BIOREFINE

Recycling inorganic chemicals from agro- and bio-industrial waste streams

Project/Contract number: 320J - Biorefine

Document number: BIOREFINE – WP2 – A5 – P1, 2, 5, 8 – D

Techniques for nutrient recovery from digestate derivatives

Date: 17/07/2015

Start date of project: 1 May 2011 Duration: 56 months

Authors: L. Bamelis, S. Blancke, M. A. Camargo-Valero, L. De Clercq, A. Haumont, B. De Keulenaere, F. Delvigne, E. Meers, E. Michels, D. R. Ramirez-Sosa, A. B. Ross, H. Smeets, C. Tarayre, N. Tarayre, P. T. Williams

Authors' Institution: AILE, Biogas-E, DLV InnoVision, Gembloux Agro-Bio Tech, Ghent University, University of Leeds

Project funded by the European Regional Development Fund through INTERREG IV B		
Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Table of contents

1 Glossary

AAD: Advanced Anaerobic Digestion

AD: Anaerobic Digestion

CHP-unit: Combined Heat and Power unit

DM: Dry Matter

DS: Dry Solids

g/L: Gram per litre

H: Hydrogen

H_2S: Hydrogen sulphide

K: Potassium

Kg/h: Kilogram per hour

kW : Kilowatt

kWe: Kilowatt-electric

kWh/m^3: Kilowatt hour per cubic metre

kW th: Kilowatt-thermal

L: Litre

m^3/d: Cubic metre per day

m^3/h: Cubic metre par hour

Mg: Magnesium

mg/L: Milligram per litre

MF: Microfiltration

MW: Megawatt

N: Nitrogen

NH_3: Ammonia

NH_4-N, NH_4^+-N: Ammoniacal nitrogen nm: Nanometre

N-S fertiliser: Nitrogen-Sulphur fertiliser

N_{tot}: Total Nitrogen

P: Phosphorus

P_2O_5: Phosphorus concentration expressed in phosphorus pentoxide

RO: Reverse Osmosis

SBR: Sequencing Batch Reactor

t: Ton

t/d: Ton per day

t/h: Ton per hour

t/year or t/y: Ton per year

UF: Ultrafiltration

WWTP: Waste Water Treatment Plant

2 Introduction

Anaerobic digestion (AD) is a well-established method for the treatment of organic waste streams and the generation of biogas for the production of renewable energy. The main products for AD are biogas and digestate.

Digestate is the solid/liquid material produced by AD of organic feedstocks. Digestate is a mix of microbial biomass and undigested material. AD and gasification converts around 15 % of the feedstock to gas and 85 % remains as organic solid/liquid material. Characteristics of digestate are: high content of nitrogen (2.3 - 4.2 kg/tonne), phosphorus (0.2 - 1.5 kg/tonne) and potassium (1.3 - 5.2 kg/tonne) and as a consequence, digestate has value as an organic fertiliser (Chambers, 2011).

Just like for animal manure, there are lots of techniques suitable for the processing of digestate. An overview commonly used digestate processing techniques, including nutrient recovery techniques, is given in the inventory 'Techniques for nutrient recovery from digestate' published by Lebuf et al. (2013) under the Interreg IVB project ARBOR. In this brochure, nutrient recovery techniques are defined as techniques that (1) create an end-product with a higher nutrient concentration in comparison to the raw product or (2) separate the envisaged nutrients from organic compounds with the aim to create an end-product that can be used by the chemical or fertiliser industry (Lebuf et al., 2013). This report focuses on existing case studies of different nutrient recovery techniques from digestate or digestate derivatives.

It must be kept in mind that the composition of digestate is variable and depends on the input materials that are digested. Consequently, the processes described in this report will not always show the same efficiency.

3 State-of-the-art nutrient recovery techniques from digestate

Different techniques can be applied to digestate to extract nutrients. The following techniques mainly refer to pilot plants. These installations must cope with the variability of digestate composition. This high heterogeneity is a constraint which makes the upscaling of the processes more difficult.

3.1 Separation and thickening of the thin fraction

3.1.1 General description

The following scheme (**Figure 1**) shows the general description of the treatment scheme.

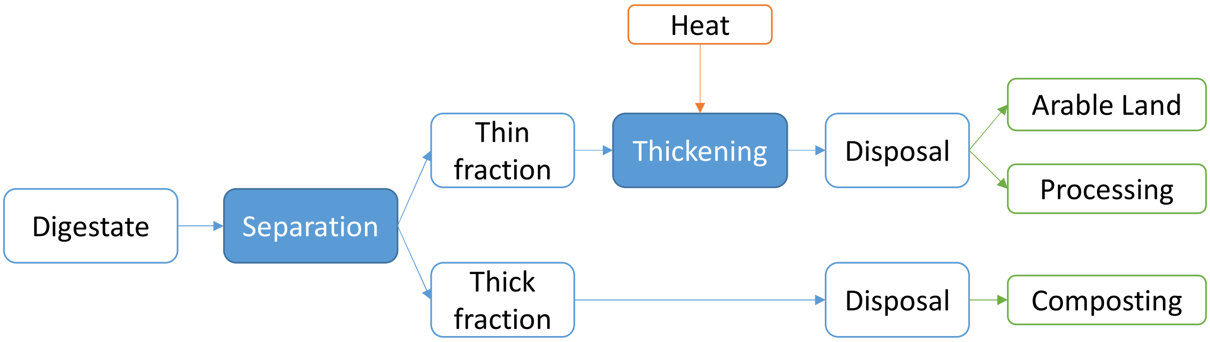

Figure 1: Scheme of the process of separation and thickening of the thin fraction of digestate.

Source: DLV InnoVision

All the raw digestate is forwarded to a separation step. The composition of the thin and thick fraction after this separation depends on the type of separation techniques applied.

Table 1 below gives an overview of the different compositions of both the thick and the thin fraction just after the separation step in 3 different separation techniques. These figures are calculated both from efficiencies found in literature and practical experience.

Table 1: Composition of the thick and thin fractions of digestate after the separation step achieved through 3 different techniques.

			Centrifuge **with polymer**	**Screw press**	**Belt press**
Thin fraction	DM	%	3 %	8 %	3 %
	N_{tot}	kg/ton	5.0	5.7	3.9
	P_2O_5	kg/ton	1.0	3.8	0.5
Thick fraction	DM	%	35 %	26.6 %	24 %
	N_{tot}	kg/ton	7.5	4.5	9.4
	P_2O_5	kg/ton	14.1	5.6	11.6

Source: Beste Beschikbare Technieken (BBT) voor composteer - en vergistingsinstallaties; Verhoeven J.T.W., (2013) After the separation step, the thick fraction will not further be treated – it is disposed of as such. This can be either an application on arable land or, if impossible on a composting site which will further transform the thick fraction into compost.

The thin fraction will go through a thickening stage in which water will be evaporated. This is required in order to minimize the volume of thin digestate as much as possible as the more volume, the higher the disposal costs.

The composition of the thin fraction after the thickening step is highly dependent on the amount of heat that can be used for the evaporation of the water. If we assume that about 3000 kW is to be used for evaporation purposes for a 60,000 ton/year installation, the final composition of the treated thin fraction will be close to the figures shown in **Table 2**.

Table 2: Composition of the thin fraction of digestate after the thickening step.

			Centrifuge **with polymer**	**Screw press**	**Belt press**
Thin fraction After evaporation	DM	%	6.5 %	16.8 %	11.0 %
	N_{tot}	Kg/ton	6.5	6.0	6.3
	P_2O_5	Kg/ton	2.6	8.0	1.7

Source: Beste Beschikbare Technieken (BBT) voor composteer - en vergistingsinstallaties; Verhoeven J.T.W., (2013)

This thin fraction will be used on arable land as a fertiliser.

3.1.2 Unit operations of separation techniques

Centrifuge

In a centrifuge, the non-soluble components are separated by using centrifugal forces. The centre of a decanter centrifuge (**Figure 2**) consists of a drum with a screw inside. By giving the drum a high rotational speed, a G-force develops. The basic operation of a centrifuge is based on the centrifugal force on the incoming stream, making the insoluble components heavier than water migrate to the wall of the drum. The screw inside the drum pushes the heavier parts to the opposite side of the stream direction, making the thick stream still thicker.

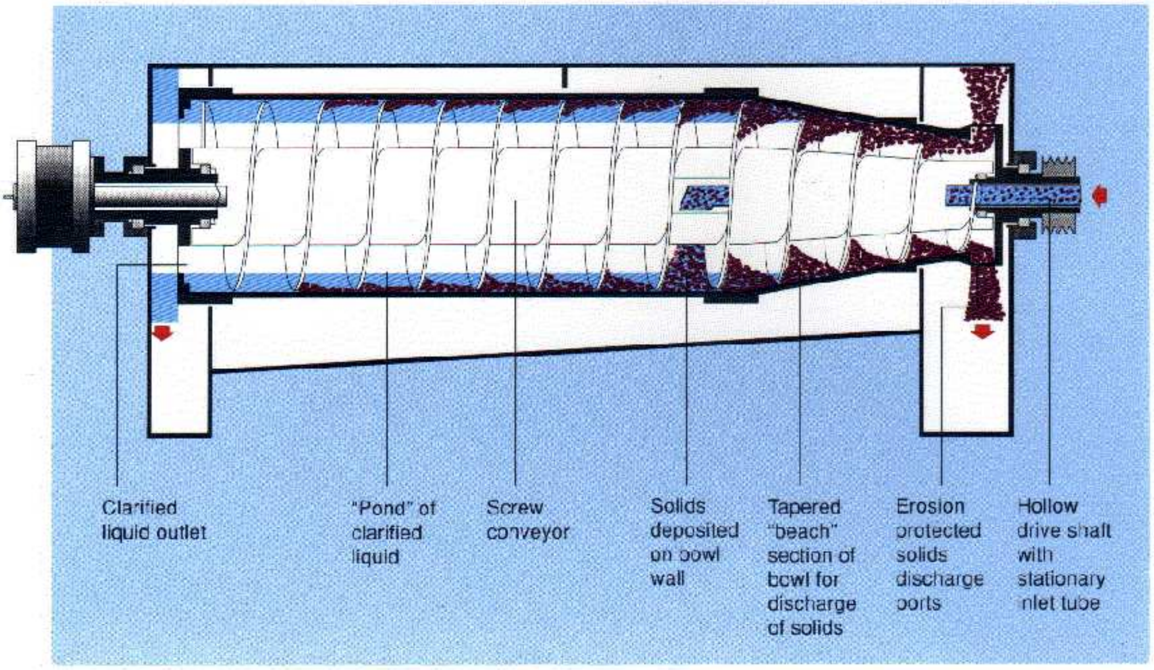

Figure 2: Scheme of a centrifuge, showing that the insoluble components heavier than water are separated on the right side while water is recovered on the left side.

Source: Poirier M.R. et al., (2002)

Screw press

Inside a screw press (**Figure 3**) a screw turns inside a perforated cylindrical trough with holes of 0.15 – 1.0 mm. Through these holes, the thin fraction is separated from the incoming manure/digestate/mixture of both. The screw presses the thick fraction out of the machine (Verhoeven, 2013).

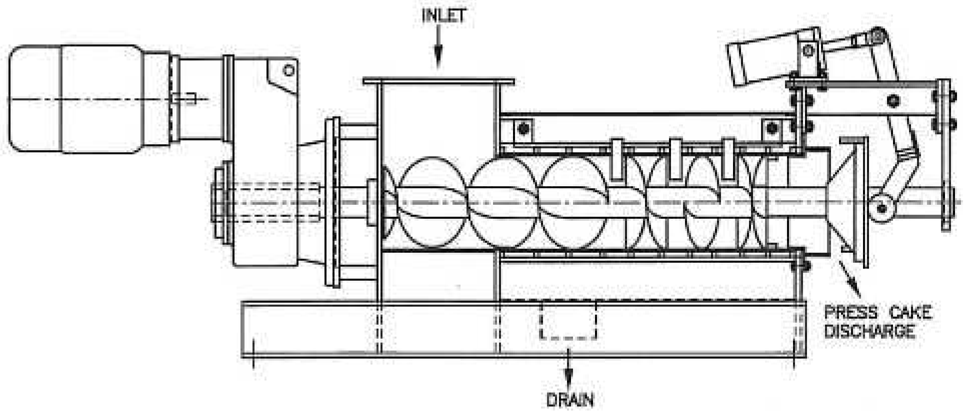

Figure 3: Scheme of a screw press, indicating the inlet, drain and cake discharge.

Source: VINCENT Corporation, (year not specified)

Belt press

In a belt press (**Figure 4**), the stream of manure or digestate is pressed between two conveyors. At least one of the two conveyors needs to function as a belt press. In most belt presses, the bottom conveyor acts as a filter. The upper conveyor is typically a closed press belt which is pushed to the bottom belt with rollers (Verhoeven, 2013).

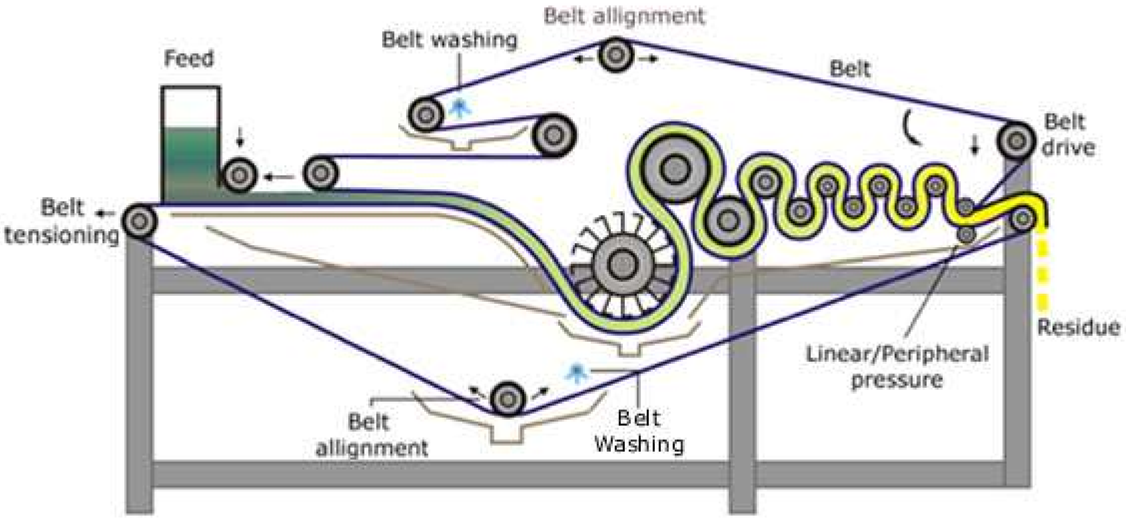

Figure 4: Scheme of a belt press.

Source: Schwarz Global Consulting, (year not specified)

3.1.3 Unit operations of thickening techniques

The regular application for the thickening of the thin fraction is in Flanders the use of a rotating wheel. This wheel (or multiple wheels – see **2** in **Figure 5**) will elevate thin layers of the material into the area where hot air (see **3** in **Figure 5**) is blown through. This contact of the hot air with the thin layer of the material will cause the required evaporation.

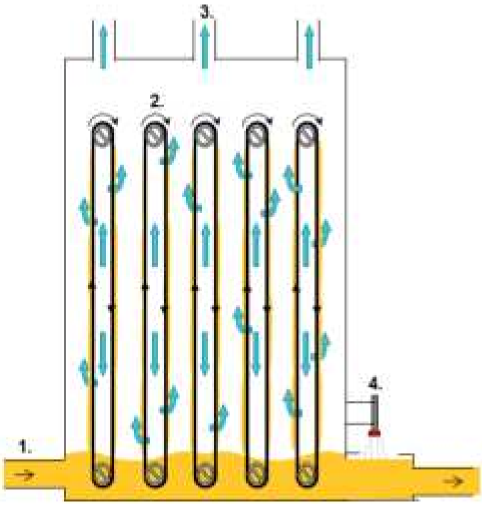

Figure 5: Schematic overview of a thickening system.

Source: Biogas Plus (year not specified)

3.1.4 Unit operations of air treatment

Blowing the hot air through the thin fraction of the material will cause a significant evaporation of the available ammonia. Apart from the ammonia, further odour components will be taken along with the waste air.

This waste air has to be treated before it is emitted into the air in order to prevent odour problems. The treatment required varies from load to load, but in normal circumstances, a treatment consisting of at least 3 phases is needed. **Figure 6** provides an overview of the system.

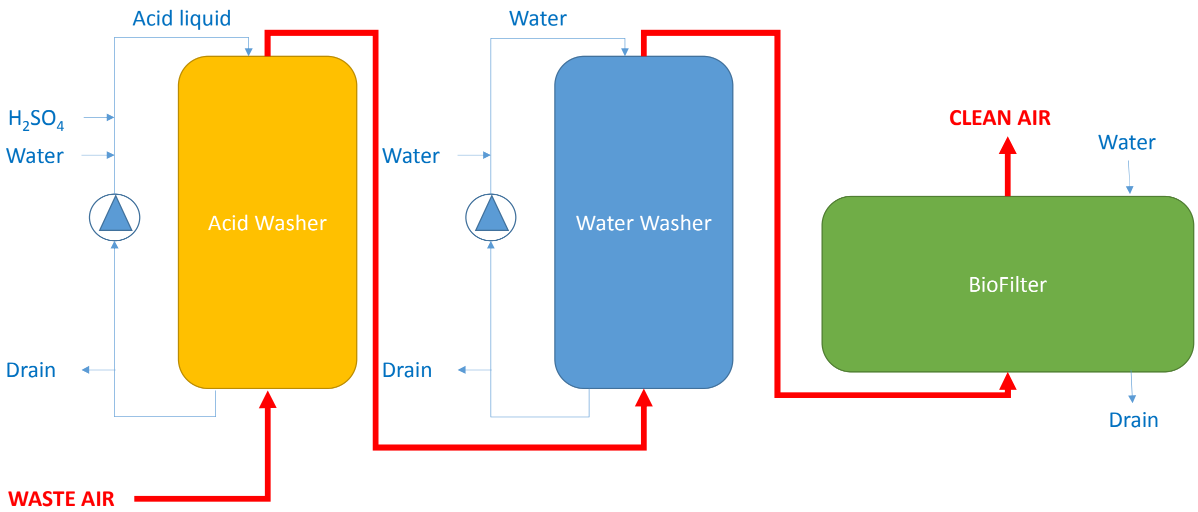

Figure 6: Schematic overview of the air treatment system.

Source: DLV InnoVision

The process consists of 3 stages:

- Acid Washing - by washing the air with an acid fluid (i.e. water combined with sulphuric acid) the ammonia present in the waste air flow will be washed out as ammonia sulphate.
- Water washing – after going through the acid washer, the waste air is washed with water (high liquid / air ratio) in order to remove other components such as dust and more acid components.
- Biofilter – in the final phase of the treatment, the waste air will go through a biofilter – this biofilter consists of wooden particles and is constantly moisturized. The bacteria which will remove the remaining odorous substances from the waste air are grown on this wood.

The drain of all the different steps is mostly mixed up with the thin fraction of the digestate for disposal on arable land.

3.1.5 Useful contact(s) for further information

DLV InnoVision (Belgium)

Email address: lies.bamelis@dlv-innovision.be

3.2 Drying of the thick fraction of digestate

3.2.1 General description

The scheme below shows the treatment scheme (**Figure 7**).

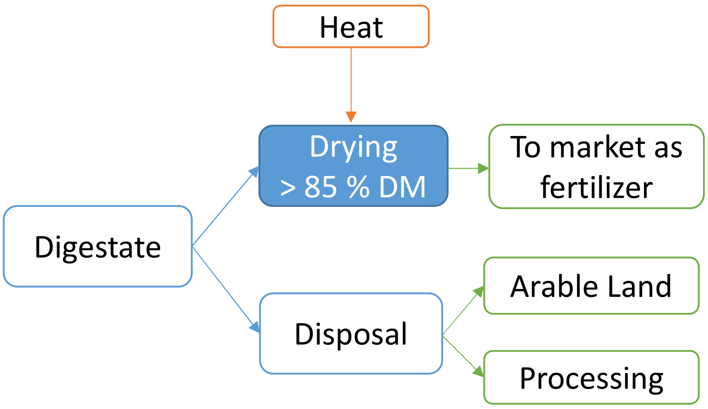

Figure 7: General overview of the drying process of the thick fraction of digestate.

Source: DLV InnoVision

In this treatment scheme, there is actually only 1 treatment step: the raw digestate is dried as much as possible – consuming all the available waste heat from the cogeneration engine (CHP-unit).

The dried material should be > 85 %DM in order to be valuable on the market as a fertiliser. It is a stabilized product that can be stored. It can then either be sold on the local market or exported. The raw digestate that is not treated can be disposed of on arable land or further processed, which can be done either on the digester site (consisting in most cases in separating the thin fraction from the thick one) or in an external composting plant or manure treatment plant.

3.2.2 Unit operations of the drying process

The most common application for drying of digestate in Flanders is the use of a belt dryer. This type of dryer has the benefit that it can work within a wide range of temperatures – which means that the lower temperature range coming from the CHP unit (55 – 65 °C) can be used in this type of dryer. The disadvantage of this type of dryer – especially if used at lower temperatures – is that a large volume of air is required to optimize the process. All this air has to be treated in an air treatment system – which induces addition operation costs. **Figure 8** shows the structure of a typical belt dryer.

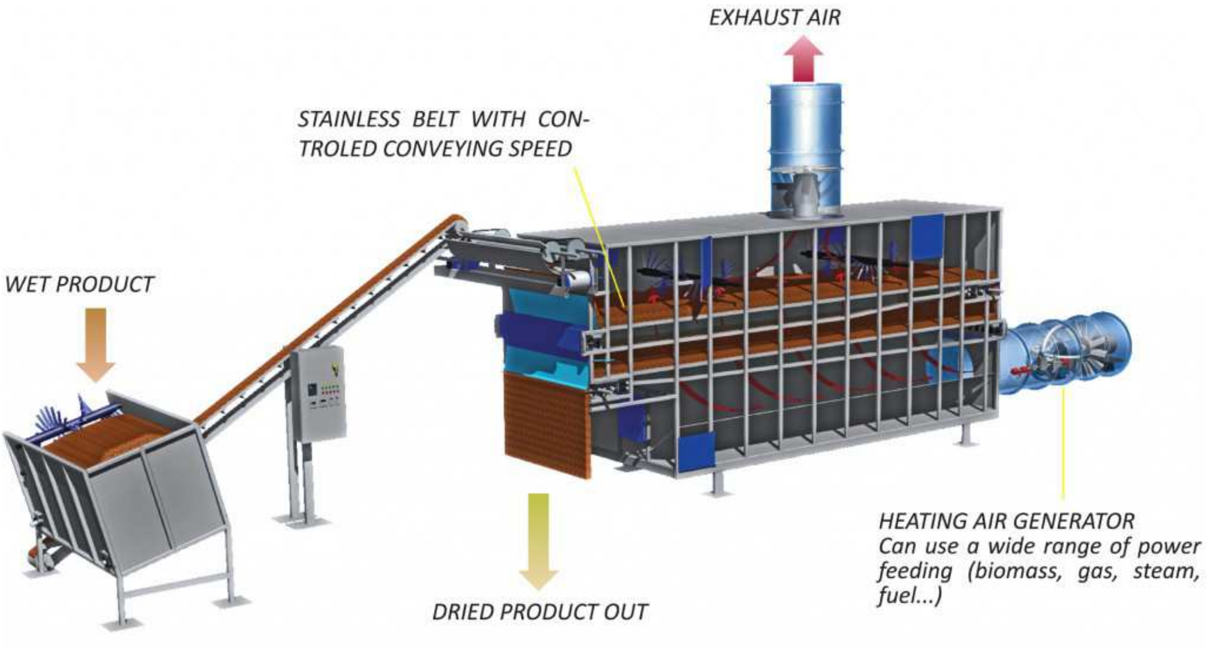

Figure 8: Structure of a typical belt dryer.

Source: Biogreen (year not specified)

In this type of dryer, the wet product will be disposed of over a ventilated rotating belt. As there is a significant recirculation of dried material to the point where fresh (wet) material is added, the material remains in the dryer for rather a long time.

There are other types of dryers that do indirect drying where the hot air is not in contact with the wet material. The advantage of such systems is that there is no need for air treatment though they require higher temperature and a higher economic investment.

3.2.3 Unit operations of air treatment

The system is the same as under **3.1.3.** However, a specific dust-remover is required for the removal of small particles from the waste air.

3.2.4 Additional comments

One of the most important issues of this type of treatment is the risk of fire in the dryer. Several installations in Flanders have had fire-issues that all started in the dryer. The main issue is that in order to go from the digestate to the dried material, one has to pass a danger range from 40 – 55 % DM. Within this range, a spontaneous ignition of the material (if allowed to pile up) is possible.

Therefore, it is always necessary to be very vigilant when shutting the dryer down for maintenance or similar situations. At that moment, some of the not completely dried matter will be left in the dryer and can start a spontaneous combustion if the period is long enough. So, when shutting down, one should always remove all the material present in and around the dryer site.

3.2.5 Useful contact(s) for further information

DLV InnoVision (Belgium)

Email address: lies.bamelis@dlv-innovision.be

3.3 Separation, thickening of the thin fraction and drying of the thick fraction

3.3.1 General description

The scheme below shows the general description of the treatment scheme (**Figure 9**).

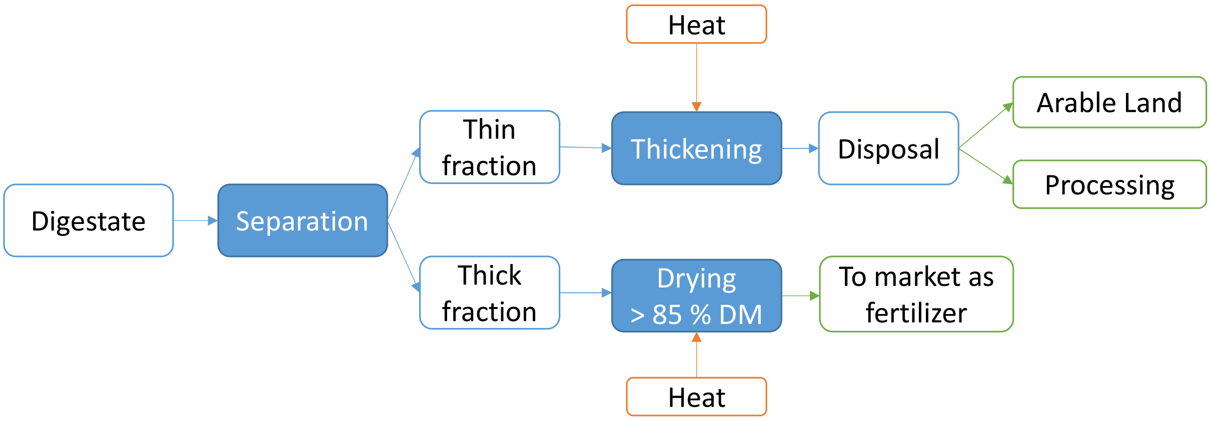

Figure 9: General description of the process of separation, thickening of the thin fraction and drying of the thick fraction of digestate.

Source: DLV InnoVision

This process is the combination of the different techniques described in **3.1.** and **3.2.** In this treatment scheme, all the raw digestate will be submitted to a separation process. After that, a further processing of both the thin and the thick fraction is achieved on the digester site. For both processes, the waste heat from the CHP-engine is used. The plant owner can decide how much heat he'll devote to either thickening or drying though, under normal circumstances, the heat will first be used in order to dry the whole thick fraction. The remaining heat will then contribute to thickening the thin fraction as much as possible.

The composition of the thin fraction throughout the process is given in **Table 3**. It is assumed that for a 60,000 ton installation, about 3 MW thermal can be used for drying and thickening. Of these 3 MW, about 2 MW will go into thickening and one into thick fraction drying.

Table 3: Composition of the thin fraction before and after the thickening step.

			Centrifuge **with polymer**	**Screw press**	**Belt press**
Thin fraction	DM	%	3 %	8 %	3 %
	N_{tot}	kg/ton	5.0	5.7	3.9
	P_20_5	kg/ton	1.0	3.8	0.5
Thin fraction after thickening	DM	%	4.5 %	14.5 %	5.4 %
	N_{tot}	kg/ton	4.5	5.2	3.1
	P_20_5	kg/ton	1.8	6.9	0.8

Source: DLV InnoVision

3.3.2 Unit operations of the separation techniques

The unit operations are the same as in **3.1.**

3.3.3 Unit operations of the evaporation techniques

The unit operations are the same as in **3.1.**

3.3.4 Unit operations of the drying step

The unit operations are the same as in **3.1.**

3.3.5 Unit operations of the air treatment

The unit operations are the same as in **3.1.**

3.3.6 Useful contact(s) for further information

DLV InnoVision (Belgium)

Email address: lies.bamelis@dlv-innovision.be

3.4 Separation, thickening of the thin fraction and drying of the thick fraction combined with a biological treatment

3.4.1 General description

The process is the same as before (see **3.7.**). However, it is possible to improve it by implementing an aerobic treatment in the treatment scheme. This aerobic treatment allows to reduce the nitrogen amount that is available in the thin fraction before it goes through the thickening phase. This way it will be possible to dispose much more of the thin fraction on the same surface of arable land. This biological treatment will also “level out” the impact of the chosen separation technique, as it will be managed in order to meet a certain threshold at the outlet of the biological treatment.

The composition of the thin fraction throughout the process is given in **Table 4**. It also shows the composition of the material after the biological treatment. It is assumed that for a 60,000 ton installation, about 3 MW thermal can be used for drying and thickening. About 2 of these 3 MW will go into thickening and 1 will be used to dry the thick fraction (as before).

Table 4: Composition of the thin fraction before and after the aerobic treatment.

			Centrifuge with polymer	Screw press	Belt press
After separation	DM	%	3 %	8 %	3 %
	Ntot	Kg/ton	5.0	5.7	3.9
	P205	Kg/ton	1.0	3.8	0.5
After biological treatment and thickening	DM	%	2.3 %		
	Ntot	Kg/ton	0.5		
	P205	Kg/ton	0.4		

Source: DLV InnoVision

3.4.2 Unit operations of the separation techniques

The unit operations are the same as in **3.1.**

3.4.3 Unit operations of the evaporation techniques

The unit operations are the same as in **3.1.**

3.4.4 Unit operations of the drying step

The unit operations are the same as in **3.1.**

3.4.5 Unit operations of the air treatment

The unit operations are the same as in **3.1.**

3.4.6 Unit operations of the biological treatment

The biological treatment resorted to in this type of installation is similar to the ones used in standard manure treatment systems. The treatment chosen is to consist of a nitrification – denitrification set-up in order to ensure nitrogen removal. In Flanders, both batch reactors (SBR) and continuous reactors are operational – all of them operating with activated sludge.

The excess sludge of these biological treatments can be fed to the digester for further recovering.

3.4.7 Useful contact(s) for further information

DLV InnoVision (Belgium)

Email address: lies.bamelis@dlv-innovision.be

3.5 Solid/liquid separation and stabilization (Barkip plant)

3.5.1 General description

Scottish and Southern Energy (SSE) work with Unicus scraped surface evaporators which treat the digestate liquor in order to turn it into the liquid fertiliser produced at the Barkip anaerobic digestion plant.

Barkip biogas facility is located in North Ayrshire and has a capacity to process up to 75,000 tons of food waste, manure and organic sludges/digestates. The scraped surface heat exchangers use the heat generated from the CHP process to concentrate the liquid fraction of the digestate and change it into an organic fertiliser. Although this is the first time this technique is being used to process digestate, the heat exchangers have proved to be effective in other applications such as pig manure treatment (Waste & Resources Action Programme, 2012). The techniques resorted to are: two-stage Thermophilic Anaerobic Digestion, centrifuge and scraped surface heat exchangers.

3.5.2 Unit operations

Barkip facilities comprises firstly an anaerobic digester which can treat up to 75,000 tons per annum of diverse organic streams, specially food waste, organic digestate and manure for the production of biogas. The biogas is stored and used in a CHP plant to provide heat and electricity within the installation. The energy in excess is sent to the national grid. Other saleable products from the AD are digestates usable as soil conditioners and liquid fertilisers.

The acceptable feedstock for the plant consists of wastes from local farms, businesses, local authorities and commercial collections.

Waste delivery

The waste delivered to the site is tipped into storage containers inside an enclosed reception building equipped with a bio-filter ventilation system.

Anaerobic digestion

The anaerobic digestion process takes place in closed reactors with batch feeding for the production of gas which is extracted and stored prior to use.

Biogas purification

The biogas produced is transported via a gas scrubber to remove H_2S and NH_3 to reduce the potential of odour from the gases.

CHP plant

The biogas is burnt in CHP gas engines to generate heat and power. Remaining gas is sent to an emergency release via an 8 m high, enclosed flare.

Dehydration of digestate

The digestate resulting from the AD process is dewatered and separated by internally located decanter/centrifuges to produce a solid fibre and liquid concentrate.

Acidification of digestate liquor

The digestate liquor is then pre-treated with acid prior to evaporation within the scraped surface heat exchangers to prevent ammonia loss within the evaporator. The volume of acid dosed is dependent on the digestate and the desired retention. Within the evaporator, the liquor is concentrated to approximately 20 % Dry Solids (DS).

Liquor concentration

The evaporator functions at temperatures between 50- 70 °C under vacuum. The heat required for the process is coming from the CHP plant. Barkip plant has evaporators that can treat 10,800 kg/h of digestate liquor and produce 1,565 kg/h of concentrate. In the Barkip application, the heat exchanger tubes have been constructed from Duplex steel due to the high chloride content within the feedstock.

Mixing step

The concentrated liquor can be mixed with the separated solid fibre to obtain a solid fertiliser rich in nutrients and fit for exportation (Waste & Resources Action Programme, 2012).

The process scheme is shown in **Figure 10**.

3.5.3 Process scheme

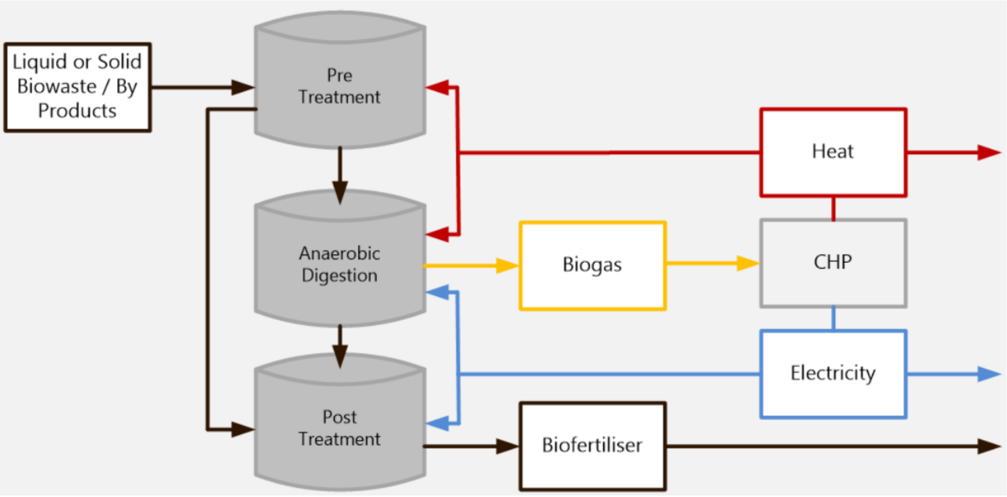

Figure 10: Anaerobic Digestion process used in the Barkip plant.

Source: Scottish and Southern Energy®

3.5.4 Useful contact(s) for further information

Scottish and Southern Energy (SSE) (United Kingdom)

Email address: see the website *www.sse.com*

University of Leeds (United Kingdom)

Email addresses: A.B.Ross@leeds.ac.uk, cndrr@leeds.ac.uk, M.A.Camargo-Valero@leeds.ac.uk

3.6 Pre-autoclaving and dehydration of digestate

3.6.1 General description

AeroThermal Group Ltd has been granted planning permission to develop a resource treatment and recovery facility on the site of Imerys Minerals Ltd at Lee Moor in South Devon.

The AeroThermal process consists in autoclaving digestate in a pressure vessel at a constant temperature and pressure, which helps to sterilise the digestate and at the same time break down organic and lignin structures in order to reduce the volume by approximately 60 %. The autoclaving process contributes to removing the contaminants contained in the feedstock, improving the generation of biogas and the quality of the digestate.

Recyclable materials will also be recovered from the waste stream and the stable digestate, a by-product of the Advanced Anaerobic Digestion (AAD) process, will be used to help restore parts of the adjoining Lee Moor Quarry (Pell Frischmann, 2012). The main feedstock in the AeroThermal process is food waste for the generation of biogas as the central product by AD and digestate as a subproduct, used as organic fertiliser.

3.6.2 Unit operations

The Lee Moor facility consists of two autoclave plants, screening and separation equipment, an anaerobic digestion plant with associated buffer and digestate storage tanks, a dewatering plant and a combined heat and power (CHP) plant (Barnes, 2012).

Loading into the autoclaves

Organic feedstock is loaded into two autoclaves in 10 ton batches. The autoclaves are fed up to 10 times per day via a system of conveyors from the weighing hopper.

Autoclaving step

Autoclaves are operated in alternating batch mode to recycle the steam from the unit that is being operated, to the autoclave that is starting a new cycle. With this procedure, steam utilisation efficiency is enhanced and there is also a reduction of steam released into the atmosphere. During the autoclaving process, the reactor is rotated to allow a continuous mixing flow. Steam is injected into the autoclave to reach 5.2 bar and 160 °C for 45 minutes.

Anaerobic digestion

Once autoclaving is finished, the temperature is returned to atmospheric conditions and fit to be fed into the anaerobic digester. Biogas will be produced by the conventional AD process under mesophilic conditions after 28 days of retention.

CHP plant

The biogas produced from AD is sent to a CHP plant to produce up to 3.2 MW of electricity and 3.8 MW of heat. The electricity is fit for exportation to the national grid while the heat is used to increase the temperature in the autoclaves or in the anaerobic digestion tanks. This technique enables the steam to be recycled between the two autoclaves, significantly reducing the amount of energy needed by the system.

Removal of contaminants

After autoclaving, some inorganic material and contaminants can be removed by mechanical separation providing a pasteurised and organic rich feedstock for AD.

Dehydration step

After AD, the digestate is dewatered in a centrifuge until 25 % of dry solids are obtained. Dewatered digestate is used for a restoration scheme at the Lee Moor quarry, which is located nearby. Digestate from the anaerobic digestion process is dewatered by a conventional centrifuge to obtain 25 % dry solids. The digestate fibre is used for land restoration at the Lee Moor quarry. Furthermore, the liquors resulting from the process are partially treated by dissolved air filtration (Barnes, 2012).

3.6.3 Useful contact(s) for further information

AeroThermal Group Ltd (United Kingdom)

Email address: see the website *www.aerothermalgroup.com*

University of Leeds (United Kingdom)

Email addresses: A.B.Ross@leeds.ac.uk, cndrr@leeds.ac.uk, M.A.Camargo-Valero@leeds.ac.uk

3.7 Drying and pelletizing (Biogas Bree case study)

In some cases, owners of anaerobic digestion plants choose to dry the digestate in order to lower transport costs. The digestate is almost always dried using thermal energy from the CHP-engine.

3.7.1 Description of the technique

Because of legislative limitations for the use of digestate from animal origin in Flanders, the Biogas Bree plant has separate reactors for input of animal and vegetable origin only. Two digestion reactors are fed with vegetable products. The digestate from these two reactors goes through a post-digestion stage after which it undergoes downstream processing. The end-product is used as a substitute for fossil-based chemical fertilisers.

A third reactor, operated independently of the ‘vegetable’ ones, is used for input of animal origin (including cow and pig manure), supplemented with smaller quantities of vegetable materials (mainly molasses and sometimes maize). The raw digestate from this ‘animal’ reactor goes through a thermal drying phase (**Figure 11**). The dryer uses heat from the Combined Heat and Power (CHP) engine. In 2014, an accidental modification of the drying process parameters resulted in the formation of digestate in granular form. After about one and a half years, the Biogas Bree operators are now able to control the granule formation using a 50 % recirculation of granular material. The grains have different particle sizes, are sieved accordingly and can be used as an organic fertiliser. At the moment, they are mainly used in horticulture and not so much for agricultural purposes.

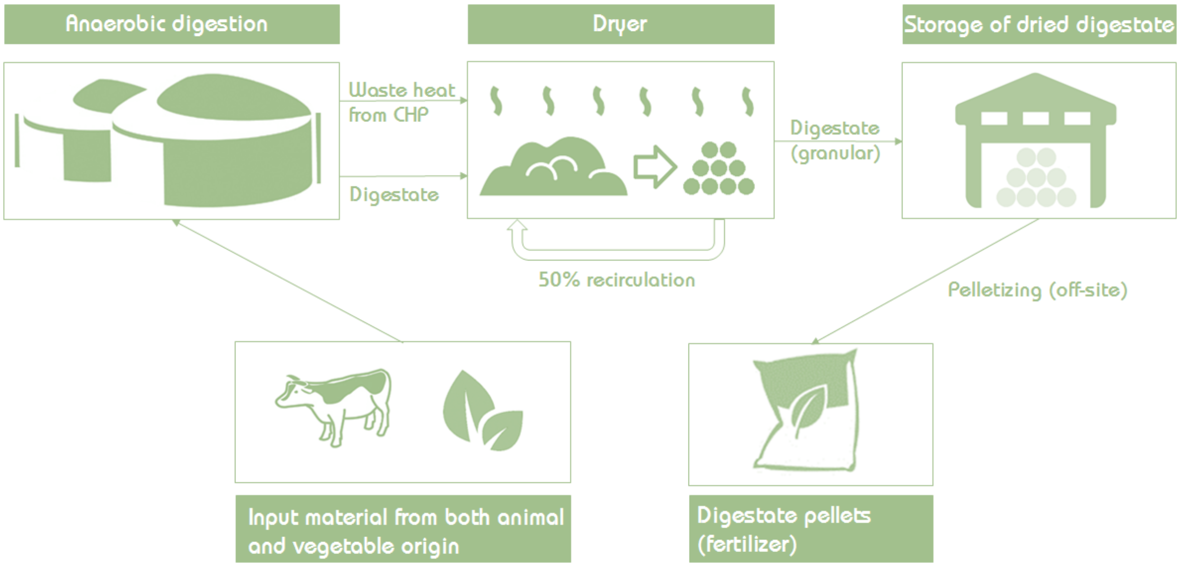

Figure 11: Schematic overview of the drying process with formation of granular material.

Source: Biogas-E

3.7.2 End-product

At the moment, the end product is dried granular digestate of different sizes. The particle size diameter is about 0.5 – 2 cm (order of magnitude).

3.7.3 Stage of development

The drying step is controlled in such a way that the particle size distribution is quite stable. In the future, one plans to pelletize the dried digestate so as to make the product more in line with market standards for both private and professional uses. Certain fertilising products (N, P, K) could be fed into the pelletizer in order to obtain a product with a suited nutrient composition.

3.7.4 Useful contact(s) for further information

Biogas Bree bvba (Belgium)

Email address: info@biogasbree.be

3.8 Membrane Filtration/Reversed Osmosis (Ampower case study)

3.8.1 Description of the technique

In pressurized membrane filtration, the input stream is forced through the membrane by means of pressure. The input stream for membrane filtration can be either the liquid fraction of digestate from anaerobic digestion or a pre-processed stream, such as the condensate from the evaporator. Membranes are categorized and named according to pore size. Different techniques have a typical range of pressure that can be applied, see **Table 5**.

Table 5: Different types of pressurized membrane filtration techniques.

Type of technique	Pore size (nm)	Pressure range (bar)
Microfiltration (MF)	> 100	0.1 - 3
Ultrafiltration (UF)	> 1	2 - 10
Reversed Osmosis (RO)	No pores	10 - 100

Source: Lebuf V. et al., (2013)

The product that is retained on the membrane is called concentrate. In a MF-concentrate, suspended solids are retained, while UF can also retain macromolecules. There is a range of techniques available that can be used as a pre-treament for reversed osmosis in order to prevent clogging/fouling of the RO-membrane, including both MF and UF.

In the case of Ampower, the largest anaerobic digestion plant in Flanders, the digestate is first sent through a centrifuge to separate the solids from the liquid fraction. Polymers are added to induce coagulation and flocculation and increase separation. The solid fraction contains from 90 % to 95 % of the total input P and is dried with waste heat from the Combined Heat and Power (CHP) engine. The dried digestate is exported as a P-fertiliser, mainly to France. The liquid fraction is sent to a reversed osmosis (RO) installation. The permeate of RO is the ‘purified’ stream. The concentrate contains most of the input stream nutrients.

The biggest problem reported in membrane filtration is clogging and fouling of the membrane, which increases the hydraulic resistance. Waeger et al. (2010) investigated that pore is strongly correlated to particle size distribution, which shows the importance of a sufficient separation step before the RO. The efficiency of RO-membranes can decrease because (1) low-soluble salts can precipitate on the membrane surface (scaling), (2) suspended solids can adsorb to the membrane surface (fouling) or (3) bacteria can colonize the membrane (biofouling) (Lebuf et al., 2013). Ampower reduces the blockage of the membrane pores by continuously dosing acid solutions to the RO-system, which is the most efficient way to reduce scaling and fouling. After some time, the membranes need to be replaced anyway. The system is represented in **Figure 12**.

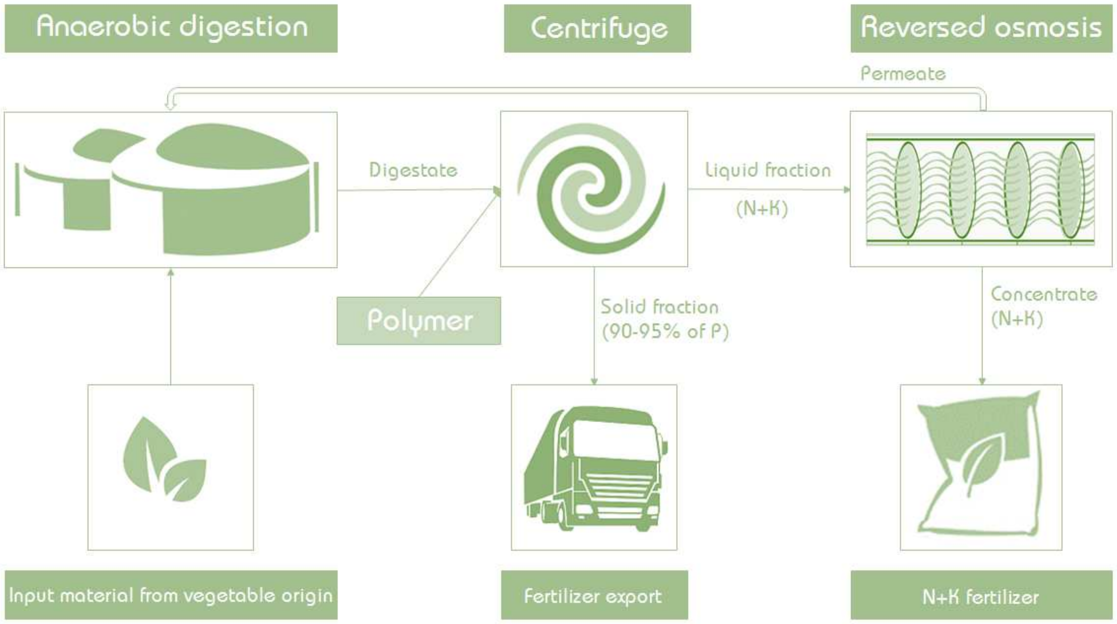

Figure 12: Schematic overview of the reversed osmosis process applied to digestate of vegetable origin.

Source: Biogas-E

3.8.2 End-product

Both permeate and concentrate can be considered as end-products of reversed osmosis, although they have different qualities. The **permeate** is quite clear and consists mainly of water and small ions. It can be discharged, if necessary after a 'polishing' step, or used as process water. Ampower uses the permeate (about 50 % of the stream sent onto the RO membrane) to mix with the dry input streams for anaerobic digestion so that a desirable (lower) dry matter content is achieved for the 'wet' anaerobic digestion process. The **concentrate** is rich in nitrogen (N) and potassium (K) and is used as a fertiliser in agriculture on a local scale. The system is shown in **Figure 13**.

Figure 13: Reverse osmosis installation at Ampower (©Biogas-e).

Source: Biogas-E

3.8.3 Stage of development

The RO technique works very well and is popular in Flanders. However, the costs for chemicals are still quite high. Further investigations to reduce the need for chemicals are necessary.

3.8.4 Useful contact(s) for further information

Ampower bvba (Belgium)

Email address: delabie.stefaan@gmail.com

3.9 Evaporative-concentration: Process K-Révert, biogas plant "Pont Langlois" in Normandy (France)

3.9.1 General description

The biogas plant "SCEA Pont Langlois" is located in Condé sur Vire in Normandy. The AD plant is part of the farm, producing biogas from 10,000 t/year substrates, since 2013. Biogas is used in a 265 kWe CHP. The electricity produced is sent to the grid. Heat supplies the AD process, the farm heating and the digestate treatment. The heat available for digestate treatment is about 165 kW th. This plant produces 9600 t of raw digestate per year. Landspreading in this sector is limited. Therefore, a large amount of digestate has to be transported 30 km away in the neighbourhood of Caen. In order to make this AD project possible, the digestate has to be treated so as to reduce the volume and therefore the transport costs. Moreover, the exported digestate had to be solid to be accepted by the farmers around Caen. That's why digestate treatment was compulsory from a legal point of view.

The objectives of this digestate treatment were:

- Reduction of digestate volume by removing as much water as possible
- Maintenance of all fertilising elements in by-products
- Limited use of chemical additives
- Optimized automation
- Solid final by-products
- Re-use of the thermal energy generated by cogeneration

Digestate treatment first consists in separating liquid from suspended matter in a screw press. The solid fraction, which contains a large amount of phosphorus, is stored. The liquid fraction, rich in ammonia and potassium, goes into a vacuum evaporator. Ammonia is carried away by distilled water. The residue of the vacuum evaporation is mixed with the solid fraction from the screw press. The distilled water is post treated by reverse osmosis after acidification in order to concentrate the NH_4^+ in a solution, although the purified liquid is returned to nature according to the European law of February 1998. The treatment plant is shown in **Figure 14**.

Figure 14: Treatment plant of digestate in the biogas plant "Pont Langlois".

Source: K-Revert

3.9.2 Unit operations

Screw press separation

The first step is a mechanical separation of the liquid from the suspended matter contained in the digestate by a screw press. Since the screw press is eco-friendly, its electrical consumption is very low. Moreover, no chemical additives are required. The liquid fraction obtained is about 25 m^3/d. The solid part has a DM content of about 23 %.

Vacuum evaporation

The liquid digestate is sucked into the vacuum evaporator. The liquid is heated to 38°C thanks to the hot water resulting from cogeneration. The water contained in the liquid phase turns into vapour carrying all the ammonia with it. The low evaporation temperature is due to the high level of vacuum in the evaporator. The post-evaporation residue is spread on the solid fraction of the screw press. The final product (7.1 t/d) is handled as a solid (DM of 20 %) and delivered 30 km away.

Acidification and reverse osmosis

The water containing ammonia is acidified with sulphuric acid in order to turn NH_3 into NH_4^+. The water is post-treated by a reverse osmosis device producing 2 t/d solution of fertiliser (ammonium sulphate) which is then used by the owner of the plant. The clean water produced is sent to the river (20 t/d). The process scheme of the treatment is shown in **Figure 15**.

3.9.3 Process scheme

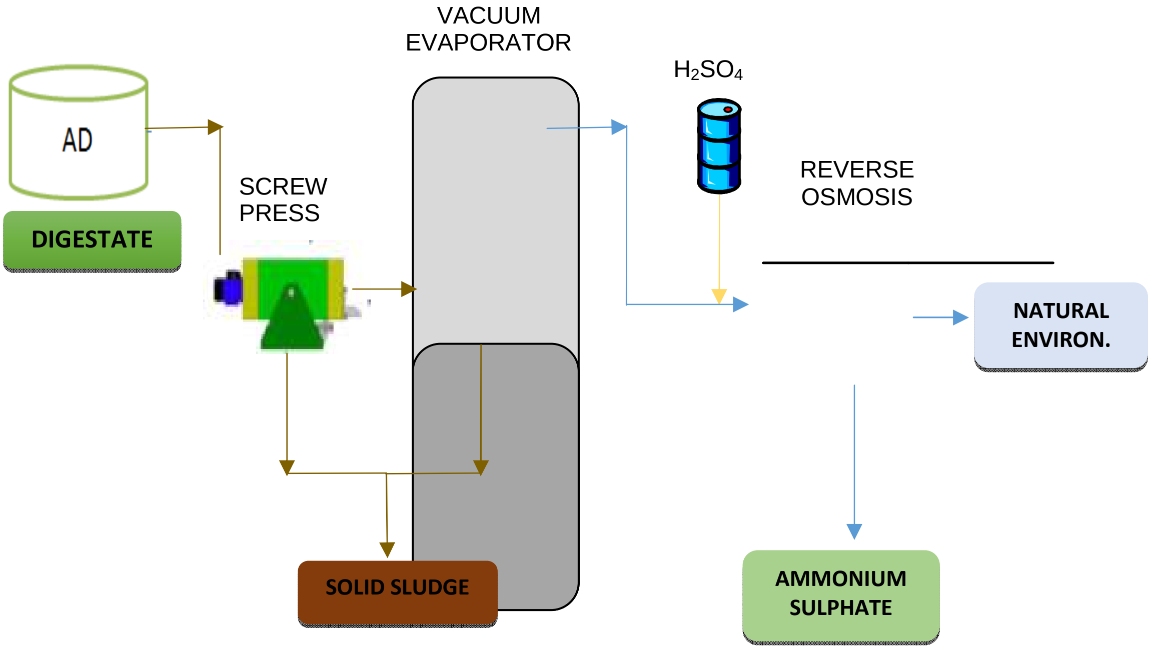

Figure 15: Process overview of the digestate treatment by K-RéVERT at SCEA Pont Langlois.

Source: K-Revert

3.9.4 Additional comments

The general catch rate of NH_3 in the raw digestate is about 98 %. The process allows the total recovery of fertilising elements. The global electrical consumption is about 0.025 kWh/m^3 of digestate.

3.9.5 Useful contact(s) for further information

K-Revert (France)

Email address: Julien.brochier@k-revert.fr

3.10 Ammonia stripping and scrubbing : Plant Biogasyl, Les Herbiers (France)

3.10.1 General description

The biogas plant “BIOGASYL” is located in Les Herbiers, in the North West of France. It is a centralised plant which has been producing biogas from 25000 t/year substrates since 2008.

The composition of the mix of substrates is as follows:

- 57 % waste from food industry
- 29 % catering and retail waste
- 14 % slurry

Biogas is used in a 615 kWe CHP. The electricity produced is sent onto the grid while the slaughterhouse located next door and the digestate processing plants are heated.

This plant produces 23,000 t of raw digestate per year. However, it can hardly be used as a fertiliser. As a consequence, a large amount of digestate has been treated since 2009 with a process designed by *Europe Environnement*. The plant is shown in **Figure 16**.

On the one hand, the digestate processed turns into organic and mineral fertiliser that is saleable and fit for exportation. On the other hand, the wastewater has to be treated on the site. Digestate processing first consists in separating liquid from suspended matter with a centrifuge separator. The solid fraction, which contains a large amount of phosphorus, is composted to meet the French standards NF U 44051. Part of the liquid fraction rich in ammonia goes into a stripping column. Evaporating ammonia is carried away by the air flow. The polluted air is then directed to a wash column to concentrate the NH_3 into a solution, although the purified liquid is directed to the WWTP. The process scheme is shown in **Figure 17**.

Figure 16: Picture of the plant "Biogasyl".

Source: AILE

3.10.2 Unit operations

Centrifugation

The first step is a mechanical separation of the liquid from the suspended matter with a centrifuge. The plant is equipped with a polymer dosing unit so as to optimize centrifugation. A 0.16 m^3 volume of polymer is added per m^3 of digestate. The liquid fraction is about 3.5 m^3/h with a content of NH_4^+ above 3 g/L. The solid part has a DM content of about 25 % and is taken to the composting platform.

Ammonia stripping

A basic solution (whitewash) is added to the liquid fraction in order to turn NH_4^+ ions into gaseous NH_3. The liquid to be treated is sprayed above a polymer lining allowing heat transfers. The amount of NH_4^+ is about 3 to 5 g/L prior to treatment whereas the effluent only contains 0.2 g/L.

Air scrubbing

The stripgas containing ammonia is transferred to a washing column. This scrubbing column is connected to the acid dosage unit. A solution of nitric acid is sprayed above an exchange surface. The ammonia is absorbed by the acid solution and turns into ammonium nitrate (NH_4NO_3) which could be ammonium sulphate if the acid used was replaced with sulphuric acid. The recovery rate of NH_3 in the air is about 99 %. The ammonium nitrate solution produced contents 150 to 200 g/L of NH_4^+ (15-20 %) although the concentration in the effluent is less than 150-200 mg/L. This effluent is transferred to the WWTP.

3.10.3 Process scheme

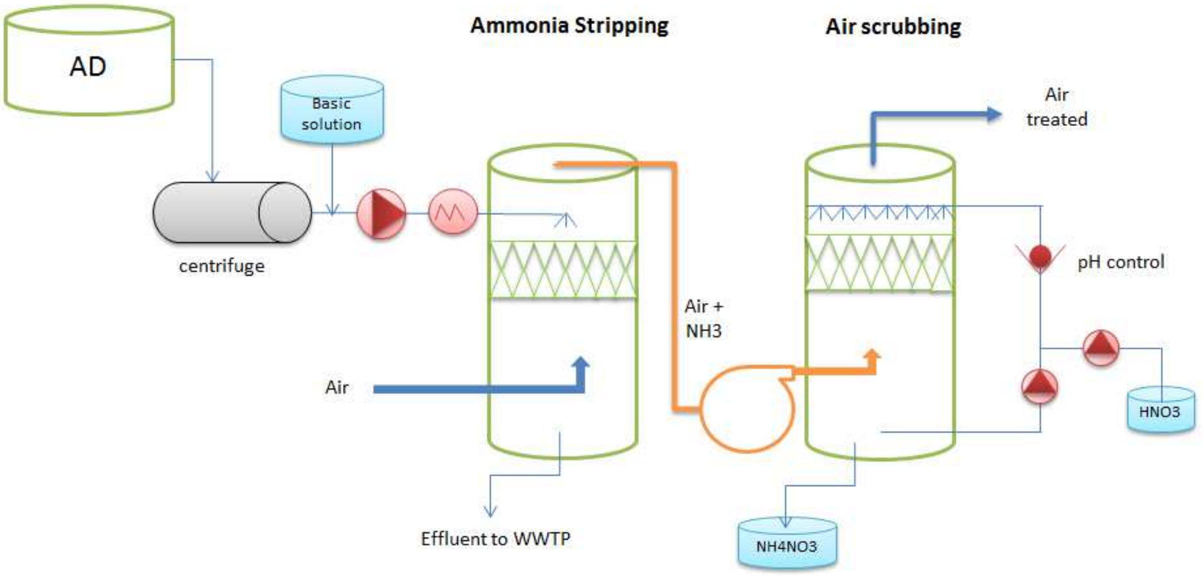

Figure 17: Process overview of the digestate treatment at Biogasyl (adapted from *Europe Environnement*).

Source: modified *from Debuchy C., (2011)*

3.10.4 Additional comments

The total recovery rate of ammonia is about 96 % depending on the incoming N concentration and optimisation of the unit operations.

3.10.5 Useful contact(s) for further information

CMI Europe Environnement (France)

Email address: europe.environnement@cmigroupe.com

Bionerval (France)

Email address: philippe.spannagel@bionerval.fr

3.11 Ammonia stripping and scrubbing (Waterleau pilot installation)

Through a combination of stripping and scrubbing, ammonia can be recovered from the liquid fraction of digestate which typically contains between 2 and 5 g/L NH_4-N. A pilot set-up for this process is being tested at the Waterleau NewEnergy plant in Ieper, Belgium. The company has already gained experience with classical ammonia stripping systems. The goal of the pilot plant is to find the most suitable system for digestate treatment and fertiliser recovery. It is also meant to help identify the optimal process parameters.

3.11.1 Description of the technique

In a first step, the ammonia is stripped out of the liquid fraction of the digestate by blowing air through the liquid stream in a tray stripper. In a second stage, the stripping gas containing ammonia is put into contact with an aqueous sulphuric acid solution in a packed scrubber, resulting in ammonium sulphate. For the time being, there have been no tests conducted with nitric acid solutions because of potential safety issues linked to the mixture. The pilot plant runs in a semi-continuous mode in which every hour, 66 L of digestate are drained from the stripper unit which is then filled with fresh influent (digestate) again. In aqueous solutions, NH_3 and NH_4^+ concentrations are in equilibrium. Changes in temperature and pH can shift the equilibrium either to the left or to the right. The optimization of both temperature and pH was achieved thanks to a series of tests.

Influence of temperature

In order to determine the optimal temperature, three types of tests were done after the start of the pilot plant:

(1) heating of the digestate liquid fraction up to 50 to 60°C,
(2) no heating of the digestate,
(3) increase in hot water flow in order to reach highest possible temperature in heat exchanger.

Other parameters were kept constant both in the stripping and scrubbing unit including digestate flow, fan flow (connection between both units) and pH. The results showed that heating the digestate stream up to 50 to 60 °C should be sufficient to efficiently remove ammonia and recover ammonium sulphate within three hours. If the stripper unit is not heated, there is low ammonia removal. Higher temperatures in the heat exchanger did not result in higher ammonium recovery rates. Owing to local circumstances, the temperatures that could be reached were lower than expected. The low recovery rate was caused by condensation in the pipeline that connects both units. It is expected that higher temperatures – up to about 80°C – are attainable and will increase efficiency in an optimal design set-up. A schematic overview of the system is provided in **Figure 18**. The plant is shown in **Figure 19**.

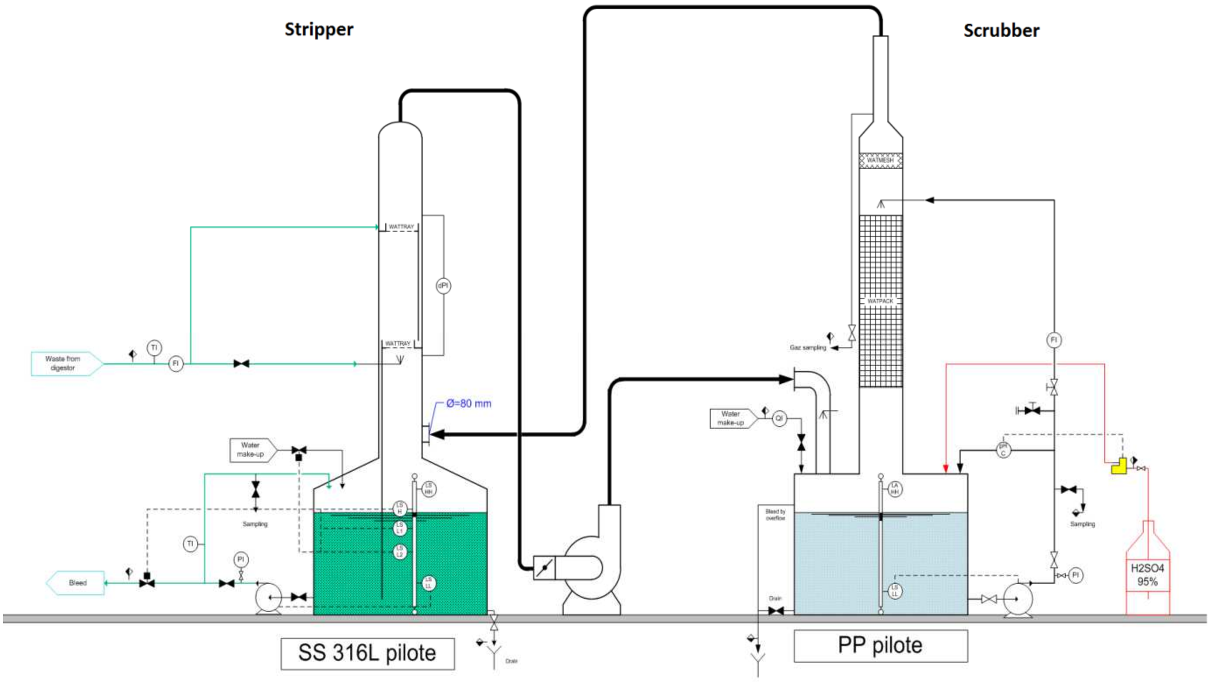

Figure 18: Schematic overview of the stripper-scrubber pilot.

Source: © Waterleau

Influence of pH

In a second testing phase, the influence of an increased pH was investigated. Two batch tests and one semi-continuous test showed that an increased pH has a slight positive effect on stripping efficiency, compared to the first series of testing where temperature influence was tested. Both a higher temperature and a higher pH have a positive effect on stripping efficiency.

3.11.2 End product

In the case of the Waterleau pilot plant, the end product is ammonium sulphate ($(NH_4)_2SO_4$) which can be used as an **inorganic N-S fertiliser**. If the stripped ammonia came into contact with, e.g. a nitric acid solution, the end product would be ammonium nitrate, which can also be used as an inorganic fertiliser.

Figure 19: Schematic overview of the stripper-scrubber pilot.

Source: © Waterleau

3.11.3 Stage of development

The target of the pilot test was to determine optimal set-up and conditions for the stripper/scrubber system for digestate treatment with the highest ammonia removal efficiency and the best separation of useful fertiliser products.

An additional evaluation of temperature increase to about 75 to 80 °C is a potential next step in the pilot testing. At these temperatures, nutrient recovery can be combined with hygienization of the fertiliser products. According to Bonmatí and Flotats (2003), it is possible remove the whole of the ammonia from the liquid fraction without any pH modifications at a temperature of 80°C. This would imply that there is no need for the addition of pH-increasing chemicals to reach maximum stripping efficiency. By increasing the temperature, the solubility of heavier precipitates ($CaPO_4$, $MgPO_4$, etc.) increases accordingly. Some of these precipitation reactions will lead to the formation of useful fertiliser products but these reactions might also contribute to increased fouling of the system. When optimizing process parameters this also has to be allowed for. In a recent set of tests, Waterleau used the stripping unit to strip raw influent during a hygienization step to reduce the amount of nitrogen that goes into the digester unit. Initial results show that a pH rise is also necessary to achieve sufficient stripping.

Future efforts should aim at attaining a maximum dry matter content of $(NH_4)_2SO_4$ at the scrubber outlet. This has a positive influence on transport costs and meets a number of practical demands from fertiliser end users. A high dry matter content also induces the crystallization of the $(NH_4)_2SO_4$ facilitating the harvesting process. In the current set-up, crystallization could not be achieved. The trouble is that the scrubbing unit is about 4 times the size of the stripping unit, which has a negative effect on $(NH_4)_2SO_4$-concentrations at the scrubber outlet.

3.11.4 Useful contact(s) for further information

Waterleau New Energy - Waterleau (Belgium)

Email addresses: stephan.tjonck@waterleau.com, ron.gerards@waterleau.com

3.12 Phosphorus precipitation (Aquafin pilot installation)

The precipitation of orthophosphate as struvite (magnesium ammonium phosphate, $MgNH_4PO_4.6H_2O$) is one of the most common P recovery strategies. However, up to now this technique has mainly been applied to water instead of sludge. At the WWTP of Leuven (120,000 inhabitant equivalent), operated by Aquafin n.v., a full scale phosphorus (struvite) recovery plant, developed and patented by © NuReSys, was used to process digested sludge for the first time (Marchi et al., 2015). The plant is shown in **Figure 20**.

Figure 20: Picture of the pilot plant of struvite production designed by Aquafin.

Source: © Aquafin

3.12.1 Description of the technique

The digested sludge first passes a cutter. As shown in **Figure 21**, the precipitation process itself consists of a CO_2 stripper tank in order to increase the pH and a crystallization reactor in which $MgCl_2$ is dosed. Subsequently, the sludge moves into the harvester, which allows a partial separation of the crystals from the sludge by means of a cyclone. The retained crystals can either be harvested or recirculated to the reactor. After one year of operation, an efficiency of 80 % of orthophosphate removal in the digested sludge between inlet and outlet of the struvite reactor was achieved. The process allows a maximum recovery potential of 15 % of the total phosphorus load of the plant (Marchi et al., 2015).

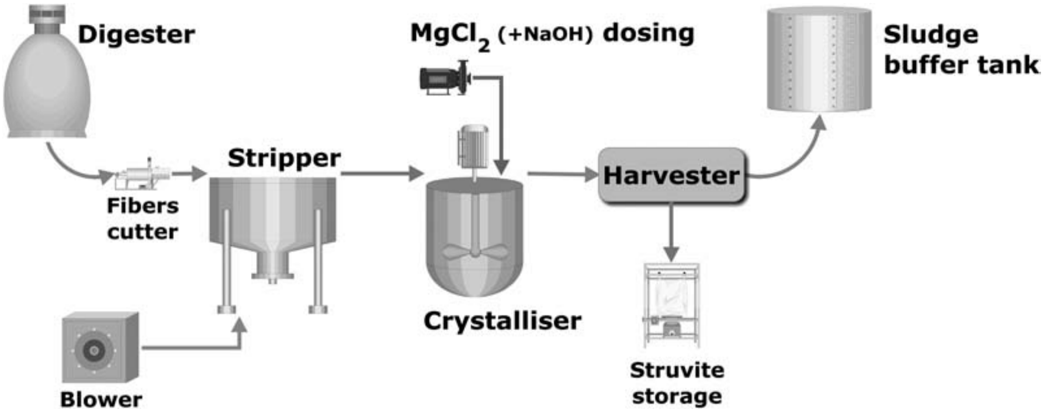

Figure 21: Schematic overview of the struvite precipitation process applied to digested sludge from the Aquafin WWTP.

Source: © Aquafin, Geerts S. et al., (2015)

Compared to an implementation on water phases, the following operational benefits – specific to implementation on digested sludge – were identified within the first year of full-scale operation by Marchi et al. (2015):

(1) an average enhanced sludge dewater-ability of 1.5 % yielding energy savings when the sludge gets transported, mono-incinerated or dried afterwards (due to the diminished quantity of water to transport or evaporate);

(2) a reduced phosphorus content in the dried sludge pellets of about 5-10 % in case of subsequent drying. In Belgium, dried sludge can be recovered in the cement industry. A lower P-content has a positive influence on the hardening properties of the cement and can be considered an improvement (Husillos Rodriguez et al., 2013).

Further operational benefits include:

(3) a reduced scaling: natural struvite precipitation in digested sludge lines are known to cause operational problems like pipe clogging and valve freezing, requiring regular and time-consuming pipe maintenance (Munch and Barr, 2001). The struvite process operation strongly decreases the orthophosphate concentration (and, to a lesser extent, the ammonium concentration) and thus reduces the speed of scaling following the process. The scaling reduction was not quantifiable during the first year of full-scale operation;

(4) a reduction of the P and N loads in wastewater. This leads to a decrease in aeration (needed for nitrification) and carbon source consumption (sometimes needed for the Bio-P removal and/or for denitrification). P in the recycled water was halved when applying struvite recovery from digested

sludge. A reduction is also obtained with the implementation of struvite recuperation from wastewater and not only from digested sludge.

3.12.2 End-product

The end product is struvite ($MgNH_4PO_4.6H_2O$), a slow release P-fertiliser. By analyzing the elements N, H, Mg and P, the ratio of $Mg:NH_4:PO_4$ could be calculated and compared with the theoretical ratio of struvite. It is clear that the produced struvite has a high degree of purity, as the measured values approach the theoretical values (Marchi et al., 2015). The appearance of struvite crystals is shown in **Figure 22**.

Figure 22: Struvite crystals obtained through the process of Aquafin.

Source : © Aquafin

3.12.3 Stage of development

The main obstacle to applying this technique to sludge is the difficult separation of the crystals from the sludge. Optimization research of the process should be further explored with a view to increasing the crystal size and thus improving the recovery rate. To date, the harvester at the Leuven WWTP could actually recover around 25 % of the precipitated struvite. The reduction of the struvite scaling speed further to the process is desirable, but the beneficial impact on pumps and dewatering devices should be evaluated over a longer period (Marchi et al., 2015).

Whether it is safe to use in agriculture should be assessed by means of plant assays and phytotoxicity tests over a long period of time. Furthermore, this full-scale experience should contribute to determining the best way to recover P from municipal wastewater: from centrate, digestate or at the end of sludge life from incinerated sludge ashes. This is currently under investigation within the wastewater sector and needs further discussion (Marchi et al., 2015).

3.12.4 Useful contact(s) for further information

Aquafin (Belgium)

Email addresses: sam.geerts@aquafin.be, adrien.marchi@aquafin.be, marjoleine.weemaes@aquafin.be

4 List of useful contacts

BELGIUM

Aquafin

Dijkstraat 8, 2630 Aartselaar

Contacts: Sam Geerts, sam.geerts@aquafin.be ; Adrien Marchi, adrien.marchi@aquafin.be ; Marjoleine Weemaes, marjoleine.weemaes@aquafin.be

Ampower bvba

Brugsesteenweg 176, 8740 Pittem

Contact: delabie.stefaan@gmail.com

Biogas Bree bvba

Houterstraat 1, 3960 Bree

Contact: info@biogasbree.be

Biogas-E vzw

Graaf Karel de Goedelaan 34, 8500 Kortrijk

Contacts: Bram de Keulenaere, bram.de.keulenaere@biogas-e.be; info@biogas-e.be

DLV Inno Vision ESV

Rijkelstraat 28, 3550 Heusden-Zolder

Contact: Lies Bamelis, lies.bamelis@dlv-innovision.be

Gembloux Agro-Bio Tech – University of Liège

Passage des Déportés 2, 5030 Gembloux

Contacts: Frank Delvigne, f.delvigne@ulg.ac.be ; Cédric Tarayre, cedric.tarayre@ulg.ac.be

University of Ghent, Faculty of Bioscience Engineering

Coupure Links 653, 9000 Gent

Contacts: Erik Meers, Erik.Meers@UGent.be ; Evi Michels, Evi.Michels@UGent.be

Vlaams Coördinatiecentrum Mestverwerking (VCM)

Abdijbekestraat 9, 8200 Bruges

Contact: info@vcm-mestverwerking.be

Waterleau

Waterleau New Energy, Bargiestraat 4, 8900 Ieper

Contacts: Stephan T'Jonck, stephan.tjonck@waterleau.com ; Ron Gerards, ron.gerards@waterleau.com

FRANCE

Association d'initiatives Locales pour l'Energie et l'Environnement (AILE)

Rue de Saint-Brieuc CS 56520, 35065 Rennes

Contacts: Adeline Haumont, adeline.haumont@aile.asso.fr

Bionerval

Avenue de la Sablière, 91150 Étampes

Contact: Philippe Spannagel, philippe.spannagel@bionerval.fr

CMI Europe Environnement (contact stripping)

Rue des Pins 1, 68700 Aspach-Le-Haut

Contact: europe.environnement@cmigroupe.com

IFIP-Institut du porc

La Motte au Vicomte, 35650 Le Rheu

Contact: Pascal Levasseur, pascal.levasseur@ifip.asso.fr

K-Revert

Impasse des Orvets 75, 38300 Saint-Savin

Contact: Julien Brochier, Julien.brochier@k-revert.fr

Laboratoire Départemental d'Analyses et de Recherche

Pôle du Griffon, Rue Pierre-Gilles de Gennes 180, Barenton-Bugny, 02007 Laon Cedex

Contact: Fabrice Marcovecchio, fmarcovecchio@aisne.fr

UNITED KINGDOM

AeroThermal Group Ltd

Dawkins Rd H1A-H1B, BH15 4JY Poole

Contact: see the website *www.aerothermalgroup.com*

Scottish and Southern Energy (SSE)

Inveralmond House, Dunkeld Rd 200, PH1 3AQ Perth

Contact: see the website *www.sse.com*

University of Leeds

Faculty of Engineering, LS2 9JT Leeds

Contacts: Miller A. Camargo-Valero, M.A.Camargo-Valero@leeds.ac.uk ; Andrew B. Ross, A.B.Ross@leeds.ac.uk

5 Bibliography

Barnes, S. (2012). WORLD FIRST: AUTOCLAVING FOR ADVANCED DIGESTION [Online]. Available at http://www.waste-management-world.com/articles/print/volume-14/issue-1/wmw-special-biowaste-focus/world-first-autoclaving-for-advanced-digestion.html.

Beste Beschikbare Technieken (BBT) voor composteer - en vergistingsinstallaties. emis.vito.be. [Online] 2005. http://emis.vito.be/bbt-studie-composteer-en-vergistingsinstallaties.

Biogas Plus, year not specified. Drying and pasteurization of digestate, manure, sludge, mais and wood chips. Online http://www.biogasplus.nl.

Biogreen, year not specified. Beltomatic© Continuous Belt Dryer. Online http://www.biogreen-energy.com/biogreen/belt-dryer/.

Bonmatí, A., Flotats, X. (2003). Air stripping of ammonia from pig slurry: characterisation and feasibility as a pre- or post-treatment to mesophilic anaerobic digestion. *Waste Manag*. 23 : 261–272.

Chambers, B (2011). Digestate Utilisation on Agricultural Land. ADAS. *In:* AQUAENVIRO, ed. Digestate Use and Management - Associated Opportunities, London, UK. AquaEnviro.

Debuchy, C. (2011). Engrais minéraux issus de l’organique, intérêts et limites. 18èmes rencontres professionnelles RITTMO agroenvironnement.

Faessel, L. (2013). Le biochar, un nouvel intrant pour les supports de culture? XXIe rencontres professionelles RITTMO agroenvironnement.

Geerts, S., Marchi, A., Weemaes, M. (2015). Full-scale phosphorus recovery from digested wastewater sludge in Belgium – part II: economic opportunities and risks. *Water Sci. Technol.* 71 : 495–502.

Husillos Rodriguez, N., Martinez-Ramirez, S., Teresa Blanco-Varela, M., Donatello, S., Guillem, M., Puig, J., Fos, C., Larrotcha, E., Flores, J. (2013). The effect of using thermally dried sewage sludge as an alternative fuel on Portland cement clinker production. *J. Clean. Prod.* 52 : 94–102.

Lebuf, V., Accoe, F., Van Elsacker, S., Vaneeckhaute, C., Michels, E., Meers, E., Ghekiere, G., Ryckaert, B. (2013). Techniques for nutrient recovery from digestate.

Marchi, A., Geerts, S., Weemaes, M., Schiettecatte, W., Vanhoof, C. (2015). Full-scale phosphorus recovery from digested waste water sludge in Belgium - part I: technical achievements and challenges. *Water Sci. Technol.* 71 : 487–494.

Munch, E. V., Barr, K. (2001). Controlled struvite crystallisation for removing phosphorus from anaerobic digester sidestreams. *Water Res.* 35 : 151–159.

Pell Frischmann, C. (2012). Enhancement and treatment of digestates from anaerobic digestion. Waste & Resources Action Programme.

Poirier, M.R., Noratok, M.A., Fink Westinghouse, S.D. (2002). Evaluation Centrifuges for Solid-Liquid Separation in the SRS Salt Processing Program. SC 29808.

Schwarz Global Consulting, year not specified. Belt presses. Online http://www.sgconsulting.co.za/industrial-equipment/flottweg/flottweg-belt-presses/.

Verhoeven, J.T.W. INEMAD – Inventory Report: Applied technologies and strategies for nutrient and agro-energy management in all countries. . s.l.: Wageningen UR – Applied Plant Research, Wageningen., 2013.

VINCENT Corporation, year not specified. Manure Series KP Screw Presses. Online www.vincentcorp.com.

Waeger, F., Delhaye, T., Fuchs, W. (2010). The use of ceramic microfiltration and ultrafiltration membranes for particle removal from anaerobic digester effluents. *Sep. Purif. Technol*. 73 : 271–278.

Waste & Resources Action Programme (2012). Enhancement and treatment of digestates from anaerobic digestion.