

Nutrient recovery from digestates: techniques and end-products

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SUMMARY

In nitrate vulnerable zones application of animal manure to land is limited. Digestate from anaerobic digestion plants competes with manure for nutrient disposal on arable land, which forms a serious hinder for the biogas sector to develop in these regions. Hence, one of its biggest challenges is to find cost-effective and sustainable ways for digestate processing or disposal. Furthermore, primary phosphorus resources are becoming scarce and expensive and will be depleted within a certain time. This urges the need to recycle P from secondary sources, like digestate or manure. From a sustainability point of view, it seems therefore no more than logical that digestate processing techniques switched their focus to nutrient recovery rather than nutrient removal.

This paper gives an overview of digestate processing techniques, with a special focus on nutrient recovery techniques. In this paper nutrient recovery techniques are delineated as techniques that (1) create an end-product with higher nutrient concentrations than the raw digestate **or** (2) separate the envisaged nutrients from organic compounds that are undesirable in the end-product, with the aim to produce an end-product that is fit for use in chemical or fertiliser industry or as a mineral fertiliser replacement.

Various nutrient recovery techniques are described, with attention for some technical bottlenecks and the current state of development. Where possible, physicochemical characteristics of the endproducts are given.

ABBREVIATIONS

CHP: Combined heat and power generation
DAF: Dissolved air flotation
ED: Electrodialysis
LF: Liquid fraction of the digestate
MAP: Magnesium ammonium phosphate (struvite)
MF: Microfiltration
RD: Raw digestate before separation
RO: Reversed osmosis
SF: Solid fraction of the digestate
TMCS: Trans-membrane-chemosorption
UF: Ultrafiltration
WSA: Water sparged aerocyclone

1. INTRODUCTION

The European Nitrate Directive, implemented in 1991, is intended to improve water quality in Europe by preventing pollution of ground- and surface water by nitrates from agriculture. The Directive originates from the fact that the use of nitrates in organic and mineral fertilizers is an important cause of water pollution in Europe. Through the Directive member states were obliged to set up an action programme and define vulnerable zones.

Because of the presence of intensive livestock production and the limited amount of arable land for manure disposal, nitrate pollution in Flemish water bodies is considerable. In 2000 the obligation to process manure was added to the manure action plan at that time (Manure Action Plan 2b). Manure processing is defined as treating manure in such a way that the N present is not brought back on Flemish soil after treatment, so that it is either exported or converted to nitrogen gas or a mineral fertiliser. Additionally, in response to the judgment of the Court of Justice from 22 September 2005, the Flemish minister of environment decided to define Flanders entirely as a nitrate vulnerable zone, with animal manure application limited to 170 kg N/ha. Because there is very limited area to spread out raw digestate, anaerobic digestion plants in Flanders and other nutrient rich areas have no other choice than to investigate and invest in digestate processing techniques.

More recently, the focus in the development of manure and digestate processing techniques has switched to techniques that recover a maximal amount of the present nutrients (N, P, K) and produce dischargeable or re-useable water. This development is i.a. triggered by the increasing worldwide awareness of the depletion of phosphorus and potassium, which are nowadays extracted through mining. Another incentive are the volatile prices of mineral fertilizers, due to the increasing costs of fossil energy. Estimates of the current phosphorus and potassium reserves are highly uncertain, but based on population growth and future nutrient demand, it is predicted that phosphorus and potassium will be depleted in 93 to 291 years for P and 235 to 510 years for K (Fixen and Johnston, 2012; Van Vuuren et al., 2010; Villalba et al., 2008; Smit et al., 2009).

These findings have led to the important challenge for anaerobic digestion plants in nutrient-rich regions to achieve optimal recovery and recycling of nutrients from the digestate in a sustainable way. There are currently two ongoing projects in Flanders that focus on this matter: ARBOR and NUTRICYCLE. ARBOR is an Interreg IVb-project that focusses on the acceleration of the development of bio-energy in North-West Europe. One of the goals is to make an inventory of existing nutrient recovery techniques from digestate in Europe and to stimulate marketing of the end-products by means of i.a. physicochemical characterisations and field trials. NUTRICYCLE is a Flemish MIP3-project that focusses on production of green fertilizers (biobased fertilizers instead of fossil-based fertilizers) from manure and digestate. Pilot plants are installed to test ammonia stripping and thorough separation. Lab tests are performed on struvite precipitation.

The aim of this paper is to give an overview of the inventory made in the framework of the ARBOR project. It shows how digestate can be used as a sustainable source of nutrients. A distinction has been made between state of the art digestate processing techniques and nutrient recovery techniques, the latter being in an earlier phase of development, but very promising with respect to the demand for more sustainability in agriculture.

2. DIGESTATE PROCESSING TECHNIQUES

There is a diverse range of techniques suitable for digestate processing (see 2.1), but certainly not all of them are to be considered as a nutrient recovery technique. Although there is no straightforward definition of a nutrient recovery technique these techniques will be delineated in this paper as techniques that (1) create an end-product with higher nutrient concentrations than the raw digestate **or** (2) separate the envisaged nutrients from organic compounds, with the aim to produce an end-product that is fit for use in chemical or fertiliser industry or as a mineral fertiliser replacement. This makes it possible to re-use the present nutrients and close the nutrient cycle.

In 2.1 the techniques that are delineated by the author as a nutrient recovery technique are indicated in grey.

2.1 Schematic overview of digestate processing techniques

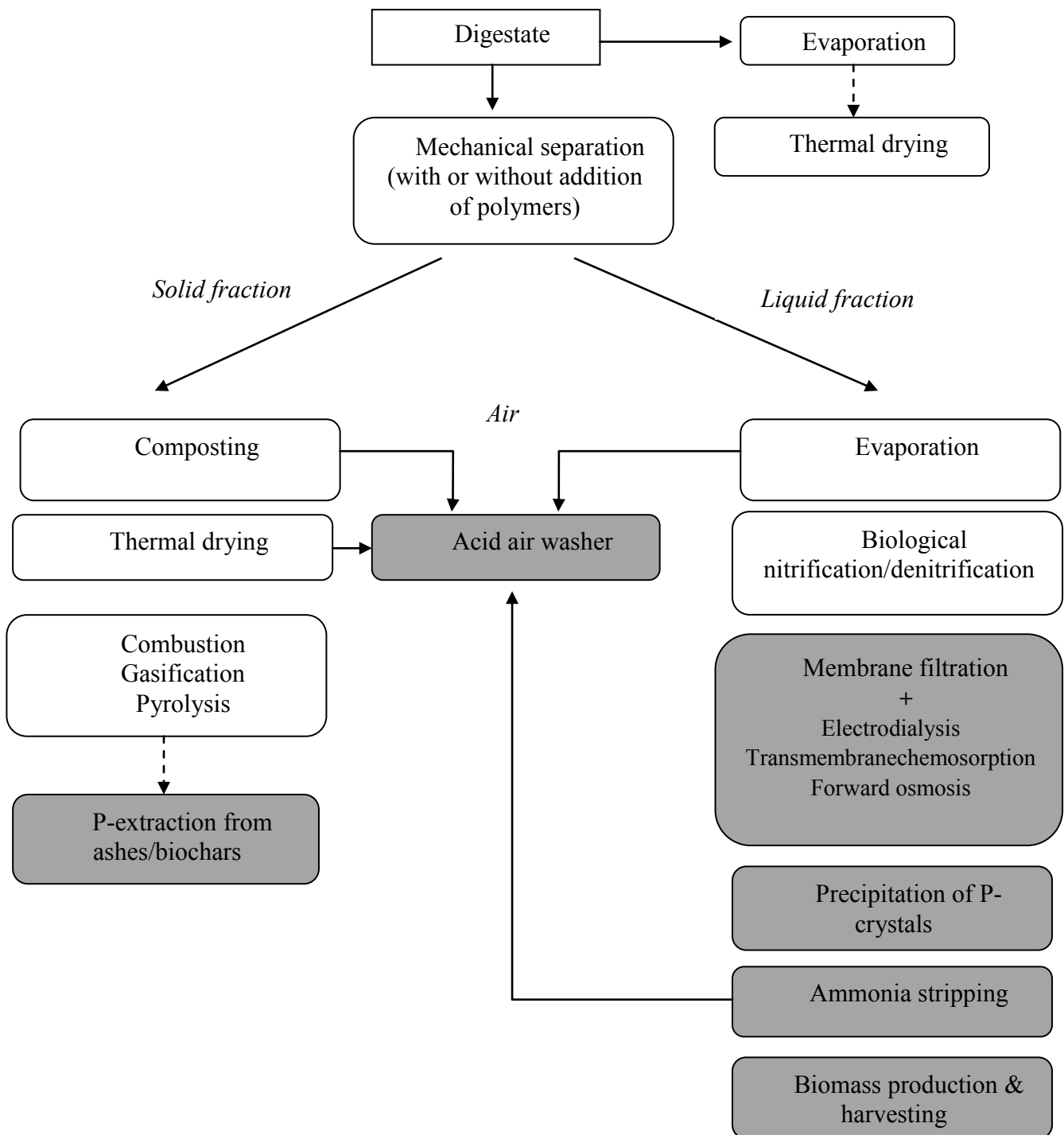


Fig. 1: Schematic overview of digestate processing techniques (grey: nutrient recovery techniques)

Digestate is often primarily separated into a liquid fraction (aqueous solution) and a solid fraction (resilient organic matter). The solid fraction offers limited possibilities to recover nutrients, since they are largely organically bound. Soluble N, P, K, and organics as well as mineral salts are present in the liquid fraction. These soluble nutrients show quite some potential for further extraction techniques.

2.2 General digestate processing techniques: short description

Since the general digestate processing techniques are not the main focus of this paper, only a short general description is given in this chapter.

2.2.1 Mechanical separation

Separation techniques for manure are well-developed. Different types are available on the market: drum filters, screw presses, filter belt presses and centrifuges.

A parameter that indicates a good separation is the dry matter content of the solid fraction, which should preferably be >25% to obtain a stackable and transportable product. For further processing of the liquid fraction, it is also preferable to have the lowest concentration of suspended solids as possible, since they can cause fouling and blocking of membranes in filtration processes.

As P application to soils is restricted to 75-95 kg P₂O₅/ha and will further be reduced coming years, there is very limited possibility to market P for direct agricultural use in Flanders. This implies that the P-content in the liquid fraction should be as low as possible, to create a P-low but N-rich fertilizer. Hence, the P-concentration in the solid fraction is also an important parameter for a good separation.

In the MIP project Nutricycle, which was mentioned in the introduction, thorough separation of digestate by means of either a belt press or a centrifuge is being tested. Different conditioning processes to pretreat the raw digestate are used to achieve a more efficient separation. The main difference with classical separation is that the conditioning process before flocculation makes it possible to retain almost all suspended solids in the solid fraction, as well as up to 98% of the P and 94% of the COD. As with classical separation the NH₄-N fraction remains in the liquid fraction whilst the organically bound N is mainly present in the solid fraction.

During the project labtests and full scale tests will be performed, new coagulants will be developed and there will be a physicochemical characterisation of the end-products followed by field trials on the fertilising value of the produced NK-fertilizer as a replacement for mineral fertiliser (Personal communication, B. Aerts, Kemira).

Although mechanical separation creates an end-product (i.e. the solid fraction) with higher nutrient concentrations than the raw digestate, it is not considered as a nutrient recovery technique because it is merely a first step that facilitates further processing.

2.2.2 Composting of the solid fraction

The composting process is well-known and involves the conversion of organic matter into CO₂ and water by micro-organisms. The heat that is produced causes the water to evaporate, which, together with the breakdown of organic matter, results in a serious mass- and volume reduction. Before composting digestate is mixed with other input streams, such as wood shavings, straw,

road shoulder grasses or dried chicken manure, to optimise the C/N ratio.

The composting process is seldom performed at farm-scale or on-site. It is a specialized process, involving a precise monitoring of several process parameters and is generally performed at centralized sites.

2.2.3 Thermal drying

Anaerobic digestion sites often have to cope with a considerable amount of heat produced by the CHP. This heat is partially used for the digesting process and can also be used to heat nearby stables or houses. However, many installations have found that drying the raw digestate or the solid fraction is an economically viable way to use the extra heat because an end-product is created that is strongly reduced in volume and stabilised in such a way that it is suitable for export. Because there is limited space in nutrient-rich areas to spread out a fertilizer with a high P-content, the dried digestate is almost always exported, either in its pure form or after pelletisation to reduce transport costs, facilitate logistics and application to the field.

2.2.4 Combustion, gasification and pyrolysis of the solid fraction

Combusting solid fraction digestate is not possible without previous drying. A dry matter content of 85-95% should be obtained before starting combustion. The goal of combustion could be to produce electricity from the released energy and to recover nutrients (mainly P) from the ashes. Also a strong reduction in volume is obtained and pathogens are killed. However, a thorough flue gas cleaning system is indispensable, which makes small-scale combustion not viable.

Furthermore, digestate is considered a waste stream that is eligible for recycling as soil conditioner, which makes it not eligible for combustion according to Flemish legislation. On the other hand, animal manure, which is not waste but biomass, can be combusted, taking into account the emission standards (Art. 4.5.2., VLAREMA, 2012).

Gasification involves an incomplete combustion at 800-1000°C with a reduced amount of oxygen. This leads to the formation of syngas, biochar and bio-oil (Lemmens et al., 2006).

The pyrolysis process exposes the digestate to a temperature of 300-550°C in the absence of oxygen. Organic matter fractionates in syngas, bio-oil and biochar (Lemmens et al., 2006).

A large-scale poultry manure combustion plant is operational in Moerdijk in the Netherlands (BMC Moerdijk). On a yearly basis 440.000 tonnes of poultry manure at an average dry matter content of 58.35% is combusted, which produces 36.5MWe.

The resulting ashes/biochar offer opportunities for recycling of phosphorus, see 2.3.2.

2.2.5 Evaporation of the liquid fraction

Evaporation of the digestate is commonly used to concentrate the nutrients in the liquid fraction and seriously reduce digestate volume. A condensate is produced, which mainly consists of ammonia and some volatile compounds, but is salt-free. Acidification before evaporation ensures that the ammonia remains in the concentrate, but can cause foaming due to the release of carbon acid. Several evaporator types are on the market and used in large scale digesters. The produced concentrate remains fluid. To further increase the dry matter content, a drying step is needed (Lemmens et al., 2006).

2.2.6 Biological nitrification/denitrification

The main goal of the biological treatment is a reduction of the N-content, the BOD and to a lesser extent the P-content of the liquid fraction of the digestate. The process is an aerobic activated sludge process with a nitrification and a denitrification step. The sludge is recirculated, N₂ is blown into the air and the effluent is applied on the field by nearby farmers, whether or not after an evaporation step to reduce the volume (Lemmens et al., 2006).

2.3 Nutrient recovery techniques: technical description, opportunities and bottlenecks

This chapter gives an overview of the so-called nutrient recovery techniques, as defined in the introduction of chapter 2. This inventory is non-limitative and further information will be added during the course of the ARBOR-project.

An overview of the state of development of these techniques, as well as some features of the end-products are given in Table 1.

Table 1: Overview of techniques and end-products

NUTRIENT RECOVERY TECHNIQUE	STARTING FROM	END-PRODUCT(S)	CHARACTERISTICS OF END- PRODUCTS	STATE OF DEVELOPMENT FOR DIGESTATE
Acid air washer	Strip gas	(NH ₄) ₂ SO ₄ solution	(NH ₄) ₂ SO ₄ solution : N-content 30-70 kg/m ³ , pH 3-7 ^{1, 2}	Full scale
P-extraction	Ashes/biochar	Acid P-extract/CaHPO ₄	Acid P-extract: P _{tot} : 0.192 g/kg ³	Full scale for ashes from incinerated sludge from wastewater treatment Lab scale for digestate treatment
Reversed osmosis	UF/MF/DAF-permeate	RO-concentrate (NK-fertilizer)	N _{tot} : 7.3 g/kg ⁴ K _{tot} : 2.9 g/kg ⁴ P _{tot} : 0.42 g/kg ⁴	Full scale
Forward osmosis	Further research needed	FO-concentrate (NK-fertilizer)	Further research needed	Full scale for desalination, food processing,... Starting interest for digestate treatment
Electrodialysis	LF	NK-fertilizer	Further research needed	Lab scale
TMCS	Tested on urine	NK-fertilizer	Further research needed	Pilot scale
P-crystallisation	Acidified RD/LF	MgNH ₄ PO ₄ /MgKPO ₄ /CaNH ₄ PO ₄	-	Full scale for veal manure & wastewater treatment Lab scale for digestate treatment
NH ₃ -stripping & acid air washing	(Decarbonated) LF	(NH ₄) ₂ SO ₄ solution	N-content: 350 kg/m ³ pH: 3-4 ⁵	Full scale
Biomass production	Diluted LF	Biomass	Further research needed	Pilot scale

¹ Personal communication, M. Heijmans, ZLTO

² Personal communication, N. Van Hemelrijck, LT Eco

³ Adam et al., 2009

⁴ Vaneeckhaute et al., 2012

⁵ Personal communication, K. Lembrechts, BioEnergy Lommel

2.3.1 Acid air washer

Thermal drying, composting, evaporation and certainly ammonia stripping result in emissions of dust particles, water vapour, ammonia and odour compounds. Air treatment is obligatory before emission to the environment. Often an acid air washer is used, which captures the NH_3 in sulphuric acid by means of a packed tower where sulphuric acid is sprayed with nozzles over the packing material and treatment air is blown into the tower in counterstream. Ammonium sulphate is produced and the wash water is recycled until it is saturated and the removal efficiency of ammonia cannot be guaranteed anymore. At that point the ammonium sulphate solution should be removed and fresh sulphuric acid added. The reject solution is variable in N-content and pH, due to the variable efficiency of acid air washers. The reject solution of acid air washers is recognised in Flanders and the Netherlands as a mineral fertiliser, but marketing is problematic, due to the variable content of N and often acid and corrosive features. It is also forbidden to mix slurry and ammonium sulphate in the slurry pit, due to the risk of H_2S release.

2.3.2 Phosphorus extraction from ashes/biochar

The remaining ashes after combusting digestate/manure contain P-, K-, Al- and Si-compounds and possibly also some heavy metals such as Cu, Zn and Cd. Several companies have designed different processes to extract phosphorus from the combustion ashes (Schoumans et al., 2010). The Finnish company Outotec for example adds MgCl_2 and heats the ashes to 1000°C to gasify the heavy metals. Phosphorus is bound as CaHPO_4 and is sold as a mineral fertiliser replacer (Outotec, 2012). Mattenberger et al. (2008) examined the influence of several parameters, such as additives, temperature and indirect or direct heating on the heavy metal removal efficiency during this process. They found that the best overall removal efficiency for Cd, Cu, Pb and Zn could be found for the indirectly heated system. The type of additive was critical, since MgCl_2 favoured Zn- over Cu-removal, while KCl acts conversely.

Concerning the fertilizing value of these thermally treated ashes, Adam et al. (2009) observed that the P-bioavailability was significantly increased due to the formation of new mineral phases such as chlorapatite, farringtonite and stanfieldite during thermochemical treatment.

The Belgian company EcoPhos developed a chemical phosphorus extraction process by adding HCl. On lab scale they have already tested this process on combustion ashes. The Swedish company EasyMining also developed a process that is suitable for ashes from incinerated manure and that is based on extraction with HCl.

In a fertiliser field trial with barley, Kuligowski et al. (2010) discovered that on sandy soils, relative agronomic effectiveness of neutralised sulphuric acid P-extract applied to barley is almost as high as for mineral fertiliser (disodium phosphate). They also state that raw ashes (without P-extraction) from thermal gasification or incineration are not suitable as starter P fertilizer for barley, but could be used to maintain the level of available P in soil.

Experiments with pyrolysis of manure cakes have been conducted. The fraction of nutrients recovered in biochar is larger than in ashes and the plant-availability of the nutrients tends to be higher, especially for phosphorus (Schoumans et al., 2010).

2.3.3 Concentration techniques for the liquid fraction involving membranes

2.3.3.1 Pressure-driven membrane filtration : microfiltration (MF), ultrafiltration (UF) & reversed osmosis (RO)

The input stream for membrane filtration is either the liquid fraction of the digestate or a pre-processed stream, such as the condensate of the evaporator. The input stream is forced through the membrane by means of a certain pressure. There are several types of membranes used in manure/digestate processing: MF- (pores $> 0,1 \mu\text{m}$, 0,1-3 bar), UF- (pores $> \text{nm}$, 2-10 bar) and RO-membranes (no pores, 10-100 bar). In a MF-concentrate suspended solids are retained, while in a UF-concentrate also macromolecules are retained. Both filtration steps are used as a pre-treatment for reversed osmosis, in order to prevent that either suspended solids or macromolecules block the RO-membrane. Another technique that is used prior to RO is dissolved air flotation (DAF), a technique that consists of blowing small air bubbles through the liquid fraction, entraining suspended solids to the surface where they form a crust. This crust is then scraped off. When using DAF coagulants and flocculants are often added.

The permeate of RO, which consists mainly of water and small ions, can be discharged, if necessary after a 'polishing' step, or used as process water.

The biggest problem reported in membrane filtration is the blocking of the membrane, which increases the hydraulic resistance. During MF and UF, this is mainly caused by suspended solids that form a cake on the surface of the membrane. Higher tangential velocities on the cross-flow stream can prevent the membranes from blocking but imply higher operational costs. Waeger et al. (2010) stress that blocking of the pores is strongly correlated to particle size distribution.

The efficiency of RO-membranes can decrease because of several reasons: 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 colonise the membrane (biofouling). Scaling can be prevented by regulating pH and using anti-scalants. Once too many pores are blocked, the membrane should be cleaned using chemicals such as NaOH and H_2SO_4 . Biofouling is very hard to remove and should be avoided at all times.

In the Netherlands a large research project is ongoing since 2008 with the permission of the European Commission on the RO-concentrate of 8 different manure/digestate processing installations. In this research project, called 'pilot mineral concentrates' the agronomic, economic and environmental effects of the production and use of mineral concentrates as mineral fertiliser replacement is investigated (Velthof, 2011a). The 8 installations use as a pre-treatment to RO either an ultrafiltration or a dissolved air flotation step (DAF).

2.3.3.2 Forward osmosis

During the last couple of years there has been an increased interest in forward osmosis as opposed to reversed osmosis. In forward osmosis there is also a semipermeable membrane, but no external pressure. The water flow is obtained by imposing an osmotic pressure by means of a draw solution such as NaCl.

Forward osmosis can be an interesting technique for use in wastewater treatment, food processing and seawater desalination, but also for the concentration of digested sludge. Evolutions in the near future will show how promising this technique could be in

manure/digestate processing.

2.3.3.3 Electrodialysis (ED)

During electrodialysis ammonia in the diluate solution is transferred by electromigration to an adjacent solution by an ion-exchange membrane under the driving force of an electrical potential. This means that the main ionic compounds in the liquid digestate (in the diluate cells) i.e. NH_4^+ , K^+ and HCO_3^- were transferred and concentrated.

Mondor et al. (2007) studied the use of electrodialysis as a pre-treatment to RO. Different types of ED membranes were evaluated based on the NH_4^+ transfer rate and membrane stability. The result of the total treatment suggested that the use of ED and RO membranes to recover and concentrate ammonia is potentially interesting but that the process must include an approach to minimise ammonia volatilization. Ippersiel et al. (2012) used ED as a pre-treatment step to ammonia stripping without pH modification. An optimal process operating voltage of 17,5V was determined. Total ammonia nitrogen in the concentrate solution reached approximately seven times the concentration in the swine manure. The maximum achievable total ammoniacal nitrogen concentration in the concentrate solution was limited by water transfer toward the concentrate solution by osmosis and electro-osmosis.

2.3.3.4 Trans-membrane-chemosorption (TMCS)

This process is used in pig slurry treatment systems in the Netherlands, where the ammonia is stripped and removed using TMCS. Ammonia is brought in the gaseous phase by means of a pH increase. The ammonia diffuses through a hollow-fibre membrane with gas-filled pores and is captured at the other side of the membrane in a sulphuric acid solution.

2.3.4 Phosphorus precipitation from the liquid fraction

Several ions can be added to a solution containing soluble phosphate (orthophosphate) to induce a precipitation reaction forming phosphate salts. Addition of calcium to a phosphate solution will form calcium phosphate. Addition of magnesium or potassium provides the opportunity to remove both ammonium and phosphorus, if pH is adjusted to 9-11, in the form of either MgNH_4PO_4 (MAP or struvite) or $\text{K}_2\text{NH}_4\text{PO}_4$ (potassium struvite). Struvite is thought to be a slow-release fertilizer (Anonymous, 2006).

The research on struvite is excessive in determining how to avoid struvite scale from forming in the piping and equipment of wastewater treatment plants and agricultural waste systems. In the recent years however, interest is shifting to the potential of struvite for P-recovery from waste streams, slurries and digestate. In i.a. the Netherlands and Japan sophisticated reactors have been developed to form larger pellets than in the simpler systems with less regard to the quality of the product formed. An important bottleneck could be the formation of fine particles that are hard to separate. This can be avoided by adjusting reactor design and process parameters (Anonymous, 2006). Wang et al. (2006) confirm that mixing strength and proper seeding materials increase crystal size and improve settling ability.

Examples of commercial struvite forming processes are the Crystalactor, developed by DHV in the Netherlands, ANPHOS developed by Colsen in the Netherlands, PHOSPAQ developed by Paques in the Netherlands, NuReSys developed by Akwadok in Belgium, Nutritec developed by Sustec in the Netherlands, SERMAP developed by Sereco Biotest in Italy and Pearl developed

by Ostara in Canada.

Researchers at the Fraunhofer Institute for Interfacial Engineering and Biotechnology in Germany have patented an electrochemical process to precipitate struvite without the addition of salts or bases. The mobile pilot plant consists of an installation with a magnesium anode and a metallic cathode. The electrolytic process splits the water molecules into negatively charged hydroxyl ions at the cathode. At the anode an oxidation takes place: the magnesium ions migrate through the water and react with the phosphate and ammonium in the solution to form struvite.

Current use of struvite precipitation is mostly limited to treatment of industrial and municipal wastewater. There is one full-scale system operating on calf manure in the Netherlands. Anonymous (2006) mentioned 3 bench scale and 1 pilot scale installation in the USA operating on hog manure.

Another option is the addition of $\text{Ca}(\text{OH})_2$. Because of pH and temperature increase ammonia is stripped out of the solution and should be scrubbed with an acid air washer. Quan et al. (2010) examined the coupling of $\text{CaNH}_4\text{PO}_4 \cdot 4\text{H}_2\text{O}$ precipitation and ammonia stripping in a water sparged aerocyclone reactor on lab scale. An example of a commercial calciumphosphate process is the PhoStrip process developed by Multi Umwelttechnologie AG from Germany.

Schoumans et al. (2010) mention that a significant P fraction is organically bound and present as phytates and lipids and may not end up directly as precipitates. They suggest an initial hydrolysis step in which organic compounds such as esters, amides and phospholipids will break down into smaller compounds. Daumer et al. (2010) investigated a process to be able to recover also the P that is bound in the organic matter by using acidification combined with solid/liquid separation. Pig slurry was acidified with formic acid and separated, resulting in a liquid fraction that contained the dissolved P. Formic acid was chosen as a reagent instead of the cheaper sulphuric acid, to avoid enriching the effluent with undesirable compound (chloride or sulphate), which increase salinity. Results were good and they concluded that the struvite product could be economically competitive with mineral fertilizer as superphosphate in less than 10 years.

A similar manure processing technique was developed by the Dutch company Ceres Milieutechniek. Their process uses a two-step digester, where the first step is an acidification that releases almost all phosphorus from its organic matrix. After this step manure is separated and the liquid fraction contains almost all ammonia, K and P. The solid fraction can be used as a nutrient-low compost. The liquid fraction is then digested (after a pH increase). The digestate then goes to a crystallisation reactor and a NK-effluent remains which can be further treated (Smit et al., 2012).

2.3.5 Ammonia stripping of the liquid fraction

Ammonia is stripped by blowing air through the liquid fraction in a packed tower. For optimal ammonia removal, the pH of the liquid fraction should be around 10 and the temperature around 70°C (Lemmens et al., 2006). However, Liao et al. (1995) observed that at a pH of 9,5 and 10,5 ammonia removal efficiency was directly dependent upon the air and liquid influent temperatures, whereas at a pH of 11,5 and a temperature of 22°C there was no appreciable improvement with a rise in air and influent temperatures. This led them to the conclusion that a pH of 10,5 is most optimal, as very high levels of nitrogen removal were obtained without incurring problems of excess lime. It was confirmed by Gustin and Marinsek-Logar (2011) that a

high pH has the most significant effect on stripping, whilst temperature had the least significant effect. However, according to Bonmati and Flotats (2003) complete ammonia removal without pH modification is possible at a temperature of 80°C.

During aeration of the digestate, there is quite a large risk of scaling and fouling of the packing material. To avoid scaling, one can install a lime softening step before stripping, which removes a large part of the Ca, Mg, carbonic acids and carbonates and increases the pH. To avoid fouling, it is important that during separation as many suspended solids as possible are retained in the solid fraction. Nonetheless, it is unavoidable that the packing material will have to be cleaned periodically.

The strip gas, which is charged with ammonia and volatile organic matter, is put in contact with a strong acid solution (H₂SO₄), which produces ammonium sulphate, as described in 2.3.1.

A combination of the ammonia stripping technique and struvite precipitation (see 2.3.5) was studied by Quan et al. (2010). Both processes were taking place simultaneously in a water sparged aerocyclone reactor (WSA). They claim that the WSA, in comparison to the traditionally used packed towers, is characterized by good mass transfer performance and self-clean function and is suitable for air stripping of wastewater with suspended particles at a temperature of 30°C and a pH > 11.

2.3.6 Biomass production in liquid fraction

In 2011 González-Fernández et al. inoculated four open ponds with microalgae-bacteria consortia to treat anaerobically digested pig slurry to observe nitrogen transformations in the ponds under realistic conditions of light and temperature. When digestate was fed to the ponds, nitrification followed by biomass uptake and denitrification were the main nitrogen transformations. In ACRRES (part of Wageningen UR) lab tests were performed where liquid fraction digestate was added to algae growing media. A maximal addition of 0.5% liquid fraction was observed. However, a second test involved the addition of small amounts of digestate to 25l cultures and it was observed that growth rate of the algae remained satisfactory (Personal communication, R. Schipperus, WUR).

Besides algae, macrophytes have also been studied to recover nutrients from digestate. Xu and Shen (2011) studied the use of duckweed (*Spirodella oligorrhiza*) for nutrient recovery from anaerobically digested pig slurry. During the growing season, the duckweed was capable of removing 83.7% and 89.4% of total nitrogen and total phosphorus respectively in eight weeks at a harvest frequency of twice a week.

The produced algae/macrophytes can serve as feedstock for chemical industry and biofuel industry or can be used as animal feed (provided that the necessary amendments in legislation are made) or spread out as a fertilizer on the fields. Nor in Flanders nor in the Netherlands there are commercial scale ponds operational at the moment that treat digestate or manure.

3. NEEDS FOR FURTHER RESEARCH

Most techniques that are described above are derived from the wastewater treatment sector where they are well-developed. Application of these techniques for digestate and manure treatment however, causes new technical bottlenecks. A lot of effort by several companies and research institutes is being put in solving these technical problems.

A research area that deserves more attention in the future, is the valorisation of the end-products and the economical evaluation of implementing nutrient recovery techniques in a centralised or decentralised approach. Both aspects are interlinked, because the added value of the end-products will affect the profitability of implementing such techniques. As discussed above, the end-products could either be used as a mineral fertiliser replacement or as a raw material for industrial processes. When farmers are the end-users, it is essential that the fertilising value of the end-product is demonstrated by incubation studies or field trials to assess plant availability of the present nutrients and the fitness of these products for several cropping systems. Industrial end-users also have both technical and regulatory requirements for the input streams of their production processes, which also have to be taken into account when valorising end-products in the industry.

Secondly, a clearly defined legislative framework is indispensable for future developments in the area of nutrient recovery techniques. Certain end-products have similar characteristics as mineral fertilisers, and if they would get the regulatory status of 'green' mineral fertilisers according to the EU regulations (EU Fertiliser regulation 2003/2003, which is currently under revision), this would enable to apply them on top of the 170 kg N/ha limit for animal manure and its derivatives. However, this issue is to be dealt with on a European level, as there are several member states with high nutrient excesses, all facing the same problem.

Finally, one of the most important topics in global policy making is the improvement of sustainability of processes worldwide. This leads to the proposition to further investigate environmental impact of digestate processing techniques. These may have some adverse effects on the environment, related to the consumption of fossil fuels, use of chemicals, possible ammonia emissions etc. However, if they could reduce mineral fertilizer production, this could mean a serious decrease in primary energy consumption. A thorough investigation and evaluation of these techniques by means of LCA could provide an objective base for further policy making.

4. CONCLUSIONS

In nutrient rich zones it has become inevitable for anaerobic digestion plants to invest in a digestate processing technique as only a small fraction of the digestate can be spread out on land. Because of increased attention for nutrient recycling and the depletion of phosphorus and potassium, digestate should be considered a valuable source of nutrients and treated accordingly.

Defining nutrient recovery techniques is not as straightforward as it seems. This paper proposes following definition: techniques that create an end-product in which nutrients are present in a higher concentration than before processing **or** those that separate the envisaged nutrients from organic compounds, with the aim to produce an end-product that is fit for use in chemical or fertiliser industry or as a mineral fertiliser replacement.

Out of the discussed nutrient recovery techniques, only acid air washers, membrane filtration plants and ammonia stripping plants are operative at full scale. However, they may need further

technical fine-tuning, especially towards energy saving and decreasing the addition of chemicals. A breakthrough in full-scale plants is to be expected for phosphorus crystallisation. In the long run also electrodialysis, forward osmosis, TMCS and biomass production could become part of commonly used digestate processing techniques. The extraction of phosphorus from ashes or biochars seems less promising, because it is questionable if combustion/gasification/pyrolysis of digestate is a sustainable treatment option and if this should be encouraged.

However, for all techniques described it is essential to put attention on fertilising value of the end-products or marketing value towards industrial end-users. To be economically profitable, the price allocated to the recovered nutrients should be in accordance to the market price of N, P and K in mineral fertilizers. Getting the regulatory status of “mineral fertiliser” is thus considered to be very important to achieve successful marketing of these products for agricultural use.

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