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First Author:	**Marieke Verbeke**
Co-author(s):	**Kimo Van Dijk, Claudio Brienza**
Name of the responsible WP Leader:	**Marieke Verbeke**
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Scenario’s and schemes of proven nutrient recovery and reuse techniques

Marieke Verbeke, Claudio Brienza, Kimo Van Dijk

Vlaams Coördinatiecentrum voor Mestverwerking, Bruges, Belgium

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Content

Preface

This public report is the final version of the report that bundles knowledge and information regarding the available full-scale proven and cost-effective nutrient recovery and reuse technologies (NRR) for digestate and related flows. Included is information about biogas plant feedstock types and composition, separation efficiencies, nutrient recovery efficiencies, end products types and characteristics.

This report is linked to and gives background information for the quantitative Excel tool for cost-benefit analysis for nutrient recovery and reuse (NRR) from digestate developed within the SYSTEMIC project. This tool can be used by existing and future biogas plants (operators) to assess the opportunities and barriers of implementing NRR from their digestate. The tool will help to determine if nutrient recovery is viable from a technical, operational and economic perspective. It will give a first impression on the potential business case, making clear if more specific and in depth assessment is worth to undertake.

The report presents a list of potential NRR cascades of techniques with anaerobic digestion (AD) as starting point. Cascades (e.g. schemes, trains) are a combination of techniques required for complete processing of a input flow into several output flows, including end products and by-products. A set of most used cascades with key techniques are included in the quantitative Excel tool for cost benefit analysis. These are cascades operational at full scale biogas plants at acceptable nutrient recovery rates: rates that are high enough to be economical viable and have shown business case potential.

The first version 0.1 of the NRR tool is now published together with the release of this report (31 January 2020). Among the required input data is the biogas plant feedstock quantity and composition, quantity digestate to be treated, operation hours, already installed separation technology, CAPEX and OPEX cost, polymer use, dry matter separation efficiency. In addition, a choice has to be made what biobased fertiliser product should be produced and consequently which linked NRR cascade had to be selected. As a result, the tool will present as an outcome the composition of the final end product(s), including dry matter (DM), nitrogen (N), phosphorus (P) and potassium (K) contents. Finally, the CAPEX investment and OPEX costs are provided in euro per year, split for the different technologies to be installed. OPEX costs are specified for the components energy, polymers, chemicals and operations costs. As input data the user can select and fill in own data based on the existing situation at their own plant. If not available or if a complete new NRR system should be developed, default data can be chosen from the tool.

A simplification of reality was made to keep the tool simple in use. During the development of the tool many assumptions were made, partly because data availability on novel NRR technology was limited. Data used in the tool calculations were as much as possible based on the SYSTEMIC Access database for nutrient recovery and reuse presented in this report. This database makes use of data sourced from literature and existing biogas plants. Examples of data covered and used are feedstock types and composition, separation efficiencies, nutrient recovery efficiencies, end product types and characteristics, and investment costs for technologies. The filled in information and data by users using the tool, will be used to get more and better data in the SYSTEMIC NRR database presented in this report and used as source of data in the tool.

Within the SYSTEMIC project, the Excel tool with NRR cascades is used as a starting point of discussion with the Demo Plants, Outreach Location plants and Associated Plants. Together with the Outreach Location plant owners and operators, a company specific business case with the inclusion of nutrient recovery is modelled and developed. The tool can be used in an interactive way, creating opportunities for learning among people from one biogas plant, among plant operators of different plants, and between biogas plants and the SYSTEMIC project tool development team. Experiences and feedback from users and workshops are used to improve the tool which will be incorporated in new versions of the tool.

The SYSTEMIC quantitative Excel **tool version 0.1** for cost-benefit analysis for nutrient recovery and reuse from digestate can be downloaded here: https://systemicproject.eu/living-labs/

Summary

The information compiled in this report will be focussing on the recovery rate or efficiency of current full scale proven nutrient recovery and reuse (NRR) techniques.

Data on recovery rates, separation efficiencies of full scale NRR techniques, the composition of feedstocks, digestates, and end-and by-products of these NRR techniques was looked for in scientific publications. Also existing biogas plants, including Demo Plants, Outreach Locations and Associate Plants were approached for acquiring this information.

The NRR technologies appearing frequently in the database were identified:

- Liquid-solid separation techniques
- Nitrogen (ammonia) stripping-scrubbing
- Evaporation and condensation
- Phosphorus stripping and precipitation
- Drying

These technologies are operational on full scale in different configurations. Combinations of these technologies ultimately led to the selection of 21 technology cascades, that are to be used in the Excel tool.

These 21 cascades are implemented in existing biogas plants or include a variation on the pre-treatment of the digestate.

The end products from these cascades include:

- Liquid fraction of digestate
- Solid fraction of digestate
- Mineral concentrate after membrane filtration-reversed osmosis
- Dischargeable water
- Nitrogen poor product
- Ammonia water
- Ammonium sulphate solution
- Phosphorus salts
- Phosphorus poor product

Other technologies were not included in the excel tool, because they did not allow to approach an average recovery rate with little variation due to lack of data or high variation due to different feedstocks or operational conditions. The technologies include:

- Biothermal drying/composting
- Biological nitrification-denitrification
- Struvite precipitation
- P-stripping by the BioEcoSIM process

Yet, these technologies are described in this report, because they have an important role to play in the future or during the transition to circular economy.

1. Creating the database

1.1 Targeted information

The information compiled in this report will be focussing on the recovery rate or efficiency of current full scale proven nutrient recovery and reuse (NRR) techniques.
The recovery rate is defined as the percentage of the initial amount of organic matter, nutrients and minerals (N, P, K) that are recovered into the end product.
The same description is valid for the separation efficiency when a separation technique is used.
Technology efficiency (Et)=(mass output x concentration output) / (mass input x concentration input)

In addition to the recovery rates, data was also be gathered on the different feedstock, the composition of the digestate and the quality of end products. Next to the technology itself, these parameters will have a large impact on the recovery rate.
Moreover, these parameters will also determine the choice of the NRR technique and marketability of the end product.

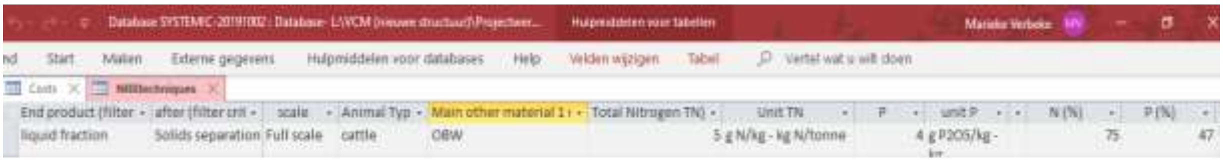
Regarding information on the composition of feedstock, digestate and end products, focus will be on the parameters in Table 1-1. If data on harmful components and heavy metals is available, it will also be included.

Table 1-1 Parameters focussed on in data collection for the database.

Parameter			
Density	Mineral nitrogen (ammonium-N + nitrate-N +nitrite-N)	Total Phosphorus	Na
Viscosity	Ammonium Nitrogen (NH_4-N)	Total P_2O_5	S
pH	Nitrite N (NO_2^-- N)	Organic phosphorus	Sulphates
Dry matter	Nitrate N (NO_3^-- N)	C:P ratio	Electrical conductivity
Organic dry matter	Organic nitrogen	Total potassium (K_2O)	Cl
Total organic carbon	Kjeldahl-Nitrogen (organic N+ ammonium-N + nitrate-N)	Mg	F
Total Nitrogen (Ntotal)	C:N ratio	Ca	

1.1 Set-up of a database

To store and retrieve the data a database was designed in Microsoft Access®. Each record in the database gives information on a specific feedstock (mix), digestate or end product and contains values (e.g. analyses values, average values, median, 10 percentiles, etc.) for the recovery rate and/or the parameters described in Table 1-1. Each record also contains the technology cascade that is required to generate a specific product. An example is showed in Figure 1-1. The figure shows which information are available in the database for a specific end product, in this case liquid fraction of digestate. The product is obtained via mechanical separation of digestate from a full scale biogas plant, processing manure and organic biological waste (OBW). Furthermore, N and P content of the end product and the recovery efficiency of these components are included as well.
Data from this database will be used to estimate recovery rates and feedstock compositions used in “the quantitative Excel tool for cost-benefit analysis and technology selection” (D 3.5).



End product (filter	after (filter cri	scale	Animal Typ	Main other material 1 (	Total Nitrogen TN)	Unit TN	P	unit P		N (%)	P (%)
liquid fraction	Solids separation	Full scale	cattle	OBW	5	g N/kg - kg N/tonne	4	g P2O5/kg -		75	47

Figure 1-1 Example of a record in the database

1.2 Collected data points

This report will show data based on the status of the database after 32 months from the beginning of the project (June 2017-January 2020). Table 1-2 gives the number of records currently available.
Data was retrieved from

- scientific literature (publications, reports, press articles) (Annex I).

This was supplemented with practical, real-life data from operational full scale biogas plants:

- the Demonstration Plants, acquired when developing the mass-and energy balances. This data can be found in D1.3. Second annual updated report on mass and energy balances, product composition and quality and overall technical performance of the demonstration plants (year 2) -confidential report.
- the European Biogas Association (EBA) database on the composition of digestates.
- the Outreach Locations and Associated Plants, acquired by direct personal communication.
- other biogas plant owners and consultants or constructors acquired through a survey (https://systemicproject.eu/3114/), which will stay open until the end of the project.

Table 1-2 Number of records in the database on composition of digestate and end products or recovery rates (January 2020)

Type of records	Number of records
Scientific literature	**560**
Other data (analyses reports, etc.)	**59**
Demo Plants	**106**
Outreach Locations	**101**
Other biogas plants	**61**
Total records full scale plant data	**887**

1.3 Feedstock types and digestate composition

The quantitative Excel tool for cost-benefit analysis (https://systemicproject.eu/living-labs/) requires the user to complete the composition of his/her digestate and the used feedstock mixture. The types of feedstock occurring most frequently in the database were selected and clustered into different types of feedstock (mono-digestion) or feedstock combinations (co-digestion) (Table 1-3).
"Organic waste" is a general term, covering different types of waste like slaughterhouse waste, waste from food-,beverage- and feed industry, agricultural residues and green household waste.
"Energy crops" are low-cost and low-maintenance crops grown solely for energy production. Examples are maize, Sudan grass, millet, white sweet clover, or waste products from biodiesel. Glycerine is also counted as "energy crop", since it is an energy rich waste product, frequently bought by biogas plant owners only to boost the biogas production.

If the user has no data available on the digestate composition, an estimation of the digestate composition is suggested, based on the composition and ratio of each feedstock as input to the biogas plant. Also an estimation will be given in that case, based on data from the database on different digestates (Table 1-3).

For some cases, there were not enough datapoints and in general, the proposed estimations of digestate composition certainly don’t claim to accurately model a digester, yet it can give the user an indication in case no data is available on the composition of his digestate. Note that for combinations of feedstock (co-digestion) it is impossible to give a standardized digestate composition based on data from the database, because of the large variability of the ratio in which different feedstock are combined, which will influence the digestate composition.

Table 1-3 Average and standard deviation of digestate composition based on the available data in the database (status January 2020). DM = dry matter, Ntotal = total nitrogen, NH4-N = ammonium nitrogen, P2O5 = ortho-phosphate, K2O = potassium oxide

Feedstock(s) entering the digester	**Average ± standard deviation**					**Number of records**
	DM	**Ntotal**	**NH4-N**	**P2O5**	**K2O**	
	%	**g/kg**				
Pig slurry	8.6 ± 6.3	6.6 ± 2.3	4.3 ± 1.5	3.8 ± 2.1	6.0 ± 2.6	7
Cattle manure	5.8 ± 1.7	3.8 ± 0.9	2.6 ± 1.0	1.5 ± 0.9	4.3 ±0.8	17
Poultry manure	12	8	3	6	5	1
Sewage sludge	4 ± 2	71.0 ± 22.6	47	39		2
Organic waste	9.2 ± 7.3	8.1 ± 11.4	4.5 ± 3.2	3.5 ± 3.7	4.1 ± 1.9	21
Energy crops	-	-	-	-	-	-

2 Technology cascades for NRR

Based on the technologies of the SYSTEMIC biogas plants, the results from the survey and case studies in literature, the following chapters describe some frequently occurring or promising process steps or technology cascades for NRR.

For the quantitative Excel tool for cost-benefit analysis, 21 cascades were selected (Annex II).
To explore the different possible technology cascades for NRR, the user of the Excel tool can choose between these 21 different options.

After the feedstock and the technology cascade are selected, the Excel tool will calculate the distribution of nutrients and dry matter (DM) in the end products formed, based on recovery efficiencies per step. The recovery efficiency of each process step or each technology cascade is based on the information sources described in 1.2.

There are other technology cascades that appear in the database, but are not taken into account in the Excel tool because not enough data was available on recovery rates or because the technology is frequently used but does not recover nutrients. These are described from Chapter 3.

2.1 Solids Separation

The first step in nutrient recovery is usually the mechanical separation of digestate into a liquid and a solid fraction.
At high separation efficiencies, phosphorus (mostly bound to the OM) will be concentrated in the solid fraction. The soluble compounds (N and K) will be mostly segregated in the liquid fraction.
For most separation technologies, the separation efficiency can be improved by addition of polymers or complexing agents (e.g. $FeCl_3$, $Fe_2(SO_4)_3$, etc.) to the digestate.
However, it was very difficult to find data for separation efficiencies making a distinction between the use of polymer or not.

Separation technologies are:

- frequently the first step towards nutrient recovery (cfr. Liquid-solid separation of digestate)
- used to separate end products
  Examples
  - a screw press to separate organic soil improver from P-poor liquid fraction (Re-P-eat system from WUR at Groot Zevert Vergisting, The Netherlands) (Figure II-18)
  - a filter press to separate ammonium sulphate solution from calcium carbonate (FiberPlus® system from GNS at Benas Biogas Plant, Germany) (Figure II-7)

2.1.1 Centrifuge

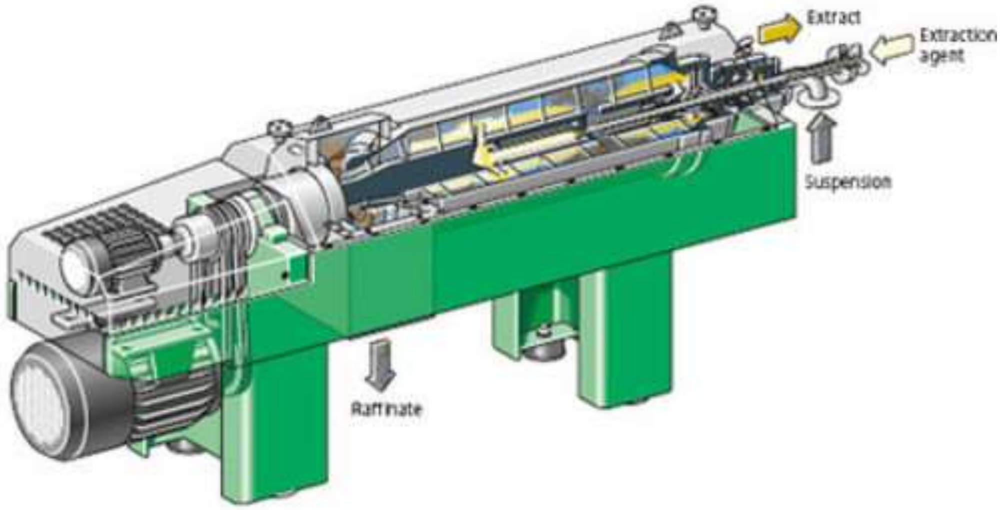


Figure 2-1 Scheme of a decanter centrifuge (Source: GEA Westfalia, 2019)

A frequently used technology to separate digestate is a decanter centrifuge. The centripetal force is used in a centrifuge to separate particles with a higher density from the liquid.

The separation efficiency is different for each type of digestate due to its texture and viscosity and composition, which are determined by the feedstock and the retention time in the digester.

When the digestate contains less fibrous material, separation can be difficult and addition of polymers or complexing agents (e.g. $FeCl_3$, $Fe_2(SO_4)_3$, etc.) can be necessary to improve the separation efficiency (GEA, personal communication, 2015).

The level of optimisation (e.g. a higher P recovery rate) is not automatically obtained by adding a higher concentration of polymer. Therefore, often consultants are relied upon to help choosing the type of polymer (water- or oil based, powder polymer) and determine the concentration that should be added to the digestate (VCM 2018b). This is done on small scale via laboratory assessment (so called jar-tests) and confirmed and fine-tuned in full scale

Figure 2-2 shows a summary of the most common technology cascade when using a centrifuge. Table 2-1 gives an overview of the recovery rates from the database (minimum and maximum values) and from some SYSTEMIC plants. It shows that the mass separation (liquid-solid fraction) is quite predictable, but the recovery rates for DM and the nutrients N, P, K are quite variable.

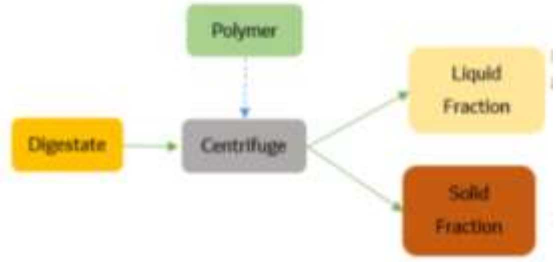


Figure 2-2 Scheme of separation of digestate with decanter centrifuge.

Table 2-1 Recovery rates (%) of centrifuges of SYSTEMIC plants and from the database. 2 values represent minimum and maximum values. DM = dry matter, Ntotal = total nitrogen, NH4-N = ammonium nitrogen, P = total phosphorus, Ktotal= total potassium

Source	**Product**	**Polymer used**	**Mass**	**DM**	**Ntotal**	**Ptotal**	**Ktotal**
Groot Zevert Vergisting [1]	Liquid fraction digestate	No	84	44	70	27	81
	Solid fraction digestate	No	16	56	30	73	19
Database [3]	Liquid fraction digestate	No	77-94	47-53	67-77	32-47	
	Solid fraction digestate	No	6-23	53-66	22-63	53-100	
AMPower [1]	Liquid fraction Digestate + LF(6:4)	Yes	91		71	13	73
	Solid fraction Digestate + LF(6:4)	Yes	9		29	87	27
Outreach Location 1 [2]	Liquid fraction Digestate	Yes		37	80-90	60	90
	Solid fraction Digestate	Yes		63	10-20	40	5-10
Outreach Location 2 [2]	Liquid fraction Digestate	Yes	79	14	55	13	86
	Solid fraction Digestate	Yes	21	86	45	87	14
Database [3]	Liquid fraction Digestate	Yes	81-88	10	53-88	0-45	53-94
	Solid fraction Digestate	Yes	11-19	37-90	12-47	55-100	16-47

1 D1.3. Second annual updated report on mass and energy balances, product composition and quality and overall technical performance of the demonstration plants (year 2) -confidential report.- Final report publicly available on 31 May 2021.

2 Personal communication, included in the database

3 Sources described in Chapter 1.2

2.1.2 Screw press

A screw press consists out of a central screw housed in a cylindrical sieve cage with a screen (Figure 2-3). Separation of digestate into a solid and liquid fraction by a screw press (Figure 2-4) is therefore based on particle size (filtration).The screw ensures a gradual increasing pressure and the solid fraction is retained by this screen and goes out through an outlet pipe. The separation efficiency can be adapted by the counter pressure of the outlet opening.

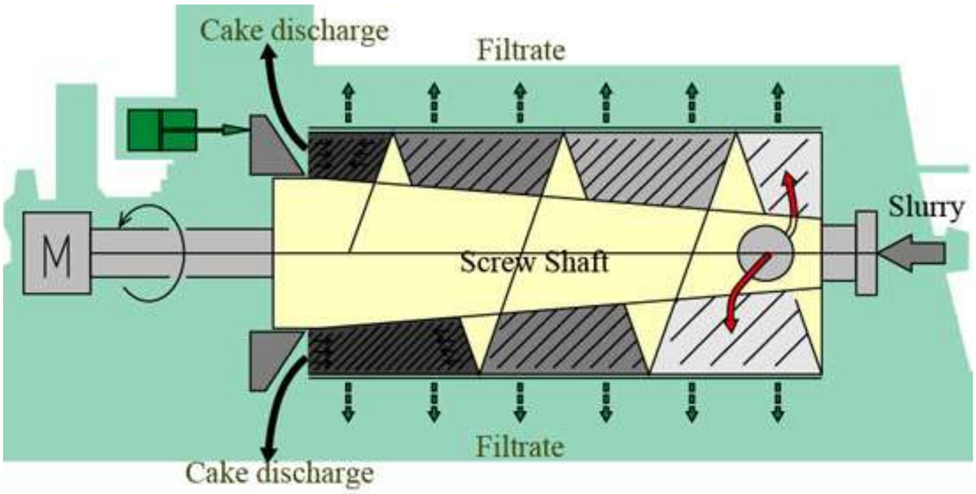


Figure 2-3 Working principle and scheme of a screw press ("Filtration, Solid/Liquid Separation : ISGK Screw Press," 2018).

In general, digestate contains very little fibres compared to (cattle) manure which makes it hard to separate with a screw press. Nonetheless, in practice, separation of digestate from mono-digestion of cattle manure or co-digestion with maize is also done with a screw press (VCM 2018b).

Besides the technology and the settings of the separator, the separation efficiency depends on the chemical characteristics of the digestate (DM-content, pH, EC, …) and operational conditions (digester retention time, temperature, mixing type, …). Again, the use of additives can improve the separation efficiency.

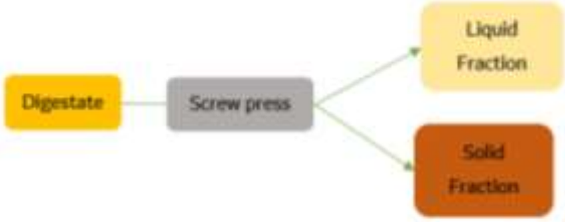


Figure 2-4 Scheme of separation of digestate with screw press and recovery rates.

Table 2-2 Recovery rates (%) of screw presses of SYSTEMIC plants and from the database. 2 values represent minimum and maximum values. DM = dry matter, Ntotal = total nitrogen, NH4-N = ammonium nitrogen, P = total phosphorus, Ktotal= total potassium

Source	**Product**	**Polymer**	**Mass**	**DM**	**Ntotal**	**NH4-N**	**Ptotal**	**Ktotal**
Benas [1]	Liquid fraction	No	80	67	75	79	74	77
	Solid fraction	No	20	33	25	21	26	23
Database [2] (feedstocks digesters >50% cattle and poultry manure)	Liquid fraction	No	80-90	60	72		0	85
	Solid fraction	No	10-20	56	28		100	15

1 D1.3. Second annual updated report on mass and energy balances, product composition and quality and overall technical performance of the demonstration plants (year 2) -confidential report.- Final report publicly available on 31 May 2021

2 Sources described in Chapter 1.2

2.1.3 Belt press

A belt press consists of two water-permeable belts guided over several rolls. The belts are pressed against each other over a certain length. This way shear forces and mechanical pressure are generated between two belts to de-water the digestate.

The process typically consists of three stages; gravity, low pressure and high pressure. The digestate is fed between the two belts where the water is first removed via gravity. In the second section, pressure is applied as the belts pass through a series of rollers and the water is pressed out under increasing pressure. The final de-watered solid fraction or "cake" is removed from the belts by scraper blades. Typically a solid fraction of 18 – 25% DM can be achieved (Pell Frischmann Consultants Ltd 2012).

Digestate treated in a belt press usually needs to be conditioned with poly electrolytes (polymers/flocculants) for efficient dewatering.

Table 2-3 gives one value of the recovery rate of digestate being dewatered with a belt press with the use of flocculants.

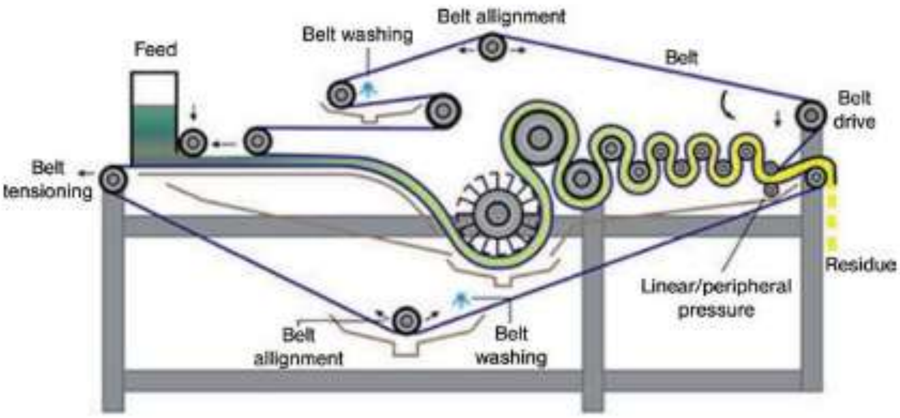


Figure 2-5 Working principle and scheme of a belt press. Source: (Deublein and Steinhauser 2010)

Table 2-3 Recovery rates (%) of a belt press from the database. DM = dry matter, Ntotal = total nitrogen, NH4-N = ammonium nitrogen, P = total phosphorus, Ktotal= total potassium

Source	**Product**	**Polymer**	**Mass**	**DM**	**Ntotal**	**NH4-N**	**Ptotal**	**Ktotal**
Database (1 value) [1]	Liquid fraction (after gravity)	Yes	60					
	Liquid fraction (after pressing)	yes	20					
	Total liquid fraction after belt press	yes	80	9		48	24	
	Solid fraction	yes	40	91		52	76	

1 Sources described in Chapter 1.2

2.1.4 Dissolved air flotation (DAF)

A DAF is mainly used as an additional separation step, to remove suspended solids, oil, fats and grease and other apolar substances from liquid fraction (Figure 2-6).

Complexing agents like $FeCl_3$, $Fe_2(SO_4)_3$, organic coagulants, etc. are used to coagulate these unwanted substances. Polymer is added to flocculate the created complexes. By decompressing compressed air, very small air bubbles are created, which are released on the bottom of the tank.

The flocs attach to the bubbles and float to the surface where they form a crust, which can be scraped off (Lebuf et al. 2013).

Again, a balance has to be found in dosage of coagulant and polymer to become good flocs and not use to much of these additives, since they are costly and can have potential environmental impact.

When a DAF is used as additional separation step, the efficiency of the first separation step will influence the recovery of the DAF. Table 2-4 gives an indication of the recovery rate of a DAF after centrifuge treating digestate.

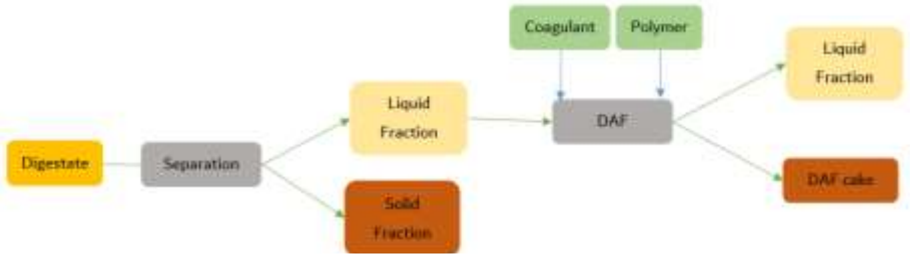


Figure 2-6 Scheme of separation of liquid fraction of digestate with DAF.

Table 2-4 Recovery rates (%) of a DAF after centrifuge treating digestate. DM = dry matter, Ntotal = total nitrogen, NH4-N = ammonium nitrogen, P = total phosphorus, Ktotal= total potassium

Source	**Product**	**Polymer**	**Mass**	**DM**	**Ntotal**	**NH4-N**	**Ptotal**	**Ktotal**
Groot Zevert Vergisting [1]	Liquid fraction after centrifuge + DAF	Yes	69	-	79	75	65	77
	Solid fraction after centrifuge + DAF	yes	31	-	21	25	35	23

[1] D1.3. Second annual updated report on mass and energy balances, product composition and quality and overall technical performance of the demonstration plants (year 2) -confidential report.- Final report publicly available on 31 May 2021

2.2 Ammonia stripping-scrubbing

The ammonia stripping-scrubbing technique can be applied on a nitrogen rich waste stream, such as (liquid fraction) of digestate, manure, waste water or air from stables (only scrubbing).

As shown in Figure 2-7, ammonia (NH_3)is removed (stripped) by blowing air or steam through the digestate in a tray or packed tower. The liquid stream enters on top of the system (on a packing material), while the air enters usually from the bottom. In this way ammonia is transferred from the liquid to the gaseous phase in a counter current system. The stripping gas, charged with ammonia, is then captured and the ammonia is removed (scrubbed) by washing it with a strong acidic solution, such as sulphuric acid or nitric acid, in the scrubbing system. The stripping gas from which the ammonia is removed can be recirculated to the stripping tower.

Depending on the technology provider, it can be important that the input steam does not contain a lot of suspended solids or fibres, since this could cause clogging of the packing material.

To obtain optimal removal, the temperature is increased to 70°C and the pH of the influent is often raised to 10 to shift the NH_4^+/NH_3 equilibrium towards free ammonia (Lemmens et al. 2007). The latter can be done with NaOH or $Ca(OH)_2$, or by stripping the influent from CO_2.

As stripping and scrubbing of ammonia occurs in a closed system, emissions will be low.

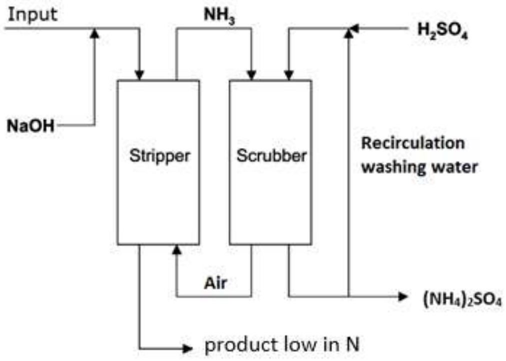


Figure 2-7 Schematic overview of the stripping and scrubbing technique to recover ammonia from manure. Source: modified from (Melse et al. 2004)

The acidic solution used to wash the ammonia (NH_3) from the air is usually sulphuric acid (H_2SO_4). A chemical reaction creates an ammonium sulphate ($(NH_4)_2SO_4$) solution.

Similar to synthetic produced mineral N fertilisers, ammonium sulphate contains N entirely in mineral form, as NH4-N. When the product is obtained by means of sulphuric acid, ammonium sulphate is also an important source of sulphur (S).

Alternatively, nitric acid (HNO_3) can also be used as scrubbing acid, which reaction with ammonia would produce ammonium nitrate. The cost of nitric acid is higher, but the N content of the end product is higher (up to 18 mass% N), and a neutral pH-value gives it a higher market potential (Digesmart 2016).

Obviously, non-volatile components, like organic-bound N, phosphorus, potassium, metals, solids etc. will not be transferred to the ammonium sulphate solution, but will stay in the stripper effluent.

The N recovery efficiency from a stripper-scrubber combination can range from 20% to theoretically 98%, since the recovery efficiency can be controlled by using higher temperatures and recirculating the wash solution (ammonium sulphate solution) until it is saturated (Vaneeckhaute et al. 2017).

This also depends on the configuration of the stripper-scrubber (2.2.1-2.2.4).

2.2.1 Air washers

In animal housing and manure or digestate processing facilities the N-rich air can be washed to prevent ammonia emissions to the atmosphere. Via fans the air is drawn into an air scrubber where the ammonia is captured into water as dissolved ammonium by a low pH 'scrubber' solution (Figure 2-8. For air washing usually a sulphuric acid solution is used and ammonium sulphate is produced (SYSTEMIC et al. 2018).

Long term monitoring of acid scrubbers at five farm locations reporting average ammonia removal efficiency of 90–99% with a minimum and a maximum peak of respectively 40 and 100%(Melse and Ogink 2005).

Table 2-5 gives an indication of the product characteristics of ammonium sulphate from air washing.

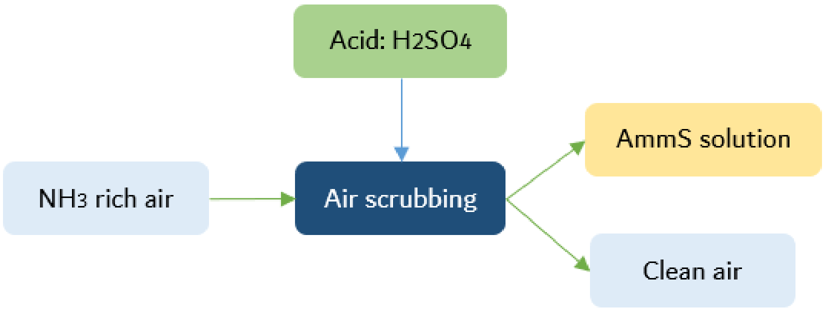


Figure 2-8 Scheme of an air scrubbing process

Table 2-5 Product characteristics of ammonium sulphate (air washing) in ranges based on average values reported in scientific studies (SYSTEMIC et al. 2018)

Parameter	**Ammonium sulphate**
Dry matter (%)	14-33
Electrical conductivity (mS/cm)	2.40-6.43
N total (g/kg)	30-86
NH4-N (g/kg)	30-86
S (g/kg)	30-114

Examples of full scale plants

- Air washing of exhaust air from drying installations (Outreach Location Biogas Bree and Demo Plant AMPower, Belgium)

2.2.2 Inline stripping

Some feedstock (such as poultry manure, protein-rich feedstock) have relatively a high N content, which may cause high concentrations of ammonia to be released in the digester during anaerobic digestion. When reaching toxic concentrations, this can cause inhibition of the Archaea and lower biogas production (Krakat et al. 2017; SYSTEMIC et al. 2018). Recirculation of N-depleted digestate after N-stripping to the AD has proven to be effective in diluting ammonia concentrations within the digester. At the same time, ammonia is recovered in the form of ammonium sulphate (Ghyselbrecht et al. 2017).

When stripping with air, the oxygen in the stripping gas can also lower the activity of the anaerobic bacteria and therefore stripping with biogas can lead to higher biogas production (Bousek et al. 2016; VCM 2018a).

In this kind of inline N stripping (Figure 2-9), a balance has to be made: strip enough nitrogen to prevent ammonia toxicity in the digester but prevent stripping too much and having a larger acid consumption (H_2SO_4). Table 2-6 gives the obtained at Demo Plant Acqua e Sole.

Figure 2-9 Scheme inline ammonia stripping-scrubbing from digestate

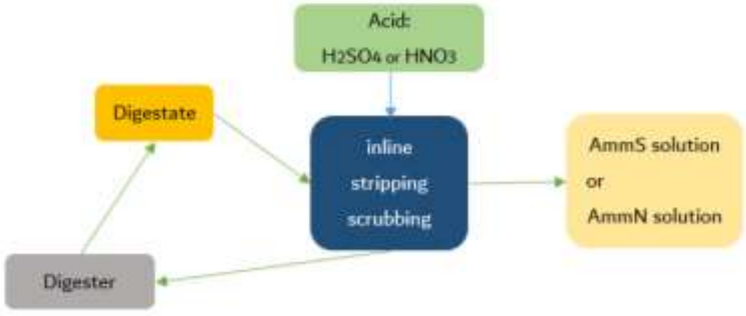


Table 2-6 Recovery rates (%) from inline ammonia stripping-scrubbing from digestate. Ntotal = total nitrogen, NH4-N = ammonium nitrogen

Source	**Product**	**Ntotal**	**NH4-N**
Acqua e Sole [1]	ammonium sulphate	10	22

2.2.3 End of pipe stripping

Ammonia stripping-scrubbing can also be useful before or after biological treatment), when focussing on lowering and recovering the nitrogen from the digestate for marketing reasons (f.e. low N fertilising application limits in nitrate vulnerable zones). Table 2-7 gives an indication of recovery rates of NH_4-N for this kind of end of pipe stripping-scrubbing of digestate when operated at pH higher than 8,5.

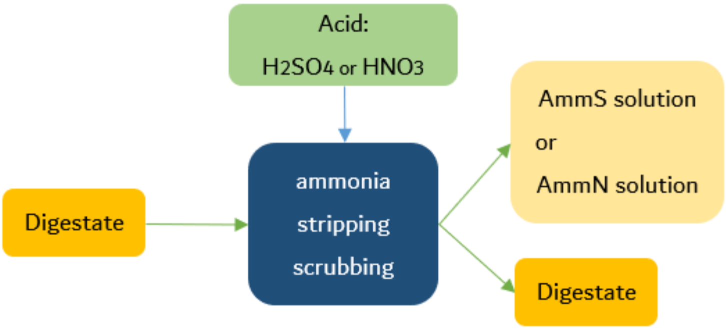


Figure 2-10 Scheme of ammonia stripping-scrubbing from digestate

Table 2-7 Recovery rates (%) of ammonia stripper-scrubbers on digestates occurring in the database. NH4-N = ammonium nitrogen

Source	**Product**	**NH4-N**
Database [1]	ammonium sulphate	50-95

[1] Sources described in Chapter 1.2

2.2.4 Fiberplus® ammonia stripping-scrubbing system

Company GNS has designed a ammonia stripping-scrubbing system for digestate that does not rely on acid during the scrubbing step. Instead, the FiberPlus® system strips ammonium from the solution as gaseous ammonia. In a conversion reactor, the N-rich stripping gas is brought into contact with gypsum to produce a suspension of ammonium sulphate and calcium carbonate. Finally, the suspension is sent to a filter press for further separation to obtain ammonium sulphate solution and a lime slurry.

This stripper-scrubber system is also an inline stripper-scrubber. Meaning that it is integrated with the anaerobic digestion reactor, and digestate lowered in ammonia is recirculated back in the digester. Table 2-8 includes the N recovery rate of ammonium of the Fiberplus® stripping-scrubbing system .

Table 2-8 Recovery rate (%) of ammonia stripper-scrubber on digestates at Demo Plant Benas using gypsum. Ntotal = total nitrogen, NH4-N = ammonium nitrogen

Source	**Product**	**Ntotal**	**NH4-N**
GNS fiberplus® system [1]	ammonium sulphate	30	57

[1] D1.3. Second annual updated report on mass and energy balances, product composition and quality and overall technical performance of the demonstration plants (year 2) -confidential report.- Final report publicly available on 31 May 2021

2.3 Membrane technologies

Membrane technology is mostly used on pre-treated (liquid fraction of) digestate stream.

Membranes can be made of different materials to have specific affinity for certain kinds of molecules (positively or negatively charged, apolar, etc.). The pore size of the membrane also determines which molecules go through and the pressure to be used: for micro-filtration (MF) pores > 0,1 µm and 0,1-3 bar, for ultra-filtration (UF) pores > nm and 2-10 bar, and for reverse osmosis (RO) no pores and 10-100 bar.

A MF can retain suspended solids, while an UF membrane can also retain macromolecules.

Both can be put in series and thus serve as pre-treatment for RO, preventing the blockage of the RO-membrane. Each membrane step produces a concentrate stream rich in suspended solids, macromolecules or ions. These are called "mineral concentrates" (MC).

The permeate stream generated from RO contains low concentrations of nutrients and can be discharged to sewer or surface water or re-used as process water (Hoeksma and De Buisonjé 2011; Hoeksma, de Buisonjé, and Aarnink 2012).Therefore, membrane techniques are often used to reduce the volume of the digestate stream (Lebuf et al. 2013).

, RO membranes need to be regularly cleaned with chemicals to prevent fouling and scaling. When clogged, they need to be replaced. The frequency of membrane replacement and the amount of cleaning products necessary depends on the input stream flow and characteristics, and the efficiency of the pre-treatment steps.

Ranges of recovery rates for UF and RO are shown in Table 2-9 and Table 2-10 respectively. The recovery rates for UF coming from the database are characterized by a large variability, probably due to the different types of input streams, pre-treatment efficiencies and operational conditions. Those for the RO step show high values, because RO is usually the last step of a separation cascade.

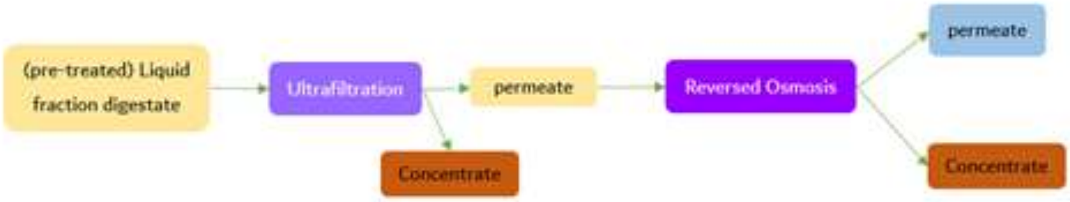


Figure 2-11 Scheme of membrane cascade (ultra-filtration and reverse osmosis) from (pre-treated liquid fraction of) digestate

Table 2-9 Recovery rates (%) for ultra-filtration. DM = dry matter, Ntotal = total nitrogen, NH4-N = ammonium nitrogen, P = total phosphorus, Ktotal= total potassium

Source	**Product**	**Mass**	**DM**	**Ntotal**	**NH4-N**	**Ptotal**	**Ktotal**
Groot Zevert Vergisting [1]	Concentrate	30		59	42	96	41
	Permeate	70		41	58	4	59
Database [2]	Concentrate	20-40		21-59	20-42	69-96	20-41
	Permeate	70-80		41-79	58-80	4-31	59-80

D1.3. Second annual updated report on mass and energy balances, product composition and quality and overall technical performance of the demonstration plants (year 2) -confidential report.- Final report publicly available on 31 May 2021

2 Sources described in Chapter 1.2

Table 2-10 Recovery rates (%) for reverse osmosis. DM = dry matter, Ntotal = total nitrogen, NH4-N = ammonium nitrogen, P = total phosphorus, Ktotal= total potassium, DAF=Dissolved air flotation, MF=microfiltration, UF=Ultrafiltration

Source	**Product**	**Mass**	**DM**	**Ntotal**	**NH4-N**	**Ptotal**	**Ktotal**
Groot Zevert Vergisting [1] Pretreatment: centrifuge+DAF+MF	Concentrate	35		98	98	100	99
	Permeate	65		2	2	0	1
Database 2 Pre-treatment: screw press+UF	Concentrate	45		100			
	Permeate	55		0			
Database [2] Pre-treatment: Screw press+centrifuge+UF	Concentrate	28-30	87-100	97-100	97-100	86-100	98-100
	Permeate	70-72	0-13	0-3	0-3	0-14	0-2

1 D1.3. Second annual updated report on mass and energy balances, product composition and quality and overall technical performance of the demonstration plants (year 2) -confidential report.

2 Sources described in Chapter 1.2

2.4 Drying and evaporation

2.4.1 Evaporators

Evaporation is a technique that is applied to reduce the water content of liquid streams . In addition to the food industry sector, evaporators are installed at AD plants to evaporate (liquid fraction of) digestate.

Evaporation is based on water and ammonia vapour pressures (i.e. how much a molecule would like to "escape" to the gas phase at a certain temperature in a closed system) (Figure 2-12). A solution like (liquid fraction of) digestate, contains anhydrous ammonia dissolved in water, in which the ammonium ion in solution exists in equilibrium with unionized (free) ammonia, which can volatize.

NH_3 (gas)=NH_3 (aq) + H_2O = NH_4+(aq) + OH^-(aq)

This equilibrium or the "urge to escape as a gas or stay in solution" depends on pH and temperature [1].

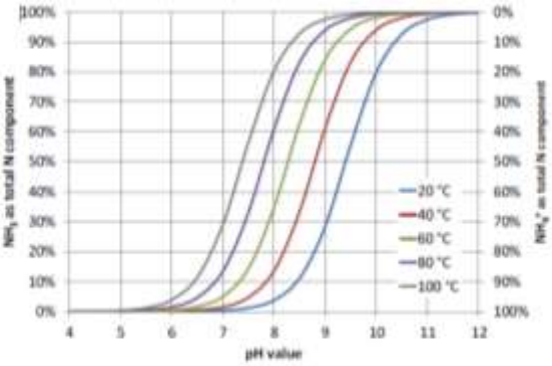


Figure 2-12: Equilibrium of NH_3 and NH_4^+ in water at different pH and different temperatures

Increasing pH and/or temperature pushes the equilibrium from soluble ammonium (NH_4^+) towards gaseous ammonia and this will volatise during the evaporation process. The water vapour containing volatile components is recovered through condensation as ammonia solution with pH of >9.

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[1] The base ionization constant is $K_b = 1.8\times10^{-5}$ and within the temperature range of 0°C-50°C and a pH range of 6.0 to 10.0, the relation with temperature is $pKa = 0.0901821 + 2729.92/Tk$ where Tk is temperature in degrees Kelvin, Tk = °C + 273.2.

In practice elevating the pH of the digestate leads to considerable operating costs, which reduces the interest in system deployment, despite its potential efficiency. From this point of view, it will be more reasonable for most biogas plants that have an excess of residual heat from the combined-heat-and-power (CHP) to raise the temperature to at least 80°C and strip at the existing pH. In theory, the recovery rate of ammoniacal-N could be 60 to 75% at this temperature (Mykkänen and Paavola 2016).

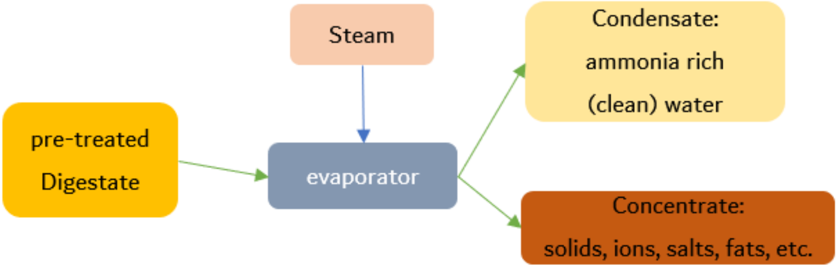

Figure 2-13 Scheme of an evaporator

To prevent volatilisation of ammonia during the evaporation step, the pH of the influent or to ammonia-vapour stream of the evaporator can be adjusted to <5.5. This approach will cause only the water (and some volatile components) to evaporate and create a more concentrated digestate which still includes the ammonia.
This process to be tested and, if successful, applied by Demo Plant AMPower, Belgium

2.4.2 Thermal drying

Thermal drying relies on heated air, preferably by (recovered) heat from the CHP, to dry slurries or solid input streams, like (the solid fraction of) digestate (Figure 2-14).
Data on different types (drum dryer, disk dryer, band dryer, own designs, etc.) of dryers are available and the end products contains up to 85% DM. The wide range in N and P content is due to the variability of the digestate feedstock (bio-waste, manure, mix manure-bio-waste) and the degree of drying.

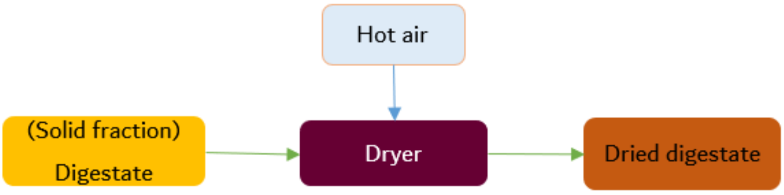

Figure 2-14 Scheme of thermal drying from (solid fraction of) digestate

2.5 Phosphorus precipitation

To recover phosphorus, technologies that involve precipitation of phosphorus salts have proven efficient on full scale, mostly in wastewater treatment plants. These technologies, like struvite precipitation are also transferable to other input streams, like digestate (Chapter 3.2).The struvite precipitation cascade is not included in the Excel tool yet. This is because getting a general estimation for the recovery rate is difficult, since this depends on the separation of the digestate before the P precipitation takes place. Meanwhile, other technologies, exploring the precipitation of other phosphorus salts from digestate are almost ready for full scale (Chapter 2.5.1 and 3.3).

2.5.1 Re-P-eat process

The Re-P-eat (Recovery of P to eat) process, developed by Wageningen University and Research is and acid-alkaline approach, operational at pilot scale (2 m³ solid fraction/hour) at Demo Plant Groot Zevert Vergisting, Netherlands (Regelink et al. 2019).

The Re-P-eat system processes the solid fraction of digestate. By adding acid to it, the pH will drop, bringing P_2O_5 in the liquid phase. By a second liquid-solid separation, a P-poor organic soil improver and a P-rich liquid fraction are created. After adding $Ca(OH)_2$ to the latter, phosphate salts can be recovered after sedimentation and drying. The alternative route now under development is P precipitation as struvite by adding a source of magnesium. A process scheme is illustrated in Figure 2-15 and an indication of the recovery rate from the initial solid fraction of digestate through this process to the P salts, can be found in Table 2-11.

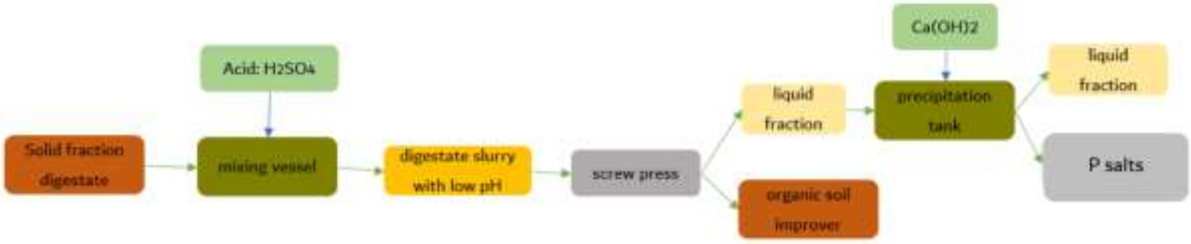

Figure 2-15 Process steps Re-P-eat system at Demo Plant Groot Zevert Vergisting

Table 2-11 Recovery rate (%) of phosphorus (P) salts from co-digested pig slurry with the Re-P-eat process on pilot scale tests. Ptotal = total phosphorus

Source	Product	Ptotal
(Regelink et al. 2019)	P salts	57%

3. Other technologies not included in the Excel tool

There are other technology cascades that appear in the database, but are not taken into account in the Excel tool because not enough data was available on recovery rates or because the technology is frequently used but does not recover nutrients.
Nonetheless, they are worth mentioning in the framework of nutrient recovery or as technology that could have potential in the transition phase towards circular economy.

3.1. Biological treatment as pre-treatment or polishing step

In Flanders, Belgium, the most frequently used technique to process the surplus of nitrogen in (the liquid fraction of) pig and cattle slurry or digestate is biological nitrogen removal (Figure 3.1-1).
This is a system in which microorganisms in active sludge use oxygen to convert the ammonium in the manure to nitrate (nitrification). In low oxygen conditions they will convert the nitrate into (harmless) nitrogen gas (denitrification) that is released into the air as an inert gas.

After the treatment, the active sludge is separated from the liquid effluent fraction by sedimentation. Part of the sludge can be recycled in order to maintain sufficient bacteria for the biological process. The majority of the sludge is used as organic fertiliser or is anaerobically digested. Effluent of biological treatment can be further purified to dischargeable water by an active carbon filter or constructed wetlands.

This technology is not included in the process cascades available in the excel tool because nitrogen is lost in the air and is not recovered a (fertiliser) product. Yet, it can find its use in the transition period from linear economy and circular economy.
This is currently, seen at some biogas plants in Flanders, which are using it as pre-treatment or polishing step, in combination with other nutrient recovery technologies.

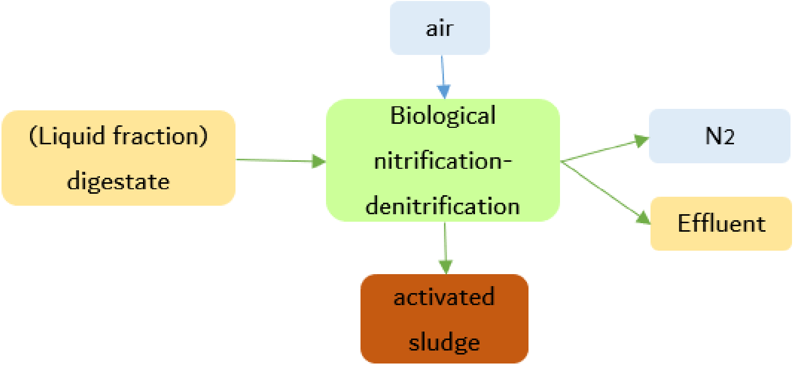

Figure 3.1-1 Scheme of biological treatment from (liquid fraction of) digestate

Cascades with other NRR technologies

- Biological nitrification-denitrification as polishing step of the N poor (the liquid fraction of) digestate (Associated Plants Group op de Beeck; IVVO; Greenlogix BioEnergy, Belgium; Outreach Locations GMB; Waternet, the Netherlands)
- Biological nitrification-denitrification as pre-treatment step of the digestate before evaporation (Outreach Location Waterleau New Energy, Belgium).
- Biological nitrification-denitrification on the liquid fraction of the belt press after pressing. The liquid fraction of the belt press resulting from gravitation (first part belt press) is treated in the membrane filtration and RO (Associated Plant Arbio BVBA, Belgium)

3.2. Precipitation of phosphorus salts

The struvite precipitation cascade (Figure 3.2-1) is not included in the Excel tool yet. This is because, the purity of the precipitated phosphorus salts is highly dependent on the pre-treatment (separation step) before the precipitation reactor. Therefore, getting a general estimation for the recovery rate is difficult, and not enough data on this relation between the separator and precipitation process has been included in the database.

Yet, phosphorus recovery from digestate as struvite (magnesium ammonium phosphate (MAP); $MgNH_4PO_4.6\ H_2O$) precipitation (Figure 3.2-1) is already proven on full scale (VCM 2018b).
CO_2 stripping by blowing air in the reactor elevates the pH and shifts the reaction equilibrium to struvite:

$$Mg^{2+} + NH_4^+ + PO_4^{3-} + 6\ H_2O \rightarrow MgNH_4PO_4.6\ H_2O$$

Addition of $MgCl_2$ or $Mg(OH)_2$ is necessary because digestate usually does not contain the required magnesium/ammonium/phosphate ratio's to promote a controlled struvite precipitation in the reactor. Table 3.2-1 gives an indication of the recovery rates of P_2O_5 from digestate by struvite precipitation occurring in the database.

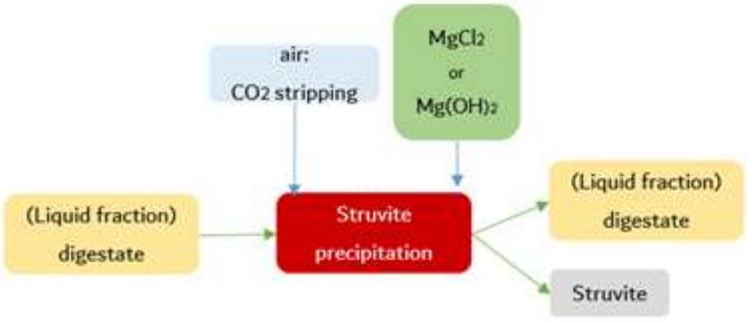

Figure 3.2-1 Scheme of phosphorus precipitation as struvite from (liquid fraction of) digestate

Table 3.2-1 Recovery rates (%) of struvite precipitation on digestates occurring in the database.

Source	**Product**	**P_2O_5**
Database (2 records) [1]	struvite	80-95

1 Sources described in Chapter 1.2

Examples of full scale plants

- Airprex® system (CNP) on raw digestate from waste water treatment sludge (Outreach Location Waternet Amsterdam West, The Netherlands)
- ANPHOS® system (Colsen) on the liquid fraction of the digestate from co-digestion (Former Outreach Location Biogastur, Spain).

3.3. P-stripping and precipitation: BioEcoSIM process

This cascade is not included in the Excel tool, since it is a variation on the first steps of Re-P-eat process (2.5.1), yet the achieved recovery rates can vary a lot from the Re-P-eat process. No data are currently available on the BioEcoSIM process, but can be acquired in a later stage, since one of the Associated Plants has a pilot scale BioEcoSIM process operational (see further).

In the framework of the BioEcoSIM project, the German research centre Frauenhofer IGB developed a technology cascade to recover phosphorus from manure and digestate.

The main difference with the Re-P-eat process is that BioEcoSIM acidifies the raw digestate to recover also P from the liquid phase. Compared to Re-P-eat, BioEcoSIM process implies higher amounts of acid, but allows for a higher P recovery (Figure 3.3-1)

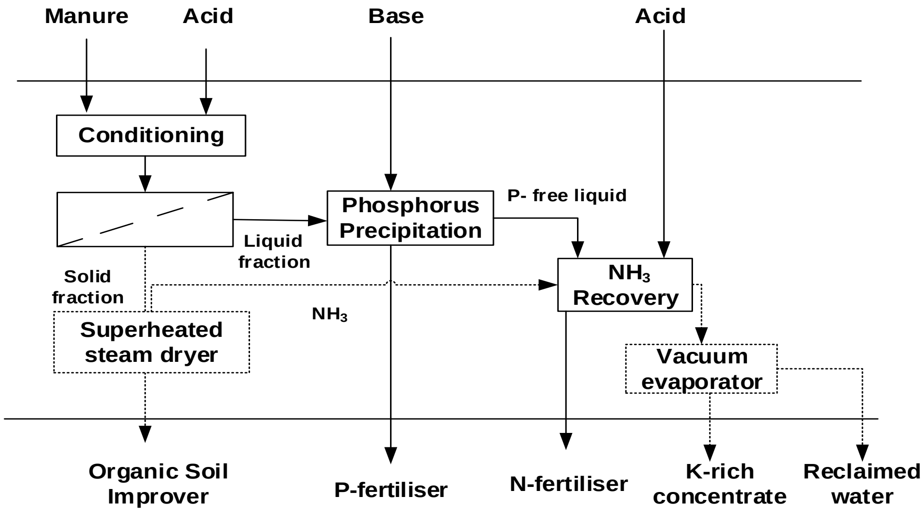

Figure 3.3-1 Process steps BioEcoSIM system (Source: BioEcoSIM project)

To precipitate phosphorus, BioEcoSIM does not add $Ca(OH)_2$ and phosphate salts are formed with the minerals (Ca^{2+}, Mg^{2+}, NH_4^+) present in the digestate.

Currently, a pilot scale system (treatment capacity of 1-2m^3/h) is running at Zorbau, Germany. Meanwhile, the BioEcoSim technology was sold to SUEZ Deutschland GmbH, a wastewater treatment and waste management company, who will distribute the technology in Europe. The R&D has achieved a technological shift up to TRL 8 and the planning and design of plants across Europe with a capacity of about 20 m^3/h each has started (presentation Siegfried Egner, ManuReSource Conference, Hasselt/Belgium, November 28th, 2019).

During the BioEcoSIM project, Geltz Umwelttechnologie GmbH was the partner constructing the demo installation. Today, they are further developing the technology separately from Frauenhofer IGB. A pilot plant (1m^3/h), called PhoskaDEmo is running at the Biogas Plant AgroEnergie Hohenlohe, in Kupferzell, Germany. The upscaled version treating 10 m^3/h or about 70.000 m^3/a, called the "NuTriSep™" is now in test-run phase at the same location (personal communication Geltz, 2020).

Table 3.3-1 Recovery rate (%) of phosphorus from digested pig manure with the BioEcoSIM process.

Source	**Product**	**P**
(Campos and Bilbao 2015)	P salts	40%

Combinations with other NRR technologies

- The system of both Frauenhofer IGB/Suez and Geltz treats the P poor digestate with ammonia stripping-scrubbing technology to recovery the nitrogen as ammonium sulphate.

3.4. Biothermal drying/composting

Biothermal drying (composting) is a natural process in which living organisms (bacteria, fungi, protozoa, etc.) convert fresh organic matter under controlled conditions and in the presence of oxygen into homogeneous, stable and humus-rich compost.

Frequently, (solid fraction of) animal manure or digestate is composted in closed systems with hygienisation as the main goal to be able to export it. It is a natural way for drying and can be regarded as nutrient recovery because all nutrients stay in the product, except for N, which might be lost in the form of ammonia. Any ammonia emission to the air should be avoided by implementing air washing systems, which allow for the recovery of N in the form of ammonium sulphate (Chapter 2.2.1). This process is not included in the tool, because it is a biological process which depends on the composition of the product entering the composting process (i.e. solid fraction of digestate), the time of composting, air supply, temperature achieved by the bacteria, etc. and recovery rates are therefore highly variable. Also, it is not regarded as nutrient recovery, more as a hygenisation or stabilisation process.

Figure 3.4-1 Biothermal drying. Source: VCM

Combinations with other NRR techniques

- The solid fraction of the digestate after a separation is composted (Associated Plant IVVO, Belgium; Outreach Location GMB, The Netherlands).

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II. Annex II

The cascades available in the SYSTEMIC Excel tool are presented below. It is an non-exhaustive list that can be updated in the remaining timeframe of the project. These cascades are based on process schemes of operational full scale biogas plants or are based on these existing cascades but include a variation in the separation steps. Some existing biogas plants even combine multiple cascades.

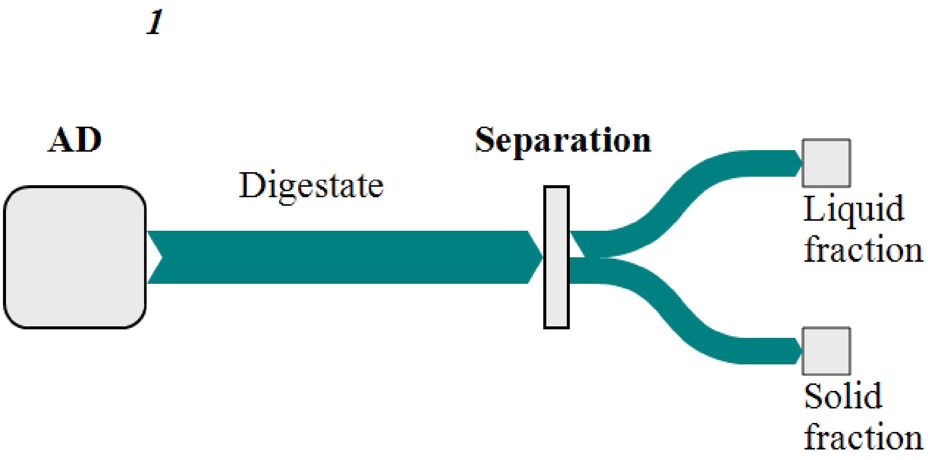

Figure II-2 Cascade 1

SCRL Kessler are separating a part of their digestate with a screw press.
Stormossen Ab/Oy(Fi) and AFBI (UK) are using a centrifuge.

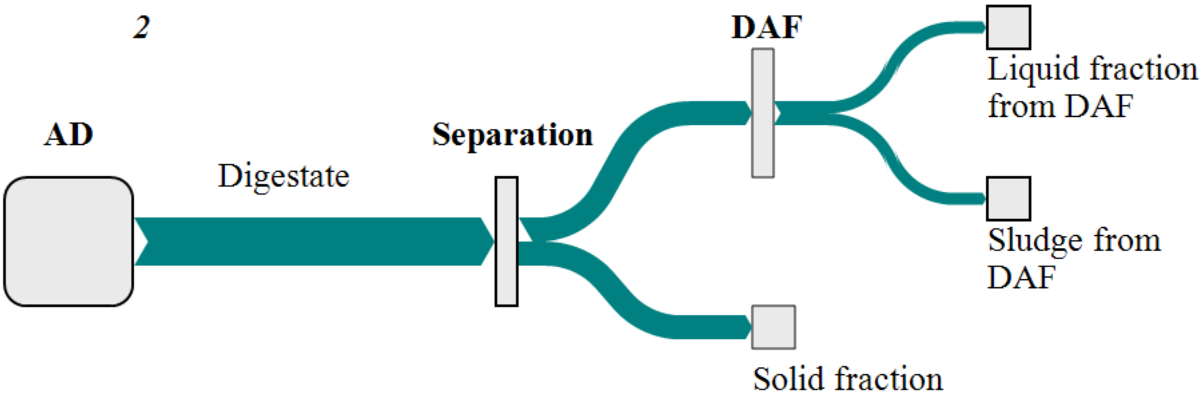

Figure II-1 Cascade 2

Demo Plant AMPower used a DAF in their original digestate treatment process and Demo Plant Groot Zevert is still using it.

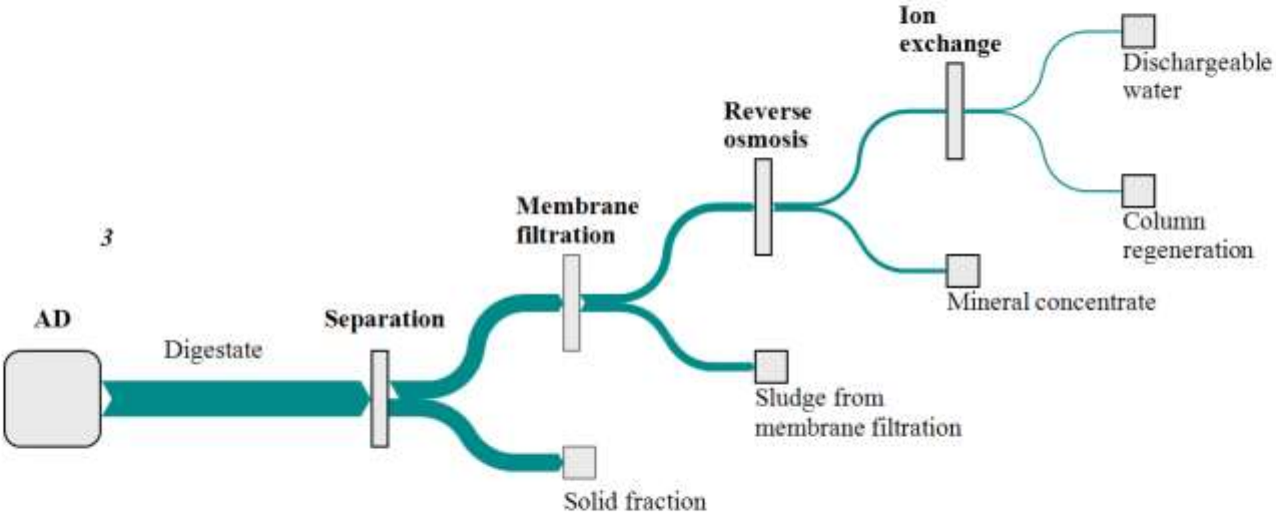

Figure II-3 Cascade 3

Associated Plant Arbio BVBA (BE) uses a belt press as separator in this process. They don’t have an ion exchanger, so they don’t produce dischargeable water but irrigation water.

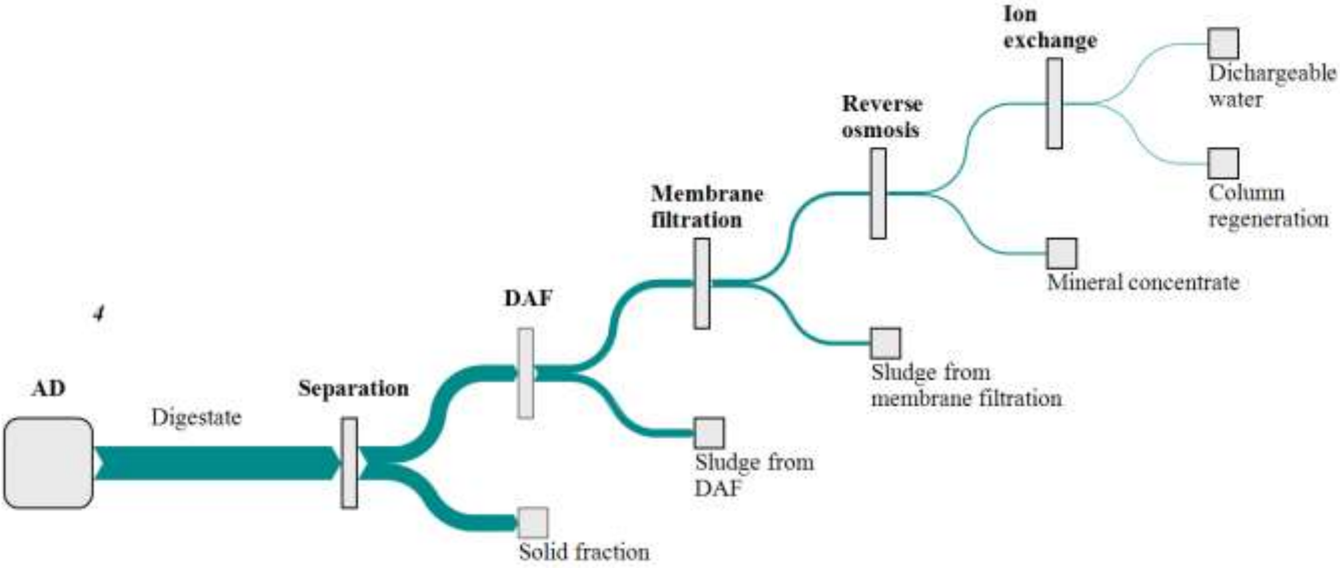

Figure II-4 Cascade 4

Demo Plant Groot Zevert Vergisting (NL) combines this cascade with Cascade 18.

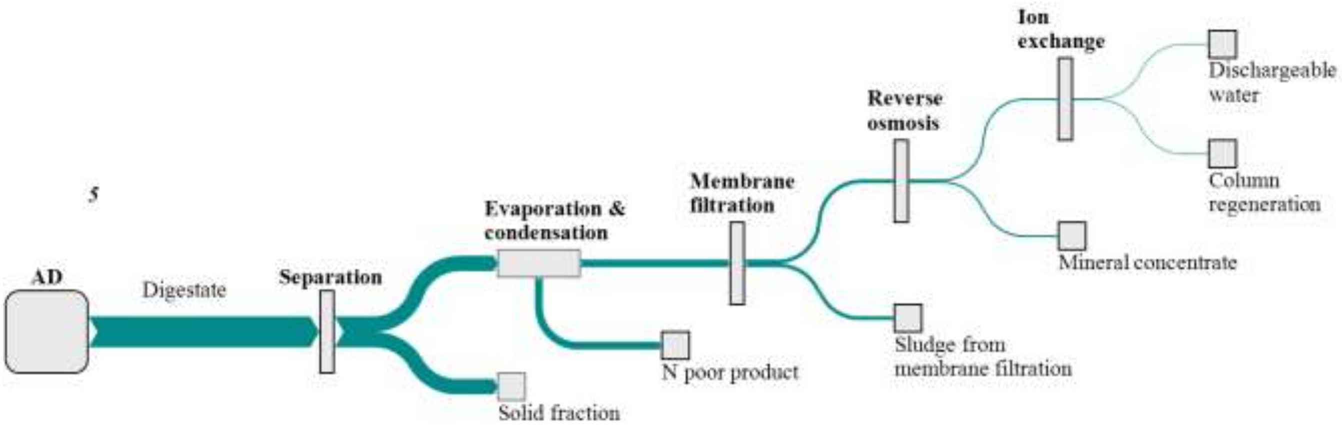

Figure II-5 Cascade 5

Demo Plant AMPower (BE) and Outreach Location Atria (FI) use this cascade without the membrane filtration and ion exchanger to produce dischargeable water. They acidify the input of the evaporator to keep the nitrogen concentrate of the evaporator product. (The N poor product becomes N rich product).

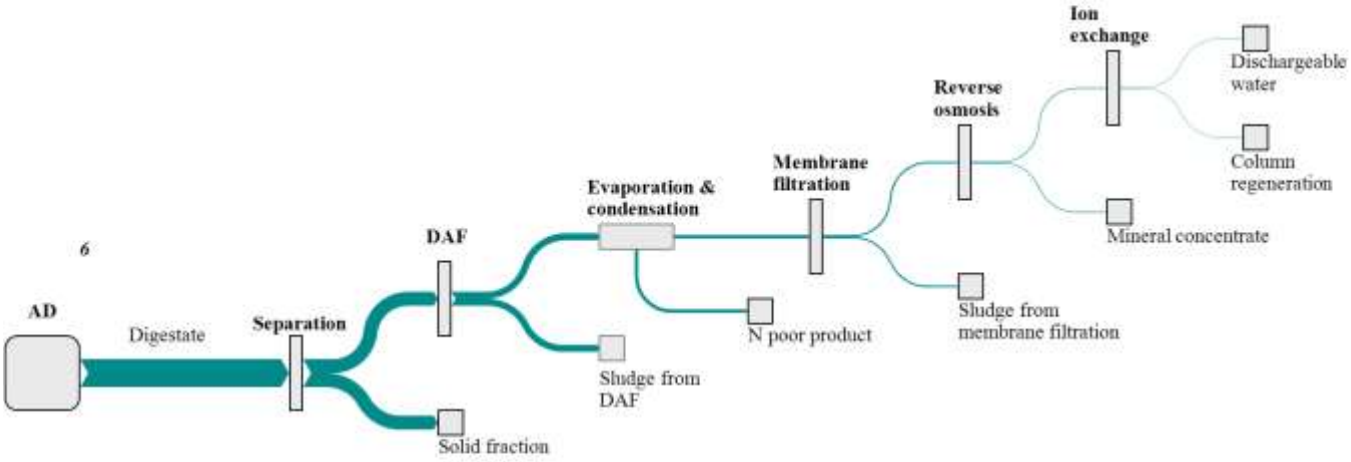

Figure II-6 Cascade 6

This cascade is a variation on Cascade 5.

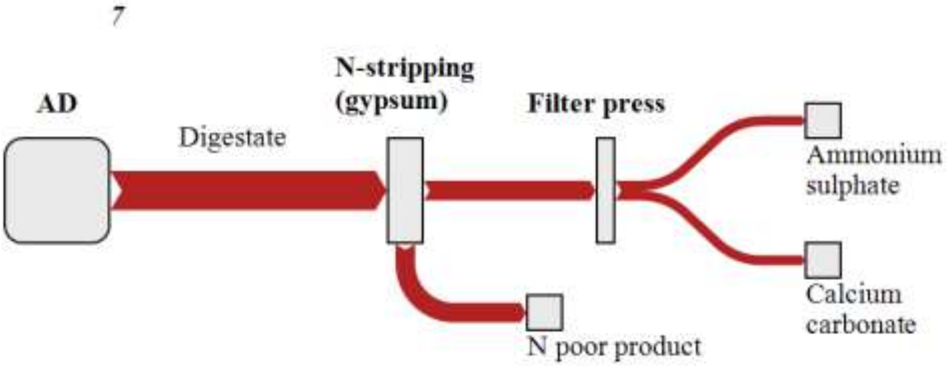

Figure II-7 Cascade 7

Demo Plant Benas (DE) uses this N-stripping-scrubbing technique.

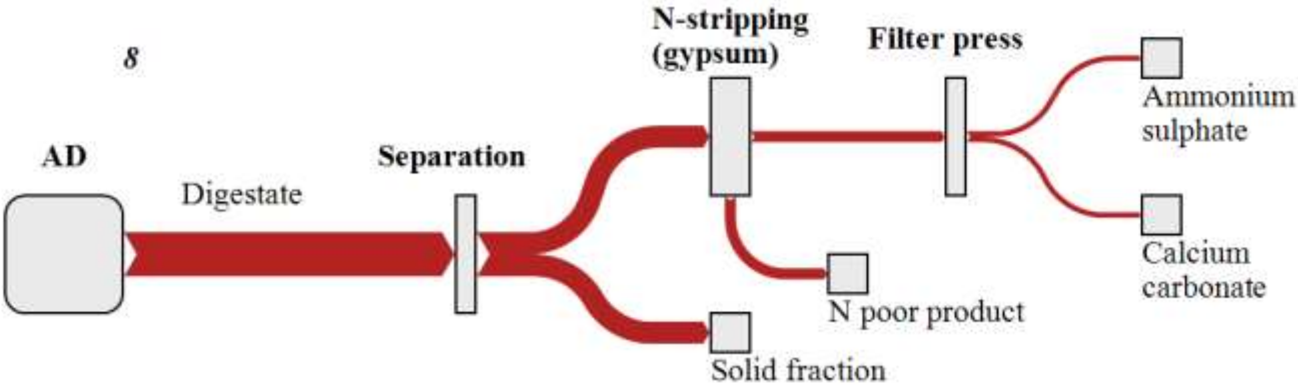

Figure II-8 Cascade 8

This cascade is a variation on Cascade 7.

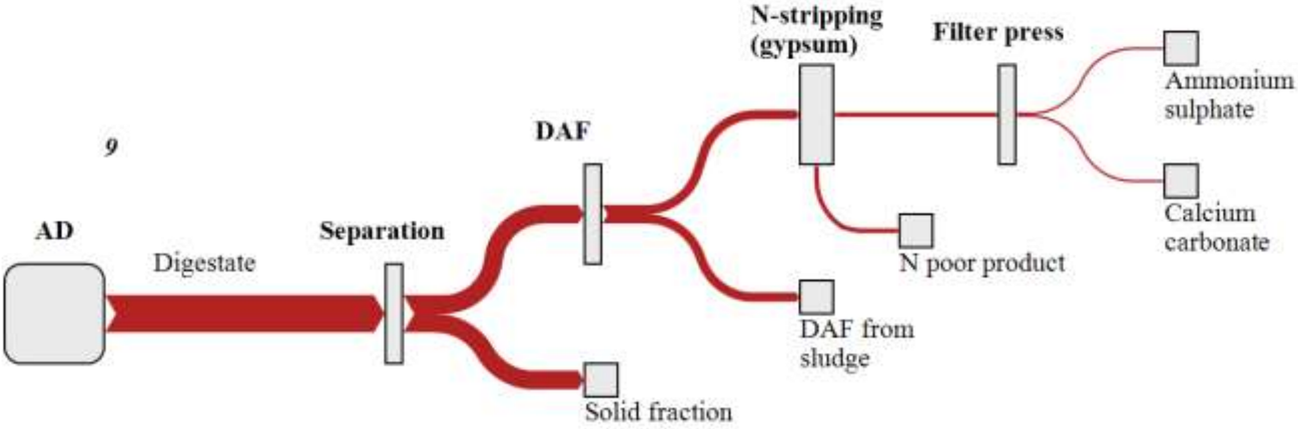

Figure II-9 Cascade 9

This cascade is a variation on Cascade 7.

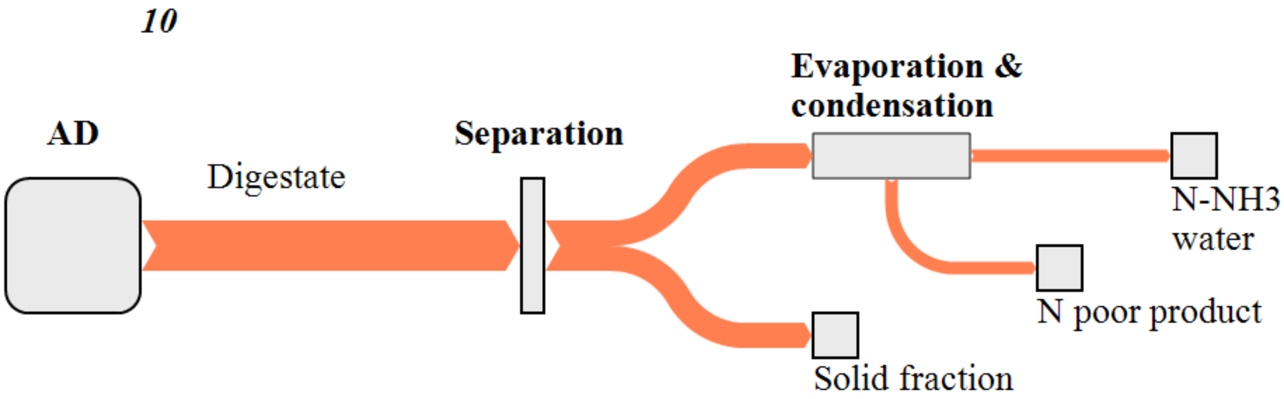

Figure II-10 Cascade 10

Associated Plants Storg (BE) and Group op de Beeck (BE) use this cascade with respectively a belt press and a centrifuge as separation technique.
Outreach Location Waterleau New Energy (BE) and Associated Plant IVVO(BE) use this cascade with biological nitrification-denitrification as pre-treatment for the evaporation.

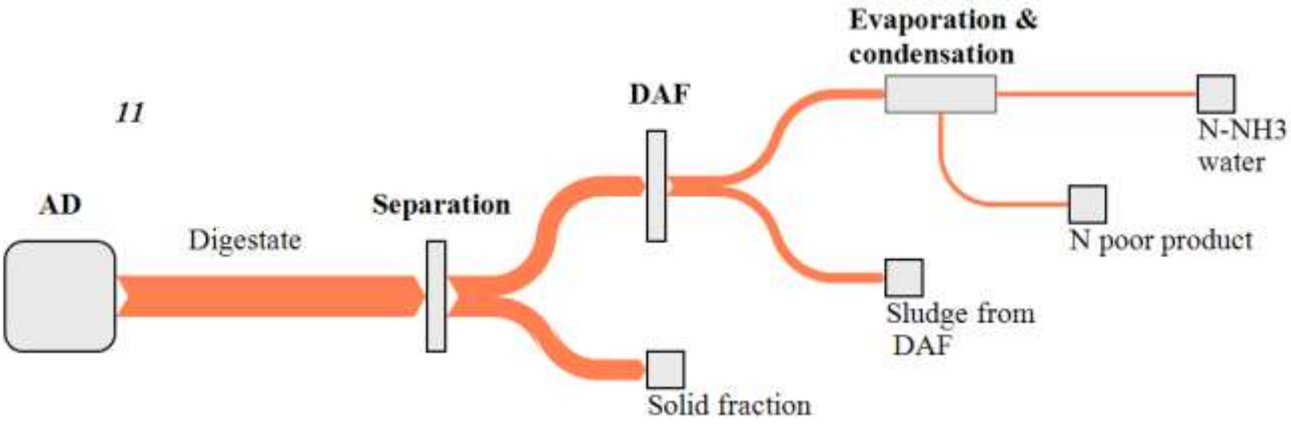

Figure II-11 Cascade 11

This cascade is a variation on Cascade 10.

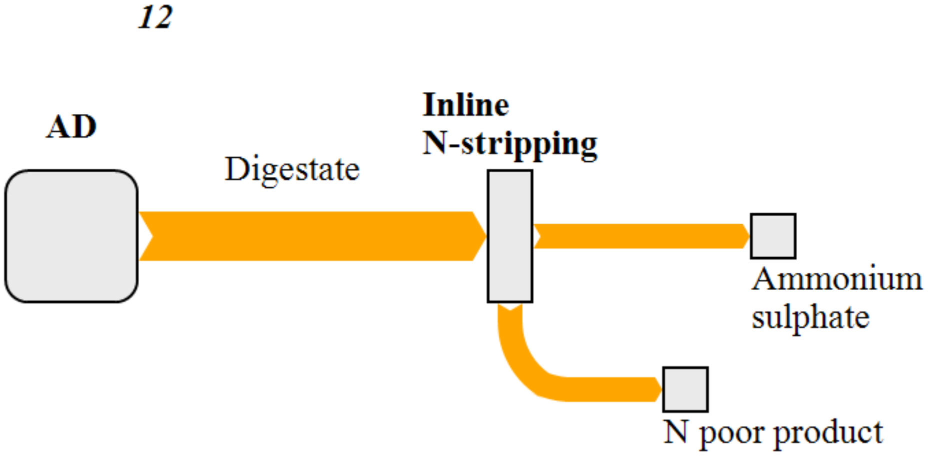

Figure II-13 Cascade 12

Acqua e Sole (IT) and Greencreate W2V Ltd Kent (UK) have inline strippers to produce a N poor product.

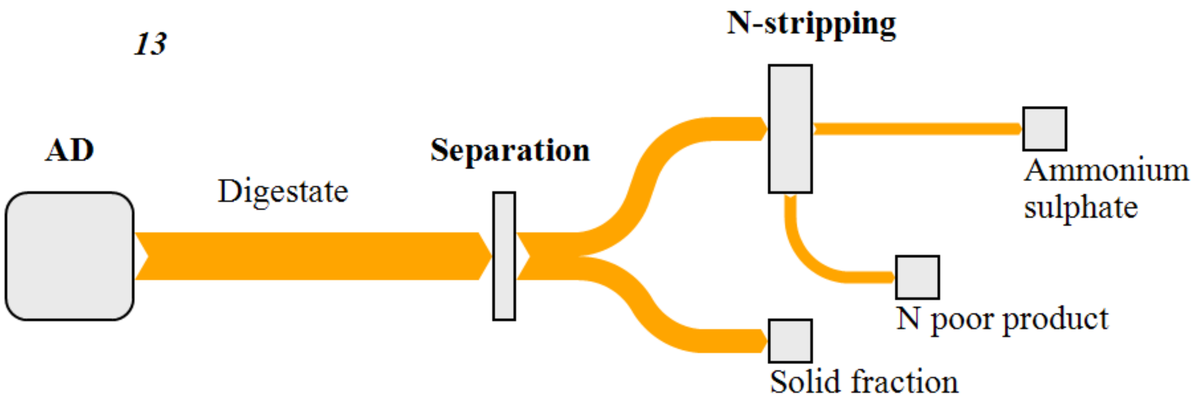

Figure II-12 Cascade 13

Outreach Location Emeraude Bioenergie (FR) and Associated Plants Greenlogix BioEnergy (BE), NDM (DE) are doing ammonia stripping-scrubbing on the liquid fraction of their digestate.

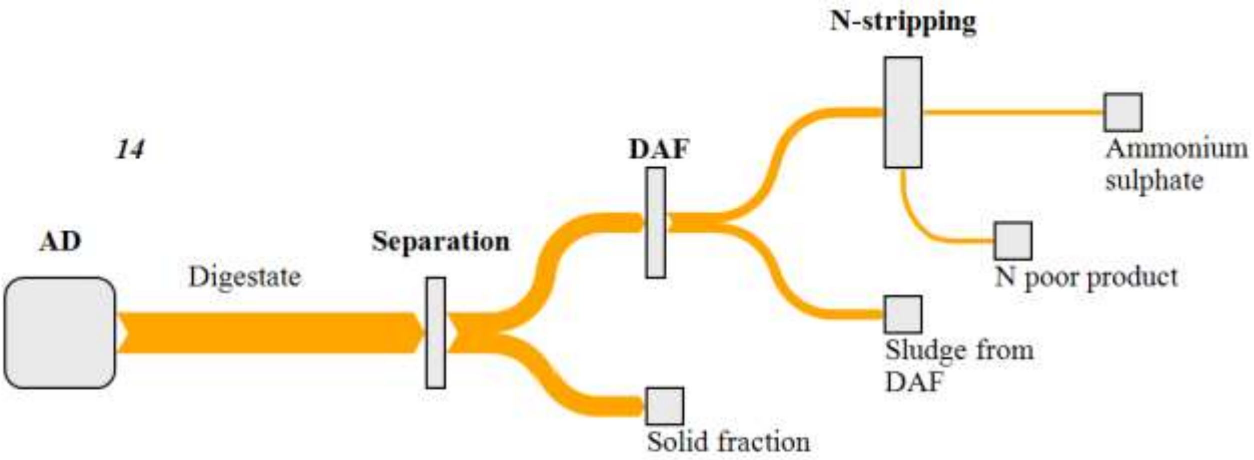

Figure II-14 Cascade 14

This cascade is a variation on Cascade 13.

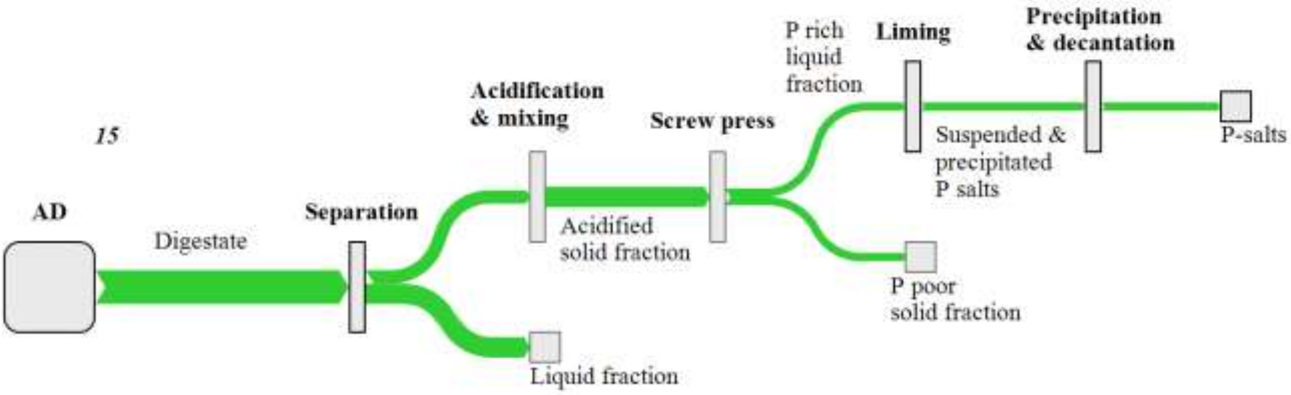

Figure II-15 Cascade 15

This cascade is a variation on Cascade 18, which is currently operational at a biogas plant.

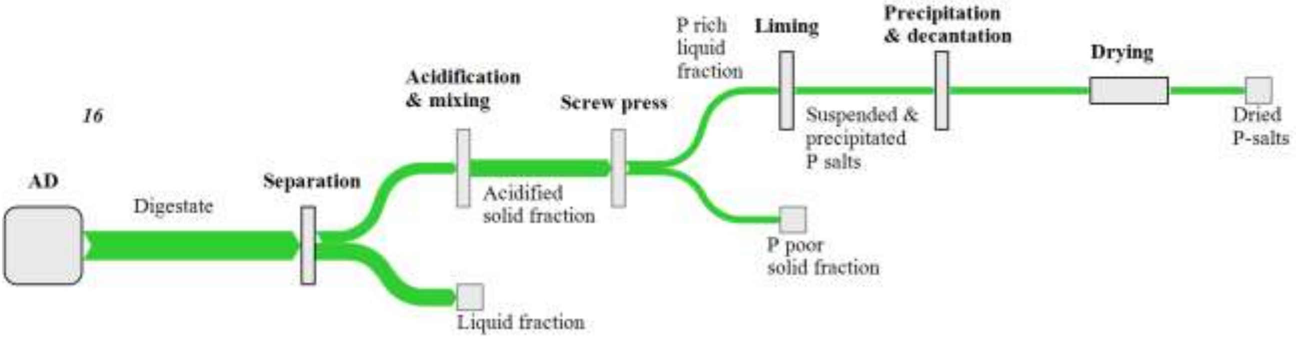

Figure II-16 Cascade 16

This cascade is a variation on Cascade 18, which is currently operational at a biogas plant.

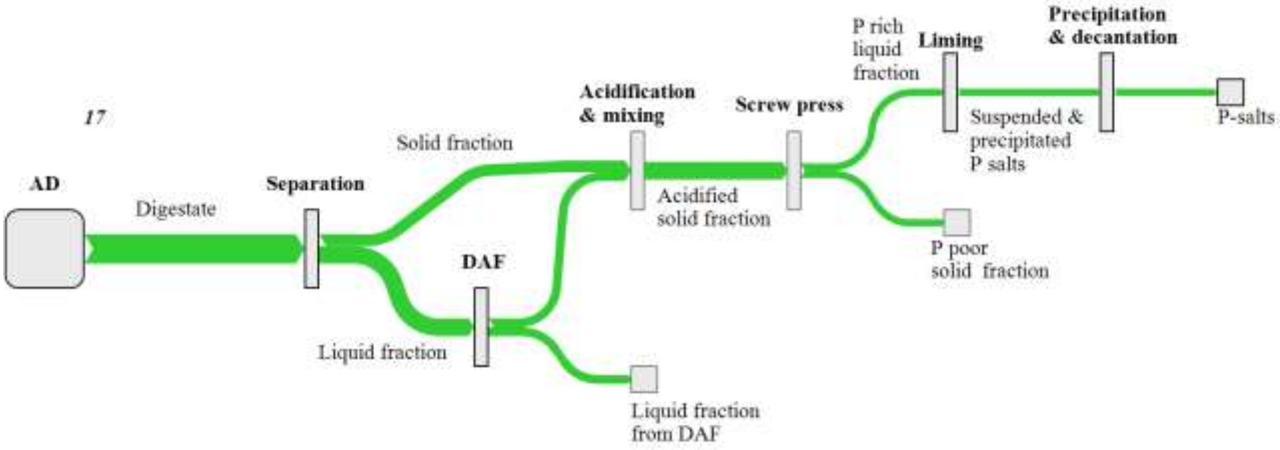

Figure II-19 Cascade 17

This cascade is a variation on Cascade 18, which is currently operational at a biogas plant.

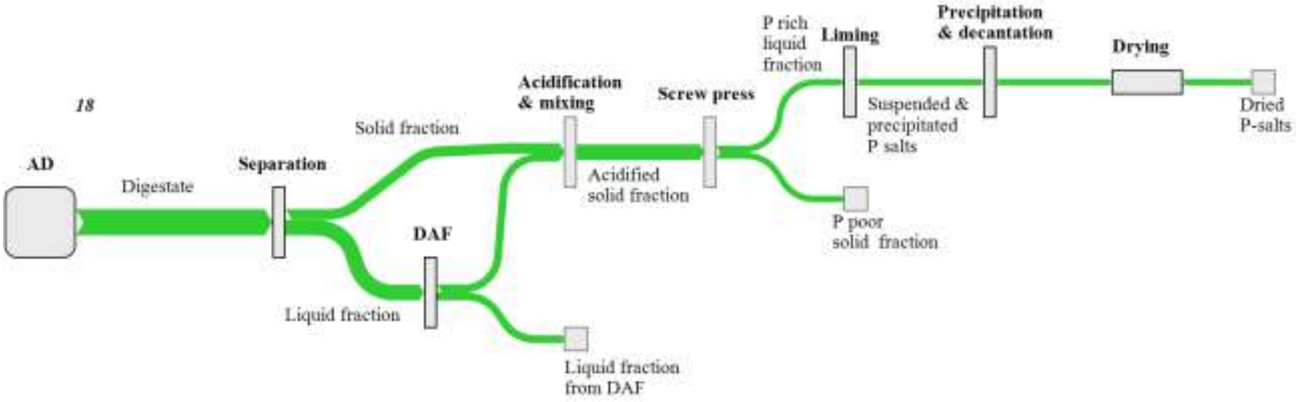

Figure II-18 Cascade 18

This cascade is operational at Demo Plant Groot Zevert Vergisting, where it is combined with Cascade 4.

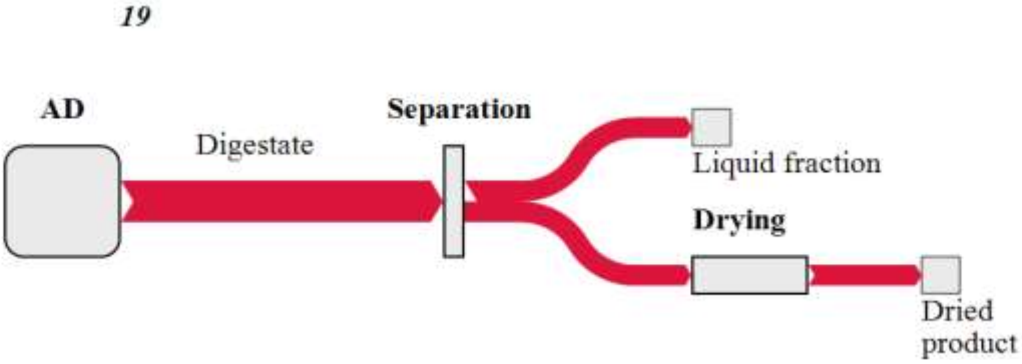

Figure II-17 Cascade 19

Outreach Location Waterleau New Energy(BE) is drying the solid fraction after centrifugation in a Hydrogone® dryer.
Outreach Locations Biogas Bree (BE) is drying the solid fraction of the digestate after centrifuge with an in-house developed drying system combined with acid air scrubbing of the exhaust air.
Associated Plant Arbio (BVBA) is drying the solid fraction of the digestate mixed with N-rich concentrate from the membrane filtration.

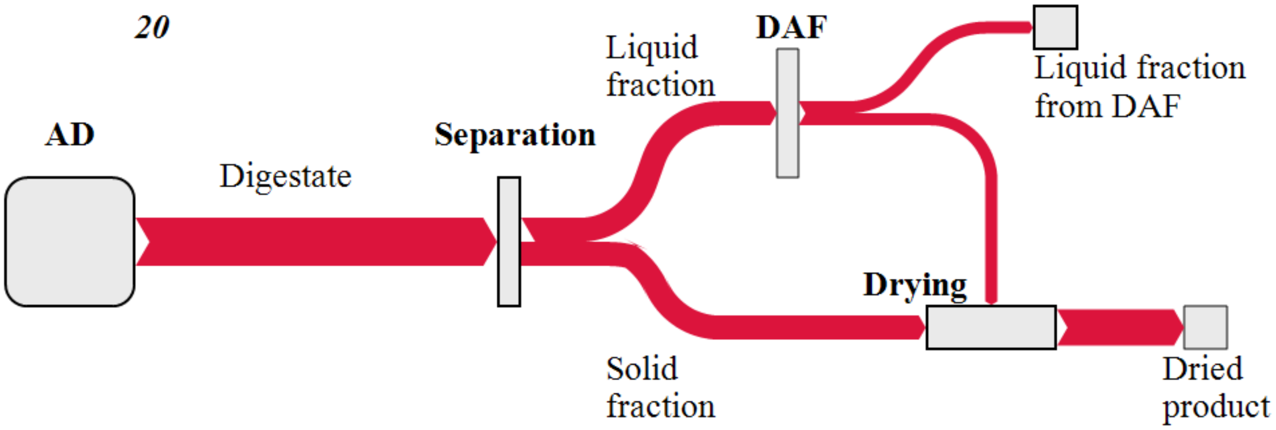

Figure II-20 Cascade 20

This cascade describes a part the old process at Demo Plant AMPower. It was combined with Cascade 3, without the membrane filtration and ion exchanger.

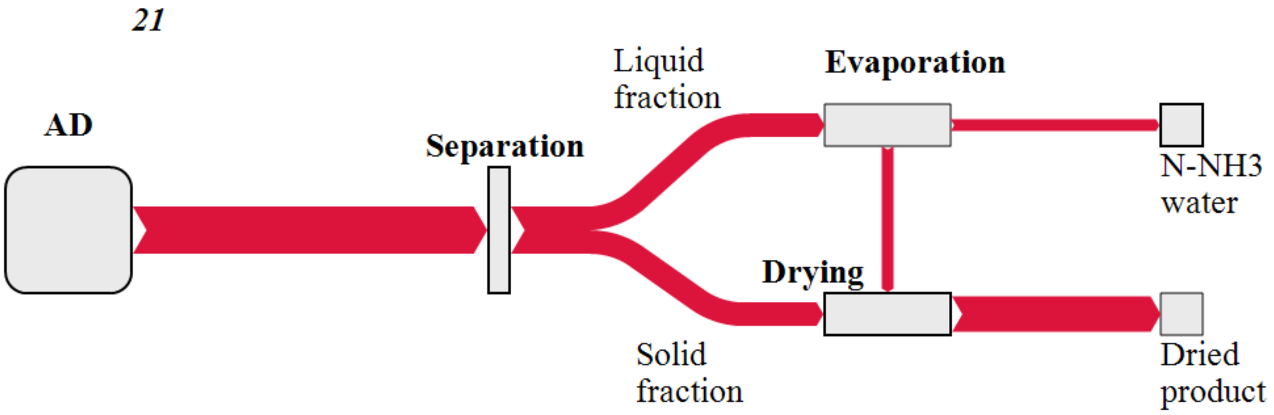

Figure II-21 Cascade 21

Demo Plant AMPower (BE) is currently drying the concentrate after evaporation in a fluidized bed dryer together with the solid fraction after centrifuge. This cascade is combined with Cascade 5.

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Systemic large-scale eco-innovation to advance circular economy and mineral recovery from organic waste in Europe

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AM Power (BE)
Groot Zevert Vergisting B.V. (NL)
Acqua & Sole S.r.l. (IT)
RIKA Biofuels Development Ltd. (UK)
GNS Gesellschaft für Nachhaltige Stoffnutzung mbH (DE)
A-Farmers Ltd (FI)
ICL Europe (NL)
Nijhuis Water Technology (NL)
Proman Management GmbH (AU)
Ghent University (BE)
Milano University (IT)
Vlaams Coördinatiecentrum Mestverwerking (BE)
European Biogas Association (BE)
Rural Investment Support for Europe (BE)

Project coordinator

Oscar F. Schoumans
Oscar.Schoumans@wur.nl
Wageningen Environmental Research
The Netherlands

Project website: www.systemicproject.eu

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