

Nutrient Recovery by Biogas Digestate Processing

Bernhard Drosig
Werner Fuchs
Teodorita Al Seadi
Michael Madsen
Bernd Linke

SUMMARY

This report reviews various approaches for processing of biogas plant digestate for the purpose of nutrient recovery. It covers both established and emerging technologies and assesses technical performance and where possible economics. Techniques for nutrient recovery from digestate are developing rapidly and aim to improve nutrient management in agriculture and in waste treatment systems.

The report is aimed at biogas plant developers and operators as well as agriculture policy makers and was produced by IEA Bioenergy Task 37. IEA Bioenergy Task 37 addresses challenges related to the economic and environmental sustainability of biogas production and utilisation.





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Technical Brochure prepared by:

Bernhard DROSG

Werner FUCHS

Teodorita AL SEADI

Michael MADSEN

Bernd LINKE

Edited by David BAXTER

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Executive Summary

Improved yields from farming practice and food processing are necessary in order to sustain positive growth around the world. A key element to achieve this aim is adequate supply of fertiliser.

Biogas plants produce, along with biogas, digestate, which is an excellent plant fertiliser, rich in both organic matter and in macro- and micronutrients. The physico-chemical characteristics of digestate vary, strongly depending on the nature and composition of the digested substrates as well as on the operational parameters of the biogas processes.

Digestate is normally used as fertiliser for crops without any further processing, substituting industrially produced mineral fertilisers. However, the need for efficient nutrient management, required by restrictions on manure application in areas with high livestock density, along with depletion of the global natural reserves of phosphorous and potassium, make recovery and recycling of plant nutrients from manure, waste streams, and other resources increasingly important for farmers, technology providers, investors, and decision makers.

This report focuses on digestate from biogas plants, where animal manures and slurries, crop residues, organic wastes and residues from agri-food processing industries and from other industrial processes are the principal substrates.

The nutrients contained in digestate can be extracted and concentrated through application of a range of technologies and processes, although there is no unified approach in the published literature about what defines digestate processing for nutrient recovery. The present report presents the technologies that are commercially available. Nutrient recovery technologies are those that result in an end-product with higher concentrations of plant nutrients than the unprocessed digestate, or technologies that are capable of separating out nutrients in mineral form, or of creating another marketable end-product, suitable for recycling as biofertiliser, and closing the nutrient cycle.

Digestate processing can be partial, primarily for the purpose of volume reduction, or it can be complete, refining digestate to pure water, a solid biofertiliser fraction and fertiliser concentrates. While partial processing uses relatively simple and cheap technologies, for com-

plete processing complex methods and technologies are currently available with various degrees of technical maturity, higher energy input, and higher investment and operating costs.

The first step in digestate processing is to separate the solid phase from the liquid phase. The solid fraction can subsequently be directly applied as biofertiliser in agriculture or it can be composted or dried for intermediate storage and transport. Depending on the consistency of the digestate, screw presses or centrifuges are most commonly used for solid–liquid separation.

For complete digestate processing for nutrient recovery, membrane technology can be used, such as nanofiltration and ultrafiltration followed by reverse osmosis. Membrane filtration produces a nutrient concentrate and purified (process) water. A further possibility for concentrating digestate is evaporation utilising excess heat from the biogas plant CHP unit. Nitrogen recovery from digestate can be carried out by ammonia stripping, ion exchange or struvite precipitation. Whatever the technology applied, complete digestate processing requires high energy input, use of chemical reagents which, along with high investment costs for appropriate machinery, imply considerable costs for such applications.

Due to diversified support schemes in different countries, it is not easy to generalise whether a specific technology always is feasible in connection with a biogas plant. Some countries stimulate biogas plant owners to utilise excess heat through subsidies, while others have not implemented such fiscal instruments.

The techniques for nutrient recovery from digestate are developing rapidly, aiming to improve nutrient management in agriculture and in waste treatment systems. In parallel, there is a general need to increase the degree of commercialisation of organic fertilisers from digestate processing through product standardisation.

The information contained in this report should be of interest to biogas and digestate producers, to livestock and crop farmers supplying manure to biogas plants or using digestate as fertiliser, to agro-food industries and other organic waste producers, that supply organic wastes to biogas plants as well as to policy makers, regulators, investors and end-consumers.

1. Introduction

The growing awareness over the last decades about pollution problems arising from organic waste streams and manure management has led to restrictions for nutrient input per hectare in many places with intensive animal production around the world. Anaerobic digestion of animal manures and slurries is often required by national nutrient management regulations or environmental regulations in such areas, aiming to close the nutrients cycle, to improve veterinary safety, and to provide air quality/odour control. At the same time, depletion of phosphorus and potassium reserves as well as the necessity to preserve and secure their future supply has changed the focus of digestate processing from nutrient removal and disposal towards nutrient recovery and recycling. The techniques for nutrient recovery from digestate are developing rapidly, aiming to improve nutrient management in agriculture and in waste treatment systems.

The report outlines the prevailing techniques for digestate processing for the purpose of nutrient recovery. The aim of the report is to provide information about possibilities for nutrient recovery from digestate, thereby highlighting the potential of digestate as a sustainable source of nutrients for agricultural use.

The technical information provided in the report is mainly based on an existing publication on digestate processing technologies, elaborated by University of Natural Resources and Life Sciences (Department IFA Tulln) in 2010 (Fuchs and Drosch, 2010), which was updated and completed with new information from the IEA Bioenergy Task 37 member countries and from available technical and scientific literature.

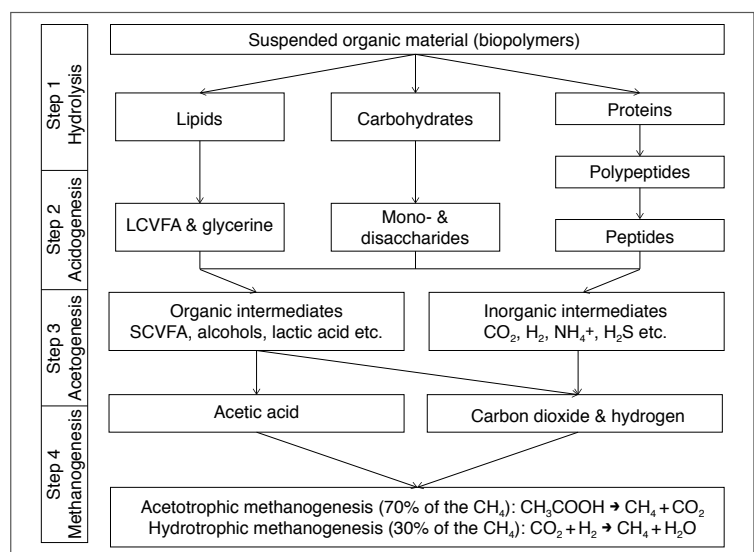
Key words: *nutrient recovery, digestate processing, digestate conditioning, nitrogen recovery, phosphorus recovery, digestate use as fertiliser, solid-liquid separation*

Figure 1. Breakdown of the AD process (Madsen et al., 2011)

2. Digestate

2.1 What is digestate?

Along with biogas, digestate is a product of anaerobic digestion (AD) and represents the effluent or digested substrate which is removed from the AD reactor (digester) after recovery of biogas. Digestate is normally liquid, but it can also be a solid, stackable material when originating from, for example, a dry state AD process. During the biogas process, the substrate, which can be a mixture of various AD substrates or a pure monosubstrate, is retained inside the digester for several weeks. During that time it is sequentially decomposed by a variety of microorganisms through a complex biochemical process in the absence of oxygen (anaerobic conditions). Figure 1 outlines the interconnections between the four major steps taking place during AD: decomposition of organic matter during hydrolysis, formation of organic acids during acidogenesis, formation of the main intermediate acetate during acetogenesis, and finally formation of methane during methanogenesis from either acetate or carbon dioxide and hydrogen. Digested substrate is removed from the digester tank as digestate and stored in designated containers. What makes digestate an interesting product is its excellent plant fertiliser qualities, based on a rich content of plant macronutrients including nitrogen (N), phosphorus (P), potassium (K), and sulphur (S), various micronutrients and also organic matter. Digestate is normally applied as fertiliser to crops without the need for any further processing.



2.2 Digestate characteristics – relevant for its use as fertiliser

The physico-chemical characteristics of digestate vary, strongly depending on the nature and composition of the substrates as well as on the operational parameters of the AD process (see Annex 1). Literature (Holm-Nielsen et al., 1997; Chantigny et al., 2007; Möller et al., 2008; Tambone et al., 2010; Fouda, 2011) indicates that, when compared with raw animal manures and slurries, digestate generally has lower total solids (TS) and total organic carbon (C) content, lower carbon to nitrogen ratio (C:N), and lower viscosity. On the other hand, the pH value and the share of ammonium (NH_4^+) are higher in digestate compared to raw animal manures and slurries. Some characteristics relevant for the ferti-

liser quality of digestate are outlined below.

In Europe, the traditional substrates are agricultural/livestock by-products (manure and slurries), biogenic waste (food waste, municipal organic waste, etc.), energy crops (maize whole crop silage, sugar beet, grass silage), by-products from food and agro-industries (animal by-products from abattoirs, brewers' spent grains and solubles, etc.). More recently, residues from the bioethanol and the biodiesel industries are used. The influence of various substrate materials on digestate characteristics is illustrated in Table 1. These characteristics greatly influence the choice of digestate processing technology.

The AD process conditions also influence digestate composition, as shown in Table 2.

Table 1: Substrate parameters influencing digestate composition (adapted after Fuchs and Drosig, 2010)

Substrate parameter	Impact on digestate composition	Comments
Organic wastes	<ul style="list-style-type: none"> low total solids (TS) content low percentage of organics in TS 	In general, most organic wastes show high contents of organics in the total solids (e.g. >90 % for food waste). This however, depends on the waste type. The organic content in wastes is often readily degradable and converted to biogas, hence leaving a lower amount of (inert, not utilised) organic matter in the digestate.
High amount of abattoir waste	<ul style="list-style-type: none"> high nitrogen concentration high percentage of ammonia in total nitrogen 	
High amount of manure	<ul style="list-style-type: none"> low total solids (TS) content considerable nitrogen concentration 	Some pig manure, sow manure, fattening pig manure will lead to relatively low total solids content, however cattle manure full of undigested plant material and bedding material will give rise to relatively high total solids content in the digestate. The percentage of ammonia in total nitrogen depends on many factors, distribution coefficient between types (cattle, pig, and poultry probably being the most relevant). Typically, no more than 50 % of the total nitrogen in raw cattle slurry is ammonium (based on > 200 representative manure samples (ENVO Group, 2014)).
Energy crops	<ul style="list-style-type: none"> high total solids (TS) content high percentage of organics in TS (VS/TS ratio) 	

Table 2: Process parameters influencing digestate composition (Fuchs and Drosig, 2010)

Process parameter	Impact on digestate composition
High amount of fresh water	<ul style="list-style-type: none"> high amount of digestate produced low salt/ammonia concentration low total solids (TS) content
High amount of recirculation liquid (reutilisation of the liquid fraction of digestate as process water)	<ul style="list-style-type: none"> lower amount of digestate produced high salt/ammonia concentrations elevated total solids (TS) content
Short hydraulic retention time	<ul style="list-style-type: none"> high VFA (volatile fatty acids) concentration high percentage of organics in TS low percentage of ammonia in total nitrogen

2.2.1 Total solids content (TS)

The content of total solids (also called dry matter) decreases during AD, so digestate can contain 50% to 80% less TS compared to the incoming substrate (Holm Nielsen et al., 1997; ARBOR, 2013). The TS content of digestate mainly depends on the initial TS content of the substrate (e.g. 3–15% TS for wet state AD, and up to 30% TS for dry state AD), as well as on the content of easily digestible organic matter. It is generally accepted that woody materials containing relatively large amounts of the structural plant polymer lignin have a very low digestibility, while substrate containing fats, sugars and alcohols have very high digestibility. Up to 70% of the TS content of digestate can be organic, represented by volatile solids (VS). This implies that digestate application on soils has the potential of improving soil structure through input of inert organic matter and fibers (primarily lignocellulose), which contributes to the formation of humus in the medium to long term.

2.2.2 pH value

The pH value of fresh digestate typically ranges from 7.5 to 8.0 pH. This is higher than the average pH of 7.1 for raw manure (ARBOR, 2013). The pH is mainly influenced by the biochemistry of the AD process, while the characteristics of substrates will also influence it (ARBOR, 2013, and WRAP, 2012). For example, the formation of ammonium carbonate ($(\text{NH}_4)_2\text{CO}_3$) as well as the removal of CO_2 as a result of the transformation of CO_3^{2-} and $2 \text{H}_3\text{O}^+$ to CO_2 and H_2O , result in increased pH (BiotecVisions, 2012). The consumption of volatile fatty acids (VFA) during AD increases the pH. The same effect is produced by the concentrations of basic cations like Ca^{2+} and K^+ (ARBOR, 2013). On the other hand, precipitation of carbonates such as calcite CaCO_3 and of iron phosphates contribute to decreasing the pH (Hjorth et al., 2010). On the one hand an increased pH indicates the degradation of offensively smelling VFAs, which reduces odour emissions. On the other hand the degree of ammonia volatilisation increases. Consequently, digestate should be immediately incorporated in soil after application, or even via direct soil injection to prevent

excess ammonia emissions. However, the superior infiltration speed of digestate into soil compared to raw manure/slurry lowers the risk of excess ammonia volatilisation if digestate is handled according to best agricultural practice. Storage of digestate until field application should take place in closed storage tanks (manure storage tanks with flexible plastic coverage).

2.2.3 Nitrogen content

The AD process degrades organic nitrogen compounds, releasing ammonium $\text{NH}_4\text{-N}$, which is immediately bioavailable for growing plants. The content of ammonium in digestate is directly related to the total N content in the substrate. As pig slurry has higher N-total and $\text{NH}_4\text{-N}$ contents than cattle slurry, this will be reflected directly in the digestate dominated by such substrates (Holm-Nielsen et al., 1997; Fouda, 2011). Specific differences of nitrogen concentrations in digestate deriving from the AD of energy crops compared to digestate from organic waste and industrial by-products are shown in Figure 2 a and b. The figure shows that nitrogen concentrations in energy crop AD plants are rather similar, whereas in biogas plants co-digesting organic wastes, the nitrogen concentration varies widely, mainly due to variations in nitrogen contents in the respective substrates. In addition, process parameters such as the amount of fresh water and degree of recirculation can influence the total nitrogen concentrations. In the case of mono-digestion of industrial by-products, the influence of nitrogen concentration in the substrate is easily recognised. So is the influence of sulphate.

2.2.4 Phosphorus content

The phosphorus content of digestate is either given as total phosphorus or as phosphate equivalents. The AD process does not affect the content of phosphate in digestate, which is completely dependent on the content in the substrate. Nevertheless, co-digesting substrate with high content of phosphate like pig slurries with substrate with lower phosphate content will consequently lower the phosphate content in the digestate produced due to simple dilution (ARBOR, 2013).

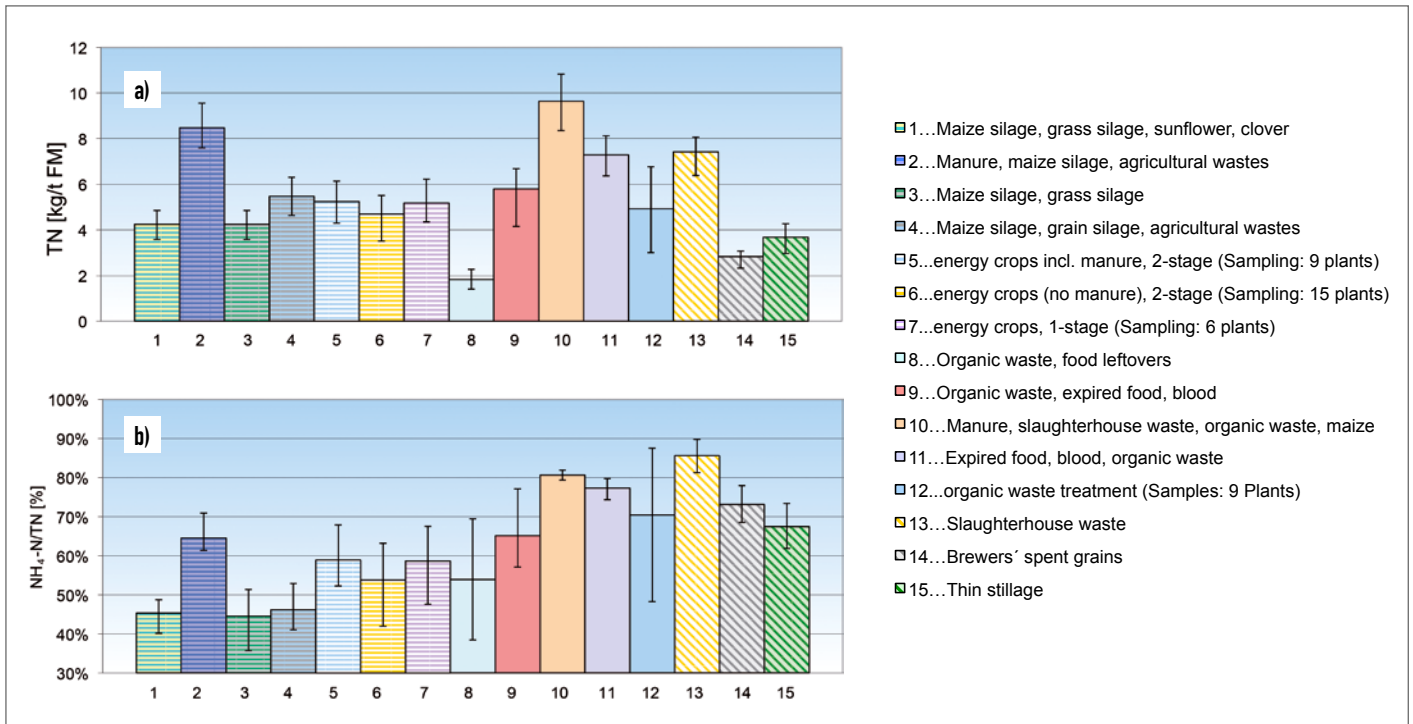


Figure 2: Examples of the variation of nitrogen in the digestate of biogas plants with different substrate types (a) total nitrogen concentration in kg per ton fresh matter (FM), (b) ammonium nitrogen as percentage of total nitrogen). Horizontally striped columns indicate digestate from typical agricultural plants, diagonally striped columns indicate digestate from mono-digestion of industrial by-products, and unstriped columns indicate digestate from typical waste treatment plants. (Source: Fuchs and Drosig, 2010)

2.2.5 Impurities and contaminants

The presence of impurities and contaminants in digestate, whether they are of physical, chemical or biological nature, is highly dependent on their abundance in the original substrates. The biological contaminants (pathogens and weed seeds) can be effectively degraded during the AD process to an extent, which depends on the process temperature and the retention time inside the digester. According to Angelidaki and Ellegaard (2003) thermophilic treatment at a temperature of at least 52°C and a minimum guaranteed retention time of 10 h effectively corresponds to a controlled sanitation at 70°C for 1 h. Most problematic weeds and pathogens are removed under these conditions. This is, however, not the case for the physical contaminants (pieces of inert materials or larger pieces of digestible ones) as well as the chemical contaminants (heavy metals and persistent organic pollutants), which are mainly able to pass through the AD process unaffected. The presence of any kind of impurities in digestate is a potential environ-

mental hazard and has a negative impact on its quality and suitability to be used as fertiliser, and on the farmers' acceptance of the product (Al Seadi and Lukehurst, 2012). Careful selection of "clean" substrates or alternative conditioning of substrates prior to AD is therefore the most sustainable way to avoid impurities and contaminants ending up in the digestate. There are quality standards, national certification systems, and positive lists of substrates already adopted in several countries, aiming to ensure that only high quality digestate is certified as fertiliser (Al Seadi and Lukehurst, 2012). Research results (Kern, 2008) indicate that the concentration of heavy metals in phosphorus recovered as the mineral struvite from digested sewage sludge is many times below the threshold values for crop fertiliser in Germany. The explanation is that pollutants present in the anaerobic sludge, such as heavy metals and persistent organic pollutants are not involved in the crystallisation process of struvite. Hence, they are present in the struvite product only in minute amounts (Kern, 2008).

3. Digestate processing for nutrient recovery

In this report digestate processing is approached from the point of view of nutrient recovery and digestate conditioning. Here the aim is to produce a standardised biofertiliser (solid or liquid), where the quality and marketability of the digestate is improved. However, digestate processing can also be approached from the point of view of digestate treatment. This approach is similar to wastewater treatment, where nutrients and organic matter from the effluent are removed in order to allow discharge to the sewage system, to the wastewater treatment plant on site or to a receiving water body. In practice, digestate processing concepts show aspects of both approaches. Nevertheless, technologies where nutrients cannot be recovered (e.g. denitrification in aerobic wastewater treatment) are not considered here. Consequently, the present report defines digestate processing for nutrient recovery as the technology that results in an end-product with higher concentrations of plant nutrients than the unprocessed digestate, or technologies that are capable of separating out nutrients in mineral form, or of creating another marketable end-product, suitable for recycling as biofertiliser, thus closing the nutrient cycle.

3.1 Overview of digestate processing technologies

Digestate processing involves the application of different technologies. These technologies are mostly com-

parable to existing technologies from manure processing, sewage sludge treatment, and wastewater treatment. Digestate processing can be partial, primarily for the purpose of volume reduction, or it can be complete, refining digestate to for example pure water, a solid biofertiliser fraction, and fertiliser concentrates.

The first step in digestate processing is to separate the solid phase from the liquid phase. In order to distinguish the different fractions in digestate processing, the term ‘digestate’ or ‘whole digestate’ is used in the report for the untreated effluent from the biogas plant, and “solid fraction”, respectively “liquid fraction” for the products of the solid–liquid separation. The solid fraction can subsequently be directly applied as biofertiliser in agriculture or it can be composted or dried for intermediate storage and viable transport. To enhance solid–liquid separation, flocculation or precipitation agents can be added.

While partial processing uses relatively simple and cheap technologies, for complete processing different methods and technologies are currently available, with various degrees of technical maturity, higher energy input, and higher investment and operating costs. For nutrient recovery, membrane technology, such as nano- and ultrafiltration followed by reverse osmosis, can be used (Fakhru’l-Razi, 1994; Diltz et al., 2007). Membrane filtration produces a nutrient concentrate and purified

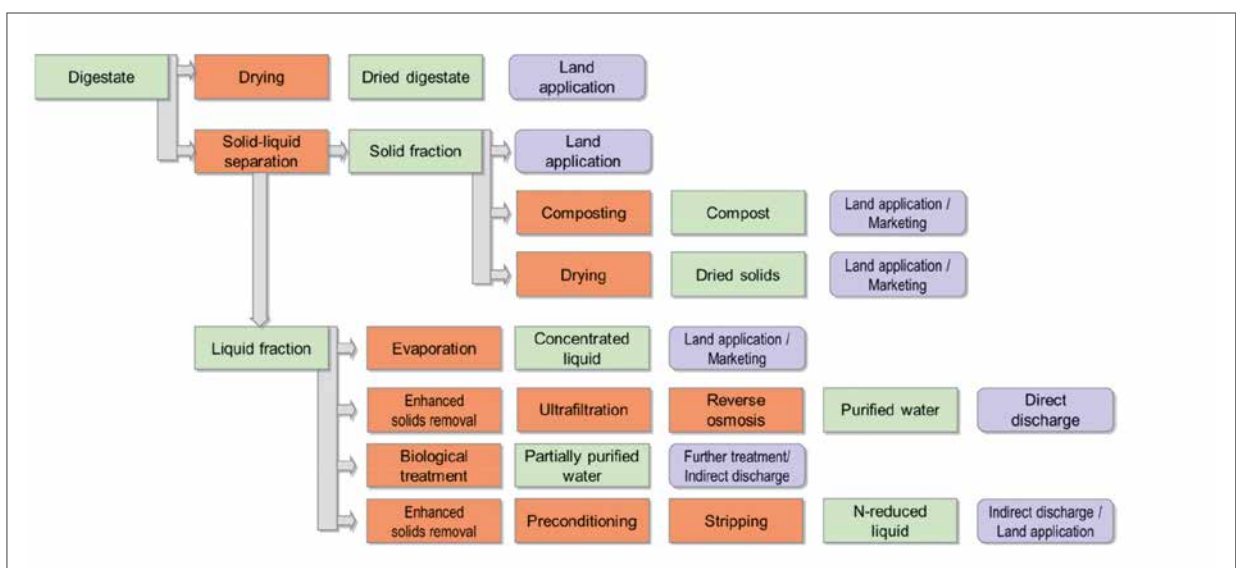


Figure 3: Overview of viable options for digestate processing (Source: Fuchs and Drosig, 2013)

process water (Castelblanque and Salimbeni, 1999, Klink et al., 2007). The liquid digestate can also be purified through aerobic biological wastewater treatment (Camarero et al., 1996). However, because of the high nitrogen content and low biological oxygen demand (BOD), addition of an external carbon source is often necessary in order to achieve sufficient denitrification. A further possibility for concentrating digestate is evaporation with excess heat from the biogas plant CHP unit. In order to reduce the nitrogen content in the digestate, ammonia stripping (Siegrist et al., 2005), ion exchange (Sánchez et al., 1995) or struvite precipitation (Uludag-Demirer et al., 2005; Marti et al., 2008) have been proposed. Whatever technology is applied, advanced digestate processing in most cases requires high energy input and chemical reagents. Together with increased investment costs for appropriate machinery, considerable treatment costs also arise. An overview of viable digestate processing technologies is given in Figure 3.

3.2 Applied processes at industrial scale

As illustrated above (Figure 3) a very broad range of technologies are currently being applied for digestate processing, depending on the boundary conditions. Up to now, no market leading technology has evolved. The most abundant approach is solid–liquid separation of

digestate, where, depending on the consistency of the digestate, screw presses or centrifuges are most commonly applied. Solid–liquid separation can be improved by the addition of precipitating agents.

Among the technologies for further treatment of the liquid fraction of digestate, membrane purification is the only process that can achieve a degree of purification that can allow direct discharge to receiving waters. It is also among the most frequently applied approaches in more complex digestate processing facilities in Germany, Switzerland, and Austria (Figure 4). Nevertheless, membrane purification is the most expensive technology, with high potential for optimisation in large-scale applications. If excess heat is available, evaporation is an interesting option, although it gives rise to some controversy. In Germany digestate processing technologies using heat (e.g. evaporation, drying) are being used more frequently due to the subsidies for waste heat utilisation at biogas CHPs. Evaporation of the liquid fraction of digestate is a rather robust technology, however, if the liquid fraction contains considerable amounts of fibrous material it is necessary to remove this beforehand to avoid clogging in the heat exchangers. Other technologies that are less commonly applied include ammonia stripping, ion exchange, solar drying, etc.

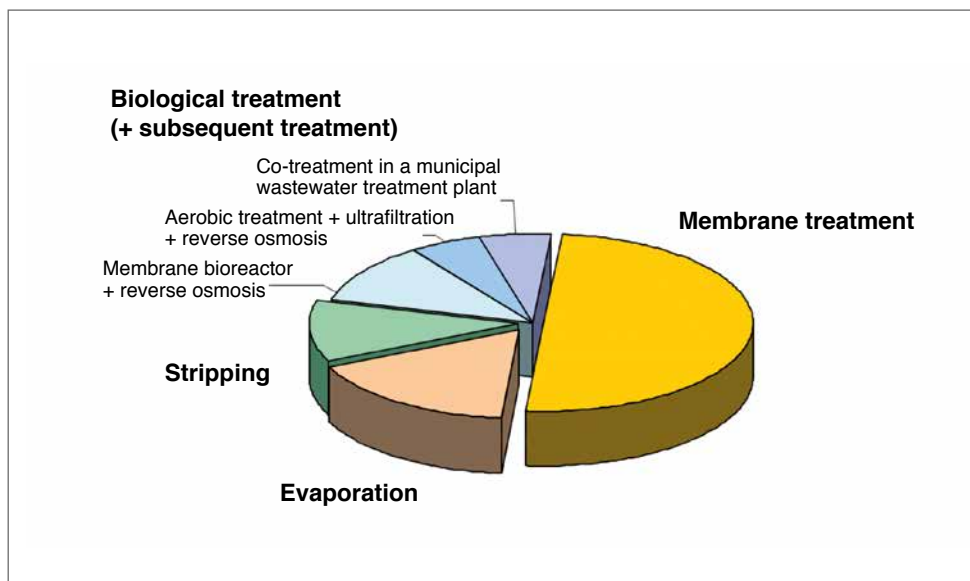


Figure 4: Overview of the distribution of industrial-scale applications for further treatment of the liquid fraction of digestate in Germany, Austria and Switzerland, Status from 2009 (Fuchs and Drogg, 2013)

4. Drivers for digestate processing for nutrient recovery

The standard utilisation of digestate is application as fertiliser and soil conditioner in agriculture, horticulture, forestry etc. Direct application is possible immediately following its removal from the digester (whole digestate) without the need for any further processing.

However, digestate is rather dilute with respect to nutrients, which makes the costs of transportation relatively high compared to conventional fertiliser. Other significant costs are related to investments in storage capacity, required by environmental regulations in many countries, like for instance in the case of Denmark, Germany and France, where not only the nutrient input per hectare is restricted, but also the period of application is limited to the growing season.

Nevertheless, many crop cultivators agree that synergistic effects arise from applying digestate as organic fertiliser compared to conventional fertiliser.

4.1 Legal frameworks

At EU level, the European Nitrate Directive 91/676/EEC limits the annual load of nitrogen that can be applied to agricultural land in EU member states. In many parts of Europe and around the world, livestock production is intensive, concentrated in areas with limited land available for manure application. This creates a permanent excess of nutrients, making such areas highly vulnerable from the point of view of nutrient pollution of ground and surface waters. When animal feed is being imported to such a region, efficient nutrient handling becomes even more crucial. Restrictions on the nutrient input per hectare require the excess nutrients to be recovered, exported, and recycled outside the vulnerable areas. To deal with the problem, digestate processing technologies, aiming first of all at volume reduction and nitrogen removal, have consequently been implemented in many places during the last decade.

More recently, also concerns regarding phosphorus surplus from manure application in many areas and excessive levels of phosphorus found in surface and ground waters have greatly increased demand for nutrient management and export of excess of nutrients.

4.2 Resources management

An ever growing aspect of digestate processing is its contribution to effective resource management. Nutrients recovered from digestate are important as a sustainable source of phosphorus and potassium. The natural reserves of phosphates and potassium are concentrated in few areas around the globe and extracted through mining activities. It is estimated that the easily available resources of phosphorus will be depleted by the end of this century (Neset & Cordell, 2012), while the global demand for nutrients will increase continuously, creating an imbalance between availability and demand, with the consequence of rising prices for essential plant nutrients (Vaneekhaute et al., 2013).

4.3 Logistics

Storage, transport, handling and application of digestate as fertiliser imply significant costs for farmers, due to its large volume and low nutrient concentration compared with its fertiliser value. For small to medium-scale biogas plants, transportation of substrate and digestate accounts for roughly 33% of the overall biogas production costs (Bojesen et al., 2014), which makes transport minimisation a crucial cost reduction criterion.

Significant transportation costs savings can be realised for the farmers and crop cultivators associated with a biogas plant, if the tanker trucks collect raw manure from stables and deliver digestate in storage tanks nearby the fields where digestate is to be applied. Hence, individual parties should settle on a fair distribution of the transportation costs in order to optimise savings for the farmers.

4.4 Product standardisation

Up to now, the market for organic fertilisers produced through digestate processing is poorly developed in most countries. From the point of view of commercialisation of organic fertiliser from agricultural substrates, this should be feasible if there is a suitable legal frame. For industrial wastes, the legal situation will depend on the origin of the waste and the process in question. It is nev-

5. Solid–liquid separation – the first step in digestate processing

ertheless expected that in the near future, the degree of commercialisation of organic fertilisers from digestate processing will increase. Local policies and markets influence the marketability of compost and dried digestate. Quality standards and legislation for fertilisers and compost products need special consideration. Especially in the case of digestate originating from co-digestion of industrial waste and household waste, the presence of heavy metals, persistent organic pollutants and other chemical pollutants may be a barrier for marketing of digestate products. It must be emphasised that these consumer-induced barriers are often not based on quantifiable parameters, rather on social attitude towards waste and its inherent heterogeneity. Legal frameworks in most countries stipulate the quality conditions for the marketing of waste based digestate products.

4.5 Other drivers

Because of high water content, application of whole digestate (as well as of raw animal slurries) could lead to “soaking” of land in very rainy, humid climates or in water sensitive areas. Such conditions too, make digestate processing for nutrient concentration attractive.

Solid–liquid separation is the most frequent first step in digestate processing. Only in very few cases, whole digestate is processed without a prior solid–liquid separation step (e.g. drying of whole digestate). The principle of solid–liquid separation is shown in Figure 5.

In order to establish the best solid–liquid separation process, the focus has to lie on finding the right technology (or technology combination) for an efficient but cost-effective solid fraction separation step. Especially for consecutive membrane treatment, but also for evaporation, the right degree of separation of the solid fraction from the digestate is essential (for enhanced solids removal see section 5.5).

Typical ranges for the distribution of the main constituents between the solid fraction and the liquid fraction are provided in Figure 6. The separated solid fraction can be applied directly for agricultural purposes with the advantage of considerably lower transport costs due to the reduced water content. Another advantage is that the solid fraction can be stored under much simpler conditions. As an alternative to direct land application further stabilisation and transformation into a marketable product can be achieved, e.g. through drying or composting. Typically the solid end-products obtained are used as a biofertiliser. Another application, the production of pellets for heating purposes, is currently the subject of investigations. However, with regard to the high nitrogen content and associated increased NO_x emissions, the suitability of the pellets for thermal recovery is not yet sufficiently clarified.

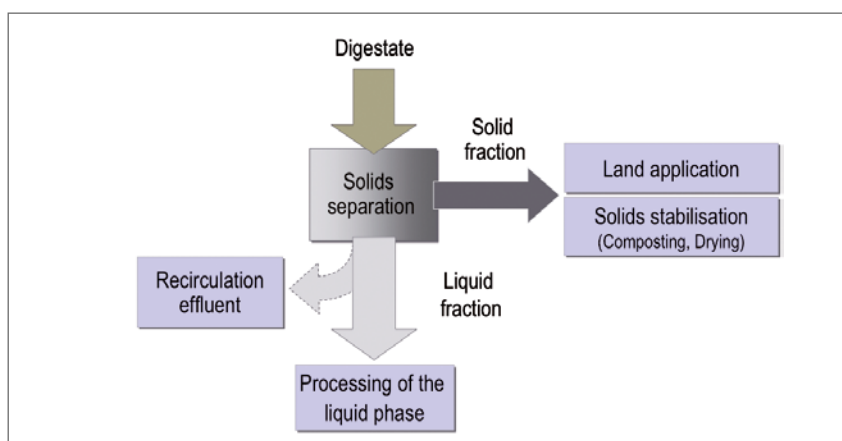


Figure 5: Solid–liquid separation step in digestate processing (Source: Fuchs and Drosig, 2010)

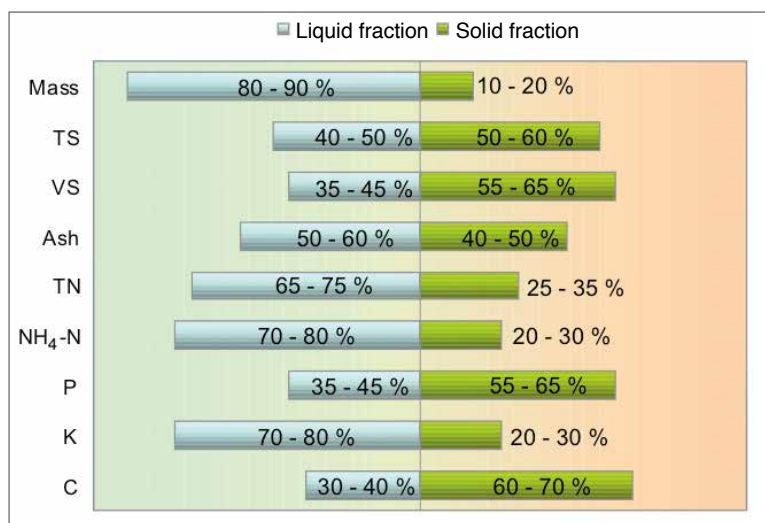


Figure 6: Distribution of the principal constituents after solid–liquid separation (data based on own investigations and various references; adapted after Bauer et al. (2009))

The major fraction deriving from the separation step is the liquid fraction. Depending on the characteristics of the whole digestate and the efficiency of solids removal, its composition is subject to wide variation. Frequently, part of the liquid fraction is recycled to adjust the dry matter concentration of the input substrate (Resch et al., 2008). For the remaining liquid fraction, there are a variety of recovery and treatment options. In the simplest case, it is spread on agricultural land. Here the advantage of solid–liquid separation can be that a solid fraction gives rise to improved storage and residues management logistics. Nevertheless, further treatment with the aim of volume reduction and recovery of nutrients can be applied. In most cases, these objectives will be achieved only through a sequence of several steps. As a general rule, the necessary procedures are relatively complex and therefore expensive.

5.1 Screw press

Screw press separators (see Figure 7) are often used if the digestate has high fibre content. In Figure 8 the detailed set-up of a screw press separator is shown. A screw presses the fibres against a cylindrical screen. The liquid fraction of digestate leaves the separator through the sieve. Because of the increasing diameter of the screw the pressure is increases as the fibres advance along the separator. Finally, the solid fraction (containing the fibres) exits at the end of the separator, where the resistance can be adjusted mechanically. The degree of separation can be influenced by the mesh size of the screen, smaller particles (diameter of 0.5–1 mm) remain in the liquid (Weiland, 2008).

Unlike decanter centrifuges, screw press separators cannot separate small sludge particles from the digestate. If the digestate contains mainly fibres, the amount of solid fraction that will accumulate is dependent on the



Figure 7: Screw press separator (Source: Fuchs and Drosig, 2010)

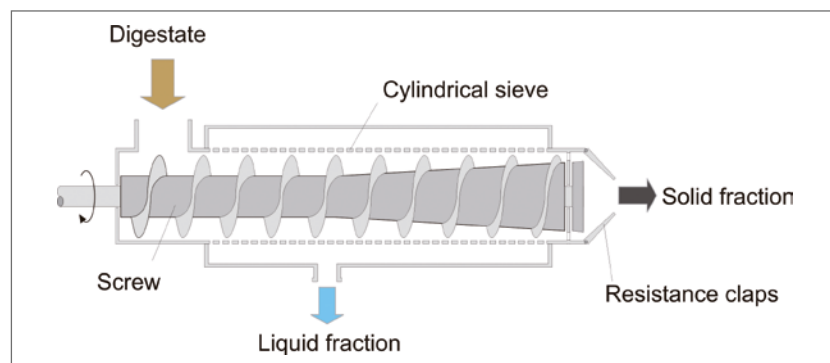


Figure 8: Detailed set-up of a screw press separator (Source: Fuchs and Drosig, 2010)

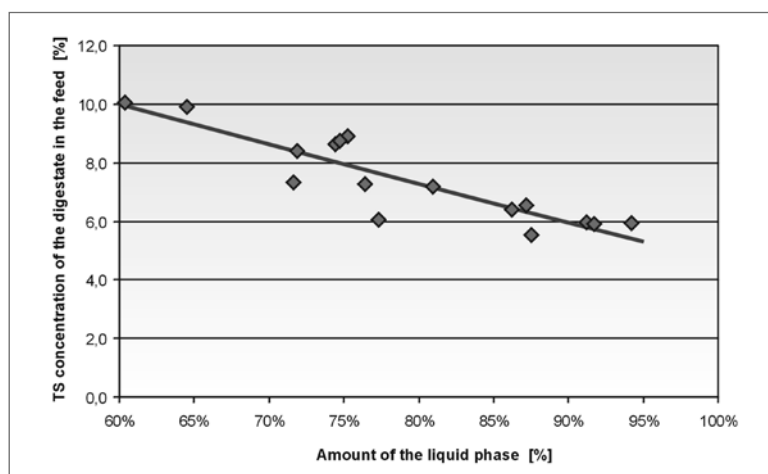


Figure 9: Relationship between the dry matter content in the inflow and the proportion of liquid phase (pooled data from screw extractor and rotary screen separator experiments). (Source: Bauer et al, 2009)



Figure 10: Decanter centrifuge

dry matter content of the digestate. Bauer et al. (2009) found a correlation between dry matter content in digestate and the amount of solid fraction accumulated (Figure 9).

The separation efficiency of different components in the digestate was investigated by KTBL (2008). In Table 3, an overview of the observed separation efficiency is given. The advantages of a screw press separator compared to the decanter centrifuge are the low investment costs (approximately 20,000€ for a 500 kW_{el} biogas plant, Bauer et al, 2009) and low energy consumption (0.4–0.5 kWh/m³, Fuchs and Drosig, 2010).

With respect to nutrient distribution, Table 4 shows the calculated percentage of nutrients in the solid phase, as function of degree of TS separation by means of a screw press, on the base of field data from agricultural biogas plants (Wendland, 2009).

5.2 Decanter centrifuge

Decanter centrifuges (see Figure 10) are frequently applied in digestate processing. They are used to separate small particles and colloids from the digestate. In addition, they can be used to separate the majority of the phosphorus contained in digestate with the solid frac-

Table 3: Typical separation performance of screw press separators (KTBL, 2008)

	Percentage of fresh matter [%]	Degree of separation [%]						
		TS	VS	COD	NH ₄ -N	TN	PO ₄ -P	K
Solid fraction	10.0	48.1	56.3	48.8	9.2	17.0	21.8	10.0
Liquid fraction	90.0	51.9	52.4	51.2	82.0	83.0	78.0	90.0

Table 4: Distribution of TS and nutrients in slurry, solid and liquid fraction after separation (Wendland, 2009)

	TS [%]	TN [g kg ⁻¹]	NH ₄ -N [g kg ⁻¹]	P ₂ O ₅ [g kg ⁻¹]	K ₂ O [g kg ⁻¹]
Slurry (average)	6.5	5.1	3.2	2.3	5.5
Solid fraction	24.3	5.8	2.7	5.0	5.8
Liquid fraction	5.7	4.9	3.0	2.3	6.2

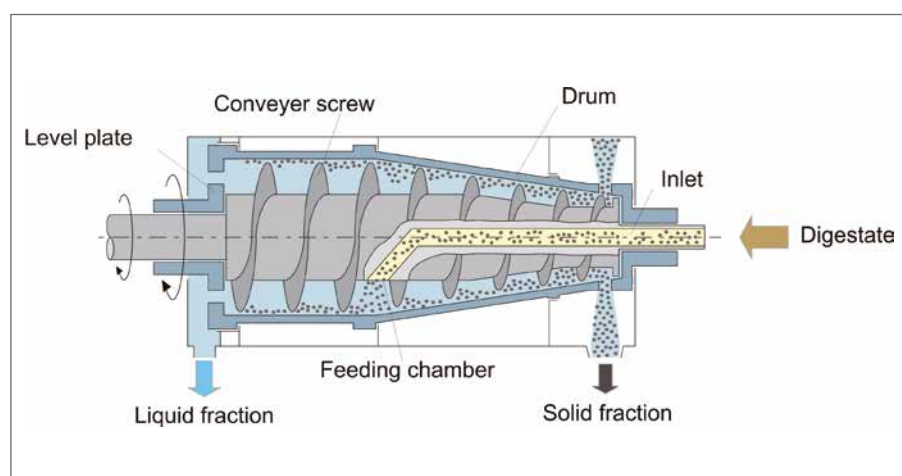


Figure 11: Detailed set-up of a decanter centrifuge (Source: Fuchs and Drosig, 2010)

tion (Møller, 2001). There are several commercial brands of decanter centrifuges in use today for digestate separation, with similar performances. In Figure 11 the detailed set-up of a decanter centrifuge is shown. The digestate enters the centrifuge via a central inlet and is fed into the centre of the centrifuge. The particles are separated by the centrifugal force. The separation performance depends on the particle size and shape, the difference in density between particles and fluid, as well on the fluid viscosity. The separated particles accumulate on the walls

of the cylinder and are transported and further compressed by a screw. At the final outlet (right-hand side in Figure 11) the solid fraction leaves the decanter. On the left side, the clarified liquid leaves the decanter. Energy consumption is rather high (3–5 kWh/m³, Fuchs and Drosig, 2010), compared with other solid–liquid separation technologies.

In Tables 5 and 6 technology test results of the GEA Westfalia decanter centrifuge are shown (DANETV, 2010). The test was made on 5 batches of minimum four hours each, with a fixed start and end time for each batch.

For each batch the weight or volume of input digested biomass, liquid output fraction and solid output fraction were measured and concentrations of solids and nutrients were determined by analysing representative samples of the inlet flow and the two outlet flows. During the 5 batch tests, the decanter centrifuge treated 283 m³ of digestate, corresponding to an average capacity of 13.72 m³ biomass treated per hour.

A specific example of the effect of digestate separation by decanter centrifuge is given in Table 7.

Table 5: Digestate separation by decanter centrifuge – average content of total solids, ashes, volatile solids, suspended solids and pH over 5 batches (adapted after DANETV, 2010)

Fraction	TS [%]	Ash [%]	VS* [%]	Suspended solids [g/L]	pH [-]
Input digestate	4.85	1.46	3.39	35.0	7.64
Liquid fraction	2.31	0.82	1.49	8.4	7.94
Solid fraction	27.66	6.46	21.20	Not relevant	8.12

* Values for volatile solids are not measured but calculated as the difference between total solids and ashes.

Table 6: Digestate separation by decanter centrifuge – average concentrations of nutrients over 5 batches (adapted after DANETV, 2010)

Fraction	TN [g kg ⁻¹]	NH ₄ -N [g kg ⁻¹]	Org N* [g kg ⁻¹]	TP [g kg ⁻¹]	Total sulphur [g kg ⁻¹]
Input digestate	4.08	2.87	1.21	0.94	0.42
Liquid fraction	3.49	2.63	0.86	0.31	0.29
Solid fraction	8.15	4.50	3.65	6.52	1.56

* Values for organic nitrogen are not measured but calculated as the difference between total-N and ammonium-N.

Table 7: Separation of digestate (TS = 2.8%) by decanter centrifuge. (Adapted after Jørgensen, 2009)

Specification	Digestate	Solid fraction	Liquid fraction
Quantity [kg]	1,000	80	920
TS [kg]	28	24	4
Water [kg]	972	56	916
TN [kg]	5	1.25	3.75
NH ₄ -N [kg]	4	0.3	3.7
TP [kg]	0.9	0.7	0.2
K [kg]	2.8	0.2	2.6

the next step material is pressed between two filter belts. Subsequently varying mechanical forces are applied so that the filter cake is dewatered further. Finally the dewatered cake is removed from the filter belt by a mechanical device. The filter belt is then cleaned by spray-

5.3 Belt filters

Belt filters can be used for digestate processing. There exist two types: belt filter presses and vacuum belt filters. A belt filter press can be seen in Figure 12. It consists of a closed loop of textile belt wound around cylinders. Digestate is applied continuously at the start of the belt filter. The first pre-dewatering occurs by gravitation. In

washing (often filtrate is used for washing) and is then used again for filtration.

The second option is a vacuum belt filter, as illustrated in Figure 13. In vacuum belt filters, digestate is applied onto a filter belt and vacuum is applied to its underside, whereby water is sucked through the filter and the filter cake remains on the belt.

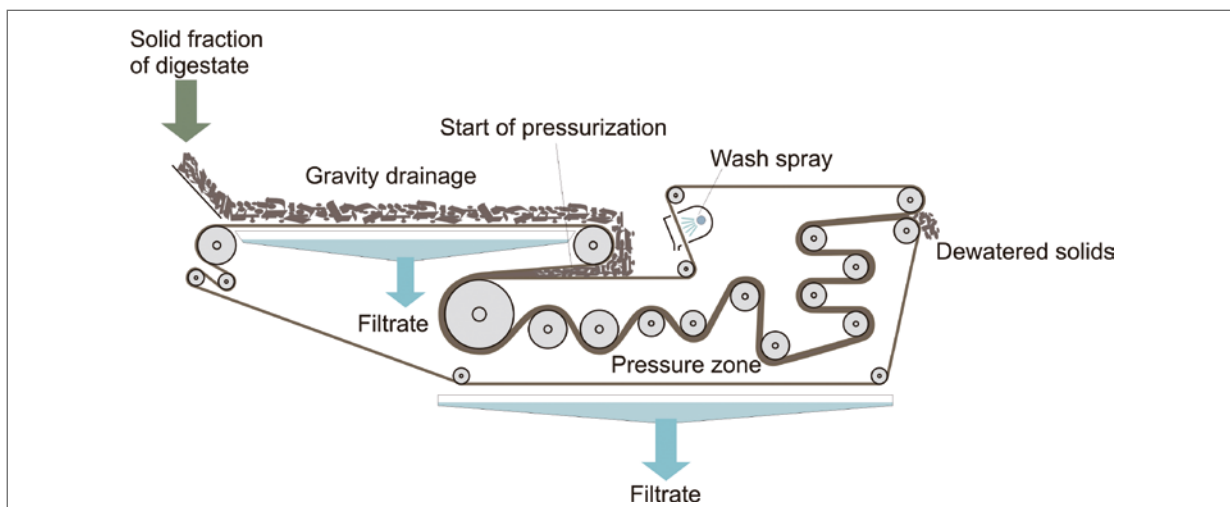


Figure 12: Scheme of a belt filter press (Source: Fuchs and Drosig, 2010)

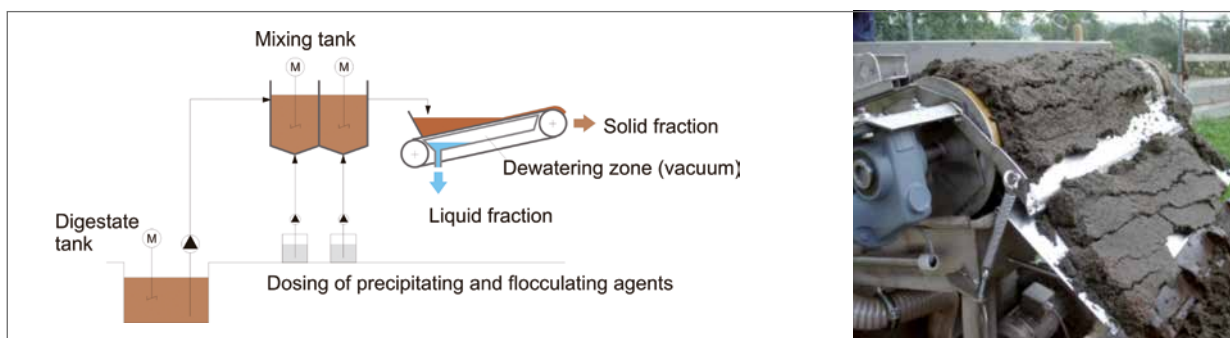


Figure 13: Vacuum belt filter (Source: Fuchs and Drosig, 2010)

For digestate processing on belt filters, the addition of precipitating and flocculating agents (see section 5.5.1) is indispensable in order to improve separation efficiency. Factors that influence separation efficiency are characteristics of digestate, amount and type of precipitating and flocculating agents added and mesh size of the filter. The advantages of the belt filter are higher separation efficiency compared to the screw press and lower energy demand ($1.5\text{--}2\text{ kWh/m}^3$) compared to a decanter centrifuge. A drawback is, however, the high amount of precipitating/flocculating agents needed, which can be two to three times higher than what is needed for a decanter centrifuge.

5.4 Discontinuous centrifuge

Apart from decanter centrifuges, also discontinuous centrifuges (see Figure 14) can be used for digestate processing. These centrifuges are operated batch wise, which means that in consecutive cycles each time a certain amount of digestate is centrifuged. In these cycles whole digestate is fed to the centrifuge continuously. The supernatant (liquid fraction) also leaves the centrifuge continuously whereas the separated solid fraction remains in the centrifuge and is removed at the end of each cycle. Subsequently a new cycle is started.

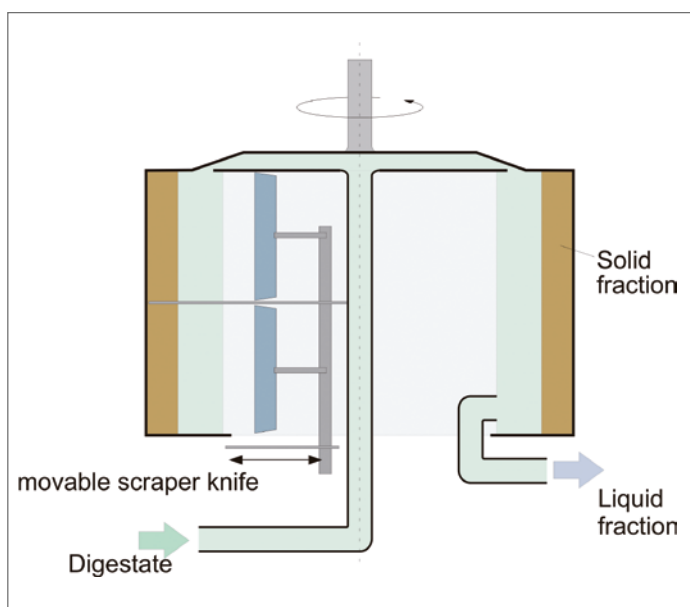


Figure 14: Scheme of a discontinuous centrifuge (Source: Fuchs and Drosig, 2010)

Energy demand and efficiency are comparable with decanter centrifuges, however, a slightly higher total solids concentration of the solid fraction can be achieved. Although a discontinuous centrifuge can be operated fully automated, it can show higher risks of process failure due to batch wise operation. In practice, discontinuous centrifugation of digestate is not widespread, so few practical experiences are available. Data for the centrifugation of digestate from thin stillage (a by-product from bioethanol production) can be found in Meixner et al. (2015).

5.5 Enhanced solids removal

The following solids removal processes differ from the main separation processes, as described above, where the majority of the solids are removed. They are applied to polish the liquid fraction by a subsequent solids removal step. The necessity for enhanced solids removal depends on the overall digestate processing concept. Enhanced solids removal is indispensable if the liquid fraction is, for example, treated in a membrane process. Another issue is if for example a high level of phosphorus removal is demanded.

5.5.1 Precipitation/Flocculation

Precipitating agents and flocculants are often added to digestate in order to increase separation efficiency of for instance suspended solids or phosphorus in practically any solid–liquid separation process. In addition, a separate precipitation/sedimentation step after the main solid–liquid separation can also be considered. In general, although phosphorus is concentrated in the solid fraction in any solid–liquid separation process (see Figure 6), the separation efficiency can be increased drastically ($> 95\%$ total separation) by adding precipitating/flocculating agents (Meixner et al., 2015).

The principle of flocculation can be seen in Figure 15 where small suspended particles in digestate are often negatively charged and therefore remain in solution. Here precipitating agents and flocculants come into play. Positively charged ions aggregate around particles and this process leads to the formation of larger particles (coagulation). As a consequence, larger particles formed by flocculation can be separated more easily. Organic

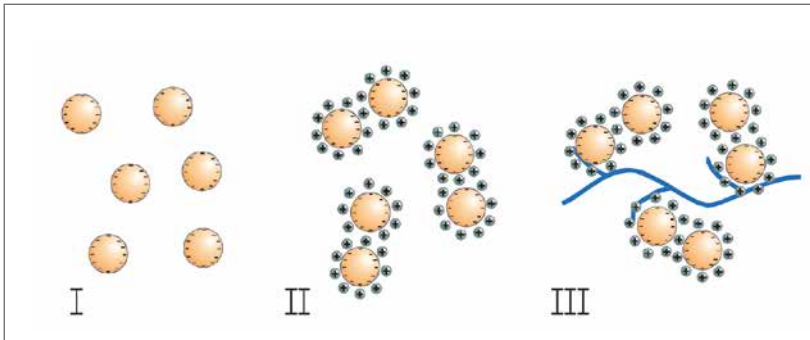


Figure 15: Simplified illustration of the different phases in flocculation I: suspended colloids, II: destabilisation of colloids by flocculation agents, III: linkage and increase of flocks by flocculation agents (Source: Fuchs and Drosig, 2010)

polymers (e.g. acrylamide) may be added to increase the linkage of the flocks and therefore flocculation performance.

Common precipitating agents are aluminium sulphate ($\text{Al}_2(\text{SO}_4)_3$), ferric chloride (FeCl_3), ferric sulphate ($\text{Fe}_2(\text{SO}_4)_3$), and lime ($\text{Ca}(\text{OH})_2$). The dosage of the precipitating agents or flocculants can either be done separately in mixing tanks prior to solid–liquid separation or in-line, which means that they are injected directly into the transfer pipes, where mixing systems are integrated to provide sufficient turbulence.

Polymers are widely used in wastewater treatment plants during dewatering of sludge, which is then applied on farmland. Some agricultural co-digestion plants have also applied polymers, but the use appears to be limited to a few plants. However, there is still insufficient documentation with respect to the potential toxicity and ultimate fate of certain polymers when applied to farmland. Extensive use of polymers in the wastewater treatment sector has not led to reporting of negative impacts on the environment, however detailed controlled studies have not been undertaken. Hence, the precautionary principle prevails in many cases

and can be a barrier towards acceptance of polymer-containing digestate products (Henriksson, 2010).

The uncertainty about polymer usage has led to regulatory restrictions. For instance in Sweden the quality standards applied to digestate used as fertiliser (SPCR120) do not allow for addition of polymers due to insufficient knowledge about their environmental impact when spread on soils. In Germany this aspect has been taken into consideration in the amendment to the Fertilizer Regulation (DüMV) from November 2012 (BGK

e.V., 2012). For polymers that do not degrade in the soil, a transitional period until 31.12.2013 was set. Meanwhile, for a better transition to alternative products this period was extended to 31.12.2016. In addition, the required degradation rate for permitted polymers was more exactly specified: >20% degradation within 2 years.

5.5.2 Flotation

Flotation is a process that is rarely applied in digestate processing due to the additional costs. The principle of flotation is that the lifting force of suspended particles is increased by the attachment of small gas bubbles to them. Consequently, they are lifted to the surface where they produce a floating layer that can then be harvested. In general, flotation equipment occupies 30–50% less

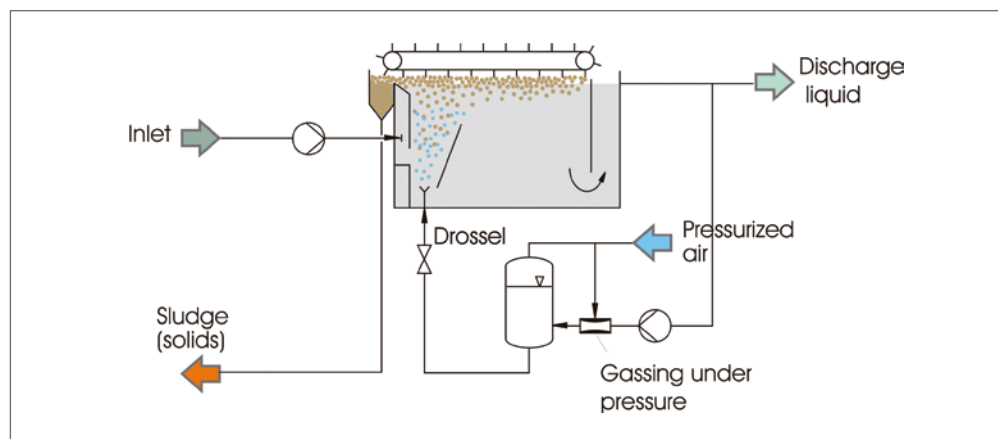


Figure 16: Scheme of flotation (Source: Fuchs and Drosig, 2010)

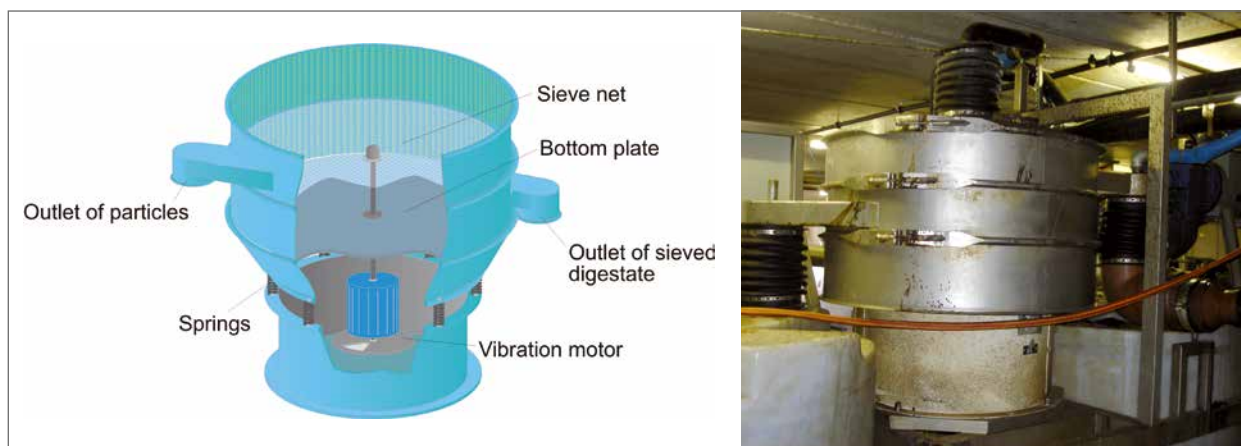


Figure 17: Vibrating screen (Source: Fuchs and Drogg, 2010)

space than standard sedimentation equipment as the lifting force is generally much higher than the sedimentation force. Two different flotation processes exist: flotation by decompression or by gassing. In the first process, pressurised water saturated with air is injected into the flotation chamber (see Figure 16). The sudden reduction in pressure leads to the formation of microbubbles. In the second process air is directly injected via special nozzles that produce small air bubbles. The first process produces smaller bubbles and is more commonly applied in wastewater treatment. For any efficient flotation process the addition of flotation agents is necessary, which are comparable to precipitating/flocculating agents (see section 5.5.1). Apart from increasing flock size and volume, also the ability of the air bubbles to attach to the flocks is enhanced.

5.5.3 Screens and filters

Vibrating screens (see Figure 17) and vibrating curved screens (see Figure 18) are commonly applied in digestate processing. The liquid fraction of the digestate is applied on the screen and any solid material (screenings) remain on top of the screen (and are con-

stantly removed), whereas the liquid passes through. In order to prevent rapid clogging of the screens, they are operated under vibration. Typical mesh sizes are 150–250 μm for vibrating screens and 100–300 μm for vibrating curved sieves. However, too small mesh sizes can lead to rapid clogging. Apart from screens, security filters are also used which have the function of retaining larger particles, e.g. prior to a membrane system, which have accidentally passed previous solid–liquid separation steps. As they have a different function than the screens, the retained material is not constantly removed.

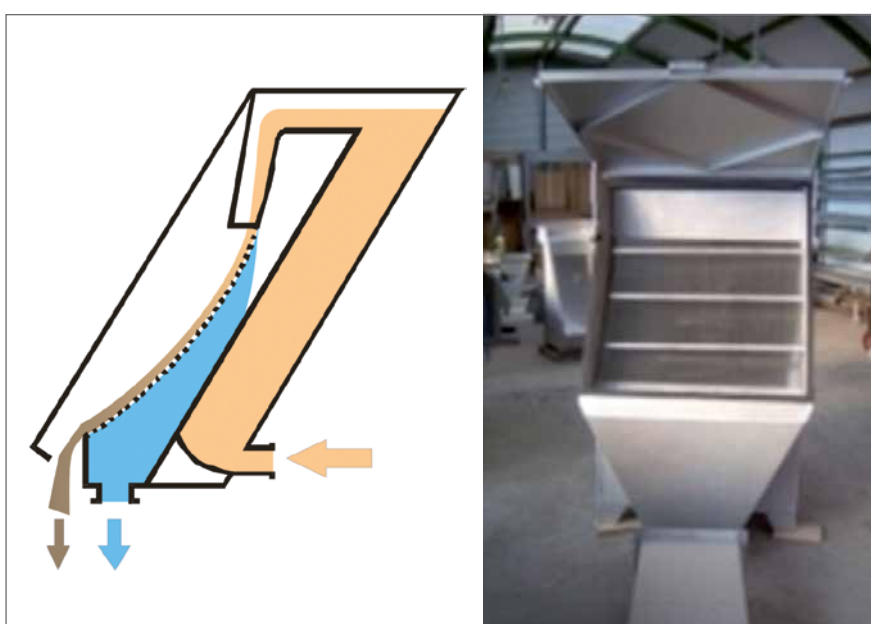


Figure 18: Vibrating curved screen (Source: Fuchs and Drogg, 2010)

6 Processing of the solid fraction

The solid fraction which accumulates in solid–liquid separation shows TS concentrations in the range of 20–30%. This fraction is partially stabilised so that appropriate storage and direct application as biofertiliser or soil improver on agricultural land is facilitated. Nevertheless, this fraction still contains biodegradable material, in other words microbial activity can still happen and odour emissions can occur. If it is desired to obtain a stable and marketable biofertiliser product, further processing is necessary, which can be composting, drying or another form of stabilisation.

6.1 Composting

In the composting process microbes degrade and transform the organic material under aerobic conditions to compost, which is stabilised organic matter, containing humic substances. Compost is an ideal biofertiliser as it slowly releases nutrients and shows good performance as soil improver. However, as the solid fraction from digestate is wet and already partially degraded, the addition of bulking material (such as woodchips) is necessary for a stable composting process to occur. The bulking material helps air to enter the compost heap and aerobic conditions are more easily maintained. Depending on the local availability of bulking material, it may be advantageous to do the composting at a centralised composting facility (examples shown in Figure 19). A special application of composting is vermiculture using

earthworms. In general, composting of the solid fraction increases the concentration of nutrients in the solid fraction, but also may result in nitrogen loss.

6.2 Drying

Processes for drying of the solid fraction of digestate aim at stabilising the product as well as reducing its total mass and increasing the nutrient concentration. If electrical power is produced at the biogas plant, for example in a CHP unit, the excess heat can be utilised for drying. Apart from drying the solid fraction it is also possible to dry the whole digestate (without prior solid–liquid separation). However, as excess heat is not sufficient to dry all of the digestate, drying of the solid fraction is more frequently applied.

The principles of the drying process are illustrated in Figure 20. The following techniques can be applied in order to dry the whole digestate or the solid fraction: belt dryer, drum dryer, feed-and-turn dryer, and fluidised bed dryer. For digestate applications, the belt dryer (see Figure 21) is more commonly applied. As an alternative, solar drying systems are applied for digestate (see Figure 22). These systems can be supported by excess heat from a CHP unit. As the exhaust of the digestate dryers contains dust, ammonia, and other volatile substances (e.g. volatile acids), exhaust gas cleaning systems have to be applied in order to reduce emissions. Such systems contain a dust filter as well as washer/scrubber units.



Figure 19: Composting facilities in an open (left) or closed (right) environment (© Erwin Binner, Institute of Waste Management, University of Natural Resources and Life Sciences, Vienna)

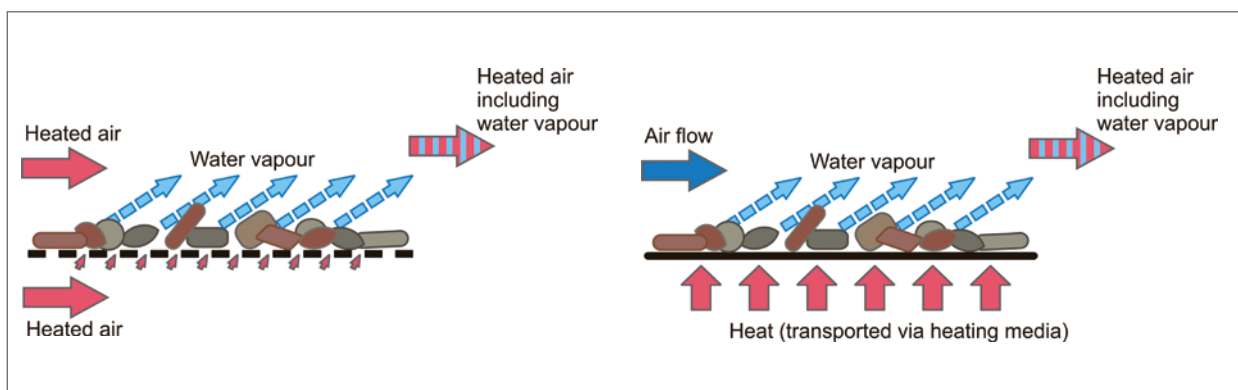


Figure 20: Principles of drying processes, drying by convection (left) and drying by contact (right) (Source: Fuchs and Drosig, 2010)

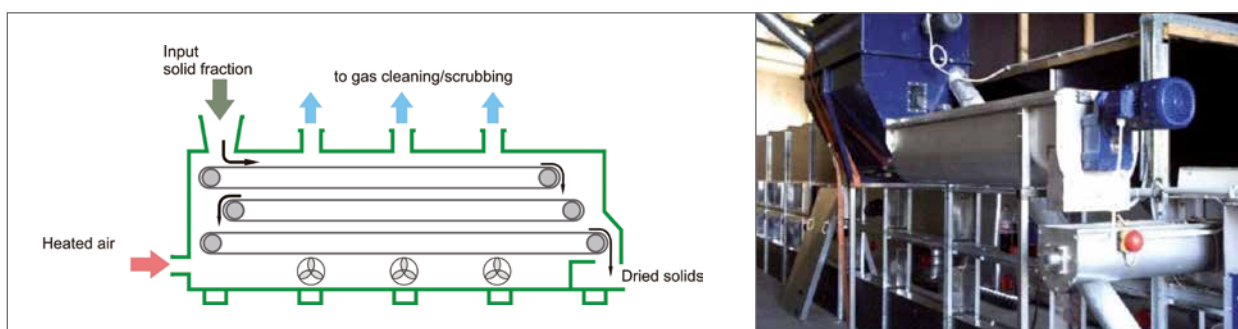


Figure 21: Scheme of a belt dryer (Source: Fuchs and Drosig, 2010)

7 Processing of the liquid fraction of digestate

After solid–liquid separation the liquid fraction still contains considerable amounts of suspended solids and nutrients. The exact concentrations depend on the substrate, as well as the separation technology, and any applied enhanced nutrient removal. The liquid fraction obtained by solid–liquid separation will not meet the environmental standards for direct discharge to receiving streams. Part of the liquid fraction can be used during mashing of the substrate going into the AD process. This amount depends on one hand on the water content of the substrate, and on the other hand on the concentration effect of ammonia nitrogen and salts in the process, which could lead to inhibition in the digester. In any case, at least partial reutilisation as process water is recommended as this reduces the treatment effort for the liquid fraction. In countries where composting facilities are located next to biogas plants, the liquid fraction is

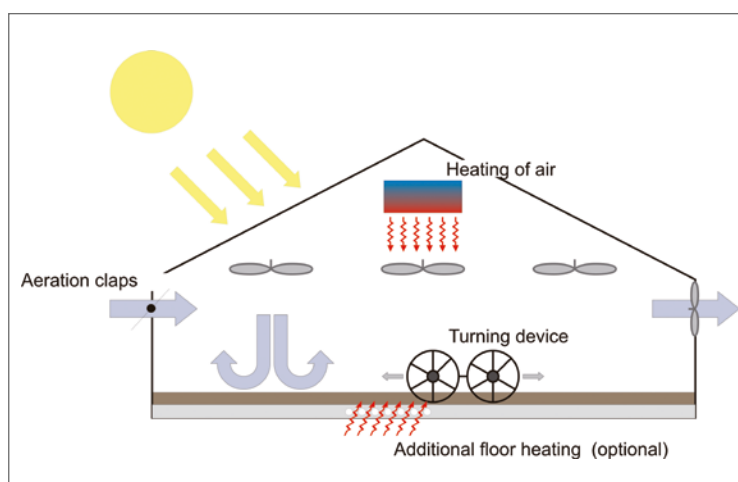


Figure 22: Solar drying of digestate (Source: Fuchs and Drosig, 2010)

The dried digestate can be marketed as it is or can be pelletised for better marketability. Such products are already available as biofertilisers on horticulture or gardening markets, for example in Germany. The material can also be used in nurseries or for special cultivation systems, such as mushroom production.

used to moisturise compost heaps. In such cases, the reduction of the ammonia concentration is recommended in order to reduce ammonia emissions.

7.1 Nitrogen recovery

7.1.1 Ammonia stripping

Gas stripping is a process whereby volatile substances are removed from a liquid by gas flow through the liquid. In digestate processing the aim is to remove/recover nitrogen, in the form of ammonia, from the liquid. The volatility of ammonia in an aqueous solution can be enhanced by increasing the temperature and the pH (as shown in Figure 23). So in digestate processing, excess heat can be used for heating up the digestate and the pH can be increased by degassing to remove CO_2 or by the addition of alkali.

For ammonia stripping in digestate, mainly two processes are applied: air stripping and vapour stripping. In air stripping (see Figure 24) heated digestate enters a stripping column. As a pre-treatment CO_2 is removed, this lowers the buffer capacity. In a subsequent stripping

column filled with packing material to increase surface area available for the ammonia mass transfer, ammonia is transferred from the liquid digestate to the stripping gas stream. After this, ammonia is recovered from the gas phase by a sulphuric acid scrubber, where a valuable commercial-grade ammonium sulphate fertiliser is produced. The cleaned gas can be reused in the stripping column. For vapour stripping, a much higher temperature is needed to produce the vapour. The setup can be comparable to Figure 24, only that there is no need for a final scrubber, as the ammonia can be directly condensed together with the vapour to produce ammonia-water with a concentration of up to 25–35% ammonia.

A big problem for the stripping of digestate is the usage of packed columns, because residual solids can clog the column. As a consequence, efficient solid-liquid separation is necessary beforehand. In addition, a high maintenance and cleaning effort may be necessary. As an alternative, promising results have been obtained with a stripping method performed in simple stirred tank reactors (see Figure 25). A first large-scale facility using such a type of process principle

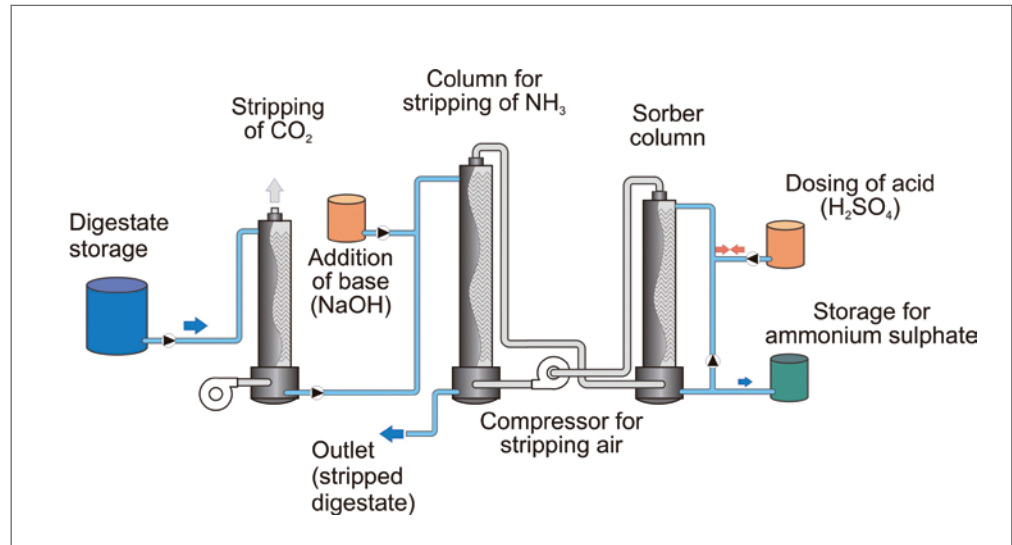


Figure 24: Ammonia air stripping including CO_2 removal and ammonia recovery by sulphuric acid scrubbers (Source: Fuchs and Drosig, 2010)

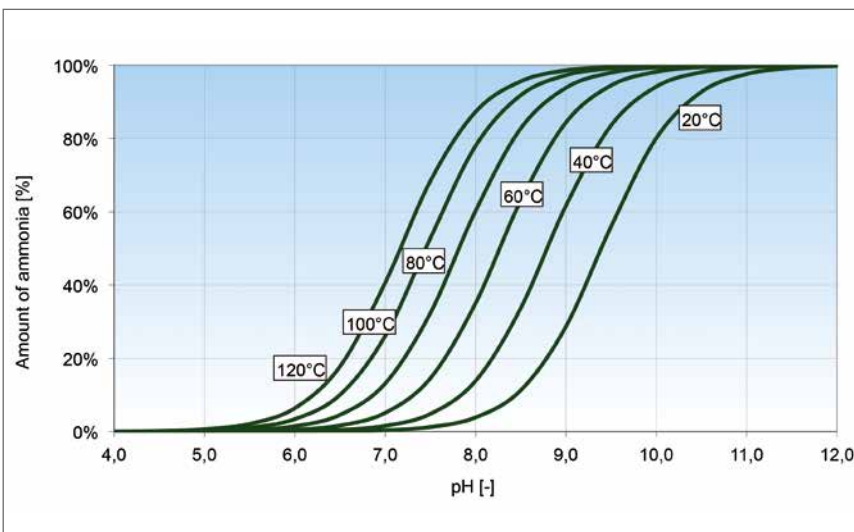


Figure 23: Dependence of the volatility of ammonia in water on temperature and pH (Source: Fuchs and Drosig, 2010)

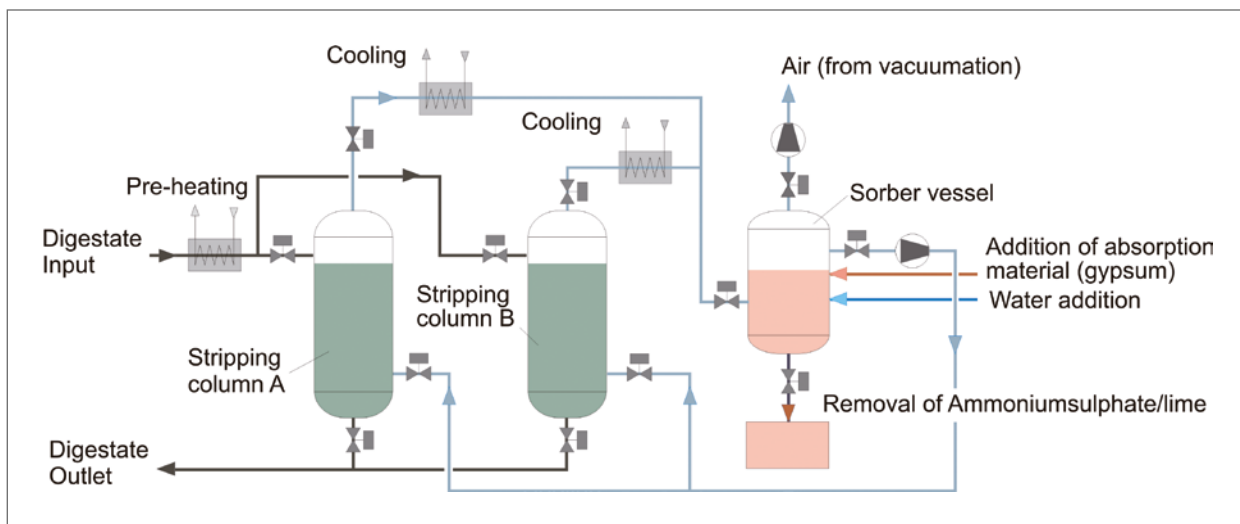


Figure 25: Details of a simplified in-vessel stripping process without stripping columns (Bauermeister et al., 2009)

is already in operation (Bauermeister et al., 2009). To what extent the above-mentioned method can meet the targeted benefits will emerge from further practice.

The big advantage of ammonia stripping is that a standardised, pure nitrogen fertiliser product can be recovered. In addition, such a fertiliser liquid can be used to enrich other digestate fractions in digestate processing to a standardised nitrogen concentration, and this can increase their marketability.

7.1.2 Ion exchange

The principle of ion exchange processes can be seen in Figure 26. The material in ion exchangers are mainly resins which have charged side chains. The charged ions (e.g. Na^+) which are bound to these side chains of the resin can be replaced by other equally charged ions (e.g. NH_4^+ in the case of digestate). By doing so, their concentration in the liquid is reduced. Such ion exchange resins contain high amount of cavities, so that a high contact and exchange area is available. As ions are replaced stoichiometrically, after a certain time the ion exchange resin is fully loaded and has to be regenerated by for example sodium chloride, NaCl . Then a new cycle can be started.

In practice, ion exchange is marginally applied in digestate processing. One of the reasons for this is that for usage of ion exchange the digestate has to be free of any

particles, which is only the case after membrane processes. So, for example, ion exchange is applied for final ammonium removal after two steps of reverse osmosis in a membrane purification concept (see section 7.2.1).

7.1.3 Struvite precipitation

Ammonium and phosphate can be removed from the digestate by struvite precipitation, also known as MAP (magnesium ammonia phosphate) precipitation. The

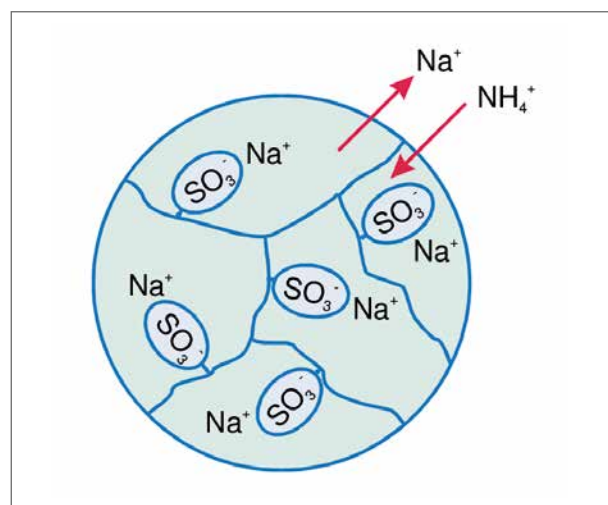


Figure 26: Principle of ion exchange resins (Source: Fuchs and Drosig, 2010)

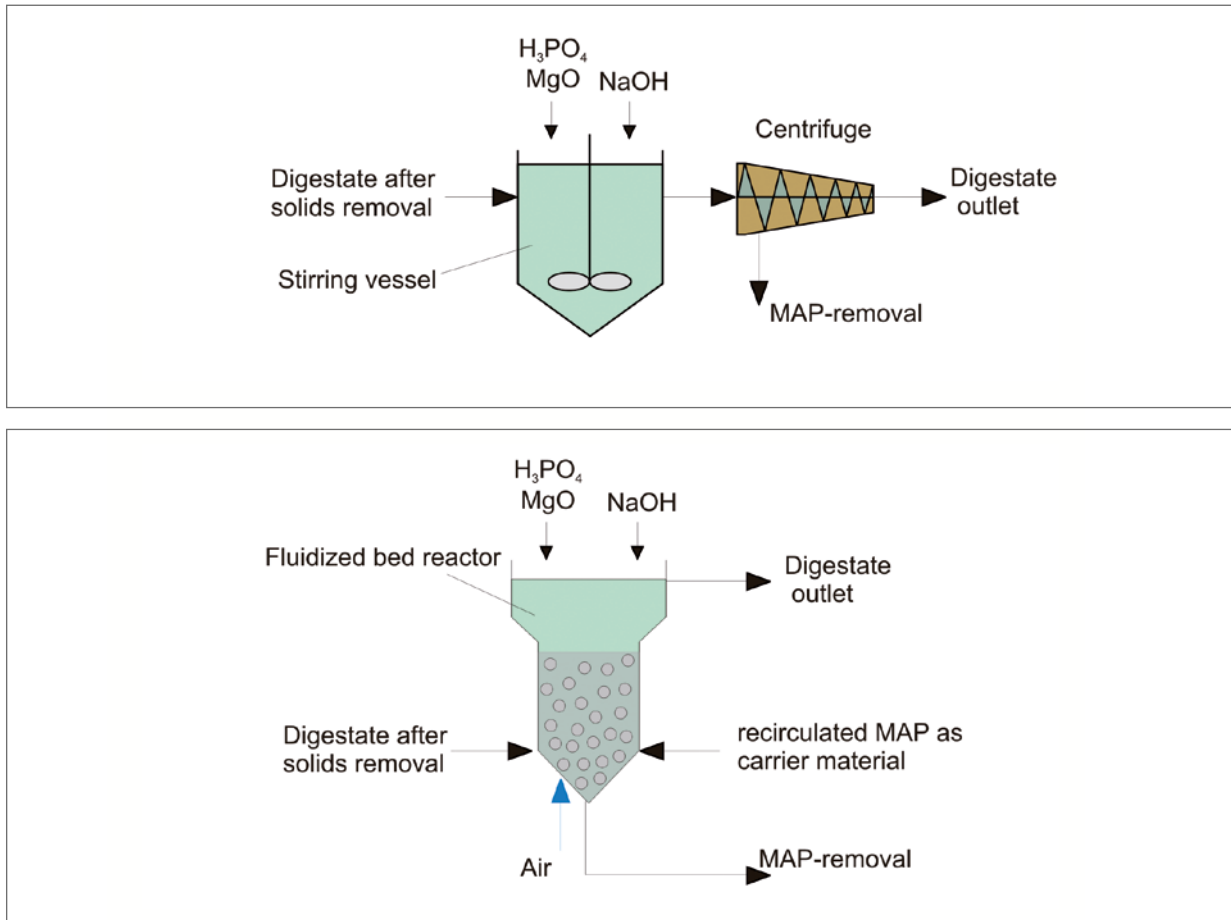
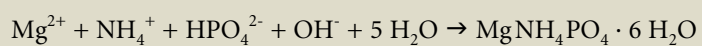


Figure 27: Possible process options for struvite precipitation (adapted after Lehmkuhl, 1990)

reaction is described by the following equation:



In order to achieve best nutrient recovery performance in practice, magnesium is added in excess so that nutrient concentrations are approximately 1.3:1:0.9 for Mg:N:P. As ammonia is almost always in excess in digestate, magnesium oxide and phosphoric acid are added to the digestate. In addition, pH is slightly increased to 8.5–9.0. The resulting struvite is a good fertiliser as N, P, and Mg are valuable plant nutrients. As illustrated in Figure 27, the chemicals can be added either in a first step with subsequent separation by centrifugation, or chemical addition and sedimentation of the struvite crystals occur in the same vessel.

The main disadvantage of struvite precipitation is that a large amount of chemicals are

needed, and this translates into high operational costs. An alternative process can be to recover the chemicals, as struvite releases ammonium and water after heating to well above 100°C. The resulting magnesium hydrogen phosphate can then be reused for precipitating ammonium.

7.2 Nutrient concentration and water purification

7.2.1 Membrane technologies

The principle of membrane processes is shown in Figure 28. It is a physical separation process where the

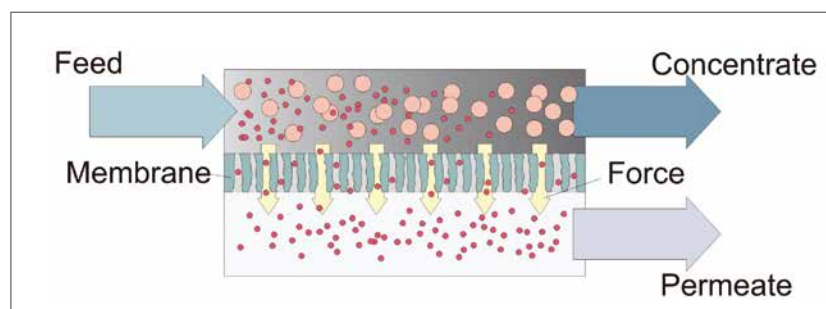


Figure 28: Principle of membrane separation (Source: Fuchs and Drosig, 2010)

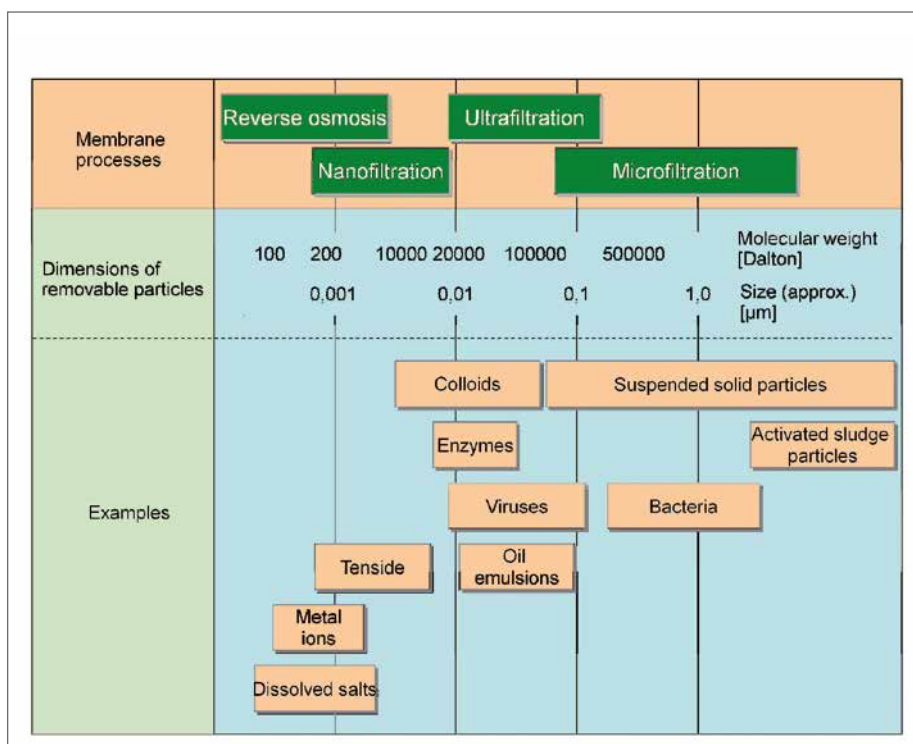


Figure 29: Overview of membrane separation processes (Source: Fuchs and Drogg, 2010)

liquid to be purified (feed) passes through a membrane. Depending on the pore size of the membrane and the trans-membrane pressure, some particles are retained by the membrane and remain in the concentrate. Other particles and the partially purified water, the permeate, pass through the membrane.

are not able to enter the pores of the membrane. Alternatively, solution-diffusion membranes can be used. Here the principle of separation is the ability of substances to dissolve in the membrane material and consequently be separated by differences in their diffusion velocity. Either polymer membranes or ceramic membranes are used.

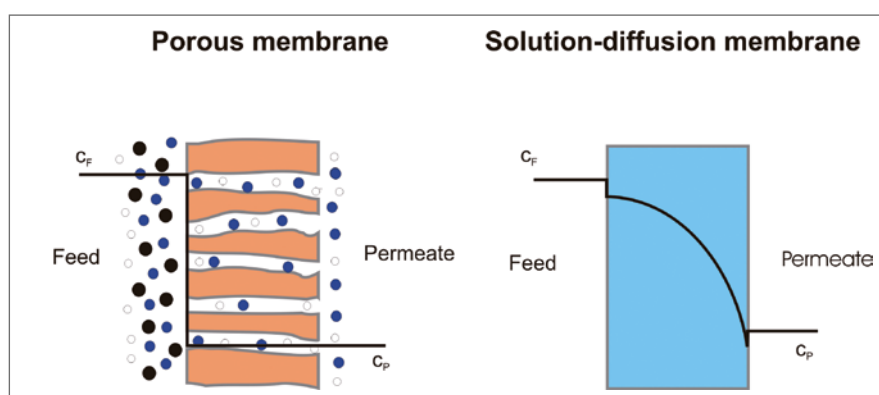


Figure 30: Different types of membranes: porous membranes (left) and solution-diffusion membranes. (c_F stands for the feed concentration of the substance, which is separated in the process and c_P for its concentration in the permeate) (Source: Fuchs and Drogg, 2010)

Membrane processes are categorised depending on their pore sizes (see Figure 29). For microfiltration, depending on the corresponding membrane, particles down to diameters of $0.1 \mu\text{m}$ can be separated, whereas ultrafiltration is able to separate colloids even down to diameters below $0.01 \mu\text{m}$. With nanofiltration and reverse osmosis, even dissolved salts (ions) can be separated from pure water.

In general, there exist two types of membrane (Figure 30). Porous membranes are applied where the particles are retained by size-exclusion, because they

The latter are only applied in micro- and ultrafiltration and have the advantage that they are more robust and can withstand harsh chemical cleaning.

Membrane purification is a complex process consisting of several steps (see Figure 31). First, solid-liquid separation is applied. Subsequently the liquid fraction of digestate is subject to enhanced solids removal (see section 5.5). This is a crucial stage in membrane purification processes due to the possibility of membrane fouling.

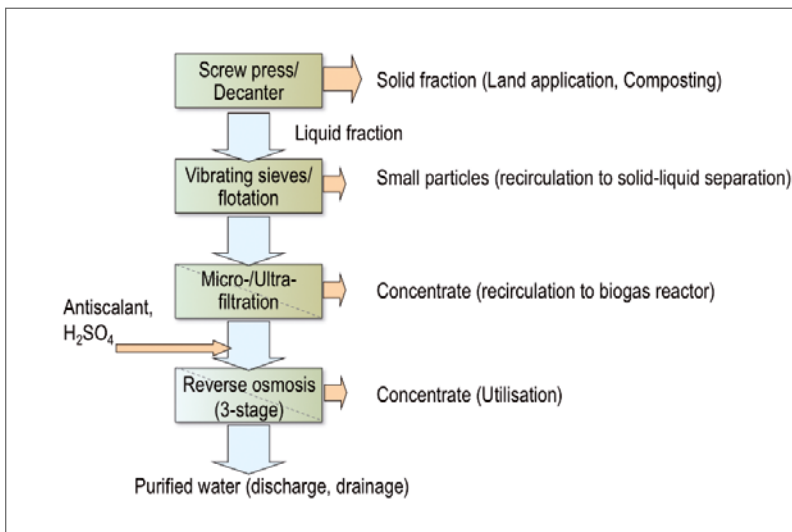


Figure 31: Typical process steps for digestate processing by membrane purification (Source: Fuchs and Drogg, 2010)

Parameter	Unit	Two-step reverse osmosis	Three-step reverse osmosis
TS	[mg/L]	0	0
COD	[mg/L]	50 – 60	< 5
NH ₄ -N	[mg/L]	300 – 320	–
TN	[mg/L]	320 – 340	3.5
TP	[mg/L]	53	< 0.05

Table 8: Examples of permeate quality after a 2-step reverse osmosis (Schulze und Block, 2005) and a 3-step reverse osmosis (Brüß, 2009)

Therefore, decanter centrifuges are usually used in the first solid–liquid separation step, and often precipitating agents are added enabling increased solids removal. The next step is ultrafiltration and finally reverse osmosis is

used for removal of ammonia and COD (organic matter expressed as the equivalent chemical oxygen demand). Normally, three steps of reverse osmosis are needed to reach discharge levels for ammonia. The permeate quality, depending on 2- or 3-step reverse osmosis, is shown in Table 8. As an alternative, the last reverse osmosis step can be replaced by ion exchange.

A drawback of such membrane purification processes is that only a limited amount of the digestate will be purified water, about 50% of the digestate is accumulated as by-products. The following fractions accumulate in the process: solid fraction, ultrafiltration retentate, reverse osmosis concentrate. In order to reduce the amounts, the ultrafiltration retentate is often recycled into the biogas plant and/or the solid–liquid separation step. Membrane purification is quite expensive and requires a considerable amount of energy.

7.2.2 Evaporation

The evaporation of digestate is only interesting for biogas plants where excess heat is available in sufficient amounts, or where excess heat from other sources near the biogas plant can be used. As many biogas plants are located in rural areas remotely from

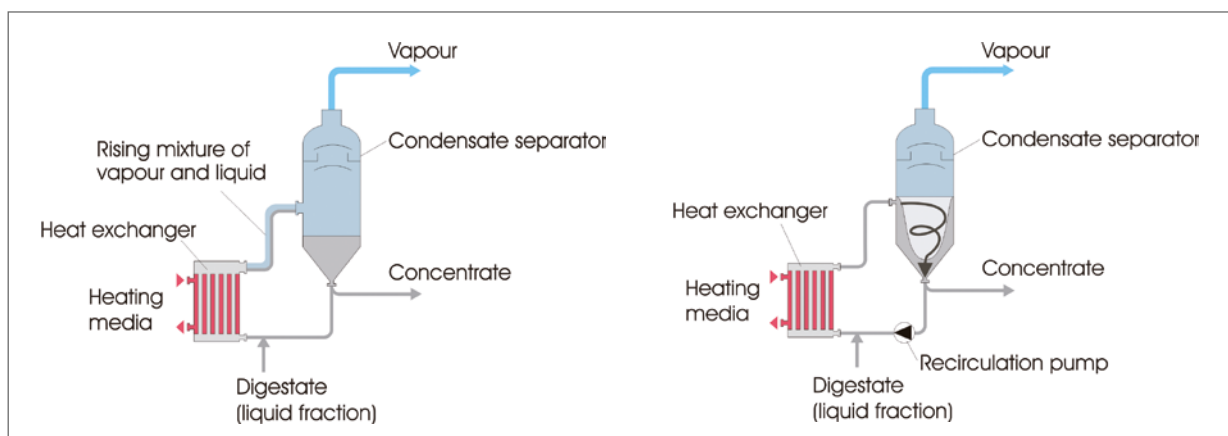


Figure 32: Forced circulation evaporator (left) and natural circulation evaporator (right) (Source: Fuchs and Drogg, 2010)

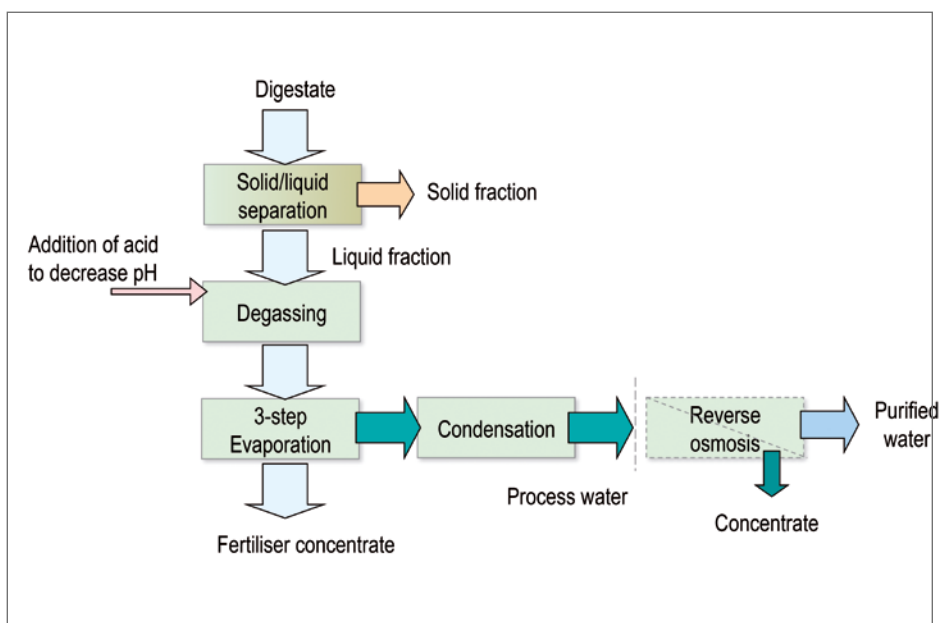


Figure 33: Different process steps in digestate evaporation (Source: Fuchs and Drogg, 2010)

other industries, heat utilisation can be problematic. In Germany biogas plants receive extra funding for heat utilisation, which is an incentive for thermal digestate processing, and consequently, a handful of evaporation plants have been constructed.

As prevailing technologies in digestate evaporation, forced circulation evaporators (see Figure 32) are used, alternatively also natural recirculation evaporators (see Figure 32) are applied. In these evaporation processes, digestate is heated above evaporation temperature in a heat exchanger and then held in the evaporation vessel. In forced circulation evaporators a pump is applied to achieve circulation of the digestate, whereas in natural circulation evaporators, circulation takes place automatically as the vapour digestate mixture rises into the evaporation vessel. The reason why these two type of evaporators are applied is that they are relatively robust with regard to the solids content in the digestate.

In a typical digestate evaporation process (see Figure 33) the

solid fraction is first removed. This can be done for example by combining a screw press and a vibrating screen. In such a process especially the fibres are removed in order to reduce possible clogging of the evaporators. As a next step sulphuric acid is added and CO_2 is stripped. By addition of acid, pH is reduced to typically 4.5 and nitrogen is entirely in the form of NH_4^+ . By these means practically

all nitrogen remains in the concentrate during the evaporation process.

After the acidification step, digestate is concentrated via a 3-step low-pressure evaporation system, as illustrated in Figure 34. As low pressure is applied, excess low-grade heat at 90°C can be used for evaporation. The vapour is condensed in the process, and as it contains low amounts of ammonia and volatile acids (see Table 9) it cannot be directly discharged. Therefore, it is normally used as process water in the biogas plant. Alternatively it can be discharged to a wastewater treatment plant. If direct discharge limits have to be met, post treatment like reverse osmosis or ion exchange is necessary. If the excess heat from a CHP unit is used, typically a volume reduc-

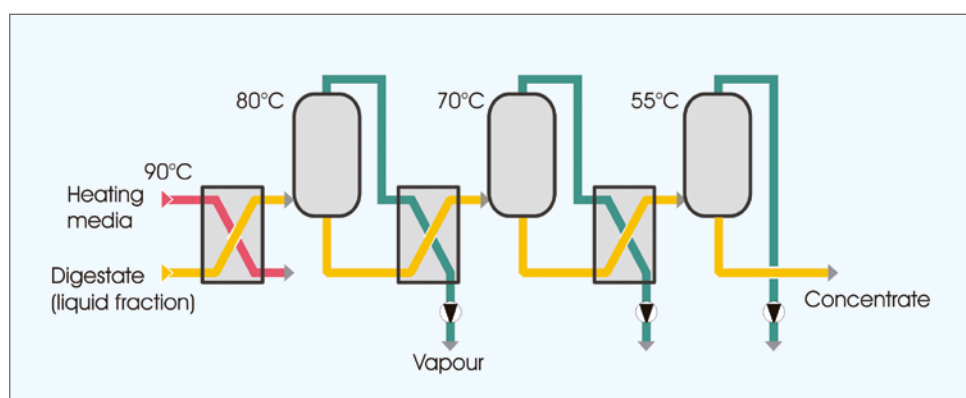


Figure 34: Multistage evaporation system (Source: Fuchs and Drogg, 2010)

Table 9: Examples of evaporation performance data (Heidler, 2005 – modified according to personal communication)

Digestate	TS [%]	VS [%]	TN [mg/kg]	PO ₄ -P [mg/kg]	COD [mg/kg]
Inflow	3.1	1.7	3,100	300	45,000
Concentrate*	10 – 12 (max. 15)	7.5 – 9	8,000 – 10,000	800 – 1200	95,000 – 120,000
Condensate	0.05	0.05	30 – 50	0	< 1000

* depending on the concentration factor

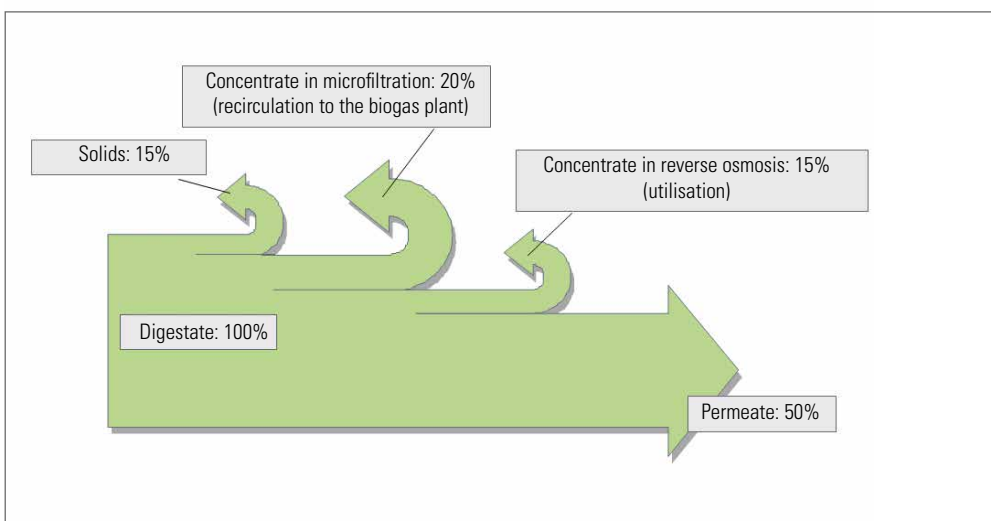


Figure 35: Side streams and residues in membrane purification of digestate (Fuchs and Drosig, 2010)

tion of 50% of the digestate can be obtained. Based on general experience, a thermal energy demand of about 300–350 kWh_{th} is needed per ton of water evaporated. Typical performance data for an evaporation process are provided in Table 9.

7.2.3 Residue management in nutrient recovery processes

Another very important issue, especially in complex and large-scale nutrient recovery applications, is the accumulation of by-products through digestate processing. With the example of a membrane treatment process

(see Figure 35), it is shown that only approximately 50% of the treated digestate will become purified water. The rest will accumulate as by-products/residues in the process. For these fractions, economically viable utilisation concepts have to be established. If additional treatment costs occur, this will decisively affect economics of digestate processing. However, these fractions normally contain higher nutrient concentrations (e.g. concentrate from reverse osmosis), so their market value should be high. Nevertheless, further treatment can be necessary for commercialisation.

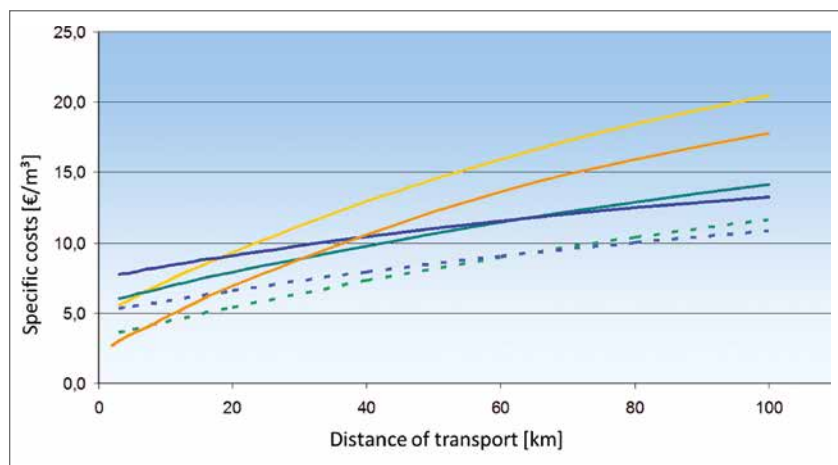
8. Economics of digestate processing for nutrient recovery

One very important criterion when deciding which digestate processing technology to use is cost. This is a quite complex issue because both the quality of the digestate product and local conditions have a strong influence on the actual economic performance. There are several studies available in literature that discuss costs of digestate processing (Pietsch and Köttner, 2007; Schulze and Block, 2005; Bauermeister et al., 2009), although only a few mainstream technologies are compared.

In the following, the primary driver for investing in digestate processing technology is discussed; this is the increasing digestate land application costs with distance from the biogas plant. After that, digestate processing costs are given for a model biogas plant.

8.1 Digestate land application costs

From an economic point of view investment into digestate processing technologies is mainly driven by increasing digestate land application costs. The costs for different digestate transportation and application approaches are given in Figure 36. It is clear that specific digestate transportation and land application costs increase considerably with transportation distance. It can also be seen that classical digestate spreading with manure spreading vehicles is cheapest at shorter distances. When distances become larger, a combination of digestate transport with trucks and local spreading with spreading vehicles is cheapest. So although digestate application costs will also vary depending on the local conditions, Figure 36 can give a first rough estimation which transportation distance can justify which digestate processing (and application) costs.



8.2. Detailed cost analysis of 6 digestate processing scenarios for a model biogas plant

In a study conducted by KTBL (KTBL, 2008), a model biogas plant (50 % manure, 50 % corn silage) with an electric capacity of 500 kW_{el} and an annual digestate production of 30,000 m³ is considered. For the reference scenario (no digestate processing), it is assumed that about half of the digestate can be applied on agricultural land around the biogas plant (costs: 3.34€/t) and the other half has to be transported to remoter areas (approx. 20km away, costs: 5.47€/t). For the cost analysis both machinery and storage facilities are included. A price of 0.03 €/kWh is assumed for the heat demand, and a bonus for waste heat utilisation (KWK Bonus) of 0.02 €/kWh is calculated according to the German subsidy system. For the digestate products, a theoretical economic value is assumed according to their nutrient content (0.60 € per kg N, 0.51 € per kg P₂O₅ and 0.26 € per kg K₂O).

The following scenarios are investigated:

- I. Reference – direct land application
- II. Separation (screw press) and separate land application of solid fraction and liquid phase
- III. Separation (screw press) and drying of the solids with a belt dryer
- IV. Separation (decanter centrifuge) and purification of the liquid phase by ultrafiltration and reverse osmosis
- V. Separation (decanter centrifuge) and concentration of the liquid phase by evaporation
- VI. Separation (decanter centrifuge) and further treatment of the liquid phase by nitrogen removal (NH₃-stripping and precipitation)

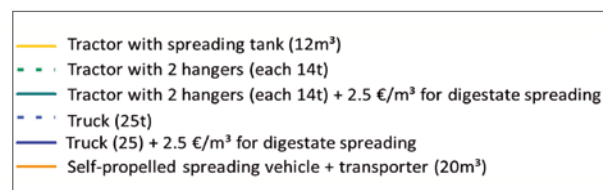


Figure 36: Costs of digestate land application depending on distance of transport (Bärenthaler et al., 2008). The stippled curves show only transportation costs, without costs for application.

The results of the study can be seen in Figure 37. It should be noted that for most of the presented processes there are still greater uncertainties and limited experiences with regard to accurate investment and running costs. Also the theoretical revenues (e.g. for nutrient fertiliser values) are currently difficult to achieve on the market.

In Figure 38a the data from KTBL (2008) are shown with dependency on the distance of transportation. In the biogas plant, a slight cost reduction occurs for membrane purification and evaporation only if transport distances exceed 80 km, whereas for stripping a cost reduction occurs with transport distances more than 50 km. The reason why stripping shows the best performance is that nitrogen can be directly removed and brought into a marketable form. As nitrogen loads are the legal limiting factor for land application, this leads to a direct reduction of transportation costs.

Economic viability of digestate processing depends very much upon whether additional benefits and/or synergies can be achieved. This is illustrated in Figure 38b. Here the effect of synergies (replacing fresh water,

excess heat utilisation) on the economics of the model biogas plant was considered. Consequently, stripping and evaporation becomes economically viable already at distances of 30 km, and membrane purification at 60 km. This example shows again that whether digestate processing can become economically viable and which technology is to be preferred is very site specific. It has to be stated though that in this calculation no additional benefits/synergies for the separator were assumed which is slightly misleading, as solid-liquid separation is the process which is most often applied. A typical benefit of solid-liquid separation can be the partial reutilization of the liquid fraction as process water which reduces the volume of the digestate and thereby will decrease costs. Moreover, all digestate processing concepts which involve thermal treatment steps (drying, evaporation) are considered to utilize excess heat free of charge in order to be economically more attractive.

The presented example shows that for most biogas plants, standard land application of digestate will be more economically attractive than digestate processing. However, if transport distances are very large and syner-

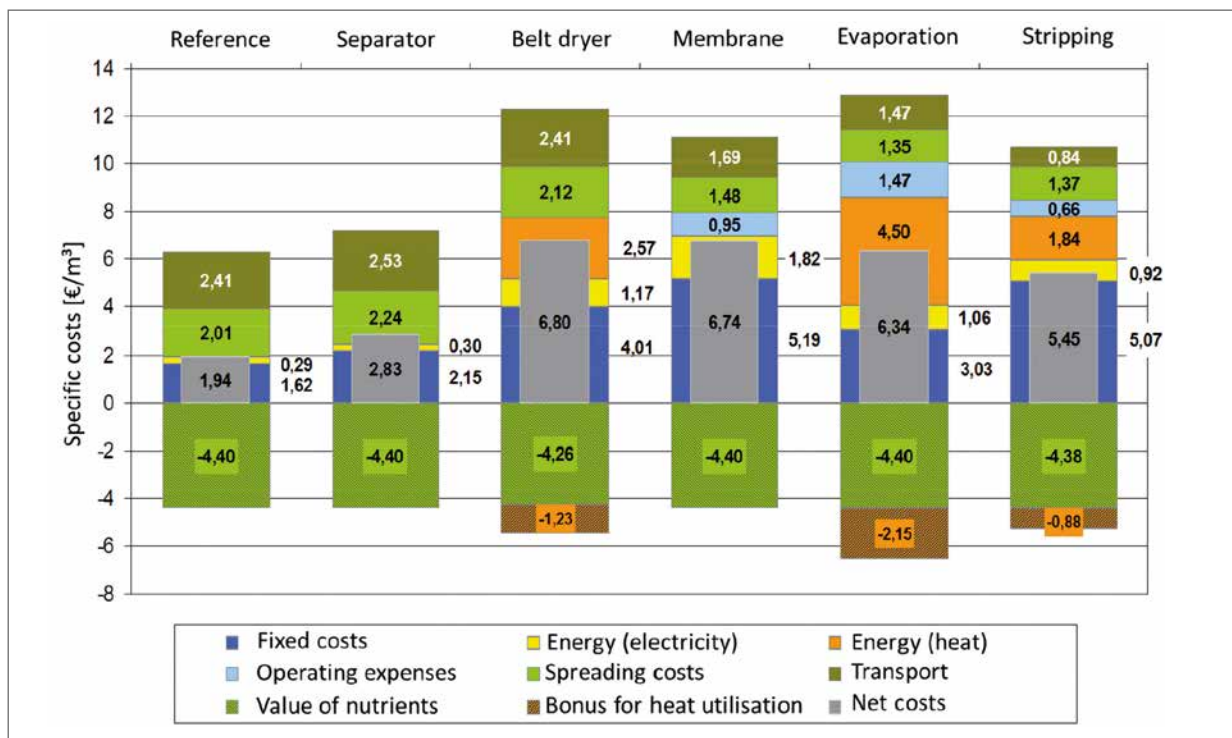


Figure 37: Comparison of specific costs for digestate processing at a model biogas plant (KTBL, 2008)

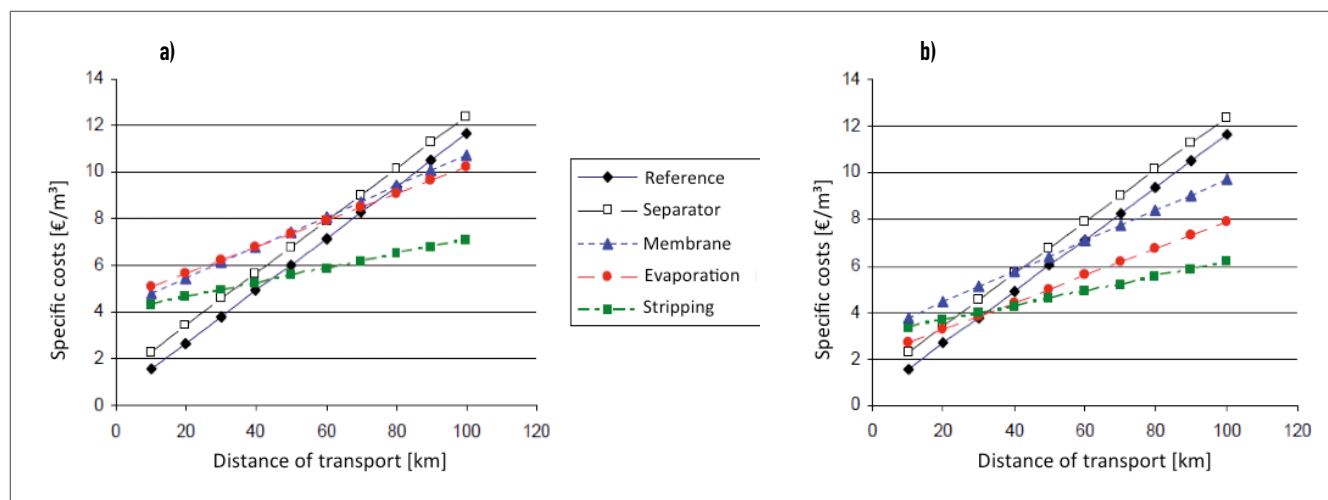


Figure 38: Comparison of specific costs of digestate processing including land application costs (a) no beneficial side effects were assumed (b) beneficial side effects such as replacing fresh water and utilisation of excess heat without costs were considered (KTBL, 2008)

gies of digestate processing at the site of the biogas plant can be found, the overall cost of digestate processing can be reduced. In addition, the establishment of a market for biofertilisers from digestate can prompt digestate processing to be deployed.

8.3 General remarks on costs

The data presented reveal that the successful and economically justified implementation of digestate processing is highly site specific. Depending on local conditions, significant differences in the individual expenses as well as in savings, for example for reduced storage facilities or revenues from the marketing of the resulting products are achieved. Even for the similar treatment concept large variations of the total costs may occur. Nevertheless, typical cost ranges for different treatment schemes can be provided and compared with the respective costs for digestate disposal. An overview of the breakeven point for certain treatment schemes is provided in Figure 39. Costs for

digestate transportation and disposal are taken from a study investigating the economics of large scale industrial biogas plants (Baerenthaler et al., 2008). Specific treatment costs include investments and operational costs as well as a small but realistic market value for products. It must also be kept in mind that several technologies only partially reduce the amount of digestate for disposal. Therefore the specific costs refer to the actual amount of digestate saved by a certain processing scheme.

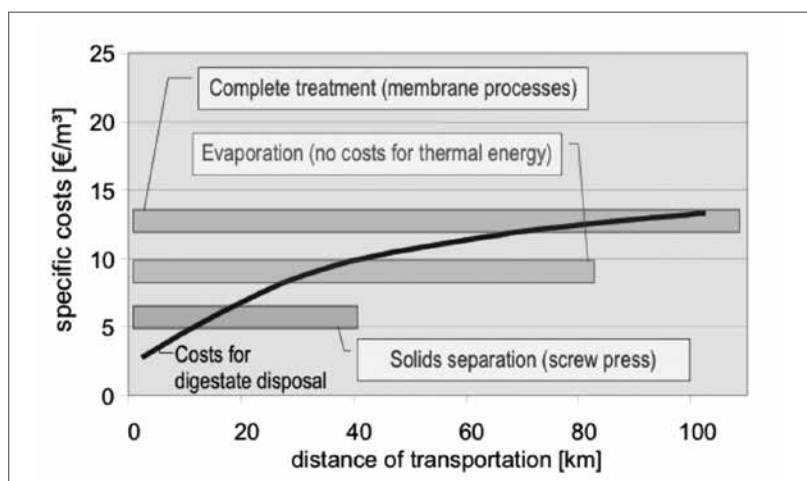


Figure 39: Comparison of cost ranges for specific treatment options versus costs for digestate disposal (Fuchs and Drog, 2013).

9. Concluding remarks and recommendations

As defined in this report, digestate is the liquid effluent from anaerobic digestion (AD) of animal manures (slurries, solid manure, deep litter), organic residues and wastes, and energy crops. If treated appropriately digestate possesses excellent agricultural fertiliser qualities. The AD process is primarily applied with the aim of generating renewable energy in the form of biogas, and with respect to the substrates handled, to improve nutrient management, strengthen veterinary safety and to facilitate air quality/odour control when applying manure to farmland.

In many countries, environmental regulations concerning manure/digestate management restrict the nutrient input per hectare as well as the period for nutrient application. This imposes considerable costs for farmers for seasonal storage, transport from stables to storage tanks, handling, and application of digestate as biofertiliser. The costs are significant due to the large volume and low nutrient concentration in digestate. Further costs are related to investments in digestate storage capacities required by environmental regulations in many countries. Volume reduction both reduces transport and application costs and facilitates export of excess nutrients to nutrient deficient areas. This requires digestate to be further processed after being removed from the digester.

Digestate processing involves the application of a range of possible technologies to digestate, comparable to the existing technologies for manure processing, sewage sludge treatment, and, in some cases, for wastewater treatment. The last decades have seen a trend of increased emphasis on improved sustainability in agriculture and preservation of natural resources like minerals phosphorus and potassium, consequently changing the focus of digestate processing from nutrient removal and disposal towards integrated nutrient recovery and recycling. This trend needs to be continued.

Digestate processing, as described by this report, can be partial, usually targeting volume reduction and separation of digestate into a liquid and a solid fraction, or it can be complete, refining digestate to for example pure water, a solid biofertiliser fraction and fertiliser concentrates. The first step in digestate processing is to separate the solid from the liquid. The solid fraction, often rich in

phosphorus, can subsequently be directly applied as biofertiliser in agriculture or it can be composted or dried for intermediate storage and feasible long-range transport. For nutrient recovery, various methods and technologies are currently available, with various degrees of technical maturity. Of these, membrane technologies, such as nanofiltration and ultrafiltration, followed by reverse osmosis are increasingly applied. The end-products of membrane filtration consist of a nutrient concentrate and purified process water.

While partial processing using relatively simple solid-liquid separation technologies (decanter centrifuge, screw press etc.) are considered comparatively inexpensive, complete processing requires far more sophisticated process equipment and often has a high specific energy consumption, which implies high additional costs.

The techniques for nutrient recovery from digestate are developing rapidly, aiming to improve nutrient management in agriculture and in waste treatment systems. In parallel, there is a general need to increase the degree of commercialisation of organic fertilisers from digestate processing through product standardisation.

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11. Glossary of terms and abbreviations

- AD:** Anaerobic Digestion (Syn. Digestion, Anaerobic Fermentation, Biogas Process) A complex microbiologically mediated process, where decomposition of organic matter, in the absence of oxygen, is carried out by the concerted action of a wide range of microorganisms. Resulting intermediate organic products are ultimately converted into the end-product biogas with the main constituents methane (the energy carrier) and carbon dioxide. The other main product of AD is digestate. Anaerobic digestion takes place naturally in lake sediments and in the digestive tract of ruminants.
- Biofertiliser:** (Used in the case of digestate) defines a material of biological origin, utilised as fertiliser to facilitate growth of plants. Biofertiliser contains important plant macro- and micronutrients. Further, the presence of living microorganisms promotes plant biomass growth by increasing the availability of nutrients.
- BOD:** **Biochemical Oxygen Demand** is the amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down organic material present in a given water sample at certain temperature over a specific time period. BOD is thus a measure of the quantity of oxygen used by microorganisms (e.g., aerobic bacteria) in the oxidation of organic matter.
- Chemical Precipitation:** A chemical reaction, in which two compounds react to form a precipitate and another product is present inside the aqueous medium. Chemical precipitation results in the formation of a separable solid substance from a solution, either by converting the substance into an insoluble form or by changing the composition of the solvent to lower the solubility of the substance in it.
- CHP:** (Syn. Co-generation) Abbreviation for combined heat and power generation. Commonly applied onsite or in an adjacent CHP plant.
- COD:** **Chemical Oxygen Demand** is a measure of the capacity of water to consume oxygen during the decomposition of organic matter and the oxidation of inorganic chemicals such as ammonia and nitrite. COD measurements are commonly made on samples of wastewaters or of natural waters contaminated by domestic or industrial wastes. Proper COD analysis provides swift estimates of the strength (energy content) of a substrate, although it does not allow for differentiation between biologically degradable and biologically undegradable chemical energy.
- Condensate:** A product of condensation, as a liquid reduced from a gas or vapour.
- Decanter Centrifuge:** A mechanical installation using high rotational speed to separate components of different densities. Decanter centrifuge is frequently used for separation of solid fractions of materials from liquids in e.g. wastewater slurry, animal slurry, and digestate.
- Digestate:** (Syn. AD Residues, Digested Biomass, Digested Slurry): The digested effluent from the AD process. Digestate is the semi-solid or liquid product of anaerobic digestion of biodegradable substrate.
- Digestate Processing:** Digestate processing involves the application of different technologies to digestate arising from anaerobic digestion. The technologies applied in digestate processing are comparable to the known technologies from manure processing, sewage sludge treatment, and wastewater treatment. Digestate processing can be approached in two ways: as digestate conditioning (or enhancement) aiming at production of standardised biofertilisers, and as digestate treatment, similar to wastewater treatment, applied in order to remove nutrients and organic matter from the effluent and to allow discharge to the sewage system, to the wastewater treatment plant on site or to a receiving water body.
- DM:** see TS
- Evaporation Process:** Conversion of a liquid into a gas. Frequently used in wastewater treatment, evaporation converts the water component in the wastewater slurry to vapor that condenses into clean water, with a significant reduction of the volume of the slurry that needs to be disposed of. It is also occasionally applied in processing of animal slurry and digestate.
- Flocculation (in polymer science):** Reversible formation of aggregates in which the particles are not in physical contact.
- Flocculation Agents** (Syn. Flocculants, Flocking agents), are chemicals that promote flocculation by causing colloids and other suspended particles in liquids to aggregate, forming a floc. Flocculants are used in wastewater treatment processes to improve the sedimentation or filterability of small particles, aiding removal of microscopic particles, difficult or impossible to remove by filtration alone.
- Flotation Agent:** A chemical, which alters the surface tension of water or makes it froth easily.
- Macronutrients:** Vital plant nutrients such as nitrogen (N), phosphorus (P) and potassium (K), along with calcium (Ca), sulphur (S) and magnesium (Mg) are called macronutrients, as they are required in large amounts, as opposed to micronutrients, which are required by the plants in very small amounts.
- MAP – Precipitation:** (Syn. Struvite precipitation) Magnesium ammonium phosphate (MAP) precipitation is a process of precipitation, crystallisation, and separation of MAP (also known as struvite) in process waters. Commonly used for phosphorus removal/recovery from e.g. digestate or wastewater sludge. It is noted that struvite generally is not pure MAP, as other substances co-precipitate with struvite.
- Membrane Fouling:** A process, whereby solutions or particles are deposited onto a membrane surface or in the membrane pores, decreasing the performance of the membrane (e.g. flux decline). Membrane fouling includes inorganic fouling/scaling, organic fouling, articulate/colloidal fouling, and biofouling (or microbial/biological fouling). Fouling due to organic and inorganic components and microorganisms can occur simultaneously and interactively.
- Micronutrients:** (Syn. Microelements, Trace elements) Vital elements, necessary in very small amounts for plants. Seven nutrients are essential to plant growth and health: boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn).
- Nanofiltration:** Nanofiltration is a membrane filtration based method that uses nanometer sized cylindrical through-pores that traverse the membrane at a 90° angle. Nanofiltration membranes have pore

sizes ranging from 1-10 nanometers (nm), smaller than that used in microfiltration and ultrafiltration, but just larger than that in reverse osmosis. Membranes used are predominantly created from polymer thin films.

NH₄-N: Total ammonium nitrogen which is either present as NH₃(aq) or NH₄⁺ in an aqueous solution.

pH: pH is a measure of the acidity or alkalinity of a solution and relates to the concentration of oxonium ions (H₃O⁺). A solution with pH = 7 is neutral, pH below 7 is acidic, and pH above 7 is alkaline. pH is a vital process parameter in anaerobic digestion and is influenced by many factors including the production/consumption of VFA. However, due to the complexity of the chemistry in an AD process, a pH measurement can never stand alone and must be augmented by for instance assessment of the buffer capacity, VFA concentration etc.

Retentate: In a filtration process, the part of a solution that does not pass through the membrane is called retentate, as opposed to the difusate.

Reverse Osmosis: Reverse osmosis is a separation process that uses pressure to force a solvent through a membrane, which retains the solute on one side and allows the pure solvent to pass through to the other side.

Stoichiometry: The calculation of relative quantities of reactants and products in chemical reactions.

Struvite: (Syn. Magnesium Ammonium Phosphate -MAP) A mineral phosphate with the formula: NH₄MgPO₄·6H₂O. Struvite is present in AD plants, and can form a scale on lines and belts, in centrifuges and pumps, clog system pipes and other equipment including the anaerobic digester itself, causing operational problems for plants operation. See also MAP-Precipitation.

TS: (Syn. DM – dry matter, DS- dry solids) Abbreviation for dry matter content. TS represents the dry residue resulting after drying according to the specified drying process. It is expressed as a percentage or in grams per kilogram. TS analysis does not take into account chemical substances with a boiling point lower than the temperature at which the analysis is performed. Hence, readily biodegradable substances such as ethanol and acetated acid, can erroneously be characterised as water.

VFA: Volatile fatty acids Organic acids produced by certain microorganisms during acidogenesis and consumed by other microorganisms during methanogenesis. VFA is an important process monitoring parameter and can be used to assess, whether an AD process is stable or not. Simple as well as advanced analytical procedures have been developed and are applied on a routine basis. VFA can be classified according to the length of the carbon skeleton, and so C1–C6 are commonly referred to as short-chained VFA (SCVFA) and routinely measured, while higher order VFAs with more than six carbon atoms are also present, but not routinely quantified.

VS: Volatile solids (Syn. ODM–Organic Dry Matter) Abbreviation for volatile solids content. VS represents the dry residue resulting after glowing (incineration) according to the specified glowing (incineration) process. It is expressed as a percentage or in grams per kilogram.

ENERGY CROPS +MANURE	FEEDSTOCK	pH	COD	TS	VS	VS/TS	TN	TN/TS	NH ₄ -N	NH ₄ -N/TS	NH ₄ -N/TN	ΣVFA
Range		7 – 8	50 – 100	6.0 – 9.0	4.5 – 7	70 – 80	4.5 – 10	60 – 120	2.5 – 6	30 – 80	50 – 70	50 – 1,000
Single plant	Corn silage, manure, agricultural residues	7.7 – 8.1 (Ø 7.9) n=11	60 – 105 (Ø 84.9) n=8	6.1 – 8.3 (Ø 7.1) n=10	4.4 – 6.3 (Ø 5.0) n=9	74 – 77 (Ø 75.2) n=9	7.6 – 9.6 (Ø 8.5) n=10	113 – 129 (Ø 119.7) n=10	4.9 – 6.1 (Ø 5.4) n=10	71 – 85 (Ø 77.3) n=10	61 – 71 (Ø 64.6) n=10	80 – 350 (Ø 200) n=11
Samples from various plants (9 plants)	Crop digestion with manure (2-stage fermentation)	7.7 – 8.0 (Ø 7.8)	–	6.5 – 8.6 (Ø 7.6)	4.8 – 6.4 (Ø 5.6)	69 – 78 (Ø 73.5)	4.3 – 6.1 (Ø 5.3)	57 – 88 (Ø 69.5)	2.3 – 4.2 (Ø 3.2)	33 – 61 (Ø 42.0)	52 – 68 (Ø 58.9)	60 – 550 (Ø 220)
ENERGY CROPS												
	FEEDSTOCK	pH	COD	TS	VS	VS/TS	TN	TN/TS	NH ₄ -N	NH ₄ -N/TS	NH ₄ -N/TN	ΣVFA
Range		[–]	(kg/ton)	[%]	[%]	[%]	(kg/ton)	(kg/ton TS)	(kg/ton)	(kg/ton TS)	(%)	(mg/L)
I	Crop digestion	7.4 – 7.9 (Ø 7.63) n=49	–	6.2 – 8.6 (Ø 7.3) n=13	4.8 – 6.2 (Ø 5.4) n=13	71 – 78 (Ø 73.8) n=13	3.6 – 5.2 (Ø 4.3) n=6	55 – 61 (Ø 58.8) n=6	1.5 – 2.5 (Ø 2.0) n=6	23 – 29 (Ø 26.6) n=6	34 – 49 (Ø 45.3) n=6	160 – 3,890 (Ø 1,420) n=49
	Crop digestion	7.2 – 7.9 (Ø 7.5) n=42	–	7.8 – 9.0 (Ø 8.5) n=3	5.7 – 6.7 (Ø 6.2) n=3	70 – 77 (Ø 73.1) n=3	4.6 – 6.3 (Ø 5.5) n=4	–	1.3 – 3.6 (Ø 2.3) n=13	–	40 – 56 (Ø 46.2) n=4	280 – 5,730 (Ø 2,060) n=42
III	Corn silage, Grass silage	7.6 – 8.0 (Ø 7.8) n=54	75 – 113 (Ø 95.3) n=6	6.6 – 9.3 (Ø 7.7) n=43	4.8 – 6.9 (Ø 5.6) n=43	71 – 75 (Ø 73.2) n=43	3.6 – 4.9 (Ø 4.2) n=12	44 – 57 (Ø 51) n=12	1.3 – 2.4 (Ø 1.7) n=24	17 – 26 (Ø 20.3) n=23	34 – 54 (Ø 44.6) n=12	40 – 200 (Ø 110) n=53
	Liquid fraction of digestate	as above	44 – 70 (Ø 57.2) n=4	4.5 – 6.0 (Ø 5.4) n=5	2.9 – 4.0 (Ø 3.6) n=5	64 – 68 (Ø 66.5) n=5	3.3 – 4.0 (Ø 3.7) n=4	63 – 79 (Ø 69.6) n=4	–	23 – 42 (Ø 31.3) n=4	–	–
Samples from various plants (15 plants)	Solid fraction of digestate	as above	268 – 323 (Ø 292.1) n=4	22.0 – 27.4 (Ø 24.6) n=5	19.5 – 24.4 (Ø 21.9) n=5	87 – 90 (Ø 89.0) n=5	4.6 – 5.7 (Ø 5.2) n=4	19 – 25 (Ø 22.1) n=4	–	5.4 – 8.0 (Ø 6.9) n=4	–	–
	Crop digestion (2-stage, no manure)	7.5 – 7.8 (Ø 7.7)	–	6.3 – 8.8 (Ø 7.4)	4.7 – 6.4 (Ø 5.5)	71 – 80 (Ø 74.2)	3.5 – 5.5 (Ø 4.7)	51 – 75 (Ø 63.0)	1.5 – 3.6 (Ø 2.6)	23 – 47 (Ø 34.4)	42 – 63 (Ø 53.8)	20 – 500 (Ø 350)
Samples from 6 various plants	Crop digestion (1-stage)	7.4 – 7.7 (Ø 7.6)	–	6.2 – 9.6 (Ø 7.8)	4.6 – 7.4 (Ø 5.8)	71 – 77 (Ø 74.4)	4.4 – 6.2 (Ø 5.2)	62 – 70 (Ø 66.9)	2.1 – 4.2 (Ø 3.1)	32 – 46 (Ø 39.1)	48 – 68 (Ø 58.6)	100 – 1,000 (Ø 480)

WASTE		FEEDSTOCK	pH	COD	TS	VS	VS/TS	TN	TN/TS	NH ₄ -N	NH ₄ -N/TS	NH ₄ -N/TN	ΣVFA
			[-]	[kg/ton]	[%]	[%]	[%]	[kg/ton]	[kg/ton TS]	[kg/ton]	[kg/ton TS]	[%]	[mg/L]
Range			7.3 – 8.3	15 – 120	1.5 – 8.0	1.0 – 6.0	50 – 80	1.0 – 11.0	60 – 240	0.5 – 9.0	20 – 180	30 – 95	20 – 5,000
Single plant	I	Food waste, blood, bio waste	8.0 – 8.3 (Ø 8.2) n=16	–	3.9 – 4.1 (Ø 4.0) n=6	2.4 – 2.8 (Ø 2.6) n=6	61 – 68 (Ø 64.3) n=6	6.4 – 8.1 (Ø 7.3) n=6	165 – 183 (Ø 172.6) n=3	5.1 – 7.2 (Ø 6.4) n=13	127 – 176 (Ø 151.3) n=5	72 – 80 (Ø 77.3) n=6	390 – 2,700 (Ø 1,370) n=16
	II	Food waste, bio waste	7.3 – 7.9 (Ø 7.5) n=38	15 – 31 (Ø 24.2) n=6	1.6 – 3.3 (Ø 2.2) n=19	1.0 – 1.7 (Ø 1.3) n=19	54 – 63 (Ø 59.5) n=19	1.4 – 2.3 (Ø 1.8) n=18	63 – 129 (Ø 88.9) n=18	0.6 – 1.5 (Ø 1.0) n=19	24 – 89 (Ø 49.2) n=19	34 – 72 (Ø 53.9) n=18	20 – 970 (Ø 406) n=27
	III	Food waste, bio waste, blood, food industry residues	7.8 – 8.2 (Ø 8.1) n=48	36 – 73 (Ø 57.1) n=48	5.6 – 8.1 (Ø 7.2) n=48	3.0 – 4.5 (Ø 3.9) n=47	52 – 57 (Ø 54.5) n=47	4.2 – 6.7 (Ø 5.8) n=48	69 – 90 (Ø 80.7) n=48	3.1 – 4.1 (Ø 3.7) n=48	47 – 57 (Ø 51.7) n=48	40 – 94 (Ø 65.1) n=48	1,410 – 4,950 (Ø 2,790) n=48
	IV	Manure, slaughter house waste, bio-waste, food and kitchen waste, corn	8.0 – 8.3 (Ø 8.2) n=11	115.2 n=1	5.7 – 7.2 (Ø 6.4) n=3	4.1 – 5.6 (Ø 4.8) n=3	71 – 78 (Ø 74.5) n=3	8.4 – 10.8 (Ø 9.6) n=4	191 – 231 (Ø 211.0) n=2	6.8 – 8.6 (Ø 7.9) n=5	121-148 (Ø 136.1) n=5	79 – 83 (Ø 80.6) n=4	9,060 – 21,180 (Ø 16,050) n=11
Samples from various plants (9 plants)		Bio waste	7.6 – 8.1 (Ø 7.8)	–	2.5 – 4.7 (Ø 3.6)	1.4 – 2.7 (Ø 2.0)	51 – 64 (Ø 56.3)	3.0 – 6.8 (Ø 4.9)	62 – 195 (Ø 145.6)	1.5 – 5.6 (Ø 3.7)	26 – 165 (Ø 111.1)	48 – 88 (Ø 70.4)	20 – 1,450 (Ø 610)

INDUSTRIAL BY-PRODUCTS		FEEDSTOCK	pH	COD	TS	VS	VS/TS	TN	TN/TS	NH ₄ -N	NH ₄ -N/TS	NH ₄ -N/TN	ΣVFA
			[-]	[kg/ton]	[%]	[%]	[%]	[kg/ton]	[kg/ton TS]	[kg/ton]	[kg/ton TS]	[%]	[mg/L]
Single plant		Slaughter house waste	7.9 – 8.3 (Ø 8.1) n=107	33 – 59 (Ø 45.7) n=17	2.2 – 4.9 (Ø 3.5) n=35	1.6 – 3.9 (Ø 2.6) n=33	68.4 – 80.5 (Ø 74.2) n=33	6.4 – 8.1 (Ø 7.4) n=32	184 – 336 (Ø 262.5) n=26	5.3 – 7.7 (Ø 6.6) n=76	151 – 291 (Ø 210.5) n=34	70 – 91 (Ø 85.6) n=32	2,780 – 11,890 (Ø 7,239) n=100
Pilot plant		Brewers' spent grains	7.3 – 7.5 (Ø 7.4) n=39	92.7 n=1	5.3 – 5.8 (Ø 5.6) n=12	4.7 – 5.3 (Ø 5.05) n=12	87.4 – 92.1 (Ø 90.33) n=12	2.3 – 3.1 (Ø 2.8) n=18	50 – 56 (Ø 53.0) n=11	1.9 – 2.3 (Ø 2.0) n=17	35 – 42 (Ø 38.0) n=11	69 – 78 (Ø 73.1) n=14	50 – 810 (Ø 360) n=36
Pilot plant		Thin stillage (Bioethanol by-product)	7.7 – 8.1 (Ø 7.9) n=95	18 – 31 (Ø 26.1) n=16	1.7 – 2.8 (Ø 2.2) n=18	0.9 – 1.6 (Ø 1.2) n=18	52.6 – 60.1 (Ø 56.1) n=18	3.0 – 4.3 (Ø 3.7) n=16	132 – 203 (Ø 177.3) n=16	2.2 – 2.8 (Ø 2.5) n=16	93 – 144 (Ø 119.2) n=16	62 – 74 (Ø 67.5) n=16	0 – 2,680 (Ø 800) n=117

Task 37 - Energy from Biogas

IEA Bioenergy

IEA Bioenergy aims to accelerate the use of environmentally sustainable and cost competitive bioenergy that will contribute to future low-carbon energy demands. This report is the result of work carried out by IEA Bioenergy Task 37: Energy from Biogas.

The following countries are members of Task 37, in the 2013 – 2015 Work Programme:

Australia	Bernadette McCABE, bernadette.McCabe@usq.edu.au
Austria	Bernhard DROSG, bernhard.drosg@boku.ac.at Günther BOCHMANN, guenther.bochmann@boku.ac.at
Brazil	Cícero JAYME BLEY, cbley@itaipu.gov.br
Denmark	Teodorita AL SEADI, teodorita.alseadi@biosantech.com
European Commission (Task Leader)	David BAXTER, david.baxter@ec.europa.eu
Finland	Jukka RINTALA, jukka.rintala@tut.fi
France	Olivier THÉOBALD, olivier.theobald@ademe.fr Guillaume BASTIDE, guillaume.bastide@ademe.fr
Germany	Bernd LINKE, blinke@atb-potsdam.de
Norway	Tormod BRISEID, tormod.briseid@nibio.no
Republic of Ireland	Jerry MURPHY, jerry.murphy@ucc.ie
Republic of Korea	Ho KANG, hokang@cnu.ac.kr
Sweden	Mattias SVENSSON, mattias.svensson@energiforsk.se
Switzerland	Nathalie BACHMANN, nathalie.bachmann@envi-concept.ch
The Netherlands	Mathieu DUMONT, mathieu.dumont@RvO.nl
United Kingdom	Clare LUKEHURST, clare.lukehurst@green-ways.eclipse.co.uk Charles BANKS, cjb@soton.ac.uk

WRITTEN BY:

Bernhard DROSG (corresponding author)
IFA-Tulln
Konrad Lorenzstrasse 20
A-3430 Tulln
Austria

Teodorita AL SEADI
BIOSANTECH
Lerhøjs Allé 14,
DK-6715, Esbjerg
Denmark

Bernd LINKE
Leibniz-Institut für Agrartechnik Potsdam-Bornim
Max-Eyth-Allee 100
D-14469 Potsdam
Germany

Werner FUCHS
IFA-Tulln
Konrad Lorenzstrasse 20
A-3430 Tulln
Austria

Michael MADSEN
ENVO Group A/S
Vestvejen 170–172
DK-6200 Aabenraa
Denmark

EDITED BY:
David BAXTER
European Commission
JRC Institute for Energy and Transport
1755 LE Petten
The Netherlands

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