2002 and the conditions for their utilisation as feedstock for biogas production. (Kirchmayr *et al.*, 2003)

Category	**Material**
CATEGORY 1 Not suitable for biogas/ AD treatment	-
CATEGORY 2 Can be processed in a biogas plant without preliminary treatment	Manure as well as digestive tract content (separated from the digestive tract; if there is no risk of spreading serious-infectious diseases) Milk and colostrum
CATEGORY 2 Can be processed in a biogas plant after sterilisation with steam pressure	All materials classified as Category 2 (e.g. perished animals or animals slaughtered, but not intended for human consumption)
CATEGORY 3 Can be processed in a biogas plant, in accordance with Article 15 of the Regulation1774	All materials classified as Category 3 (e.g. meat-containing wastes from the foodstuff-industry, slaughterhouse wastes of animals fit for human consumption)
CATEGORY 3 Can be processed in biogas plants, which are approved in accordance with provisions and methods to be adopted or according to national legislation	Catering waste, except from catering waste originating from international means of transport (e.g. catering waste from international flights and trains etc)

Effective control of biological contamination of digestate includes a number of different issues:

- Livestock health control. No animal manure and slurries will be supplied from any livestock with health problems (zoonoses, TEC etc).
- Feedstock control**.** Hazardous biomass types must be excluded from anaerobic digestion and channelled towards other disposal methods.
- Pasteurisation. The feedstock is heated at 70^0C, for one hour. The particle size must be under 12 mm in diameter.
- Pressure sterilisation**.** The feedstock is sanitised through a combination of temperature of 130^0C and pressure of 3 bar for 20 minutes.
- Controlled sanitation. For specific feedstock types, a combination of temperature and retention time inside the digester, at process temperature

can result in pathogen reduction equivalent to pasteurisation.

- Control of pathogen reduction efficiency in digestate. There are many methods. One method used is the $\log_{10}$ of FS, based on the measurement of the Faecal Streptococci in digestate.

See Section 5 for information on pathogen control.

6.3 Physical contaminants

Physical contaminants are considered to be all the non- or low–digestible materials e.g. plastic, glass, metal scrap, stones, sand, wood etc. Such physical impurities are likely to be present in all types of feedstock, but most frequently in household wastes, food waste, garden waste, straw, solid manure and other solid types or waste. The presence of physical contaminants (impurities), in particular following ‘dry digestion’ which produces a stackable compost like digestate, can cause negative public perception of digestate and aesthetic damage to the environment. Physical contaminants such as sand also increase operational costs by causing wear and tear to the pipes and pumps of the biogas plant components and to the digestate application machines.

Photo of municipal AD separation of physical contaminants

The control and management of physical impurities is mainly a matter of ensuring high quality feedstock. This can be done either by sorting at source or by on-site separation (mechanically, magnetically, other). As a supplementary safety measure, physical barriers like sieves, stone traps or protection grilles can be installed in the pre-storage tanks, at the AD plants.

The production of good quality digestate for use as a fertiliser is the end product of strict feedstock selection, adherence to strict codes of practice (government or farmer determined) and the compliance with best agricultural practice at all stages of the process from the digester to the field.

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Appendix 1: Further reading

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Appendix 2 – Useful links on crop requirements for fertiliser

1. UK - Fertiliser recommendations for agricultural and horticultural crops (RB209); available as a computerised version (PLANET); http://www.defra.gov.uk). Also available from Defra is other computer software (MANNER) which predicts the plant availability of manure nitrogen following land application.
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Appendix 3
Example of delivery note supplied with digestate

(See Appendix 5 for links to national standards)

	Au	**Br**	**Ca**	**CH**	**Dk**	**Fi**	**Fr**	**De**[1)]	**Ir**	**Neth**	**No**	**Swe**	**Tu**	**UK**	**EU**
Element (max. mg/kg DM)															
Pb	100				120			150/100				100		200	
Cd	3.0				0.8			1.5/1.0				1.0		1.5	
Cu					1,000			100/70				600		100	
Cr	100				100			100/70				100		100	
Hg	1.0				0.8			1.0/0.7				1.0		1.0	
Ni	100				30			50/35				50		50	
Zn					4,000			400/300				800		200	

Glossary, terms

Biomethanation - bacterial degradation of organic substances under exclusion of oxygen. he degradation process is also called anaerobic digestion and delivers biogas, which typically contains between 50 and 70% methane, 20 to 45% carbon dioxide and some trace gases.
Combined heat & power plant (CHP) - a power generator driven by a combustion engine, fuelled with biogas, resulting in approx. 60 % heat and 40 % electrical power.
Dry digestion (syn. dry fermentation) - anaerobic digestion at elevated dry matter content of about 30 % total solids in the digester.
Dry matter (DM) - residual substance after complete elimination (drying) of water.
Fermentation (syn. digestion) - anaerobic metabolic processes caused through microbial enzymatic activities.
Greenhouse gas (GHG) - trace gas in the atmosphere, a reason for climate change.
Hydraulic residence time - mean statistical retention time of substrates in a bio-reactor.
Mesophilic - temperature area of about 20–42°C.
Methane number - defines the pre-ignition resistance (knock rating) of a burnable gas
Odour units - amount of odorant(s) that, when evaporated into one cubic metre of neutral gas at standard conditions, elicits a physiological response from a panel (detection threshold) equivalent to that elicited by one European Reference Odour Mass (EROM), evaporated in one cubic meter of neutral gas at standard conditions. [CEN TC264 Draft]
Thermophilic - temperature area above 45°C, usually about 53–57°C
TS – Total solids - total amount if insoluble matter in a liquid.
VS – Volatile solids - total amount of organic matter in a substance.
Zoonoses

Abbreviations

BOD [mg O2.l-1] Biochemical oxygen demand
BTS [kg.kg-1.d-1] Sludge loading rate
BV [kg.m-3.d-1] Hydraulic or volumetric loading
rate
COD [mg O2.l-1] Chemical oxygen demand
CHP Combined heat and power plant
d Day
DM Dry matter
□GO` [kJ/Mol] Enthalpy
EJ [1018 J] Exajoule
GHG Greenhouse gas
GJ [109 J] Gigajoule
MJ [106J] Megajoule
Mtoe [107 Gcal] Million tons of oil equivalent
Nm3 Volume at standard conditions of
0°C, 101.325 kPa
NMHC Non methane hydrocarbons
Pa [1 N/m2] Pascal (1 bar = 105 Pa)
PJ [1015 J] Petajoule

ppm Parts per million
□[d] Hydraulic residence time
TJ [1012 J] Terajoule
TS [%] Total solids
VS [%] Volatile solids
v / v [%] Percent referred to volume
Wobbe
index
[MJ.m-3] Amount of energy introduced to
the burner
w / w [%] Percent referred to weight