Utilisation of digestate from biogas plants as biofertiliser

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IEA Bioenergy aims to accelerate the use of environmentally sound and cost competitive bioenergy on a sustainable basis and thereby achieve a substantial contribution to future energy demands

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Foreword

Greenhouse gas emissions, nitrate and phosphate enrichment of inland and coastal waters and deteriorating air quality are major issues throughout the world. While there is a growing global demand for more efficient heat, power, transport and food production, all of these processes are still largely reliant on fossil fuels. Within agriculture the manufacture and use of inorganic fertiliser is recognised to give rise to particular issues, arising both from fossil fuel use and from nitrous oxide emissions. Many governments are now giving a high priority to lowering pollution from all of these factors.

This brochure describes how Anaerobic Digestion of manures and other organic residues can be used to produce both renewable energy and organic fertiliser – as biogas and digestate. Renewed worldwide interest in Anaerobic Digestion is being driven by different factors in different parts of the world. In the EU, for example, 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 are all important factors influencing increasing levels of investment in Anaerobic Digestion. The information in this brochure is intended to inform prospective biogas/digestate producers as well as policy makers and regulators. The reference section lists valuable sources of further information; these should be helpful to anyone wishing to explore the subject of Anaerobic Digestion in more detail.

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 (Lukehurst 2010). AD can also offer a range of other benefits.

- Lowers fossil fuel use
- Lowers mineral fertilisers use
- Lowers GHG emissions from open manure stores
- Provides a highly efficient method for resource recycling
- Closes the production cycle

Over the last 50 years, increasing use of inorganic fertilisers throughout the world has been central to increased farm production. However, the volatility of world oil prices has had a major effect on the use of oil-based fertilisers. For example, high oil prices are leading both to increased costs to farmers and also to lower fertiliser consumption. The digestate is a very useful organic[1] fertiliser that can be used to offset the financial as well as the environmental costs associated with the use of mineral fertiliser.

Photo 1: Anaerobic Digestion plant in Germany

[1] In this context organic fertiliser is defined as being derived from animal or vegetable matter.

1 Understanding Anaerobic Digestion

AD is a natural process in which micro-organisms decompose organic matter (feedstock) in airtight digester tanks to produce biogas and digestate. Almost any organic material can be processed with Anaerobic Digestion. The selected feedstock can include animal manures, agricultural crops, agri-food processing residues, food residues, the organic fraction of household waste, organic fractions of industrial wastes and by-products, sewage sludge, municipal solid waste, etc. (see Section 2). The feedstock, sometimes referred to as substrate, can be either a single input (e.g. animal manure) or a mixture of two or more feedstock types (this is termed co-digestion). Most biogas plants use more than one substrate. When the dry matter content of the feedstock is below 15% the AD process is called 'wet' digestion (or 'wet' fermentation); when it is above this level the process is referred to as 'dry' digestion. Figure 1 summarises the AD process.

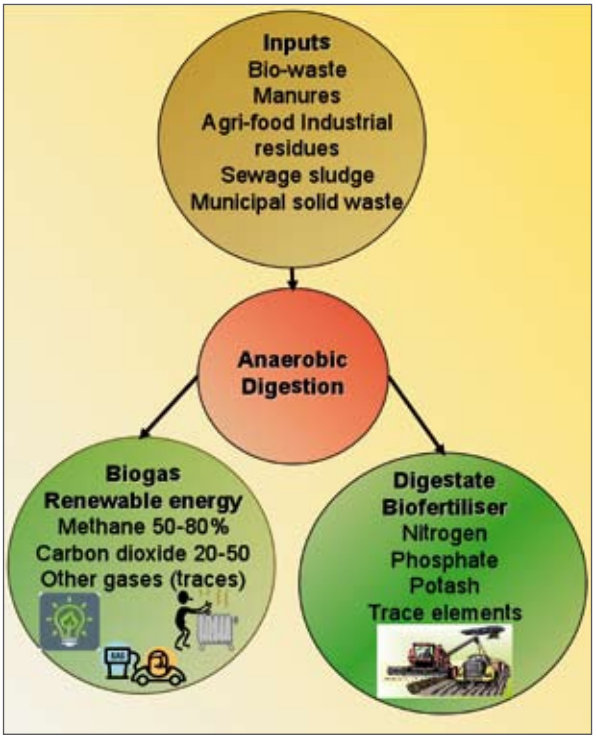


Figure 1: The Anaerobic Digestion process

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

Anaerobic micro-organisms can decompose all kinds of organic materials. Of these, short chain hydrocarbons, such as sugars, are easiest to decompose. Longer chain hydrocarbons, such as celluloses and hemicelluloses, are more difficult to decompose and the digestion process will therefore take longer. Woody materials that contain long chain hydrocarbons, such as lignin, are not suitable for decomposition by anaerobic micro-organisms.

The sources of feedstock suitable for AD are many and varied (see IEA Bioenergy, 2005 for more detail); many billions of tonnes are available worldwide. Within the EU, for example, there are over 1.2 billion tonnes of potential feedstock per annum (Table 1).

Table 1 Estimates of quantities of waste recycled to land from main industrial sectors in fifteen Member States (x10^6 tonnes fresh weight per annum) (derived from Gendebien *et al.*, 2001)

	Produced
Animal manures[1]	1,200
Paper production	2
Sugar beet processing	8
Olive oil production	3
Other fruit and vegetable processing	3
Other food and drink sectors	1
Leather production	0.25
Textile production	0.1
Mineral waste	15
Other sectors	4
Estimated total	1,236

[1] estimated annual production from housed livestock

The data in Table 1 exclude left over and out of date food from supermarkets, households and catering establishments as well as sewage sludge. 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 feedstocks contain plant nutrients (macro- and micro-nutrients) though occasionally, it can also contain heavy metals and persistent organic compounds (Table 2) in various amounts (see Section 6).

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 (nitrogen) in animal diets is excreted through faeces and urine (Oenema & Tamminga, 2005).

Table 2 Nutrients present in plant and animal products

Macro nutrients	Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Sulphur (S)
Micro nutrients/ trace elements	Boron (B), Co balt (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)

High proportions of P (phosphorus) and K (potassium) in animal diets are also excreted. Animal manures and slurries are therefore rich in plant nutrients. This is also the case for many other types of AD feedstock, making digestate a valuable biofertiliser. By making the best possible use of digestate as a biofertiliser, nutrients are returned to the land through natural cycles to replace the input of inorganic fertiliser. Recycling in this way closes an loop to create more sustainable agricultural production systems.

The composition of animal manure depends mainly on the digestive system of the animal (ruminant, omnivore, etc.) and on its diet. Other factors that effect the composition of manure include the species, sex and age of the animals as well as geographical and climatic conditions. An example of the average composition of different manures in the UK is given in Table 3.

However, manure alone as feedstock (substrate) for AD gives relatively low biogas yields per unit of fresh weight; 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 depends on what is available locally, as well as aiming to optimise biogas output. Within the EU, use of animal by-products that are not intended for human consumption as AD feedstock 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.

Table 3 Example from the UK of the 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	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

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

As previously indicated, feedstock (and thus digestate) can contain very small amounts of micro-nutrients and heavy metals (Table 5) as well as persistent organic compounds that are not biodegradable. Most of the heavy metals in manure are introduced through the diet of animals. When digestate is recycled to land as a biofertiliser, most of these micro-nutrients are fully utilised, as they are essential for plant and microbial growth. However, any heavy metals and persistent contaminants can cause problems. For this reason, the content of contaminants in the feedstock, as well as in the digestate, must be carefully monitored. Concentrations of contaminants in the digestate must not exceed the legal limits set in each country. Section 6 of this brochure contains further information about quality management of digestate with respect to the management of contaminants.

2.3 Impact of AD on nutrient value and availability in digestate

Digestate is an easy product to handle and apply and can be used successfully as a substitute for mineral fertilisers. The fertiliser value of digestate depends on the nutrients present in the feedstock. However, digestate is the result of a living process and therefore has characteristics that are specific to each digester tank. These characteristics can vary between batches from the same digester and even within the same batch of digestate, following storage.

Table 4 Examples of the nutrient content (kg/m^3 fresh weight) of some feedstock commonly used in co-digestion ([1]Institut fuer Energetik und Umwelt gGmbH, 2006; [2]Davis and Rudd, 1999; Kuhn *et al.*, 1995)

Feedstock	% TS	Total N	NH_4-N	Total P	Total K
Grass silage[1]	25 – 28	3.5 – 6.9	6.9 –19.8	0.4 – 0.8	–
Maize silage[1]	20 – 35	1.1 – 2	0.15 – 0.3	0.2 – 0.3	4.2
Dairy waste[2]	3.7	1.0	0.1	0.4	0.2
Stomach content[2]	10.1	3.1	0.3	0.7	0.5
Blood[2]	10.9	11.7	1.0	0.4	0.6
Food leftovers[1]	9 – 18	0.8 – 3	2 – 4	0.7	NA*

* Value not available

Table 5 Approximate trace elements and heavy metals concentrations (mg kg^{-1} dry matter) in some feedstock types ([1]Institut fuer Energetik und Umwelt gGmbH, 2006; [2]Davis and Rudd, 1999)

Feedstock	Zn	Cu	Ni	Pb	Cr	Cd	Hg
Animals[1]							
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[1]							
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[2]							
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	<0.01
Brewing wastes	3.8	3.7	<1.0	0.25	<1.0	<0.25	<0.01

Table 6 An example from Northern Ireland of the average nutrient composition over 52 weeks of feedstock (dairy cow slurry) and digestate in a mesophilic digester at the Agri-Food and Biosciences Institute (Frost and Gilkison, 2010)

	Dry matter (g/kg)	Total N (g/kg fresh)	NH_4-N (g/kg fresh)	NH_4-N (% Total N)	pH
Feedstock	72.2	3.5	2.0	67.0	7.4
Digestate	59.3	3.6	2.4	80.5	7.9
Change	– 17.9%	+ 2.8%	+ 20%		
Standard deviation feedstock	8.50	0.52	0.36		0.34
Standard deviation digestate	5.22	0.48	0.43		0.23

2.3.1 Effect of AD on nitrogen availability

The quantities of nutrients that are supplied to a digester via the feedstock are the same as those in the digestate. During AD, bio-chemical changes take place that alter the organic compounds in which the nutrients are present and enhance their availability to crops. For example, a part of the organic nitrogen supplied with the feedstock is converted to ammonium (Table 6), although the total nitrogen content in digestate remains the same as in the feedstock.

In the case of co-digestion it is very important that the dry matter and nutrient concentrations of each feedstock are known beforehand. If a feedstock originates from agri-food processors or other sources, its delivery and use should be accompanied by the appropriate quality assurance declarations, i.e., those that are legally required in the respective countries (see Section 6 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.

It is mainly the mineral nitrogen (ammonium nitrogen) component of digestate that is available to crops immediately after application. 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. As a consequence it is important to minimise the surface area of digestate that is exposed to air after application so as to minimise ammonia volatilisation. This can be achieved by different methods of spreading (see Section 3.2), and/or by immediate incorporation in the topsoil. The expected utilisation percentage of nitrogen is greater for digestate than for slurry; for spring applications rather than applications in

Table 7 An example from Denmark of the measured utilisation percentage and ammonium share from selected field trials in spring barley and winter wheat (Birkmose, 2009).

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 slurry co-digested with organic wastes from food industries

Table 8: Comparative utilisation % of N between slurry and digestate for winter oil seed rape and grass in Denmark (derived from Birkmose, 2009)

	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

summer; and for injection rather than trailing-shoe (Table 8).

In the long term, applications of digestate may not always lead to increased crop yields. Some work in the Netherlands showed that in the year of application, digestate from cattle slurry had a 14% higher N fertiliser replacement value than whole cattle slurry (Schroder *et al.*, 2007). Over the next 4 years, when there were no further additions of digestate or slurry, there was no difference in the total N fertiliser replacement value between digestate and slurry.

Photo 3: Shallow injection into grassland

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. of N and P). Digestate must therefore be stored until the correct time for application (see Section 3.1). 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, autumn application of digestate almost doubled the amount of N leached into the drainage waters compared with raw slurry. The potential for nutrient leaching is higher on sandy soils with poor water retention capacity. However, in all cases this problem can be minimised by avoiding the application of digestate (or any fertilisers) in periods with low plant uptake or high rainfall.

It is therefore essential to know the fertiliser composition of digestate as well as the best method for accurate application to growing crops. These issues apply to all digestate, whether produced on-farm, from another location or from a centralised biogas plant. For

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

centralised biogas plants some countries require digestate deliveries to be accompanied by a delivery note and to be certified according to the respective national bio-security regulations (see Section 6).

Digestate and other fertiliser applications should be matched with crop nutrient requirements (see Appendix 2 for links to further information). This will minimise any unintended negative impact to the environment and also maximise farmers' profits. Application rates (especially for nitrogen), length of storage periods, and timings for applications must also comply with national limits (Table 9).

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

- Crop to be grown and previous crop(s) grown
- Soil type and existing reserves of nutrients in the soil (determined by periodic soil sampling, agrochemical analysis and mapping of soils)
- Expected crop yield
- Recommended nutrient requirements of the crop to be grown (nitrogen, phosphorus, potassium and sulphur)
- Nutrient content of digestate to be applied
- Expected utilisation percentage of nitrogen in digestate
- Time and method of digestate application
- Any supplementary requirement for mineral fertilisers (including types, amounts and times of application)[1].

The use of digestate as a biofertiliser should always be incorporated into a robust fertiliser management plan for the farm. Codes of practice in different countries detail the preferred procedures for manure management, nutrient management and soil management[2].

Phosphate overload can lead to diffuse pollution and excessive P concentrations (eutrophication) of coastal and inland waters. This is particularly relevant in environmentally sensitive areas such as some part of Denmark, south west Sweden and Northern Ireland. In

Table 9: Examples of national limits regulating nitrogen loading on farmland, required storage capacity for digestate, and its spreading season (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 Feb – 5 Oct
Denmark	170 kg N/ha /year (cattle) 140 kg N/ha/year (pig)	9 months	1 Feb – harvest
Italy	170 – 500 kg N/ha/year	90 – 180 days	1 Feb – 1 Dec
Sweden	170 kg N/ha/year (calculated from livestock units per ha)	6 – 10 months	1 Feb – 1 Dec
Northern Ireland	170 kg N/ha/year	4 months	1 Feb – 14 Oct
Germany	170 kg N/ha/year	6 month	1 Feb – 31 Oct Arable land 1 Feb – 14 Nov Grassland

[1] 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).

[2] In the UK there is a Code of Good Agricultural Practice for farmers, growers and land managers (Defra, 2009). This document also provides a useful link to The PLANET Nutrient Management software which is a computerised, interactive, version of the Defra Fertiliser Recommendations (RB209).

these areas the recommended practice is to apply the digestate to meet the phosphorus needs of the crop, and to supply any shortfall of nitrogen with mineral fertiliser. A further strategy that can assist in precise fertiliser application is to separate digestate into liquid/solid fractions. Up to 90% of the phosphorus contained in the digestate can be removed in the separated fibrous fraction, depending upon the type of separator that is used (see Section 4). Professional advisory services on crop fertilisation practices are provided in many countries (see Appendix 2 for useful links).

Photo 5: Covered digestate storage tank

3.1 Storage of digestate

Digestate is produced throughout the year and must therefore be stored until the growing season which is the only appropriate time for its application as a fertiliser. The length of storage period required will depend on geographical area, soil type, winter rainfall, crop rotation and national regulations governing digestate/manure application. In a temperate climate, for example, a storage capacity for 6–9 month of digestate production is recommended. In some countries the set period for the storage of digestate is compulsory (Table 9).

Like manure, when digestate is stored in open tanks, ammonia and methane gases are given off. These emissions can be reduced if the surface of the liquid is covered by a protective layer. This layer can be a natural crust of at least 10–20cm, a floating layer of plastic pieces, clay pebbles or chopped straw, etc.. Note, however, that chopped straw can give off methane when decomposing. Unlike raw cattle slurry, digestate does not form a surface crust during storage. Two other methods that minimise both methane and ammonia losses are to cover the digestate storage tanks with air tight membranes (Photos 4 and 5) or to use flexible storage bags. Figure 2 shows that after digestion with energy crops, up to 100 days of (covered) storage would be necessary in order to ensure that the emission of methane to atmosphere from digestate is reduced to less than 1%. In European countries with a developed biogas sector (e.g. Germany, Denmark and Austria) there are now financial incentives to establish covered digestate stores, with the main objective of reducing emissions.

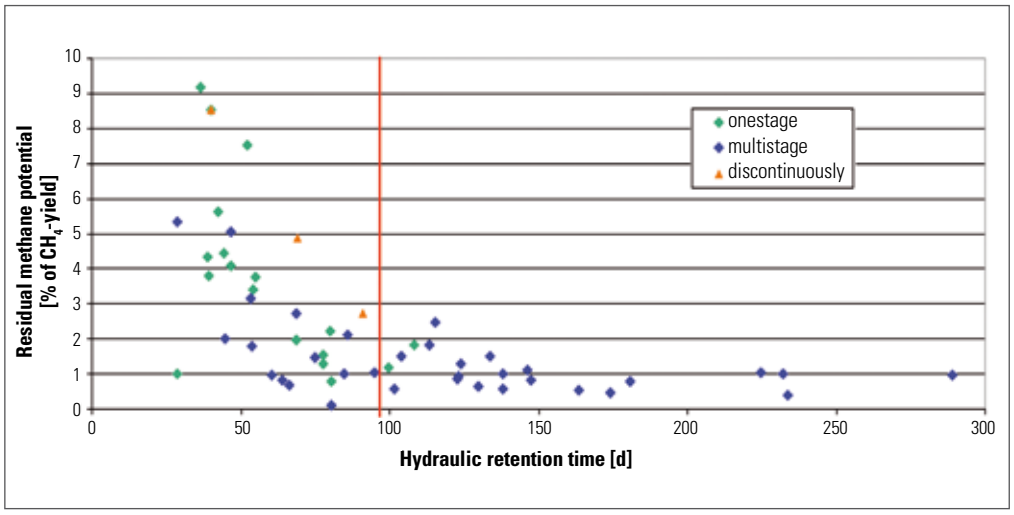


Figure 2: Losses of methane from digestate stores (Weiland, 2009)

3.2 Methods of digestate application

The equipment that is used for applying raw slurry and separated liquid can also be used for applying digestate. Similarly, the equipment that is used for spreading farmyard manure can also be used to spread separated solids. Digestate must be applied during the growing season in order to ensure its optimum use as fertiliser, and applied with the type of equipment that ensures even

Table 10: Example from Denmark summarising the characteristics of four digestate and raw slurry application methods (adapted from Birkmose, 2009)

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

application across the whole field and accurate application rates. This approach will also minimise ammonia volatilisation.

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

Although splash plate application is still used in many places, it is not recommended for the application of digestate. This is because splash plate application carries a high risk of ammonia volatilisation with its associated undesirable environmental effects. For these reasons, splash application is not only unsuitable but is also banned in some countries.

Compared with raw slurry, digestate has fewer odours, percolates more quickly into the soil and has a much lower risk of odour nuisance during and after spreading. However, because digestate is higher in ammonia content than raw slurry the potential for ammonia volatilisation during and after digestate application is greater. The most suitable methods of application are therefore those that minimise the surface area exposed to air and also ensure contact with the topsoil (trailing hoses, trailing-shoes, and injection) (Table 10). The higher costs of these methods compared with splash plate spreading are offset by the benefits of less pollution, less nutrient losses and higher utilisation of the nutrients in the digestate. Research results from Germany show that on arable land, trailing hose application of digestate, followed by immediate shallow incorporation resulted in the lowest greenhouse gas emissions (Wulf *et al.*, 2002). On grassland, it was found that trailing-shoe applications resulted in the lowest greenhouse gas emissions (Wulf *et al.*, 2002).

Photo 6: Trailing-shoe application places digestate on the soil surface beneath any foliage

4 Digestate separation

Digestate can be separated mechanically in the same manner as animal manure. Separation creates two outputs, a liquid and a fibrous material, that need to be stored and handled separately. It is recommended that the higher dry matter and fibrous fraction should be stored without disturbance, or even composted, in order to avoid any methane emission.

Some advantages of digestate/liquid manure separation for farmers are that it will:

- Produce a stackable dry fraction and pumpable liquid fraction
- Lower the volume of liquid requiring storage
- Create the potential to export separated fibre and nutrients
- 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.

There are a number of digestate/manure separation methods. Some of the commonly used mechanical separators and their efficiencies are shown in Table 11. Chemicals can be used to improve separator efficiency and help to partition differentially plant nutrients (particularly phosphorus) to the separated fibrous fraction.

Separation can also be by non-mechanical methods, such as sedimentation or filtration through geo-textile tubes. Whatever the method, separators are being used

Photo 8: Example of a rotary screen separator producing a stackable fibrous fraction and a free flowing liquid fraction

Table 11: Separator efficiency[1] of some common mechanical 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	13	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

increasingly at biogas plants, at either the post-digestion or pre-digestion stage. When used post-digestion, the partitioning of the nutrients between liquid and solid fractions (Table 11) helps the management and efficient redistribution of digestate as a biofertiliser. Pre-digestion separation of animal manure, as for example in Denmark, aims to reduce transport costs. The liquid fraction remains at source while only the separated dry solids are delivered to the centralised biogas plants. This enhances the dry matter content in the feedstock. This procedure is particularly appropriate for feedstock with low volatile solid contents, 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 with whole manure alone. However, dilute feedstock gives low biogas yields, along with high transportation costs and a further energy requirement for digester heating. Pre-separation of slurry followed by digestion of the separated solid fraction may be an option for dilute feedstock that would not otherwise be considered for anaerobic digestion.

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. Decanter centrifuges give good differential partitioning of nutrients, particularly phosphorus, into the separated fibrous fraction (Table 11). The use of chemicals to coagulate and/or flocculate the liquid prior to centrifuging can improve partitioning. However, decanter centrifuges have high capital and operating costs; 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).

Complete conditioning of digestate is a stage beyond separation. Ultimately, complete conditioning produces three refined end products: pure water, concentrated mineral 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 in this procedure are membrane separation and evaporation. Both are complex and require significant energy consumption. For these reasons, they are currently considered to be economically feasible only for large scale biogas plants, such as those in the waste water treatment industry.

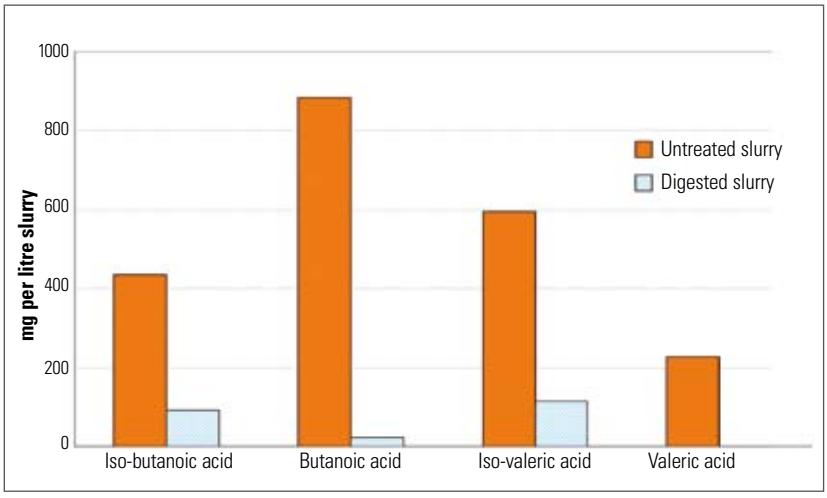
Photo 9: Decanter centrifuge mounted in a trailer unit for use in different locations

5 Environmental effects of using digestate as a fertiliser

Adoption of the best management practices outlined above will give the direct environmental benefits from use of digestate as a fertiliser. Such practices will result in lower gaseous emission into the atmosphere as well as in less diffuse pollution from surface run off and leaching. These direct benefits will help governments meet targets for reducing GHGs along with meeting the requirements of, for example, the EU Nitrates Directive and Water Framework Directive. Other major environmental benefits associated with using digestate as a biofertiliser in place of untreated manures include: reduced odours, improved veterinary safety, plant pathogen reduction and the 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. Hansen *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 was significantly reduced (Figure 3). Thereafter, the use of appropriate spreading methods can prevent the release of any residual odour. For example, injection of digestate (or slurry) into the 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 a release of odour.



Figures 3: Concentration of volatile fatty acids in untreated slurry and digested slurry (Hansen *et al.*, 2004)

5.2 Veterinary safety (see also 6.2)

The application of digestate, as well as of raw manure and waste products as fertiliser, may pose health risks for animals and humans. For this reason, 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; this 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 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°C for 1 hour or with thermophilic digestion, with a guaranteed retention of 5 hours at 53°C (in Germany: 24 hours at 55°C). However, some categories of animal by-products require pressure sterilisation before entering the digester. 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).

The eggs of common gastrointestinal worms and larvae of lungworm are inactivated in less than 4 hours at 53°C and after 8 days at 35°C. Mesophilic digesters

Table 12: Comparison of pathogen and nematode survival times in digestate and raw slurry (T90)
[1]Bendixen, 1994; [2]Test carried out by ADAS; [3]Bohm *et al.*, 1999)

	Biogas system			Raw slurry	
Pathogen	**70°C** (Seconds)	**53°C** (hours)	**35°C** (days)	**18–21°C** (weeks)	**6–16°C** (weeks)
Salmonella T.[1]	6	0.7	2.4	2.0	5.9
Salmonella D.[1]	6	0.6	2.1		
Coliform bacteria[1]	20	0.6	3.1	2.1	9.3
Staphilococcus Aureus[1]	8	0.5	0.9	0.9	7.1
Mycobacterium Para TB[1]	8	0.7	6.0		
Strep faecalis (FS)[1]	3.92 mins	1.0	2.0		
Group D Streptococococci[1]	20	?	7.1	5.7	21.4
M.Bovis (TB)[2]	90	nt	nt	22.0	nt
Larvae of nemotodes[3]	<0.6	<0.7	<2.4	<2.0	<5.9

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°C; 3 hours at 35°C) (Bendixen 1995) and Aujeszky's disease in pigs (10 minutes at 55°C; 5 hours at 35°C (Botner, 1991) and Johne's disease in cattle (M.Para tuberculosis) (0.7 hours at 55°C, 6 days at 35°C) In summary, anaerobic digestion (particularly thermophilic) can offer a useful means of reducing numbers of pathogens that could otherwise lower the productivity of livestock farms or present a risk to human health.

5.3 Plant pathogen reduction

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 these studies 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 spores are unable to survive. This in itself demonstrates the need for caution in making generalisations, since 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 their crops. AD therefore has the potential to offer real benefit to organic farmers and those wishing to reduce the use of fungicides.

5.4 Reduction of weed seeds

The reduction in 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 herbicides. The limited number of studies on the destruction of weed seeds by AD indicates that mesophilic anaerobic digestion can reduce the viability of the weed seeds and also of some crop seeds (Table 13). Inactivation time at thermophilic temperatures is shorter than at mesophilic temperatures (Engeli *et al*, 1993).

The new German biowaste ordinance requires proof that sanitation of digestate has occurred by determining inactivation of *Salmonella senftenberg*, tomato seeds and *Plasmidiophora brassicae* (club root) after digestion.

Table 13: The survival of weed seeds in cattle slurry (% of untreated control) after mesophilic digestion (35°C) 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°C
[2] Reduced to zero at 55°C at 14 days

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 its biogas potential (e.g. dry matter, nutrients and volatile solid content and pH levels). The digestate should be analysed similarly before application, to aid accurate fertiliser planning.

When off-farm material (e.g. industrial organic 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 (see also Section 6.2) 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. The regulations and quality controls applied in each country should be included in the specification/certification that would accompany every load of organic or trademarked biofertiliser supplied by the biogas plant. Storage and application of the digestate must comply with the codes of good agricultural practice and be in accordance with national guidance or legislation.

6.1 Chemical contaminants

Chemical contamination of digestate usually comes from human sources such as sewage and includes inorganic materials (e.g. heavy metals) and persistent organic compounds. Agricultural by-products can contain small quantities of antibiotics, disinfectants, and ammonium (Al Seadi, 2001). It is therefore extremely important to ensure high quality feedstock. This can be achieved by using only feedstock that is within 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[3], 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 is required.

Animal by-products that are to be used as AD feedstock require specific attention with reference to safe utilisation of the resulting digestate as fertiliser and soil conditioner. In EU countries, Regulation 1774/2002 stipulates a range of precautions against the spreading

[3] Any plant material used for plant propagation

of transmissible spongiforme encephalopathy and regulates the sanitary measures for utilisation of animal by-products as feedstock in biogas production (Table 14).

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

- Livestock health control. No animal manures or slurries will be supplied from any livestock with health problems (zoonoses, etc).
- Feedstock control. Hazardous biomass types must be excluded from anaerobic digestion.
- Pasteurisation. The feedstock is heated at 70°C, for one hour (or its equivalent). The particle size must be less than 12 mm in diameter.
- Pressure sterilisation. The feedstock is sanitised through a combination of temperature of 130°C 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 also Section 5 for more 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) can cause negative public perception of digestate as well as aesthetic damage to the environment. In addition, physical impurities in the feedstock, such as sand, will increase the operational costs of the biogas plant by causing wear and tear to pipes, pumps and other plant components and to the digestate application machines. Sand can accumulate in the digester, reducing its active volume.

The control and management of physical impurities is mainly a matter of ensuring high purity feedstock. This can be done either by sorting at source or by on-site separation (mechanically, magnetically, or by other means). 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.

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 in 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 originating from international means of transport (e.g. catering waste from international flights and trains etc)

7 Final comments

Biogas plants provide a fully sustainable and integrated system for resource and environmental management that offer governments a multipurpose technology option for fulfilling a cluster of policy needs. For example, biogas can be used to displace fossil fuels otherwise used for heating, electricity and transport. In addition, digestate is an easy to use biofertiliser that can be used to replace fossil fuels that otherwise would be used for fertiliser manufacture and its transport around the world.

Production of good quality digestate for use as biofertiliser is the result of careful control of all aspects of the process, from feedstock to field. Feedstock selection, adherence to strict standards (government and/or farmer determined) and compliance with codes of good agricultural practice are all key issues.

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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.
2. Canada: Nutrient Management Workbook. <http://www.omafra.gov.on.ca/english/nm/ar/workbook/workbk.pdf> accessed 26 January 2010
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6. Denmark: Various biogas information <http://www.landbrugsinfo.dk/Tvaerfaglige-emner/Biogasanlaeg/Sider/Engelsk_materiale.aspx>

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