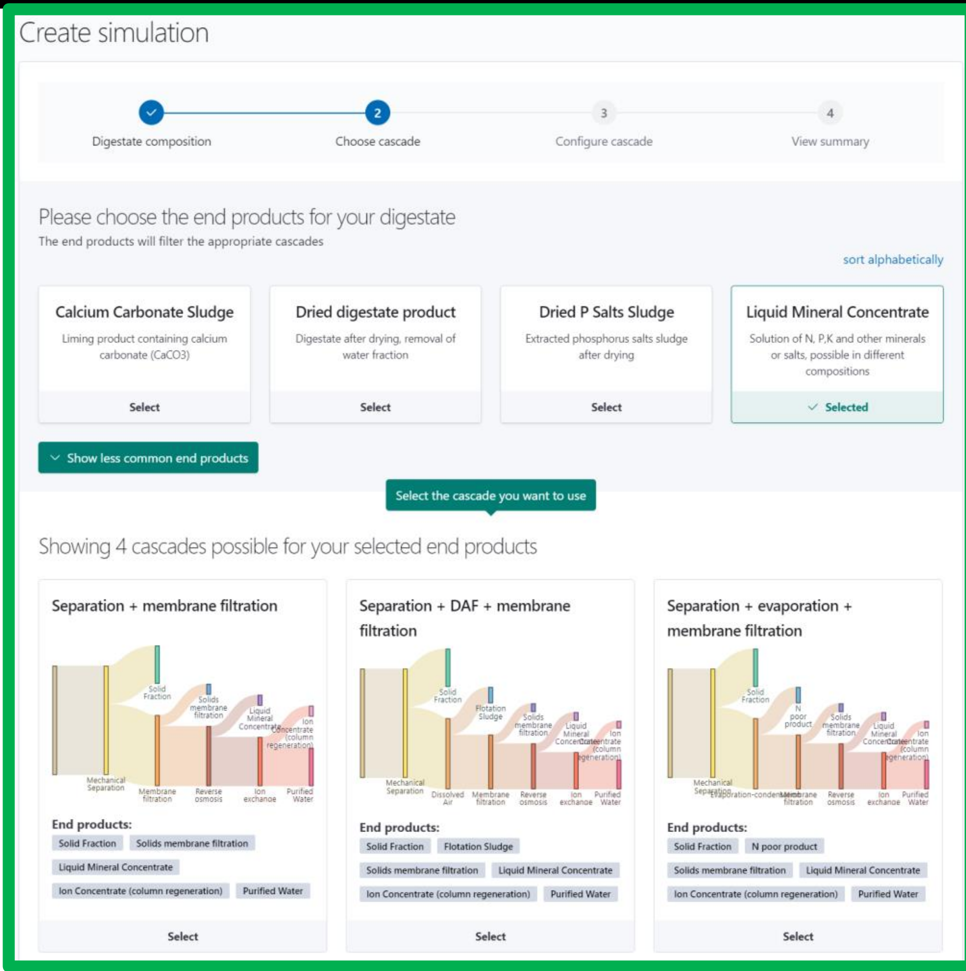
08 April 2021

D 3.6 Business Development Package and guiding materials
NUTRICAS Tool: Manual and Description of the Tool (Version 1)



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Content

Preface

This manual and guidance document was published as a part of the European demonstration project SYSTEMIC funded by the H2020 programme (project number 730400). The project SYSTEMIC focuses at five large scale biogas plants where innovative nutrient recovery processing techniques were implemented and monitored. One of the tasks within the SYSTEMIC project is to **develop a business development package (BDP) to support decision making for implementation of the innovative business cases in Europe.**

The Business Development Package (D 3.6) will be a page on the SYSTEMIC website (https://systemicproject.eu/business-development-package/)[1] where project results are summarized and available as easily digestible information for biogas plant owners. It provides a step-by-step approach in the exploration of nutrient recovery and re-use on digestate.

An important part of the BDP is the "**NUTRICAS Tool**", a calculation tool for cost benefit analysis and technology selection (D 3.5) to forecast the costs, performances and end products for selected nutrient recovery and re-use (NRR) technology combinations on digestate.

Based on the technologies that occurred most frequently in the SYSTEMIC biogas plants (Demo Plants, Outreach Locations and Associated Plants), the results from the survey and case studies in literature**,** 12 frequently occurring or promising process steps were selected.

- Liquid-solid separation techniques
    - Centrifuge (with and without polymer addition)
    - Screw press (with and without polymer addition)
    - Belt press (with polymer addition)
    - Dissolved Air flotation (with polymer addition)
- Nitrogen (ammonia) stripping-scrubbing
    - With H_2SO_4
    - With gypsum
- Evaporation and condensation
    - With prior acidification
    - Without prior acidification
- Membrane filtration technologies
    - Ultrafiltration + reversed osmosis
    - Reversed osmosis
- Phosphorus stripping and precipitation: Repeat
- Thermal drying

By combining these technologies, a final selection of 21 technology cascades was made (Annex I).

The framework in which the Tool is implemented is designed to be able to easily update, improve or extend the tool further in the future. For example adding more technology(cascades) or other types of inputs (e.g. raw manure instead of digestate) to the NUTRICAS Tool or by developing and adding additional modules like a tool to calculate the application rates of the different end products for fertilisation of crops or additional technologies.

The NUTRICAS Manual and Tool Description (D3.6) contains a description of the calculation models and assumptions that are used. It will be a living document in "the Cloud" that can be continuously updated, when the Tool is updated or when new modules of functionalities are added. This ensures that users always can consult the most recent version of the Manual.

We would like to acknowledge the plant owners and staff of Acqua & Sole, AM-Power, BENAS-GNS, RIKA/Fridays, GZV, Waterleau, Outreach Locations and Associated Plants and technology providers who for their contribution and participation in testing the tool.

The authors

[1] To ensure the open access of the deliverables of the SYSTEMIC project, all public deliverables will be available, even after the end of the project, via the library of Wageningen University and Research (https://www.wur.nl/en/Library.htm) and also via digital platform Biorefine Cluster Europe (https://www.biorefine.eu/) and websites of some of the partners (https://www.vcm-mestverwerking.be/en/faq/3921/systemic)

Abbreviations

CAPEX: Capital expenditures
OPEX: Operational expenditures
OL: Outreach Location
AP: Associated Plant
SE: Separation efficiency
SF: solid fraction
LF: liquid fraction
BDP: Business Development Package
PM: polymer
RO: reverse osmosis
DAF: dissolved air flotation
$FeCl_3$: Iron(III)chloride
$MgCl_2$: Magnesium dichloride
$FeSO_4$: Iron(III)sulphate

1 History and development

To build the calculation models for the NUTRICAS Tool, a lot of data was required on composition of feedstocks, intermediate streams and end products, costs, additives and technology efficiency. This data was gathered from the 5 Demo Plants, Outreach Locations (OL) and Associated Plants (AP), scientific publications, other project reports, consortium knowledge and technology providers.
To store and categorize the data on each technology, a database ("the SYSTEMIC database") was designed in Microsoft Excel® and available on the SYSTEMIC website https://systemicproject.eu/business-development-package/ under "Technologies and mass balances".

The **NUTRICAS Tool** was first designed as an Excel-file (D 3.5, 31 January 2020).
Rapidly it became clear that Excel™ is limited in speed when it comes to complex calculations, like the mass balance calculations and that it is difficult to make it user-friendly. It was therefore decided that the Excel tool would be translated into a web application with a server-based calculation engine.
IT consultant "Moment-4" was contacted and created a web application that provides a greater user- and administrator-friendliness because of an optimized user experience applied to the user interface. It also has a data storing function, saving the data of each user's performed mass balance calculations. This ensures that the user can see and recall the previous mass balance calculations done with the tool.

The partners in the SYSTEMIC project will be able to use aggregated data (averages, variances, distributions, correlations,…) of this data for further optimisation of the calculation models of the NUTRICAS Tool. The NUTRICAS web application source code will be accessible under conditions negotiated with the SYSTEMIC partners, meaning that it can be used as a template for new tools or new modules can be added to it in future projects. These agreements are all included in the

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Following chapters still under construction

Privacy Statement of the NUTRICAS Tool.

Suggestions for further optimisation of the Tool's calculation models are added in Chapter **Fout! Verwijzingsbron niet gevonden.**.

2 Login

The web application has a data storing function, saving the data of each user's performed calculations. This ensures the user can recall all his or hers previous calculations in the NUTRICAS Tool (see).
The following general information of the biogas plant is required (Figure 2-1).

- Location of the plant (postal code, country)
- Valid email address or login with Google or Facebook account
- Confirmation of the privacy statement

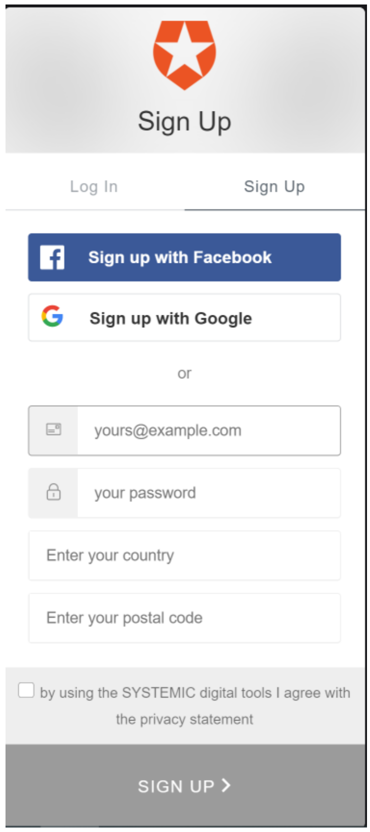

Figure 1-1 Login screen SYSTEMIC digital tools.

3 NUTRICAS Tool

The NUTRICAS Tool is a calculation tool for cost benefit analysis and technology selection. It can simulate a mass- and nutrient balance (N, P and K) and makes an estimation of the investment costs, operational costs and additive costs for selected nutrient recovery and re-use (NRR) technology combinations on a specific digestate composition. There are now 21 technology cascades implemented in the NUTRICAS Tool (Annex I).

3.1 Required input information

3.1.1 Feedstocks

The simulation will use digestate as a starting point for calculation of the mass balance and cost estimation (3.1.3 Composition of the digestate, Figure 3-3).

However, the user starts with completing the type of feedstocks and the annual amount that will be fed to the digester (Figure 3-1).

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 (see 3.1.3 Composition of the digestate).

From the types of feedstock occurring most frequently in the SYSTEMIC database 5 default types of feedstock were selected, which can be used in the tool for mono-digestion or co-digestion.

The following 5 feedstocks can be selected:

- Cattle manure
- Pig slurry
- Poultry litter
- Sewage sludge
- Organic waste
- Energy crops

"**Pig slurry**" is interpreted as faeces and urine produced by housed pigs, usually mixed with some bedding material and some water during management to give a liquid manure with a dry matter content in the range from about 1 – 10%.

"**Cattle manure**" is regarded as farmyard cattle manure, i.e. faeces and urine mixed with large amounts of bedding material (usually straw) on the floors of cattle housing.

"**Poultry manure**" are droppings mixed with a layer of, for example sawdust or wood shavings, on the floors of buildings housing poultry.

“**Sewage sludge**” is the by-product of waste water treatment that concentrates solids and bacteria in ‘activated sludge’. It contains significant quantities of plant nutrients.

“**Organic waste**” is a general term, covering different types of waste like slaughterhouse waste, waste from food-,beverage- and feed industry, agricultural residues, green household waste, etc.

“**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.

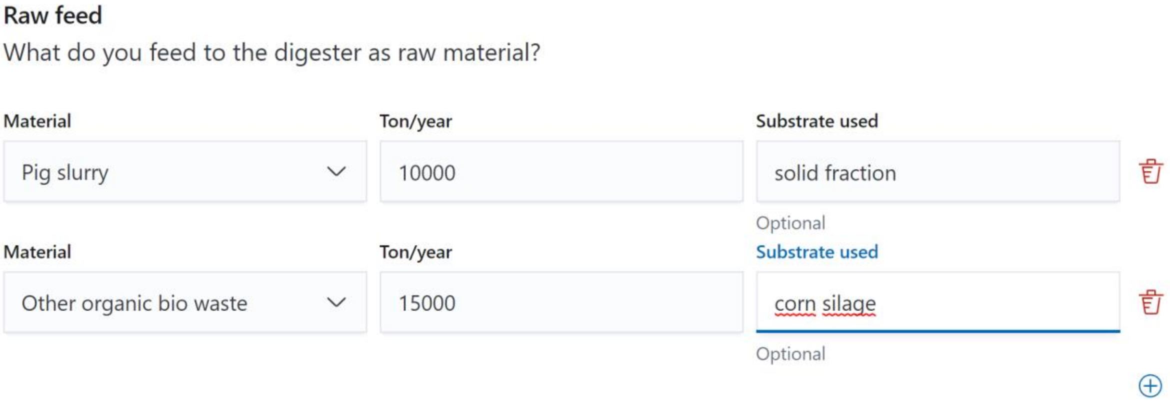

Figure 3-1 Input fields to specify the substrates that are processed in the anaerobic digester.

The user can also specify the type of input material under “Substrate used”, however this has no impact on the calculation of the digestate composition (Figure 3-1).

The NUTRICAS Tool calculates the mass balance for different fractions of the total mass and the nutrients N, P, K (Figure 3-2).

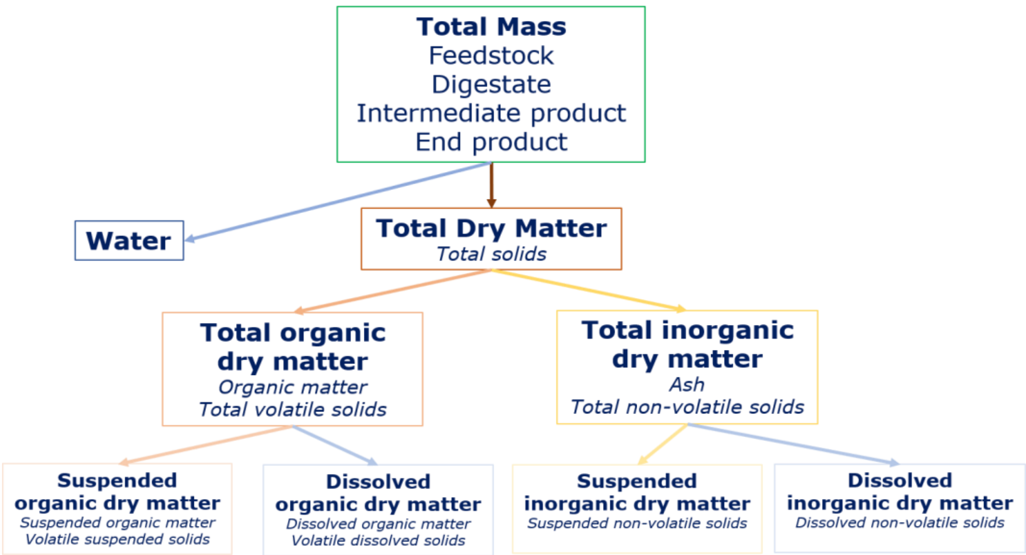

Figure 3-2 Schematic description of the fractions that are calculated for calculating the mass-and nutrient balance in the NUTRICAS Tool.

The of the terminology and definitions of the different fractions is given in Table 3-1.

This approach assures a simple way to estimate the elements that will go with the liquid (i.e. dissolved) and which with the solids (i.e. suspended). The “fraction”, expressed as a percentage, is used to calculate the amount that is suspended or dissolved.

Often the mineral components in the liquid phase (soluble minerals) react (e.g. N-stripping, P-precipitation etc.) and not the total amount of a specific component. Unfortunately, the distribution of a component over the solid phase and liquid phase (cfr. Dissolved – suspended) is often also not known by plant owners. Therefore, some **assumptions have been on how the fractions are divided in the six feedstock types (Table 3-2).**

For the mass balance calculations, the units are converted to (kg/ton):
Dry matter (DM % on fresh weight)* 10 = Total DM (kg/ton)
Organic matter (% of DM)* Total DM (kg DM/ton) = DM (org) (kg OM/ton)
Total phosphorus (g P_2O_5/kg)* 0.436= Total P (kg P/ton)
P soluble (g PO_4-P/kg)= P (inorg, diss) (kg P/ton)
Total nitrogen (g N/kg) = Total N (kg N/ton)
Soluble nitrogen (ammoniacal N) (g NH_4-N /kg)= N (inorg, diss) (kg NH_4-N/ton)
Total potassium (g K_2O/kg)* 0.830= Total K (kg K/ton)

The fractions (dissolved – suspended) are based on a publication of Schulze-Rettmer et al. from 2001, where this is investigated for pig slurry.

It is assumed that 95% of the total inorganic N is available in solution (N inorg, diss) and 5% is associated with the solids (N inorg, susp)(Schulze-Rettmer et al., 2001).

This study concluded that 66% of the organic nitrogen compounds in pig slurry like urea, uric acid and amino acids are well soluble in water (N org,diss). Therefore, 34% is attached to organic compounds and in the "solid phase" (N org, susp).

A study from Schoumans *et al.* in 2017 showed that the average P and PO_4^{3-}-P of six pig manure samples from different locations was respectively 1.73g P/kg and 0.017 g/kg, which corresponds to the factor 0.009 used to calculate (inorg, diss) (Table 3-2, "Calculation", P (inorg, diss) = P total*0.009). According to Schulze-Rettmer et al., the mineral P salts (P (inorg)) are mainly suspended PO_4-salts (P (inorg, susp) = 81%* P (inorg)).

The organic phosphorus compounds (P org, susp) are almost all found in the solid phase (75% of the total organic P) (Schulze-Rettmer *et al.*, 2001).

For potassium it is assumed that it is all in mineral form (K (inorg)) and that the main part is in the liquid phase (K (inorg,diss)=Total K*86%) as K-ions and soluble potassium salts like K-struvite. The remaining part is present in the solid phase (K (inorg,susp)) (Schulze-Rettmer *et al.*, 2001).
The assumption that a part of Mg, NH_4 and PO_4, which are ions in the liquid phase, are found in the solid phase is due to the fact that struvite can be formed with these three ions, which is an salt that only slowly dissolves. Also, nearly the half of the residual suspended ortho-phosphate is bound to calcium, probably as hydroxyl-/ chloro-apatite or as tricalcium phosphate (House, 1999). The rest of phosphate may be bound to iron or to other metals in the digestate (Schulze-Rettmer *et al.*, 2001).

Table 3-3 presents the values found in literature, from which the fractions composition in Table 3-2 were derived.

Table 3-1 Terminology and definitions of the fractions, i.e. the distribution of a component in the solid and liquid fraction. Inorg = Inorganic, Org= Organic, Susp= suspended, Diss=dissolved, DM= dry matter, N= nitrogen, P=phosphorus, K= potassium, BOD=biological oxygen demand, COD=chemical oxygen demand

water	Total water content
Total DM	Total Dry matter or total solids
DM (inorg)	Total inorganic dry matter, inorganic salts, ash or non-volatile solids
DM (inorg, susp)	Insoluble/suspended inorganic dry matter, inorganic salts, ash or non-volatile solids
DM (inorg, diss)	Dissolved inorganic dry matter, inorganic salts, ash or non-volatile solids e.g. ions, minerals
DM (org)	Total organic dry matter, organic matter, total volatile solids
DM (org, susp)	Insoluble/suspended organic dry matter, organic material, volatile solids
DM (org, diss)	Dissolved organic dry matter, organic material, volatile solids organic compounds, e.g. BOD, COD
N total	Total nitrogen
N (inorg)	Total inorganic nitrogen, nitrogen salts
N (inorg, susp)	Insoluble/suspended N salts
N (inorg, diss) [1]	Dissolved inorganic nitrogen, mineral nitrogen, e.g. NH_4-N, NO_3-N, NO_2-N
N (org)	Organic nitrogen, Kjeldahl Nitrogen – NH_4^+
N (org, susp)	Suspended organic nitrogen, e.g. humic acids
N (org, diss)	Dissolved organic nitrogen, e.g. uric acid and amino acids, proteins
P total	Total phosphorus
P (inorg)	Total inorganic phosphorus, phosphorus salts
P (inorg, susp)	Insoluble/suspended inorganic phosphorus salts, e.g. struvites, hydroxyl-/ chloro-apatite or as tricalcium phosphate or phosphorus bound to metals
P (inorg, diss)	Dissolved inorganic phosphorus, mineral phosphorus, ortho-phoshates, e.g. H_2PO_4-, HPO_4^{2-}, and PO_4^{3-} soluble ions and dissolved salts
P (org)	Organic phosphorus
P (org, susp)	Suspended organic phosphorus, P complexed in or bound to organic matter
P (org, diss)	Dissolved organic phosphorus, P bound to organic compounds that are small enough to be regarded as soluble
K total	Total potassium
K (inorg)	Inorganic potassium
K (inorg, susp)	Struvites, insoluble inorganic K salts
K (inorg, diss)	Dissolved inorganic potassium, e.g. soluble K salts, K-ions
K (org) [2]	Organic potassium
K (org, susp) [2]	Suspended organic potassium, K complexed in or bound to organic matter
K (org, diss) [2]	Dissolved organic potassium, k bound to organic compounds that are small enough to be regarded as soluble

[1] In the NUTRICAS Tool, NH_4-N is assumed to be N (inorg, diss). NO_3-N and NO_2-N are not taken into account here, because they are rarely measured in feedstocks and digestate.
[2] In the NUTRICAS Tool, these parameters are considered as negligible.

Table 3-2 Assumptions for the composition of the different feedstock types. The orange fields are based on values from the SYSTEMIC database (Table 3-3), the other values are calculated according to “Calculation”. Conc. = concentration

		Calculation	Pig slurry		Cattle manure		Poultry Manure		Sewage sludge		Organic waste		Energy crops	
	Unit		Conc.	Fraction	Conc.	Fraction	Conc.	Fraction	Conc.	Fraction	Conc.	Fraction	Conc.	Fraction
Total mass	kg		1		1		1		1		1		1	
Water	g/kg	Mass- Total DM	906.8		808.0		440.0		860.0		250.0		680.0	
Total DM	g/kg		93.2		192.0		560.0		140.0		750.0		320.0	
DM (inorg)	g/kg	DM (inorg,susp)+DM (inorg,diss)	32.2		72.0		150.0		40.0		350.0		70.0	
DM (inorg, susp)	g/kg	N (inorg, susp) + P (inorg, susp) +K (inorg, susp)+Mg (inorg, susp) + Ca (inorg, susp)+S (inorg, susp) +Cl (inorg, susp)≤DM (inorg, susp) [1]	3.6		7.7		16.1		5.8		11.1		7.0	
DM (inorg, diss)	g/kg	Total DM - DM (inorg, susp)- DM (org)	28.6		64.3		133.9		34.2		338.9		63.0	
DM (org)	g/kg		61		120		410		100		400		250	
DM (org, susp)	g/kg	DM (org)*fraction	43.3	71%	85.2	71%	291.1	71%	71.0	71%	284.0	71%	177.5	71%
DM (org, diss)	g/kg	DM (org)*fraction	17.7	29%	34.8	29%	118.9	29%	29.0	29%	116.0	29%	72.5	29%
N total	g N/kg		8.0		7.0		28.0		7.4		14.4		3.6	
N (inorg)	g N/kg	N (inorg, diss)/fraction of N (inorg, diss)	4.5		3.7		2.4		2.9		0.74		2.4	
N (inorg, susp)	g N/kg	N (inorg)*fraction	0.2	5%	0.2	5%	0.1	5%	0.1	5%	0.04	5%	0.1	5%
N (inorg, diss)	g N/kg		4.3	95%	3.5	95%	2.3	95%	2.8	95%	0.70	95%	2.3	95%
N (org)	g N/kg	Total N - N (inorg)	3.5		3.3		25.6		4.5		13.7		1.2	
N (org, susp)	g N/kg	N (org)*fraction	1.2	34%		34%		34%		34%		34%		34%
N (org, diss)	g N/kg	N (org)*fraction	2.3	66%	2.2	66%	16.9	66%	2.9	66%	9.0	66%	0.8	66%
Ptotal	g P/kg		2.5		1.5		10.0		30.0		4.0		0.6	
P (inorg)	g P/kg	P (inorg, diss)/fraction of P (inorg, diss)	0.12		0.07		0.5		1.4		0.19		0.03	
P (inorg, susp)	g P/kg	P (inorg)*fraction	0.10	81%	0.06	81%	0.4	81%	1.1	81%	0.15	81%	0.02	81%
P (inorg, diss)	g P/kg	Ptotal*0.009[2]	0.02	19%	0.01	19%	0.1	19%	0.3	19%	0.04	19%	0.01	19%
P (org)	g P/kg	Total P - P (inorg)	2.4		1.4		9.5		28.6		3.8		0.57	
P (org, susp)	g P/kg	P (org)*fraction	1.8	75%	1.4	75%	7.1	75%	21.4	75%	2.8	75%	0.43	75%
P (org, diss)	g P/kg	P (org)*fraction	0.6	25%	0.4	25%	2.4	25%	7.1	25%	1.0	25%	0.14	25%
K total	g K/kg		4.3		5.9		15.9		2.2		10.2		5.1	
K (inorg)	g K/kg	Total K - K (org)	4.3		5.9		15.9		2.2		10.2		5.1	
K (inorg, susp)	g K/kg	K (inorg)*fraction	0.6	14%	0.8	14%	2.2	14%	0.3	14%	1.4	14%	0.7	14%
K (inorg, diss)	g K/kg	K (inorg)*fraction	3.7	86%	5.1	86%	13.7	86%	1.9	86%	8.8	86%	4.4	86%
K (org)	g K/kg	Neglegible[3]	0		0				0		0		0	
K (org, susp)	g K/kg	Neglegible	0	25%	0	25%	0	25%	0	25%	0	25%	0	25%
K (org, diss)	g K/kg	Neglegible	0	75%	0	75%	0	75%	0	75%	0	75%	0	75%

[1] averages from the SYSTEMIC database and assumption for percentage:
S (inorg, susp) = 0.52 g S/kg*30%= 0.156
Cl (inorg, susp) = 1.9 g Cl/kg*5%= 0.095
Mg (inorg, susp) = 0.9 g Mg/kg*80%= 0.72
Ca (inorg, susp) = 3.2 g Ca/kg*50%= 1.6
Na (inorg, susp) = 1.1 g Na/kg*10%= 0.11

[2] Table 3.1 in (Schoumans et al., 2017)
[3] Table 2 in (Schulze-Rettmer et al., 2001)

Table 3-3 Literature included in the SYSTEMIC database from which the values in orange in Table 3-2 are derived

Variable	**Unit**	**Pig Slurry**	**Cattle manure**	**Poultry manure**	**Sewage sludge**	**Organic waste**	**Energy Crops**
Total DM	g/kg	107 [1] 79.4±7.6 [4] 10-180 [10]	92 [1] 200-500 [10]	562 [1]	250 [2] 31 [4]	612±347 [3] 285 [6] 599±167 [8] 13-910[10]	418±278[3] 237±70 [7] 233.5[12]
Total DM (org)	g/kg	79 [1] 34-70[10]	71 [1] 130-150[10]	416 [1]	175 [2] 23 [4]	583±337 [3] 208±11% [6]	390±268 [3] 213±20 [3] 370-860[11] 217[12]
Total N	g N/kg	7.0 [1] 2-16 [10]	4.0 [1] 4-9 [10]	28.4 [1]	12.5 [2] 2.2 [4]	5.4±4.1 [3] 15.7±7% [6] 22.0[8]	3.5±2.3 [3] 3.7±2 [3] 3.3-13.8[11] 3.1[12]
N (inorg, diss)	g N/kg	3.7 [1] 2.1-3.6[10]	1.9 [1] 1.5-3.1[10]	2.6 [1]	4.7 [2] 0.179 [4]	4.7±7.2 [3] 1.1±0.0 [8]	2.3±2.9 [3]
Total P	g P/kg	1.7 [1] 0.43-5.23[10] 1.73 [13] 0.64 [14]	0.7 [1] 0.43-3.48 [9]	10.0 [1]	30.0 [2] 0.83 [4]	2.3±3.3 [3] 1.6±12% [6] 5.8±0.0 [8]	0.6±0.8 [3] 0.6-2.4[11]
P (inorg, diss)	g P/kg	1.5 [1] 0.017[13] 0.565 [14]	0.6 [1]	9.0 [1]	27.0 [2]		
Total K	g K/kg	3.9 [1] 1.66-7.47[10]	4.5 [1] 3.32-9.96 [9] 2.07-9.96[10]	15.9 [1]	4.0 [2] 0.33 [4]	14.8±18% [6] 5.5±0.1 [8]	0.5-9.7[11]

[1] manure: https://www.handboekbodemenbemesting.nl/nl/handboekbodemenbemesting/Handeling/Organische-stofbeheer/Samenstelling-en-werking-organische-meststoffen/Samenstelling-organische-meststoffen.htm

[2] Sludge: ((STOWA, 2005)(Regelink, Ehlert and Römkens, 2017); K: Acqua & Sole

[3] (SYSTEMIC et al., 2020)

[4] Results VLAIO LA-project Pocket Power 2016-2020, samples pilot pocket digestion pig manure

[5] anonymous source (confidential), 2020

[6] (Hanc et al., 2011)

[7] (Götze, 2016)

[8] (Sharifi et al., 2014)

[9] (Hall 1999) in (Gendebien et al., 2001); cattle manure is farm yard manure

[10] (Gendebien et al., 2001); cattle manure is farmyard manure

[11] (Monti, Di Virgilio and Venturi, 2008)

[12] (Oleszek and Matyka, 2017): average of maize, sunflower, sorghum and triticale

[13] (Schoumans et al., 2017)

[14] (Schulze-Rettmer et al., 2001)

3.1.2 Biogas production

Based on the amount of organic matter in the feedstocks and their ratio in the digester, the annual biogas production and composition (CH_4 and CO_2) is estimated (Table 3-5).

Table 3-4 Assumptions for the amount and composition of the biogas produced from different feedstock types.

	Unit	Pig slurry	Cattle manure	Poultry Manure	Sewage sludge	Organic waste	Energy crops
Biogas production	Nm^3/kg organic matter	551	400	403	492	680	739
CH_4 in biogas	%	62	58	57	57	58	55
CO_2 in biogas	%	33	40	41	41	40	42

Table 3-5 Literature included in the SYSTEMIC database from which the values in Table 3-4 are derived.

Component	**Unit**	**Feedstock**					
		Pig Slurry	Cattle slurry	Poultry manure	Sewage sludge	Energy crops	OBW
Biogas production	Nm³/kg fresh matter	60 [1] 26 [2] 55 [3] 24-60 [8]	25 [1] 25 [2] 56 [3] 13-58 [8]	80 [1] 48 [3]	13.27 [3]	202 [1] 200 [2] 131 [3]	100 [1] 383 [2] 380 [3]
	Nm³/kg Organic matter	551 [4]	447 [4] 353 [6]	403 [4]	492 [6]	680 [4] 798 [6]	680 [4]
Degradation of organic substances [7]	%	40 54	30 37	67			
CH_4 in biogas	Nm³ CH_4/kg Organic matter	402 [5] 321 [6]	292 [5]	217 [6]	267 [6]	363 [5]	281 [5]
	%	65 [1] 60 [4] 76 [5] 58 [6] 66 [6]	60 [1] 50 [4] 63 [5]	60 [1] 57 [4] 54 [6]	67 [6]	52 [1] 55 [4] 63 [5] 52 [6] 53.2 [6]	61 [1] 53 [4] 60 [5]
CO_2 in biogas	%	33 42 [6]	35	34	34 33 [6]	35 48 [6]	33

1 (pig slurry, cattle slurry, chicken manure, corn sillage, bio-waste) Fachagentur Nachwachsende Rohstoffe e. V. (FNR): Biogas Basisdaten Deutschland Stand: Januar 2008.

2 (drijfmest varkens, drijfmest rundvee, average energy crops (Nl: „Energiegewassen"), average from from agro-waste (NL:"agrarische afvalstromen") https://groene-rekenkamer.nl/5200/de-mestvergister/

3 https://www.biogas-e.be/kenniseninnovatie/inputstromen

4 EU-AGRO-BIOGAS project: Online European Feedstock Atlas- https://daten.ktbl.de/euagrobiogasbasis/navigation.do?selectedAction=Startseite

5 Pig slurry (FR : lisier porcin), Cattle (dairy) slurry (FR : fumier bovin lait), energy crops (average of FR : ensilage de mais, ensilage d'herbe,fanes de pomme de terre, tontes), OBW (average of FR :paille de céréales, feuilles de betterave, issues de céréales humides, issues de céréales sèches, lactosérum)(Moletta, 2011)

6 (SYSTEMIC *et al.*, 2020)

7 (Deublein and Steinhauser, 2008)

8 Pocket Power (Inagro,2020)

3.1.3 Composition of the digestate

The composition of the digestate is the starting point of a simulation in the NUTRICAS tool. The user can adjust the amount of digestate that will be processed in the simulation, and the digestate composition (Figure 3-3).

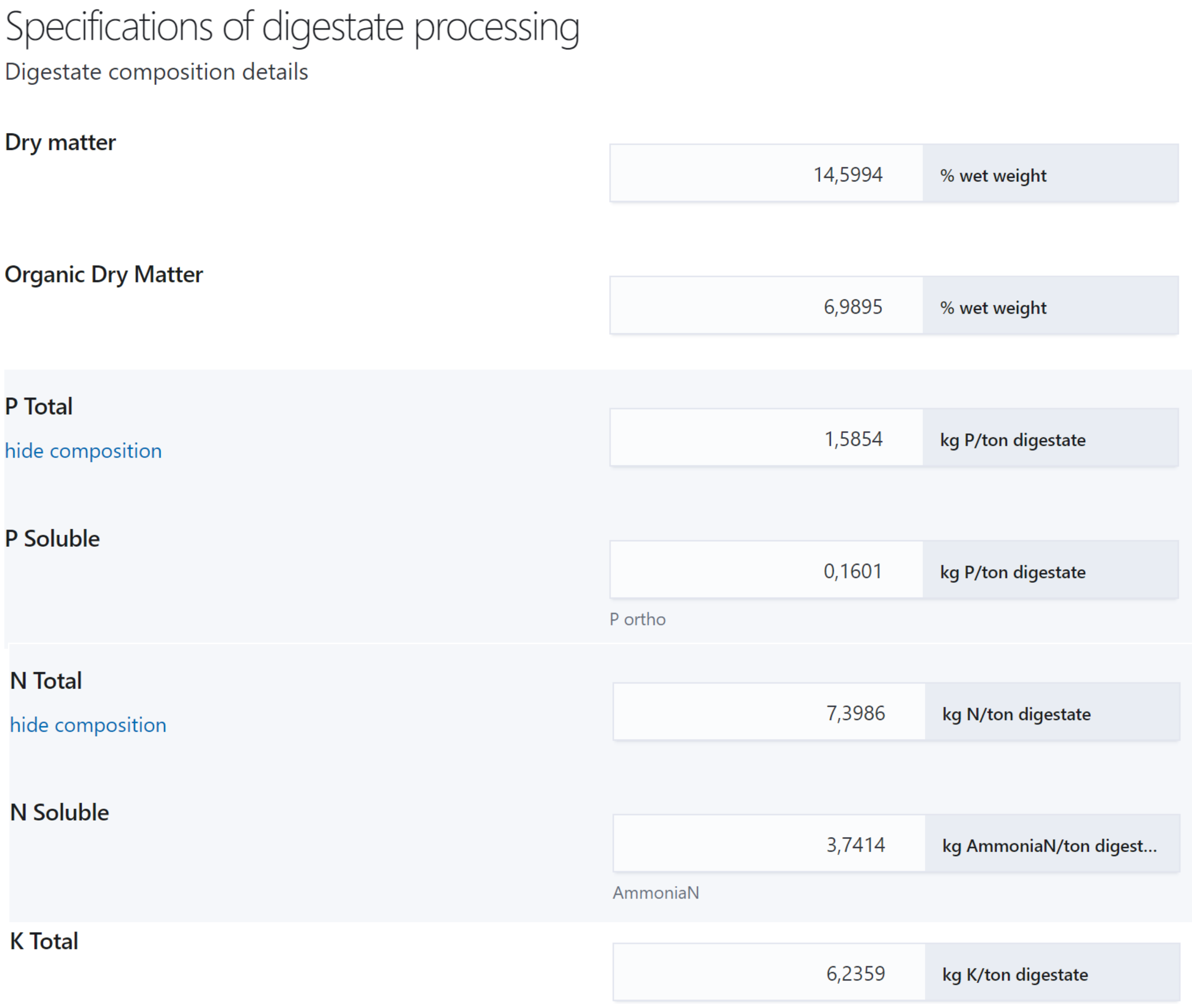

Figure 3-3 Screen of Step 1 in the NUTRICAS tool: Digestate composition, Dry matter = Total DM, Organic dry matter = DM (org), P soluble = P (inorg, diss), N soluble = N (inorg,diss)

If the user has no data available on the digestate composition, an estimation of the digestate composition is suggested (Figure 3-3), based on the composition and ratio of each feedstock as input to the biogas plant. The calculated digestate composition will take into account the decomposition of organic matter during biogas production and is calculated as follows:

$\text{mass}_{\text{digestate}} = \sum \text{mass}_{\text{feedstocks}} - \sum \text{mass}_{\text{biogas produced by feedstocks}}$

$\text{mass Biogas}_{\text{feedstock 1}}\text{(kg/ton feedstock)} = \text{mass}_{\text{feedstock}}\text{ (ton)} * \text{DM (org)}_{\text{feedstock 1}}\text{ (kg/ton)} * \text{Organic biogas production}_{\text{feedstock}}\text{ (Nm}^3\text{/kg organic matter)}$[1]$* \text{density of biogas (kg biogas/Nm}^3)$

$\text{Biogas production}_{\text{feedstock 1}}\text{(Nm}^3\text{/kg ton feedstock)} = \text{mass}_{\text{feedstock}}\text{ (ton)} * \text{DM (org)}_{\text{feedstock 1}}\text{ (kg/ton)} * \text{Organic biogas production}_{\text{feedstock}}\text{ (Nm}^3\text{/kg organic matter)}$[1]

$\text{Biogas production}_{\text{feedstock 1}}\text{(Nm}^3\text{/ton feedstock)} =$
$CO_{2\ \text{feedstock 1}}\text{(Nm}^3\text{/ton feedstock)} + CH_{4\ \text{feedstock 1}}\text{(Nm}^3\text{/ton feedstock)}$

$CO_{2\ \text{feedstock 1}}\text{(Nm}^3\text{/ton feedstock)} = \text{Biogas production}_{\text{feedstock 1}}\text{(Nm}^3\text{/kg ton feedstock)} * CO_2(\%)$[1]
$CH_{4\ \text{feedstock 1}}\text{(Nm}^3\text{/ton feedstock)} = \text{Biogas production}_{\text{feedstock 1}}\text{(Nm}^3\text{/kg ton feedstock)} * CH_4(\%)$[1]

$\text{Molar mass } CO_2\text{ (mol/ton feedstock)} = p * CO_{2\ \text{feedstock 1}}\text{(Nm}^3\text{/ton feedstock)} / R*T$ [2]
$\text{Molar mass } CH_4\text{ (mol/ton feedstock)} = p * CH_{4\ \text{feedstock 1}}\text{(Nm}^3\text{/ton feedstock)} / R*T$ [2]

mass CO_2 (g/ton feedstock) = Molar mass CO_2 (mol/ton feedstock) * MW CO_2 (44.01 g/mol)
mass CH_4 (g/ton feedstock) = Molar mass CH4 (mol/ton feedstock) * MW CH_4 (16.042 g/mol)

$DM(org)_{\text{digestate from feedstock1}} = DM(org)_{\text{feedstock1}} - (\text{mass } CO_{2\ \text{feedstock1}} + \text{mass } CH_{4\ \text{feedstock1}})$

[1] Table 3-4

[2] p.V = n.R.T (Boyle's law)

R= gas constant=8.314459848 L.Pa/K.mol

T = 298.15K =25°C

P = atmospheric pressure= 101.325Pa

n= molar mass

V= volume (L) /1000=volume (m^3)

To make an estimate for the digestate composition, the calculations are described in Table 3-6.
It is assumed that all nutrients(N,P,K) and salts remain in the digestate. Therefore, ammonia emissions are neglected.

Because the fractions in all feedstocks are the same, and the amount of DM (org) removed as biogas is done proportionally over each feedstock added, the fractions in the digestate will also be the same (Table 3-6). The user can adjust the composition of the digestate, although some constraints are built in ("Constraints", Table 3-6).

In general, the proposed estimations of digestate composition certainly don't claim to accurately model a digester, but it provides the user a digestate composition to start exploring technologies in the NUTRICAS Tool.

The actual contents of the digestate can deviate greatly from the estimated composition calculated in the NUTRICAS Tool. This is partly related to differences in feed rations of the livestock (manure), the type of sludge, various combinations of different organic biological wastes and energy crops, and variations in operational conditions of the digester. Therefore, **it is highly recommended that the user fills in the composition of their digestate** in the input fields under "Digestate composition", to get a more accurate calculation (Figure 3-3).

Table 3-6 orange values are calculated based on the composition and ratio of each feedstock that is added. Other values are calculated based on the orange values.

	unit	Calculation	Constraints
mass	kg	∑ (water + Total DM) $_{feedstocks}$	
water	g/kg	∑(water) $_{feedstocks}$	
Total DM	g/kg	∑ (DM(inorg) + DM (org)) $_{feedstocks}$	∑ N total, Ptotal, Ktotal≤ Total DM
DM (inorg)	g/kg	∑DM (inorg,susp)+DM (inorg,diss) $_{feedstocks}$	
DM (inorg, susp)	g/kg	∑ (N (inorg, susp) + P (inorg, susp) +K (inorg, susp)+Mg (inorg, susp) + Ca (inorg, susp)+S (inorg, susp) +Cl (inorg, susp)≤DM (inorg, susp)) $_{feedstocks}$	
DM (inorg, diss)	g/kg	∑ (Total DM - DM (inorg, susp)- DM (org))	
DM (org)	g/kg	∑(DM (org) $_{feedstock\ n+1}$ – (mass CO_2 + mass CH_4) $_{feedstock\ n+1}$)	max Total DM
DM (org, susp)	g/kg	71%* DM (org) [1]	
DM (org, diss)	g/kg	29%* DM (org) [1]	
N total	g N/kg	∑ (N (inorg) + N (org)) $_{feedstocks}$	
N (inorg)	g N/kg	∑N (inorg,susp)+N (inorg,diss) $_{feedstocks}$	
N (inorg, susp)	g N/kg	∑ N (inorg,susp) $_{feedstocks}$	
N (inorg, diss)	g N/kg	∑ N (inorg,diss) $_{feedstocks}$ Conversion of N (org) to N (inorg, diss) due to anaerobic digestion is not taken into account.	max 95% van N total
N (org)	g N/kg	∑N (org,susp)+N (org,diss) $_{feedstocks}$	
N (org, susp)	g N/kg	∑ N (org,susp) $_{feedstocks}$	
N (org, diss)	g N/kg	∑ N (org,diss) $_{feedstocks}$	
Ptotal	g P/kg	∑ (P (inorg) + P (org)) $_{feedstocks}$	
P (inorg)	g P/kg	∑P (inorg,susp)+P (inorg,diss) $_{feedstocks}$	
P (inorg, susp)	g P/kg	∑ P (inorg,susp) $_{feedstocks}$	
P (inorg, diss)	g P/kg	∑ P (inorg,diss) $_{feedstocks}$ Conversion of P (org) to P (inorg, diss) due to anaerobic digestion (acid pH during hydrolysis) is not taken into account.	max 23% van P total[2]
P (org)	g P/kg	∑P (org,susp)+P (org,diss) $_{feedstocks}$	
P (org, susp)	g P/kg	∑ P (org,susp) $_{feedstocks}$	
P (org, diss)	g P/kg	∑ P (org,diss) $_{feedstocks}$	
K total	g K/kg	∑ (K (inorg) + K (org)) $_{feedstocks}$	
K (inorg)	g K/kg	∑K (inorg,susp)+K (inorg,diss) $_{feedstocks}$	
K (inorg, susp)	g K/kg	∑ K (inorg,susp) $_{feedstocks}$	
K (inorg, diss)	g K/kg	∑ K (inorg,diss) $_{feedstocks}$	
K (org)	g K/kg	∑K (inorg,susp)+P (inorg,diss) $_{feedstocks}$	
K (org, susp)	g K/kg	∑ K (org,susp) $_{feedstocks}$	
K (org, diss)	g K/kg	∑ K (org,diss) $_{feedstocks}$	

[1](Schulze-Rettmer et al., 2001)

[2] Schoumans *et al.* in 2017 showed that the average P and PO_4^{3-}-P of six digestates from pig manure from different locations was respectively 2.65g P/kg and 0.024 g/kg, which corresponds to P (inorg, diss) being 0.9% of P total. However, Schulze-Rettmer et al.,2001 measure P (inorg,diss) as 88% of Total P. However, the amounts of P measured were much lower (P total = 0.64 g P/L). An arbitrary value of 23% was chosen for the calculation in the NUTRICAS Tool.

3.1.4 Selection of the cascade of NRR technologies to produce required products

The NUTRICAS tool provides **21 nutrient recovery technology cascades (Annex I)** to produce different types of end products (Figure 3-4).

The user can select several products (Figure 3-4) and the matching technology cascades will be shown, from which the user can select one to perform the mass-and nutrient balance and cost simulation (example in Figure 3-5).

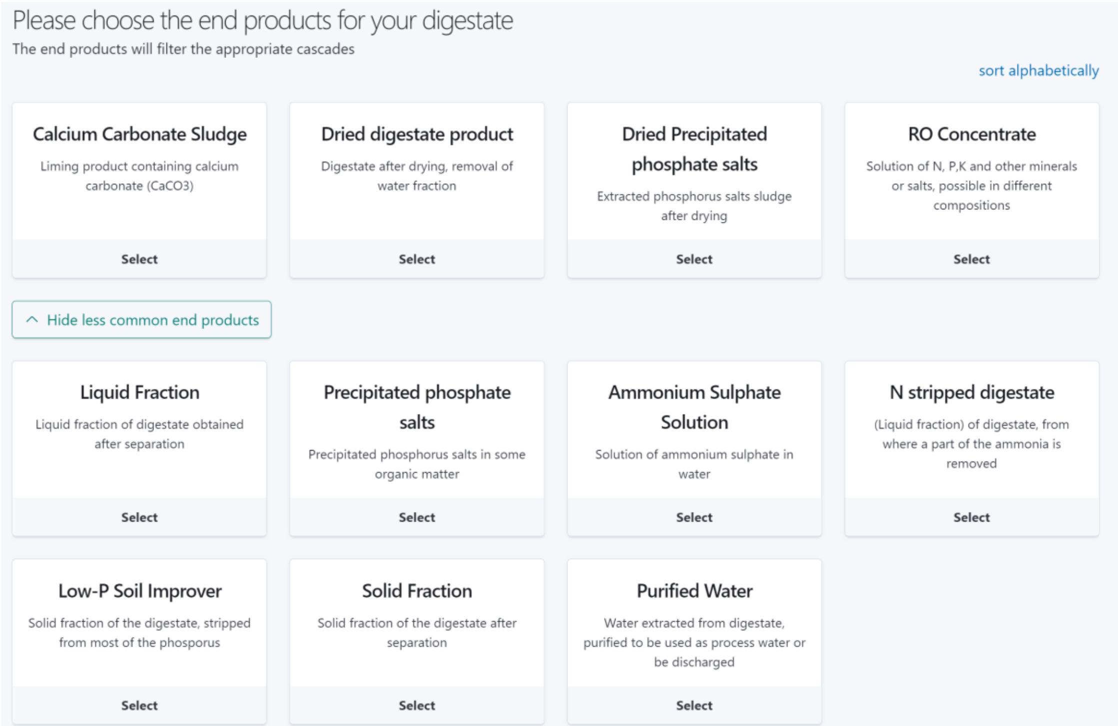

Figure 3-4. Select end products

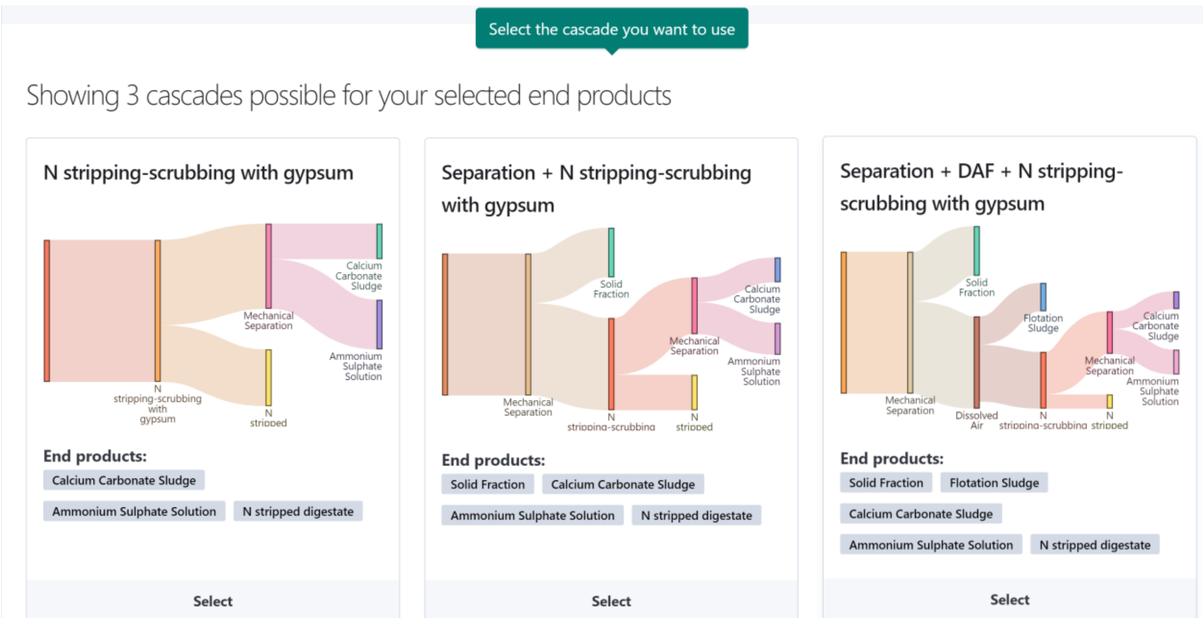

Figure 3-5 Proposed cascades after selecting "calcium carbonate" as end product

Each technology will interact with a specific component in the digestate available in the solution and/or associated with the suspended solids. Hence, the concentrations in the end products will change due to the implementation of the technology. This is taken into account with the implementation of "Recovery rates", specific for each technology.

The recovery rate is defined as the fraction of the initial amount of mass, dry matter, organic matter, nutrients or minerals (N, P, K) that is recovered in the end product. It describes how efficient a technology can separate, concentrate or recover certain elements from the input.

When a separation technology is used, the term "separation efficiency" (a.k.a. Separation Index, SI) is used for recovery rate.
The following formula is used to calculate the recovery rate.
Equation 1

$$Recovery\ rate\ (Et) = \frac{mass_{end\ product}(kg)\ \times\ concentration_{end\ product}\left(\frac{g}{kg}\right)}{mass_{input}\ (kg) \times\ concentration_{input}(\frac{g}{kg})}$$

This fraction is usually expressed as a percentage. E.g. 10% of the mass of the initial digestate that is processed in a decanter centrifuge is found in the solid fraction.

4 Nutrient Recovery and Reuse technologies

In this chapter the NRR technologies implemented in the NUTRICAS model are described in terms of technology, processing characteristics and costs. The following technologies are implemented in the NUTRICAS Tool:

- Separation technologies: centrifuge, screw press and belt press
- Dissolved air flotation unit (DAF)
- Membrane filtration technologies (MF, UF, NF)
- Reversed osmosis (RO)
- Ion-exchange
- Evaporation/condensation
- Nitrogen stripping
- Phosphorus stripping

In Annex II factsheets are given of each of the technology used in the NUTRICAS tool.

More detailed information on each technology can also be found in the Report: Schemes and scenarios for technologies of nutrient recovery.

4.1 Separation technologies

The most common separation technologies have been implemented in the tool. The user can select one of the 3 defined separators (screw press, belt press and centrifuge).
The Separation Efficiency (SE) will determine the composition of the solid fraction and is defined as follows:

Equation 2

$$Separation\ efficiency\ (SE)_{SF} = \frac{mass_{SF}(kg)\ \times\ concentration_{SF}\left(\frac{g}{kg}\right)}{mass_{input}\ (kg) \times\ concentration_{input}(\frac{g}{kg})}\ X\ 100\%$$

and *Equation 3*

$$Separation\ efficiency\ (SE)_{LF} =\ 100\% - Separation\ efficiency\ (SE)_{SF}$$

For each separation technology, for the main components a separation efficiency is suggested for decanter centrifuge (*Table 4-1*), screw press and belt press (Table 4-3)

The values for the separation efficiency - the yellow fields (*Table 4-1* and Table 4-3) - are assumptions based on values from literature and practice (Table 4-4). The composition of the solid and liquid fraction (i.e. mass balance) is calculated according to "Calculation mass balance" and other separation efficiency values (not in yellow fields) are calculated according to Equation 2 and Equation 3.

A belt press is commonly not operated without additives, therefore the SE is only shown for "with additive".

Table 4-1 Calculation of the mass balances to solid and liquid fraction of digestate separation with a ***decanter centrifuge without and with additive use.*** *SF=solid fraction, LF= Liquid fraction, SE=separation efficiency*

		Decanter centrifuge			
	Calculation mass balance	SE (%) **to SF**	SE (%) **to LF**	SE (%) **to SF**	SE (%) **to LF**
		Without additive		With additive	
mass (kg)	Water+Total DM	12	88	21	79
water	$Water_{input}$ * SE	9	91	17	83
Total DM	DM (inorg) + DM (org)	51	49	76	24
DM (inorg)	DM (inorg,diss) + DM (inorg, susp)	70	30	69	31
DM (inorg, susp)	DM $(inorg, susp)_{input}$ * SE	95	5	98	2
DM (inorg, diss)	DM $(inorg, diss)_{input}$ * SE	65	35	63	37
DM (org)	DM (org,diss) + DM (org, susp)	42	58	79	21
DM (org, susp)	DM $(org, susp)_{input}$ * SE	55	45	98	2
DM (org, diss)	DM $(org, diss)_{input}$ * SE	10	90	34	66
N total	N (inorg) + N (org)	19	81	35	65
N (inorg)	N (inorg,diss) + N (inorg, susp)	18	82	32	68
N (inorg, susp)	N $(inorg, susp)_{input}$ * SE	75	25	90	10
N (inorg, diss)	N $(inorg, diss)_{input}$ * SE	15	85	29	71
N (org)	N (org,diss) + N (org, susp)	22	78	42	58
N (org, susp)	N $(org, susp)_{input}$ * SE	60	40	95	5
N (org, diss)	N $(org, diss)_{input}$ * SE	3	97	15	85
Ptotal	P (inorg) + P (org)	60	40	85	15
P (inorg)	P (inorg,diss) + P (inorg, susp)	83	17	93	7
P (inorg, susp)	P $(inorg, susp)_{input}$ * SE	88	12	98	2
P (inorg, diss)	P $(inorg, diss)_{input}$ * SE	60	40	70	30
P (org)	P (org,diss) + P (org, susp)	40	60	79	22
P (org, susp)	P $(org, susp)_{input}$ * SE	52	48	98	2
P (org, diss)	P $(org, diss)_{input}$ * SE	3	97	20	80
K total	K (inorg) + K (org)	14	86	33	67
K (inorg)	K (inorg, diss) + K (inorg, susp)	14	86	33	67
K (inorg, susp)	K $(inorg, susp)_{input}$ * SE	70	30	98	2
K (inorg, diss)	K $(inorg, diss)_{input}$ * SE	5	95	34	66

The mass-based separation efficiency (SE_{mass}), the user is able to adjust by means of a slider (Figure 4-1). Constraints are implemented to prevent the user from adjusting the SE_{mass} to extreme values. The SE_{mass} can be adjusted within a certain range (*Table 4-2)*.

Table 4-2 Ranges within which values the separation efficiency can be adjusted by the user.

	Without additive		**With additive**	
	SE_{mass} **(%) to SF**	SE_{mass} **(%) to LF**	SE_{mass} **(%) to SF**	SE_{mass} **(%) to LF**
Decanter centrifuge	5-30	95-70	8-35	92-65
Screw press	4-25	96-75	22-55	88-45
Belt press			20-30	80-70

Table 4-3 Calculation of the mass balances to solid and liquid fraction of digestate separation with a ***screw press without and with additive use and belt press with additive use****. SF=solid fraction, LF= Liquid fraction, SE=separation efficiency*

		Screw press				Belt press	
	Calculation mass balance	SE (%) **to SF**	SE (%) **to LF**	SE (%) **to SF**	SE (%) **to LF**	SE (%) **to SF**	SE (%) **to LF**
		Without additive		With additive		With additive	
mass (kg)	Water+Total DM	13	87	34	66	20	80
water	$Water_{input}$ * SE38	11	89	31	69	15	85
Total DM	DM (inorg) + DM (org)	38	62	72	28	79	21
DM (inorg)	DM (inorg,diss) + DM (inorg, susp)	65	35	98	2	98	2
DM (inorg, susp)	DM (inorg, susp)$_{input}$ * SE	90	10	98	2	98	2
DM (inorg, diss)	DM (inorg, diss)$_{input}$ * SE	60	40	98	2	98	2
DM (org)	DM (org,diss) + DM (org, susp)	25	75	60	40	70	30
DM (org, susp)	DM (org, susp)$_{input}$ * SE	33	67	80	20	90	10
DM (org, diss)	DM (org, diss)$_{input}$ * SE	5	95	10	90	20	80
N total	N (inorg) + N (org)	19	81	31	69	57	43
N (inorg)	N (inorg,diss) + N (inorg, susp)	20	80	27	73	48	53
N (inorg, susp)	N (inorg, susp)$_{input}$ * SE	40	60	90	10	95	5
N (inorg, diss)	N (inorg, diss)$_{input}$ * SE	19	81	24	76	45	55
N (org)	N (org,diss) + N (org, susp)	17	83	39	61	80	20
N (org, susp)	N (org, susp)$_{input}$ * SE	47	53	90	10	90	10
N (org, diss)	N (org, diss)$_{input}$ * SE	1	99	13	87	75	25
Ptotal	P (inorg) + P (org)	9	91	20	80	40	60
P (inorg)	P (inorg,diss) + P (inorg, susp)	9	91	14	86	20	80
P (inorg, susp)	P (inorg, susp)$_{input}$ * SE	10	90	15	85	20	80
P (inorg, diss)	P (inorg, diss)$_{input}$ * SE	5	95	10	90	22	78
P (org)	P (org,diss) + P (org, susp)	8	92	24	76	58	43
P (org, susp)	P (org, susp)$_{input}$ * SE	10	90	30	70	75	25
P (org, diss)	P (org, diss)$_{input}$ * SE	3	97	7	93	5	95
K total	K (inorg) + K (org)	13	87	15	85	20	80
K (inorg)	K (inorg, diss) + K (inorg, susp)	13	87	15	85	20	80
K (inorg, susp)	K (inorg, susp)$_{input}$ * SE	65	35	70	30	80	20
K (inorg, diss)	K (inorg, diss)$_{input}$ * SE	5	95	6	94	10	90

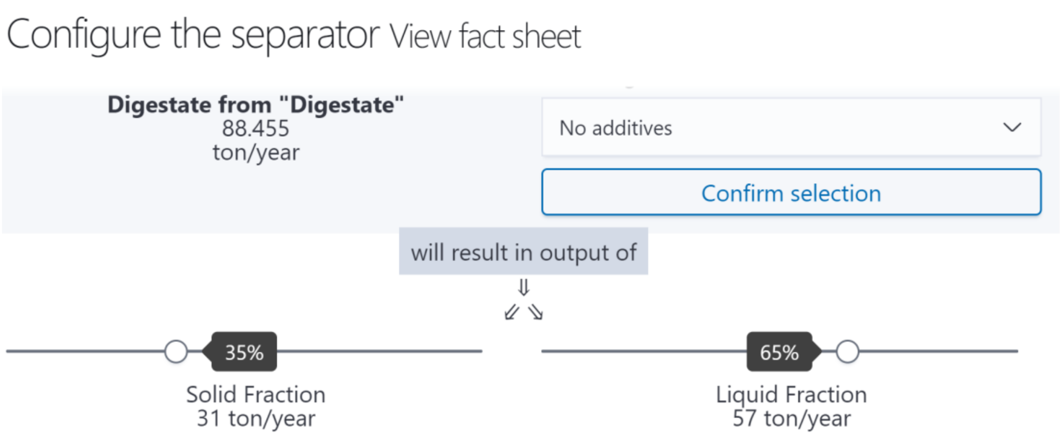

Figure 4-1. User can adjust the mass separation efficiency.

Table 4-4 ***Separation efficiencies -% to solid fraction*** *with range (minimum and maximum) for decanter centrifuge, screw press and belt press found in literature and practice. "Values in the tool" are shown in Table 4-1 and Table 4-3.*

Component	Additive	Decanter centrifuge **SE (%) to SF**	Screw press **SE (%) to SF**	Belt press **SE (%) to SF**
Mass	Without additive	14±8 [1] 10 (0-30)[2] 16[4]	12±8 [1] 10 (0-30) [2] 20 [6.3]	
	Values in the tool	**12**	**13**	
	With additive	21±12 [1] 29 (10-55)[2] 23[4] 13 [6.1] 22 [6.2] 12 [7.1] 21 [7.2]	37±18 [1]	27±3 [1]
	Values in the tool	**21**	**34**	**20**
Total DM	Without additive	59±17 [1] 63(52-75)[2] 32 (6-50) [2] (25-66) [3]	33±14 [1] 32 (6-50) [2] 31(25-37) [2] (10-45) [3] 41 [6.3]	
	Values in the tool	**51**	**38**	
	With additive	76±19 [1] 81 (64-93) [2] 84 (83-87) [2] (37-83) [3] 55 [6.1] 73 [6.2] 59 [7.1] 86 [7.2]	73 [1] (25-60) [3]	66±1 [1] (72-90) [3]
	Values in the tool	**76**	**72**	**79**
DM (org)	Without additive	81±11 [1] 86(85-87)[2] 38 (7-57) [2]	35±11 [1] 37(30-39) [2] 13 (2-57) [2] 48 [6.3]	
	Values in the tool	**42**	**25**	
	With additive	85±7 [1] 83 (73-91) [2] 87 (86-89) [2] 52 [6.1] 78 [6.2] 65 [7.1]	20±28 [1]	73 [1]
	Values in the tool	**76**	**60**	**70**
Total N	Without additive	31±21 [1] 13 (3-25) [2] 23[2] (12-57) [3] 15[4]	15±6 [1] 13 (3-25) [2] 15(12-20) [2] (5-20) [3] 22 [6.3]	
	Values in the tool	**19**	**19**	
	With additive	34±12 [1] 41 (24-51) [2] 29 (28-40) [2] (14-63) [3] 30[4] 77 [6.1] 50 [6.2] 34 [7.1] 45 [7.2]	24±9[1] (10-33) [3]	32[1] (30-52) [3]
	Values in the tool	**35**	**31**	**57**
N (inorg, diss)	Without additive	17±12 [1] 8 (2-21) [2]	11±4 [1] 12(9-15) [2] 8 (2-21) [2] 20 [6.3]	
	Values in the tool	**15**	**19**	
	With additive	24±5 [1] 23 (17-30) [2] 82 [6.1]	19 [1]	28 [1]
	Values in the tool	**29**	**24**	**45**
N (org)	Without additive	19 (13-32) [1]	19 (13-32) [1] 17(15-23) [2]	
	Values in the tool	**22**	**17**	
	With additive	78 (75-88) [2] 75 (74-86) [2]		
	Values in the tool	**42**	**39**	**80**

Component	Additive	Decanter centrifuge	Screw press	Belt press
P total	Without additive	76±18 [1] 28 (7-73) [2] 82(63-85)[2] (15-35) [3] 64-79[4]	28±11 [1] 24 [2] 28 (7-40) [2] (10-45) [3] 28 [6.3]	
	Values in the tool	**60**	**9**	
	With additive	82±14 [1] (92 -94) [2] 80(70-88)[2] 95 [3] 82-93[4] 35 [6.1] 94 [6.2] 79 [7.1] 87 [7.2]	60±25[1] (20-54) [3]	48±26 [1] (75-80) [3]
	Values in the tool	**85**	**20**	**40**
Total K	Without additive	28±12 [1] 11 (2-24) [2] (7-44) [3]	11±7[1] 11 (2-24) [2] 16 [6.3]	
	Values in the tool	**14**	**13**	
	With additive	40±12 [1] 45 (44-50) [2] (16-47) [3] 87 [6.1] 32 [6.2] 13 [7.1] 14 [7.2]	15 [1]	26±1 [1]
	Values in the tool	**33**	**15**	**20**

[1] (SYSTEMIC *et al.*, 2020)

SYSTEMIC database (December 2020): filtered on Type of input:"digestate", end product: "solid fraction", after:"separation-centrifuge",chemical: "no polymer". Average SE ±Stdev.P; mass(n=15) , DM (n=13), OM (n=6), Total N (n=13),NH4-N(n=6), Total P(n=14), Total K (n=6)

SYSTEMIC database (December 2020): filtered on Type of input:"digestate", end product: "solid fraction", after:"separation-centrifuge",chemical: "polymer". Average SE ±Stdev.P; mass(n=15) , DM (n=12), OM (n=9), Total N (n=7),NH4-N(n=4), Total P(n=7), Total K (n=2)

SYSTEMIC database (December 2020): filtered on Type of input:"digestate", end product: "solid fraction", after:"separation-screw press", chemical: "no polymer"

Average SE ±Stdev.P; mass(n=15) , DM (n=16), OM (n=12), Total N (n=7)),NH4-N(n=2), Total P(n=6), Total K (n=6)

SYSTEMIC database (December 2020): filtered on Type of input:"digestate", end product: "solid fraction", after:"separation-screw press",chemical: "polymer"

Average SE ±Stdev.P; mass(n=3) , DM (n=1), OM (n=3), Total N (n=2),NH4-N(n=1), Total P(n=2), Total K (n=1)

SYSTEMIC database (December 2020): filtered on Type of input:"digestate", end product: "solid fraction", after:"separation-belt press"

Average SE ±Stdev.P; mass(n=3) , DM (n=2), OM (n=1), Total N (n=2),NH4-N(n=1), Total P(n=4), Total K (n=2)

[2] (Guilayn *et al.*, 2019)

[3] Values excel version tool NUTRICAS, version 31 January 2020; (Low-High)

[4] (Bamelis, 2016)

5 Cocolo, 2012

[6] (Brienza *et al.*, 2020)

[6.1] Groot Zevert Vergisting: Solid fraction of digestate after decanter centrifuge 1, With $MgCl_2$ (32%) addition 1.75L/m^3 digestate average of T07-T10

[6.2] AM-Power: Solid fraction of digestate after decanter centrifuge, average of samples taken in the period (October 2020-January 2021) (n=3) Polymer addition: 26-50L (0.5%polymer solution) /ton digestate

[6.3] Benas: Solid fraction of digestate after screw press 1, average (January-April 2019) (n=12).

[7] (Verbeke, Brienza and van Dijk, 2021), Table 2-3

[7.1] Waterleau New Energy: 2 centrifuges in parallel. DC1: 4 m^3 digestate/h and DC2: 7 m^3 digestate/h. Average: 11 m^3 digestate /h. average of samples taken in the period June-December 2020 (n=5)

Powder polymer + 1200 -1300L water/h (0.3% solution)

[7.2] Emeraude bioenergy: 156kt feedstock/year: 24% pig slurry, 41% slaughterhouse waste, 34% recycled water. Estimations of recovery rate based on operator knowledge. No closed mass balance was used. 8g polymer added per kg DM of the input of the centrifuge.

4.1.1 Use of additives

When the user indicates that additives are used for separation, he/she can choose between **4 different additive solutions** to enhance the separation efficiency (*Figure 4-2*, top figure):

- cationic powder polymer in 0.5% solution
- $FeCl_3$ 40%
- $MgCl_2$ 32%
- $FeSO_4$ 40%.

When selected and confirmed, default amounts are used (Table 4-5). The effect of adding an additive in these default amounts, is included in the NUTRICAS Tool by using a different (enhanced) separation efficiency when flocculant is added or not (*Table 4-1* and *Table 4-3*, "with additive").

The **default amounts** were chosen based on information from the SYSTEMIC Biogas Plants (systemicproject.eu/plants/), scientific literature and technology providers (***Table 4-5 and Table 4-6***).

The amount of flocculants (polymers) dosed in a centrifuge ranges from 2-14 kg powder PM/ton DM of the digestate (Excel tool separation GEA;Heviánková et al., 2015; Bamelis, 2016). Some demo plants use powder polymers dissolved in water at 0.05-0.35 kg powder polymer used per m^3 digestate.

For a screw press this is more likely to be between 9-10 kg polymer/ton DM (Bamelis 2016, GEA separation tool). Amounts of polymer added to a belt press varied between 9 kg polymer/kg DM (GEA separation excel tool) and >14 (Bamelis, 2016).

The amounts of $FeCl_3$ 40%, $MgCl^2$ 42% and $FeSO_4$ 40% were based on the amounts that were added in the separators operated by Demo Plants Groot Zevert Vergisting and AM-Power (Brienza et al., 2020).

However, the amounts can vary depending on the type of digestate and the finetuning of the separation with additive addition. Therefore, the user can also choose to adjust the amount of additive that is added (*Figure 4-2*, bottom figure). However, this does not automatically change the default separation efficiency (SE "with additive"). This is because there is a lack of reliable data on the relation between the relation between added amount of additive and separation efficiency.
The user can change the separation efficiency for mass manually, by sliding the bar to a value that is more realistic to his or her opinion (*Figure 4-1*).

More detailed information on the use of additives can be found in Chapter 2.2.1 of the Report: Schemes and scenarios for technologies of nutrient recovery.

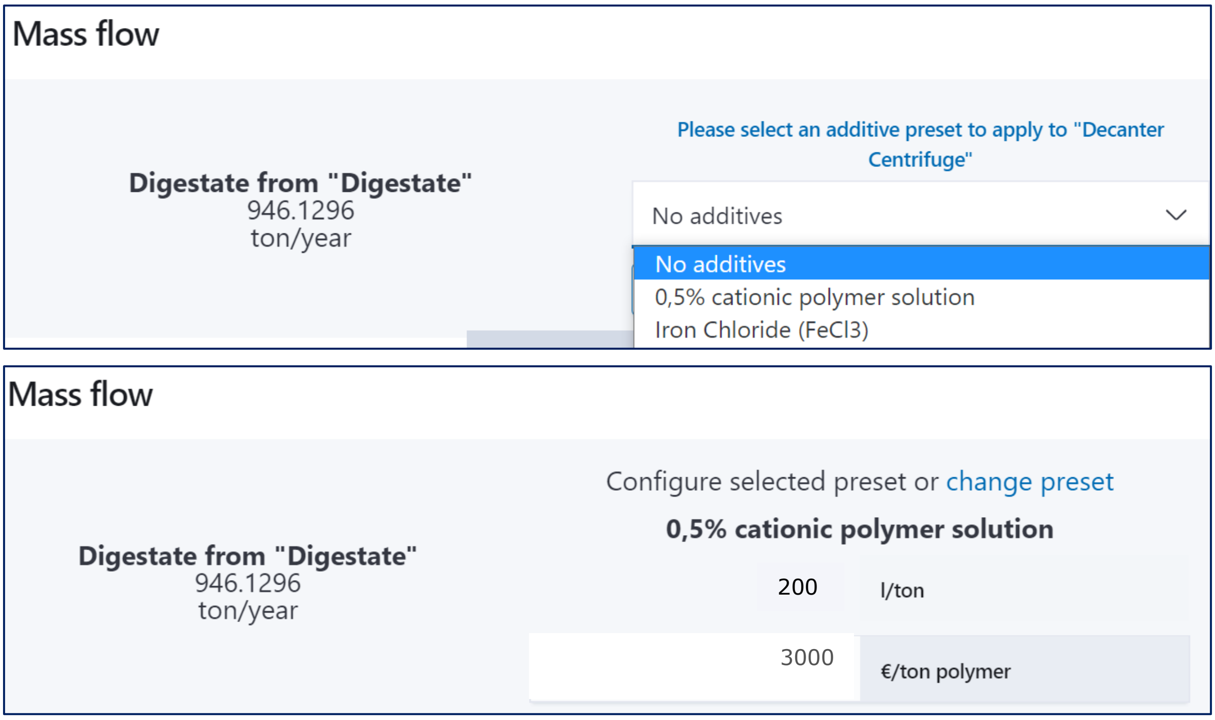

Figure 4-2 Screenshot of NUTRICAS Tool: (Top) Choose additive; (Bottom) Adjust price for additive

Table 4-5 Default amounts of additives used in the NUTRICAS Tool for different separation technologies and corresponding prices. PM= polymer

		Cationic powder polymer in 0.5% solution	**$FeCl_3$ 40%**	**$MgCl_2$ 32%**	**$FeSO_4$ 40%**
	Density (kg/L)	1	1.43	1.28	1.52
	Price (€/kg)	3	0.177	0.07	0.14
Decanter centrifuge	Amount added	7 kg powder PM per ton DM [1] 1kg PM per ton input [2]			
	L/ton input	200 [3]	2.5 [5]	1.8 [5]	0.009 [5]
	kg/ton input	200 [4]	3.575 [4]	2.24 [4]	0.014 [4]
Screw press	Amount added	10 kg powder PM per ton DM [1] 1.4 kg PM per ton input [2]			
	L/ton input	280 [3]	2.5 [5]	1.8	0.009 [5]
	kg/ton input	280 [4]	3.575 [4]	2.24	0.014 [4]
Belt press	Amount added	14.3 kg powder PM per ton DM [1] 2 kg PM per ton input [2]			
	L/ton input	400 [3]	2.5 [5]	1.8 [5]	0.009 [5]
	kg/ton input	400 [4]	3.575 [4]	2.24 [4]	0.014 [4]

[1] Excel tool separation GEA;Heviánková et al., 2015; Bamelis, 2016
[2] Based on an assumed digestate dry matter content of 14%
[3] Calculation based on 1 and 2
[4] Calculation according to density (kg/L)
[5] (Brienza et al., 2020)

Table 4-6 Composition of the additives when added to the mass balance. Input= the product entering the separation technology, f.e. digestate; add= additive

Additive	Cationic powder polymer in 0.5% solution		
	Decanter centrifuge	Screw press	Belt press
Mass (kg)	$0.2*mass_{input}$ [1]	$0.28*mass_{input}$ [1]	$0.4*mass_{input}$ [1]
Water	$Mass_{add}$ – Total DM_{add}		
Total DM	DM $(inorg)_{add}$ – DM $(org)_{add}$		
DM(inorg)	DM $(inorg,diss)_{add}$ + DM $(inorg,susp)_{add}$		
DM (inorg, susp)	0	0	0
DM (inorg,diss)	0	0	0
DM (org)	DM $(org,diss)_{add}$ + DM $(org,susp)_{add}$		
DM (org, susp)	0.007*Total DM_{input} [2]	0.01*Total DM_{input} [2]	0.0143*Total DM_{input} [2]
DM (org, diss)	0	0	0
Additives	**$FeCl_3$ 40%,**	**$MgCl_2$ 32%**	**$FeSO_4$ 40%**
	Decanter centrifuge, Screw press and Belt press		
Mass (kg)	$0.003575*mass_{input}$ [1]	$0.00224*mass_{input}$ [1]	$0.000014*mass_{input}$ [1]
Water	$Mass_{add}$ – Total DM_{add}		
Total DM	DM $(inorg)_{add}$ – DM $(org)_{add}$		
DM(inorg)	DM $(inorg,diss)_{add}$ + DM $(inorg,susp)_{add}$		
DM (inorg, susp)	0	0	0
DM (inorg,diss)	$3.575*40\%*mass_{input}$ [3]	$2.24*42\%*mass_{input}$ [3]	$0.014*40\%*mass_{input}$ [3]
DM (org)	DM $(org,diss)_{add}$ + DM $(org,susp)_{add}$		
DM (org, susp)	0	0	0
DM (org, diss)	0	0	0

[1] Calculation based on Table 4-5 (4)
[2] Calculation based on Table 4-5 (1)
[3] Calculation based on concentration (%) of additive

4.1.1 Costs

4.1.1.1 Additive costs

Because the NUTRICAS Tool calculates the mass balance for a certain amount of digestate that is treated, this corresponds to an amount of additive that will be added, which represents a cost. The default price of the additives in €/kg can be found in *Table 4-5*.

Based on data from suppliers and biogas plants a cationic powder polymer cost between 2.5-3.5 €/kg, depending on the charge density and molecular weight (Verbeke, Brienza and van Dijk, 2021). The price for $FeCl_3$ 40%, $MgCl_2$ 42% and $FeSO_4$ 40% are put default on 0.177, 0.07 and 0.14 €/kg. In practice prices can differ remarkably and also increase over time. Therefore, all these default values can be changed by the user (*Figure 4-2*, bottom figure).

The SYSTEMIC project does not take responsibility if the calculations done by the NUTRICAS Tool with the respective flocculant amounts (*Table 4-5*) or amounts given by the user, do not render the calculated separation efficiencies when applied in practice. Due to the varying flocculation characteristics of different digestates, laboratory assays or performance tests must always be carried out for each case separately to determine the required amount of the dosed polymer (Heviánková et al., 2015).

4.1.1.1 Investment costs and operational costs

In the NUTRICAS tool, the investment costs (Capital expenditures, CAPEX) are estimated in relation to the treating capacity of the DAF unit (*Table 4-7*).

Table 4-7 CAPEX vs treatment capacity of a centrifuge, screw press and belt press (Verbeke, Brienza and van Dijk, 2021). N= number of datapoints

Treatment capacity (ton/h)	CAPEX (€) Average ±Stdev.P	n
Decanter centrifuge		
2	86,333±22,965	15
5	93,321±21,892	14
7	155,000±47,081	3
8	81,535	1
12	81,535	1
15	145,000±7,071	3
20	100,000	1
30	171,667±30,641	3
50	250,000±40,825	3
90	300,000	1
Screw press		
2	25,625±14,402	4
3	36,187±10,717	8
4	30,416±14,119	3
5	39,571±14,529	7
6-6.5	28,750±13,404	4
8	34,583±9,176	6
9	44,400	1
10	24,062±4,542	4
12	52,500	1
15.5	17,000	1
Belt press		
2	107,500±40,697	6
3	70,000	1
4	70,000	1
5	106,666±48,362	6
10	112,500±37,500	2
20	125,000±50,000	2
40	112,500±37,500	2

The data from table Table 4-7 are implemented in a generalized additive model (GAM). This is a generalized linear model (GLM) in which the linear predictor is given by a user specified sum of smooth functions of the covariates plus a conventional parametric component of the linear predictor (https://www.rdocumentation.org/packages/mgcv/versions/1.8-34/topics/gam).
Figure

Based on the amount of digestate that is treated in the separation unit, **the NUTRICAS Tool will give a most likely estimation of the investment cost and an estimation range** (*Figure 4-3*).

The variability of the CAPEX is sometimes rather high because some price estimations included the cost for automatization (PLC programming) and installation costs and others didn't.

The purchase price of a polymer dosing and mixing system for separation of 10,000 ton/year in a centrifuge is estimated at between 20,000€ and 50,000€, with an average of 25,000€ (Bamelis, 2016). One unit is needed per centrifuge, screw press or belt press when adding flocculants. This will be added to the CAPEX in the final cost summary (Chapter 0) when selecting the additive "cationic powder polymer in 0.5% solution".

The operational expenditures (OPEX, here considered as the pure processing cost, excluding the cost for transportation, storage, application, etc. of the end products) can include various costs like equipment maintenance costs, replacement and labour costs.

If OPEX data was found, it generally an estimation on a yearly base, which was often reported as a percentage of the CAPEX (Table 4-8). Thus, this is how it is shown in the NUTRICAS Tool (Figure 4-3, Operational cost). The large variation in the OPEX in Table 4-8 can be attributed to the fact that it was also not always clear which cost items were included in this percentage.

Based on Table 4-8, the default values for OPEX of the decanter centrifuge, screw press and belt press were set at respectively 5%, 3% and 5% of the CAPEX.
Both CAPEX and OPEX can be adjusted by the user (Figure 4-3).

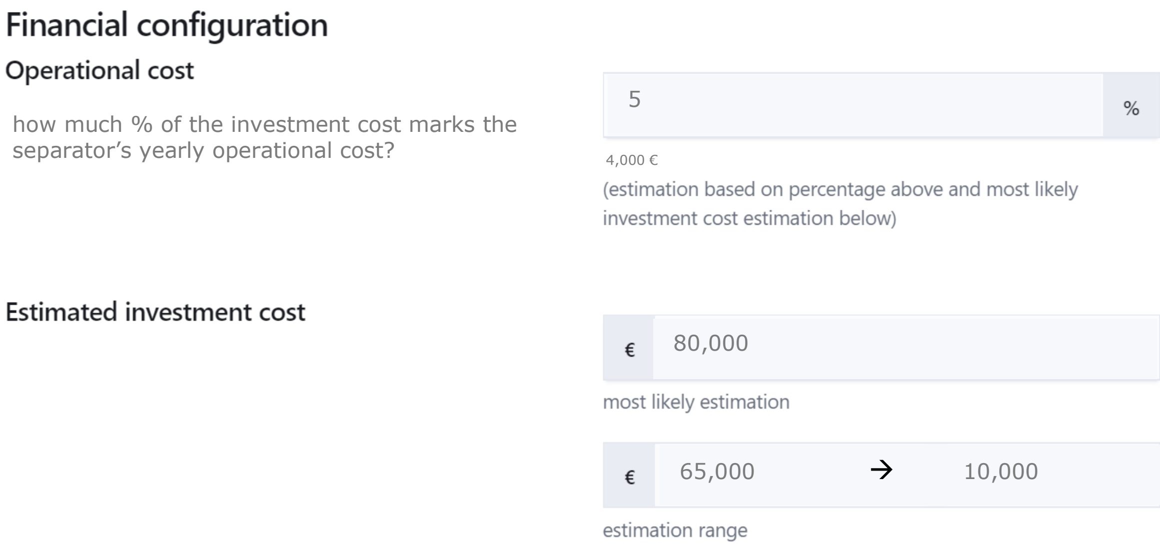

Figure 4-3 Screenshot of the financial configuration of a separation technology.

Table 4-8 Data on operational costs for decanter centrifuge, screw press and belt press from scientific publications and technology providers (Verbeke, Brienza and van Dijk, 2021).

Source	OPEX	Remarks
	Decanter centrifuge	
(Postma *et al.*, 2012)	5% of CAPEX	Cost breakdown not specified
Estimation Nijhuis, DLV-united experts	3%	Only maintenance? Cost breakdown not specified
Estimation VP Hobe	5-7%	Only maintenance? Cost breakdown not specified
(Agentschap NL, NL Energie en Klimaat, 2010)	1-5€/ton input	Excl. Storage, and with continuous use
(Block, 2009)	0.63€/m³ input	2000 kW plant Cost breakdown not specified
(Schröder *et al.*, 2009)	5%	Only maintenance
(Brienza *et al.*, 2018)	25,000 € + 1% of CAPEX	Only maintenance
(Barampouti *et al.*, 2020)	3.68€/m³	CAPEX+OPEX
(Bauer *et al.*, 2009)	15 minutes per day	Labour costs
	Screw press	
(Postma *et al.*, 2013)	5%	Cost breakdown not specified
(Evers *et al.*, 2010)	17.8%	Based on 5% interest, 10% depreciation, 5% maintenance en 10% residual value
Estimation Nijhuis, DLV-united experts	3%	Cost breakdown not specified
(Schröder *et al.*, 2009)	5%	Only maintenance
(Bamelis, 2016)	0.5-3€/ton digestate	Cost breakdown not specified
(Herbes *et al.*, 2020)	0.05€/m³ digestate	Operation and labour 500kW and 2000kWh H+; R-scenario
(Barampouti *et al.*, 2020)	0.54€/m³	CAPEX+OPEX
	Belt press	
(Evers *et al.*, 2010)	17.8%	Based on 5% interest, 10% depreciation, 5% maintenance en 10% residual value
(Bamelis, 2016)	5-10€/ton digestate	Cost breakdown not specified
(Lemmens *et al.*, 2020)	3.25€/m³ manure	Cost breakdown not specified
(Postma *et al.*, 2013)	5%	Cost breakdown not specified
Personal communication technology provider, 2020	 0.30 €/ton 0.35 €/ton	250.000 ton/year maintenance PLC automatisation

4.2 Dissolved Air Flotation unit

As an additional separation step to remove suspended solids, oil, fats and grease and other hydrophobic substances from liquid fraction, a dissolved flotation unit (DAF unit) can be added to most technology cascades in the NUTRICAS Tool.

Analogue to Chapter 4.1, for the mass and main components a separation efficiency is suggested for DAF unit The values for the separation efficiency - the yellow fields (*Table 4-9*) - are assumptions based on values from literature and practice (*Table 4-10*). The composition of the solid and liquid fraction (i.e. mass balance) is calculated according to "Calculation mass balance" and other separation efficiency values (not in yellow fields) are calculated according to Equation 2 and Equation 3.

A DAF unit is commonly not operated without additives, therefore the separation efficiency is only shown "with additive".

The mass-based separation efficiency (SE_{mass}), the user is able to adjust by means of a slider (Figure 4-1). Constraints are implemented to prevent the user from adjusting the SE_{mass} to extreme values. The SE_{mass} can be adjusted within a certain range (*Table 4-9*, "Range")

Table 4-9 Calculation of the mass balances to solid and liquid fraction of digestate separation with a ***DAF unit with additive use.*** *SF=solid fraction, LF= Liquid fraction, SE=separation efficiency*

		DAF unit	
	Calculation mass balance	**SE (%) to SF**	**SE (%) to LF**
mass (kg)	Water+Total DM	24	76
Range		8-35	92-65
water	$Water_{input}$ * SE	21	79
Total DM	DM (inorg) + DM (org)	60	40
DM (inorg)	DM (inorg,diss) + DM (inorg, susp)	40	60
DM (inorg, susp)	DM (inorg, susp)$_{input}$ * SE	85	15
DM (inorg, diss)	DM (inorg, diss)$_{input}$ * SE	30	70
DM (org)	DM (org,diss) + DM (org, susp)	70	30
DM (org, susp)	DM (org, susp)$_{input}$ * SE	90	10
DM (org, diss)	DM (org, diss)$_{input}$ * SE	20	80
N total	N (inorg) + N (org)	28	72
N (inorg)	N (inorg,diss) + N (inorg, susp)	25	75
N (inorg, susp)	N (inorg, susp)$_{input}$ * SE	50	50
N (inorg, diss)	N (inorg, diss)$_{input}$ * SE	24	76
N (org)	N (org,diss) + N (org, susp)	36	64
N (org, susp)	N (org, susp)$_{input}$ * SE	80	20
N (org, diss)	N (org, diss)$_{input}$ * SE	13	87
Ptotal	P (inorg) + P (org)	41	59
P (inorg)	P (inorg,diss) + P (inorg, susp)	23	77
P (inorg, susp)	P (inorg, susp)$_{input}$ * SE	20	80
P (inorg, diss)	P (inorg, diss)$_{input}$ * SE	35	65
P (org)	P (org,diss) + P (org, susp)	58	43
P (org, susp)	P (org, susp)$_{input}$ * SE	75	25
P (org, diss)	P (org, diss)$_{input}$ * SE	5	95
K total	K (inorg) + K (org)	23	77
K (inorg)	K (inorg, diss) + K (inorg, susp)	23	77
K (inorg, susp)	K (inorg, susp)$_{input}$ * SE	85	15
K (inorg, diss)	K (inorg, diss)$_{input}$ * SE	13	87

Table 4-10 ***Separation efficiencies -% to solid fraction*** *with range (minimum and maximum) for DAF unit found in literature and practice. "Values in the tool" are shown in Table 4-9.*

Component		DAF unit SE (%) to SF
Mass		58±8 [1] 24 [3.1] 19 [3.2] 31 [4.1]
	Values in the tool	**24**
Total DM		60 (30-80) [2] 42 [3.2]
	Values in the tool	**60**
DM (org)		60 [3.1]
	Values in the tool	**70**
Total N		34±1 [1] 26 3.[1] 26 3.[2] 21 4.[1]
	Values in the tool	**28**
N (inorg, diss)		24 [3.1] 19 [3.2] 25 [4.1]
	Values in the tool	**24**
N (org)		45 [3.1]
	Values in the tool	**36**
P total		92±4 [1] 70 [3.1] 17 [3.2] 35 [4.1]
	Values in the tool	**41**
Total K		24 [3.1] 18 [3.2] 23 [4.1]
	Values in the tool	**23**

[1] (SYSTEMIC et al., 2020): filtered on Type of input:"digestate", end product: "solid fraction", after:" separation-DAF" Average SE ±Stdev.P; mass(n=3) , DM (n=0), OM (n=0), Total N (n=3),NH4-N(n=0), Total P(n=3), Total K (n=0)

[2] Values excel version tool NUTRICAS, version 31 January 2020; (Low-High)

[3] (Brienza *et al.*, 2018)

[3.1] Groot Zevert Vergisting: calculated and estimated figures by Nijhuis Industries, Polymer addition 0.063 kg PM/ton input

[3.2] AM-Power: September-October 2018 average of samples taken (n=2) . Polymer added

[4] (Brienza *et al.*, 2019)

[4.1] Groot Zevert Vergisting: April 24th and May 7th 2019, average of samples taken (n=2) . Polymer added

.

4.2.1 Use of additives

When configuring the DAF unit in the NUTRICAS Tool, the user must choose between **4 different additive solutions**.

- cationic powder polymer in 0.5% solution
- $FeCl_3$ 40%
- $MgCl_2$ 42%
- $FeSO_4$ 40%.

When selected and confirmed, **default amounts** are used, based on information from the SYSTEMIC Biogas Plants (systemicproject.eu/plants/), scientific literature and technology providers (***Table 4-11* and *Table 4-12***).

Amounts of polymer dosed in a DAF range from 0.06 kg polymer per m³ of digestate (GZV, (Brienza *et al.*, 2018) to 0.3 kg polymer/ton input (Hoeksma and De Buisonjé, 2011).
However, the amounts can vary depending on the type of digestate and the finetuning of the separation with polymer addition. AM-Power used a combination of to 0.3 kg polymer/m³ input (46L 0.7% polymer solution/m³ input) in combination with 3.5L $FeCl_3$ (40%) /ton (AM-Power 2017-2018). This was added before the centrifuge so the additives improved the performance of both the centrifuge and the DAF. The amounts of $FeCl_3$ 40%, $MgCl_2$ 42% and $FeSO_4$ 40% were based on the amounts that were added in DAF units operated by Demo Plants Groot Zevert Vergisting and AM-Power (Brienza et al., 2020).

However, the amounts can vary depending on the type of digestate and the finetuning of the separation with additive addition. Therefore, **the user can also choose to adjust the amount of additive** that is added (*Figure 4-4*). However, this does not automatically change the default separation efficiency (SE "with additive"). This is because there is a lack of reliable data on the relation between the relation between added amount of additive and separation efficiency.
The user can change the separation efficiency for mass manually, by sliding the bar to a value that is more realistic to his or her opinion (*Figure 4-1*).

More detailed information on the use of additives can be found in Chapter 2.2.1 of the Report: Schemes and scenarios for technologies of nutrient recovery.

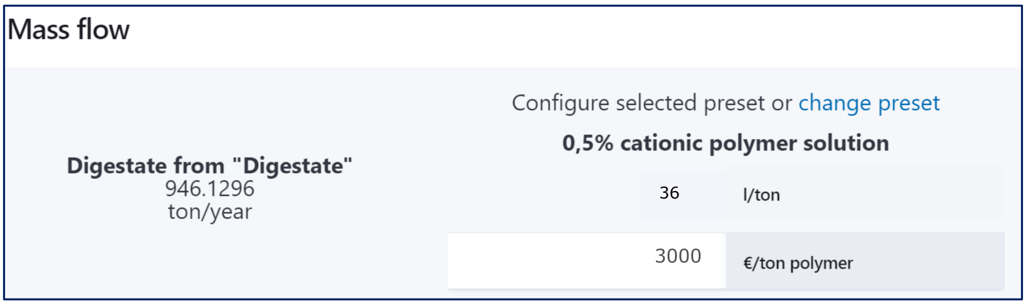

Figure 4-4 Screenshot of NUTRICAS Tool: Adjust price for additive

Table 4-11 Default amounts of additives used in the NUTRICAS Tool for DAF unit and corresponding price. PM= polymer

		Cationic powder polymer in 0.5% solution	**$FeCl_3$ 40%**	**$MgCl_2$ 42%**	**$FeSO_4$ 40%**
	Density (kg/L)	1	1.43	1.28	1.52
	Price (€/kg)	3	0.177	0.07	0.14
DAF unit	Amount added	7 kg powder PM per ton DM [1] 0.18 kg PM per ton input [2]			
	L/ton input	36 [3]	5 [5]	2.2 [5]	0.014 [5]
	kg/ton input	36 [4]	7.2 [4]	2.9 [4]	0.022 [4]

[1] Groot Zevert Vergisting in (Brienza *et al.*, 2018); (Hoeksma and De Buisonjé, 2011).
[2] Based on an assumed dry matter content of 2.5% for liquid fraction of digestate
[3] Calculation based on 1 and 2
[4] Calculation according to density (kg/L)
[5] (Brienza et al., 2020)

Table 4-12 Composition of the additives when added to the mass balance for DAF unit. Input= the product entering the separation technology, f.e. liquid fraction of digestate; add= additive

Additives	Cationic powder polymer in 0.5% solution	$FeCl_3$ 40%,	$MgCl_2$ 32%	$FeSO_4$ 40%
	DAF			
Mass (kg)	$0.036*mass_{input}$ [1]	$0.0072*mass_{input}$ [1]	$0.0029*mass_{input}$ [1]	$0.000022*mass_{input}$ [1]
Water	$Mass_{add}$ – Total DM_{add}			
Total DM	DM $(inorg)_{add}$ – DM $(org)_{add}$			
DM(inorg)	DM $(inorg,diss)_{add}$ + DM $(inorg,susp)_{add}$			
DM (inorg, susp)	0	0	0	0
DM (inorg,diss)	0	$7.2*40\%*mass_{input}$ [3]	$2.9*32\%*mass_{input}$ [3]	$0.022*40\%*mass_{input}$ [3]
DM (org)	DM $(org,diss)_{add}$ + DM $(org,susp)_{add}$			
DM (org, susp)	0.007*Total DM_{input} [2]	0	0	0
DM (org, diss)	0	0	0	0

[1] Calculation based on Table 4-11 (4)
[2] Calculation based on Table 4-11 (1)
[3] Calculation based on concentration (%) of additive

4.2.2 Costs

4.2.2.1 Additive costs

Because the NUTRICAS Tool calculates the mass balance for a certain amount of digestate that is treated, this corresponds to an amount of additive that will be added, which represents a cost. The default price of the additives in €/kg can be found in Table 4-11.

Based on data from suppliers and biogas plants a cationic powder polymer cost between 2.5-3.5 €/kg, depending on the charge density and molecular weight (Verbeke, Brienza and van Dijk, 2021). The price for $FeCl_3$ 40%, $MgCl_2$ 42% and $FeSO_4$ 40% are put default on 0.177, 0.07 and 0.14 €/kg. In practice prices can differ remarkably and also increase over time. Therefore, all these default values can be changed by the user (Figure 4-4).

The SYSTEMIC project does not take responsibility if the calculations done by the NUTRICAS Tool with the respective flocculant amounts (Table 4-11) or amounts given by the user, do not render the calculated separation efficiencies when applied in practice. Due to the varying flocculation characteristics of different digestates, laboratory assays or performance tests must always be carried out for each case separately to determine the required amount of the dosed polymer (Heviánková et al., 2015).

4.2.2.2 Investment costs and operational costs

The treating capacity of a separation technology can vary and different models of the technology are available (with different capacity ranges). On the other hand, the treating capacity also depends on the amount of dry matter in the input: for example for a centrifuge, the lower the DM content, the higher flow can be separated with the centrifuge, the residence time being the limiting factor (personal communication GEA,2020).
So the input stream (i.e. digestate composition, DM content) influences the capacity, which influences the model, which influences the CAPEX. This relation is not included in the NUTRICAS tool, but the investment costs (Capital expenditures, CAPEX) are estimated in relation to the treating capacity of the DAF unit (*Table 4-13*)

Table 4-13 CAPEX vs treatment capacity of a DAF unit (Verbeke, Brienza and van Dijk, 2021). N= number of datapoints

Treatment capacity (ton/h)	CAPEX (€) Average ±Stdev.P	n
	DAF unit	
15	375,760	1
22	500,000	1
70	55,000±20,000	2
75	49,000±8981	3
80	55,000±20,000	2

The data from table Table 4-7 are implemented in a generalized additive model (GAM). This is a generalized linear model (GLM) in which the linear predictor is given by a user specified sum of smooth functions of the covariates plus a conventional parametric component of the linear predictor (https://www.rdocumentation.org/packages/mgcv/versions/1.8-34/topics/gam).

Figure

Based on the amount of digestate that is treated in the DAF unit, **the NUTRICAS Tool will give a most likely estimation of the investment cost and an estimation range** (*Figure 4-5*).

The variability of the CAPEX is sometimes rather high because some price estimations included the cost for automatization (PLC programming) and installation costs and others didn't.

The purchase price of a polymer dosing and mixing system is estimated at between 20,000€ and 50,000€, with an average of 25,000€ (Bamelis, 2016). One unit is needed per DAF unit. This will be added to the CAPEX in the final cost summary (Chapter 0) when selecting the additive "cationic powder polymer in 0.5% solution".

The operational expenditures (OPEX, here considered as the pure processing cost, excluding the cost for transportation, storage, application, etc. of the end products) can include various costs like equipment maintenance costs, replacement and labour costs.

The OPEX is generally an estimation on a yearly base, which is often reported as a percentage of the CAPEX. Thus, this is how it is shown in the NUTRICAS Tool.

Yearly maintenance costs of the DAF at Groot Zevert Vergisting has been estimated at around 1% of investment (Brienza et al. 2018).

The default value for OPEX of DAF unit press were set at 1% of the CAPEX.
Both CAPEX and OPEX can be adjusted by the user (*Figure 4-5*).

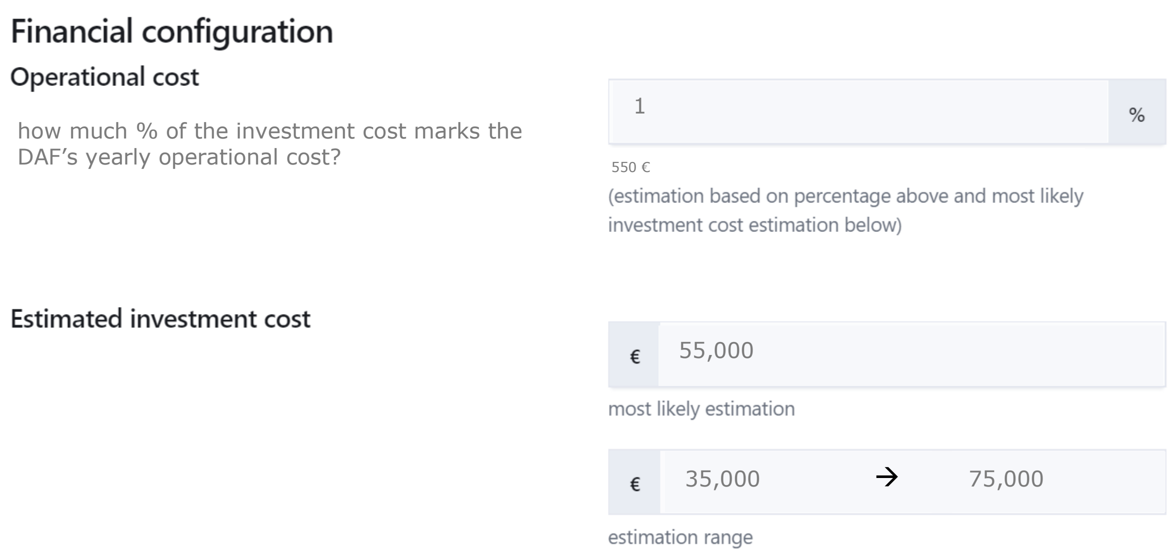

Figure 4-5 Screenshot of the financial configuration of a DAF unit.

4.3 Membrane filtration

Membrane filtration is another physical technology to remove particles of different sizes and characteristics (including the associated nutrients) from a liquid stream. The membrane is a barrier with characteristics that allows only specific components to pass the membrane. Pressure is required to force the liquid through the membrane. The smaller the pores of the membrane the higher the required pressure.
There are 4 main types of membrane technology with decreasing pore size and increasing required pressure: microfiltration (MF,100-1000 nm), ultrafiltration (UF,1 – 100 nm), nanofiltration (NF, 0.5 – 5 nm) and reverse osmosis (RO, 0.1 – 1 nm). The last one will be discussed in the next section.

NF and RO membranes technically don't have pores, their separation ability is not based on particle size but on differences in diffusion velocity of ions and particles. The pore size indicated here give an indication on the size of the particles that can be retained by these membranes.

Micro filtration (MF) and/or ultra-filtration (UF) separate all remaining suspended solids and colloidal dispersed fraction (MF), macromolecules (UF) into a "concentrate". The water with dissolved compounds like ammonium is not retained by these membranes and this stream is called the "permeate".

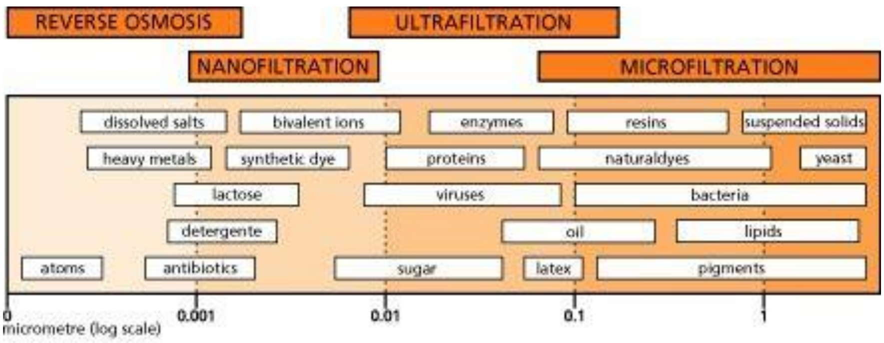

Figure 4-6 Removal of components from the liquid fraction by different membrane technologies (https://www.triqua.eu/site/membrane-filtration).

Analogue to the previous chapters, **the mass and main components a separation efficiency is suggested for micro filtration membranes**. The values for the recovery rate - the yellow fields (*Table 4-14*) - are assumptions based on values from literature and practice (*Table 4-15*). The composition of the concentrate and permeate (i.e. mass balance) is calculated according to "Calculation mass balance" and other recovery rates efficiency values (not in yellow fields) are calculated according to Equation 1.

Table 4-14 Calculation of the mass balances to solid and liquid fraction of digestate separation with ***membrane filtration technology using micro filtration membranes.*** *Conc=concentrate, Perm=permeate, RR= recovery rate*

	Membrane filtration with micro filtration membranes		
	Calculation mass balance	**RR (%) to conc**	**RR (%) to perm**
mass (kg)	Water+Total DM	42	58
water	$Water_{input}$ * SE	39	61
Total DM	DM (inorg) + DM (org)	74	26
DM (inorg)	DM (inorg,diss) + DM (inorg, susp)	37	63
DM (inorg, susp)	DM $(inorg, susp)_{input}$ * SE	95	5
DM (inorg, diss)	DM $(inorg, diss)_{input}$ * SE	25	75
DM (org)	DM (org,diss) + DM (org, susp)	91	9
DM (org, susp)	DM $(org, susp)_{input}$ * SE	95	5
DM (org, diss)	DM $(org, diss)_{input}$ * SE	81	19
N total	N (inorg) + N (org)	62	38
N (inorg)	N (inorg,diss) + N (inorg, susp)	52	48
N (inorg, susp)	N $(inorg, susp)_{input}$ * SE	98	2
N (inorg, diss)	N $(inorg, diss)_{input}$ * SE	50	50
N (org)	N (org,diss) + N (org, susp)	86	14
N (org, susp)	N $(org, susp)_{input}$ * SE	98	2
N (org, diss)	N $(org, diss)_{input}$ * SE	80	20
Ptotal	P (inorg) + P (org)	86	14
P (inorg)	P (inorg,diss) + P (inorg, susp)	81	19
P (inorg, susp)	P $(inorg, susp)_{input}$ * SE	95	5
P (inorg, diss)	P $(inorg, diss)_{input}$ * SE	20	80
P (org)	P (org,diss) + P (org, susp)	91	9
P (org, susp)	P $(org, susp)_{input}$ * SE	95	5
P (org, diss)	P $(org, diss)_{input}$ * SE	80	20
K total	K (inorg) + K (org)	18	82
K (inorg)	K (inorg, diss) + K (inorg, susp)	18	82
K (inorg, susp)	K $(inorg, susp)_{input}$ * SE	95	5
K (inorg, diss)	K $(inorg, diss)_{input}$ * SE	5	95

*Table 4-15 **Recovery rate -% to concentrate** with range (minimum and maximum) for microfiltration membrane technology unit found in literature and practice. "Values in the tool" are shown in Table* 4-14.

Component		**Microfiltration** RR (%) to conc
Mass		30 [1] 41 [2] 27±8 [3]
	Values in the tool	**42**
Total DM		67 [2] 50±9 [3]
	Values in the tool	**74**
DM (org)		83 [2]
	Values in the tool	**91**
Total N		59 [1] 55 [2] 29±13 [3]
	Values in the tool	**62**
N (inorg, diss)		42 [1] 41 [2] 22±2 [3]
	Values in the tool	**50**
P total		96 [1] 81 [2] 79±21 [3]
	Values in the tool	**86**
Total K		41 [1] 41 [2] 22±2 [3]
	Values in the tool	**18**

[1] (Brienza *et al.*, 2019) Groot Zevert Vergisting: April 24th and May 7th 2019 average of samples taken (n=2), micro filtration on LF after DAF unit.

[2] (Brienza et al. 2020) Groot Zevert Vergisting: (T07 – T10):22-10-2019 – 29-1-2020; average (n=4)

[3] (SYSTEMIC et al., 2020): filtered on Type of input:"digestate", end product: "concentrate", after:"separation+Ultrafiltration", Average SE ±Stdev.P; mass(n=5) , DM (n=4), Total N (n=4),NH4-N(n=2), Total P(n=4), Total K (n=2)

4.3.1 Use of additives

To mitigate fouling of the membranes, usually physical methods like are cross flow filtration is used. Fouling can also be reduced by ultrasonication or intermittent backwashing by air or permeate water. In case physical methods are insufficient, chemical means such as acidic or alkaline media, surfactants, chelants, oxidants oxidants, should be used to recover the capacity of the membranes (Shi et al. 2018).

The use of these chemicals in micro filtration is not included in the NUTRICAS Tool because the frequency of membrane cleaning and the amount of cleaning products necessary depends on the input stream flow and characteristics, and the efficiency of the pre-treatment steps. Therefore, the cleaning regime needs to be optimized for each case (personal communication technology provider, 2020).

The key is to find a balance in optimizing the performance of a specific membrane configuration and digestate composition, while minimizing administration of cleaning agents (caustic) and anti-scalant. By closely monitoring the DM level of the input stream, the design software of the suppliers can predict relatively accurate the performance and the cleaning intervals needed (personal communication technology provider, 2020).

4.3.2 Costs

4.3.2.1 Investment costs and operational costs

In the NUTRICAS tool, the investment costs (Capital expenditures, CAPEX) are estimated in relation to the treating capacity of the membrane filtration unit with micro filtration membranes (*Table 4-16*)

Table 4-16 CAPEX vs treatment capacity of a membrane filtration unit with microfiltration membranes (Verbeke, Brienza and van Dijk, 2021).

Treatment capacity (ton/h)	CAPEX (€) Average ±Stdev.P
UF or MF	
1	25,000
1	74,000
2	369,700
10	260,000

The data from *Table 4-16* are implemented in a generalized additive model (GAM). This is a generalized linear model (GLM) in which the linear predictor is given by a user specified sum of smooth functions of the covariates plus a conventional parametric component of the linear predictor (https://www.rdocumentation.org/packages/mgcv/versions/1.8-34/topics/gam).
Figure

Based on the amount of digestate that is treated in the separation unit, **the NUTRICAS Tool will give a most likely estimation of the investment cost and an estimation range** (Figure 4-7).

The operational expenditures (OPEX, here considered as the pure processing cost, excluding the cost for transportation, storage, application, etc. of the end products) can include various costs like equipment maintenance costs, replacement and labour costs.

The OPEX is generally an estimation on a yearly base, which is often reported as a percentage of the CAPEX. Thus, this is how it is shown in the NUTRICAS Tool (Figure 4-7).

For the GENIUS cascade at Groot Zevert (Figure I-4), the yearly maintenance costs of MF have been estimated at around 1% of the total investment (Brienza et al. 2018).

The default value for OPEX of membrane filtration unit with micro filtration membranes was set at 2% of the CAPEX.
Some values on OPEX estimations found in literature are shown in Table 4-17.
Both CAPEX and OPEX can be adjusted by the user (Figure 4-7).

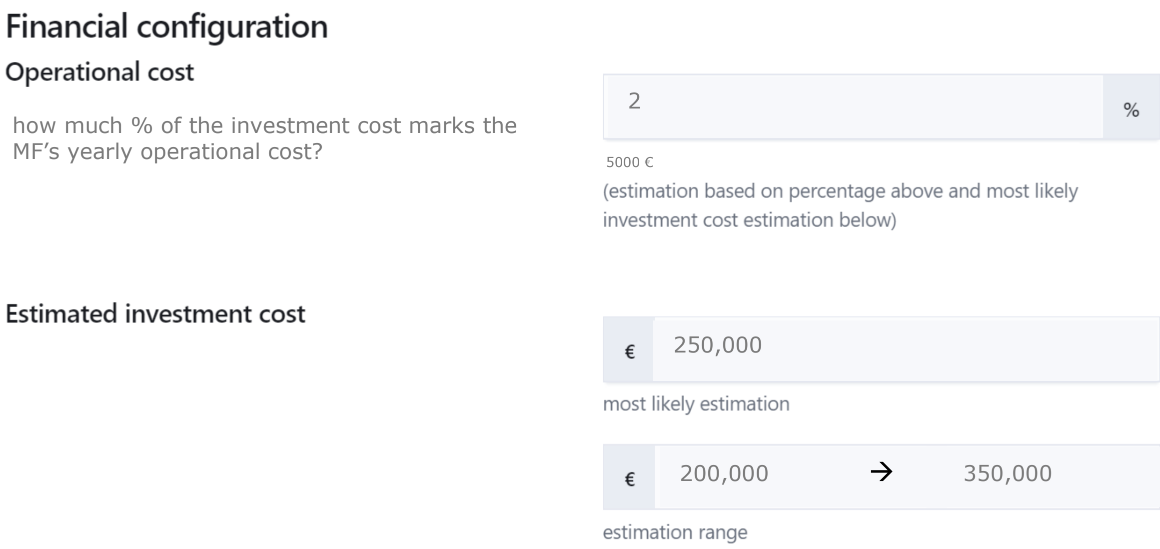

Figure 4-7 Screenshot of the financial configuration of a membrane filtration unit.

Table 4-17 Data on the OPEX of membrane filtration (Verbeke, Brienza and van Dijk, 2021).

Source	OPEX	Remarks
(Charlebois 2000)	4.22€/m³	Ultrafiltration + reverse osmosis
(de Hoop et al. 2011)	9-13€/m³ 2% of CAPEX per year	Ultrafiltration + reverse osmosis
(David Fangueiro et al. 2017)	4-12€/m³	Centrifuge + ultrafiltration
(Buckwell et al. 2014)	6.05€/m³	Ultra-filtration
(Gerardo et al. 2015)	0.52€/m³	MF 1m³/h

Following chapters still under construction

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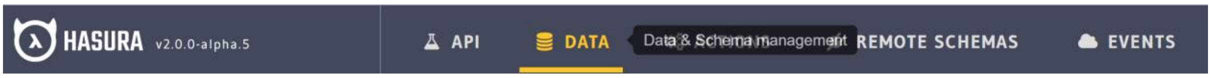
5 Privacy Statement

The most recent version of the privacy statement of the NUTRICAS Tool, can be found at https://systemicproject.eu/wp-content/uploads/H2020-SYSTEMIC-NutriCas-Tool-Privacy-Policy_final-1.pdf

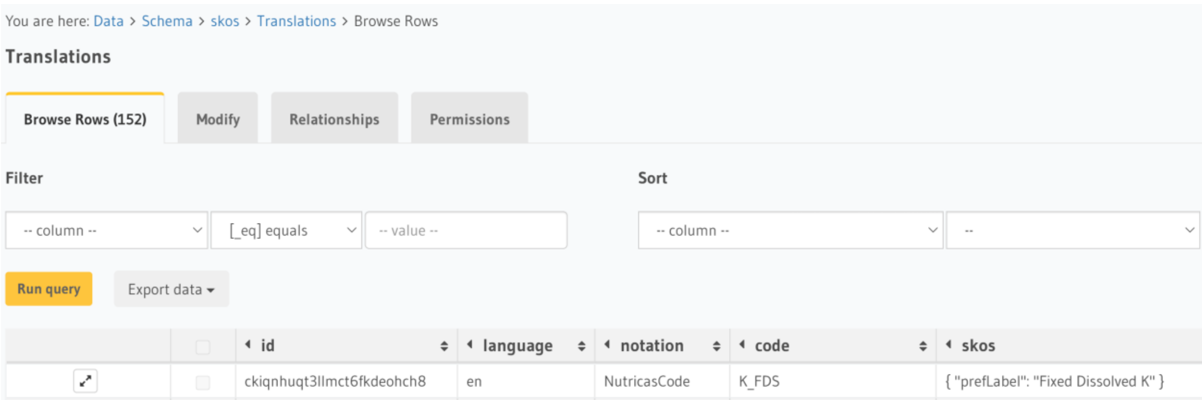
6 Manual admin tool

6.1 Adjusting the 'labels'

Go to https://systemic-nrr-store.herokuapp.com/console/data/default
and log in as administrator with login and password.

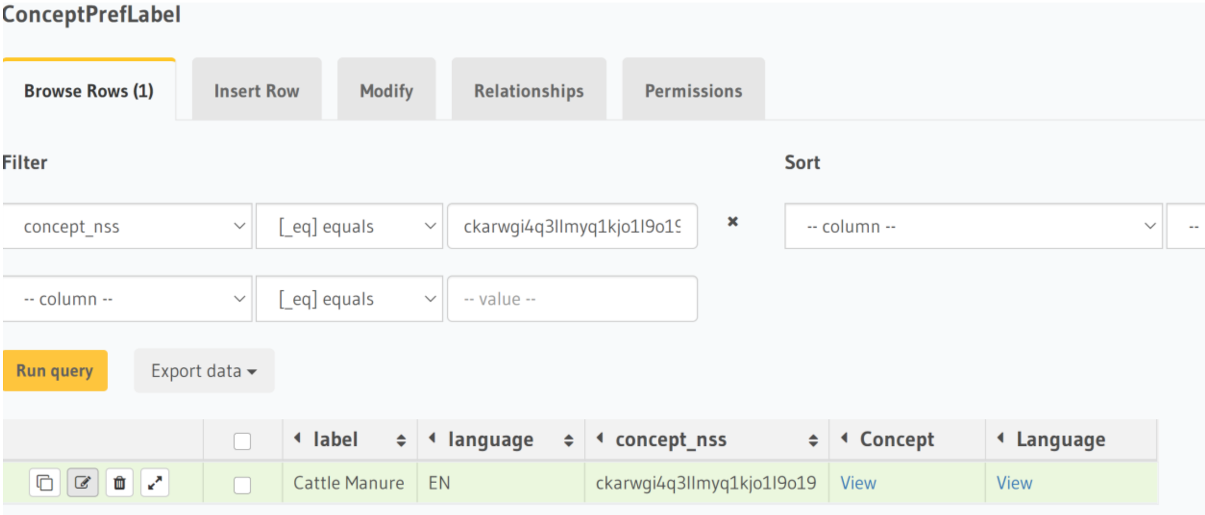


Update labels

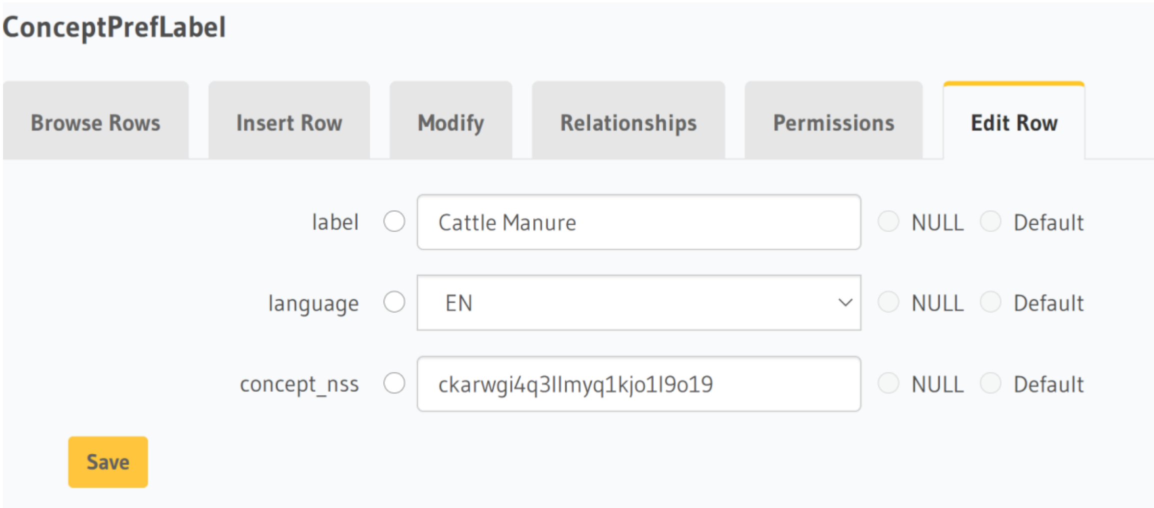


In the table you see for each parameter an 'id', 'language', 'code' and 'skos'.
The skos contains the prefLabel, which is the text that will be visible in the tool.

To change the preflabel, go to Data>Schema>skos>ConceptPreflabel
Use the filter to search for the parameter you want by searching on the 'id' or search on Label.
Filter: "concept_nss (eq) id of the parameter you would like to change.
For example the Id of Cattle Manure is ckarwgi4q3llmyq1kjo1l9o19

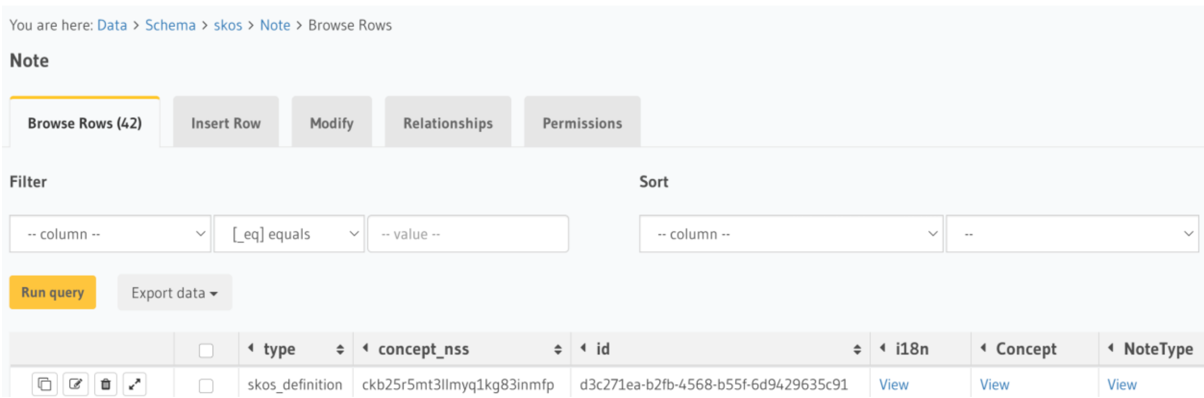


Via  you can now change the name of the lable.



To add a new language, you can copy a row, and change the language and fill in the lable in the desired language.

Definitions:
You can add a definition to each parameter.
Go to Data>Schema>skos>Note
and **Filter** on a certain concept_nss (from Data>Schema>skos>ConceptPreflabel)



Copy the id in Data>Schema>skos>NoteValue
Go to Data>Schema>skos>NoteValue
Search via **Filter** to the Note_Id and paste the id you copied
Note_Id (equals) (paste id)
In the corresponding row you can type in **Object** the definition you want

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I. Annex I

Technology cascades

The cascades available in the NUTRICAS 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.

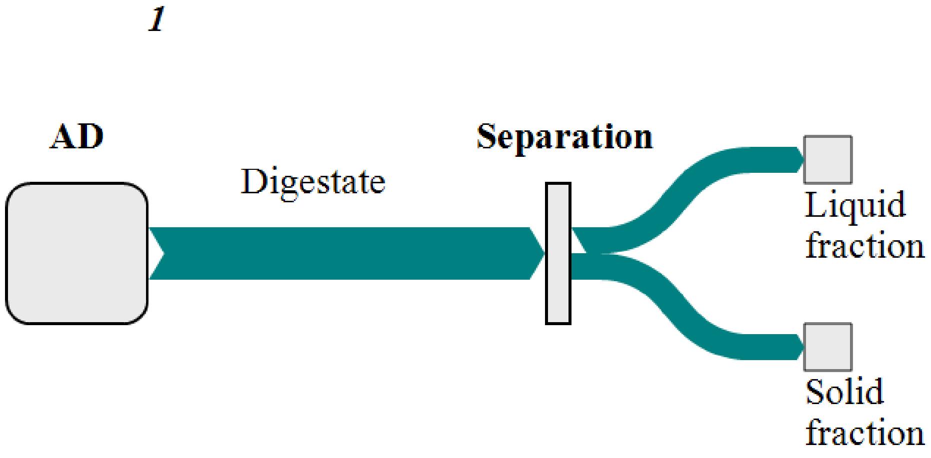


Figure I-2 Cascade 1

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

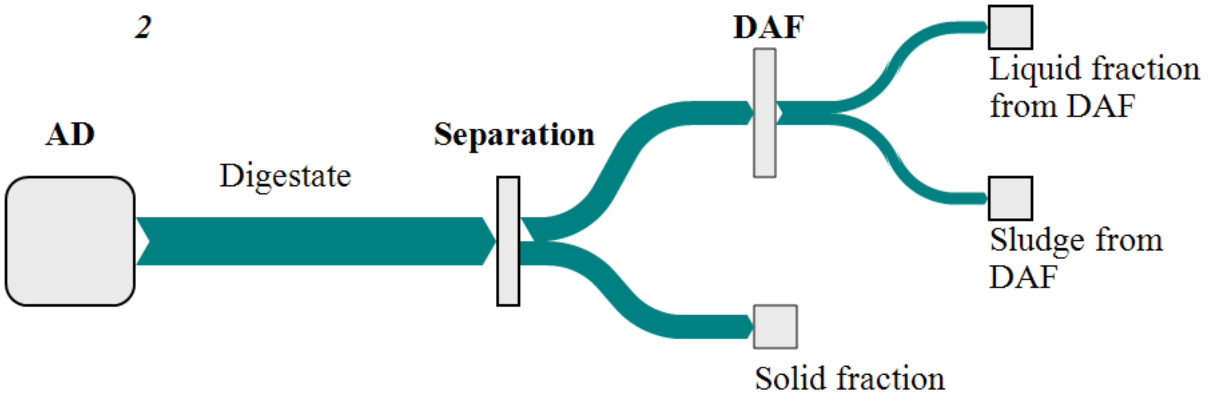


Figure I-1 Cascade 2

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

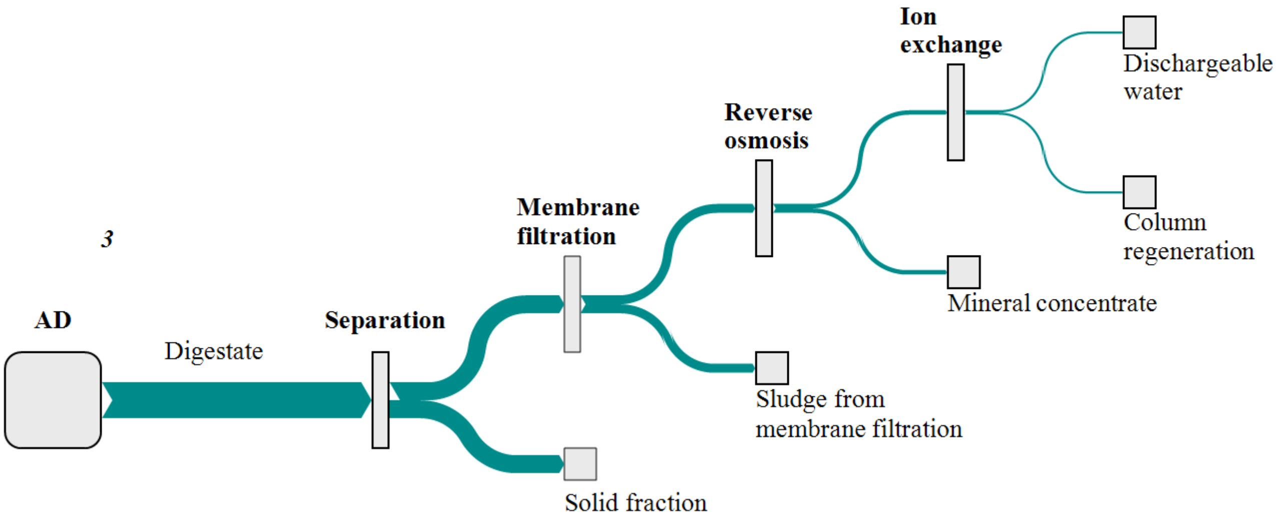


Figure I-3 Cascade 3

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.

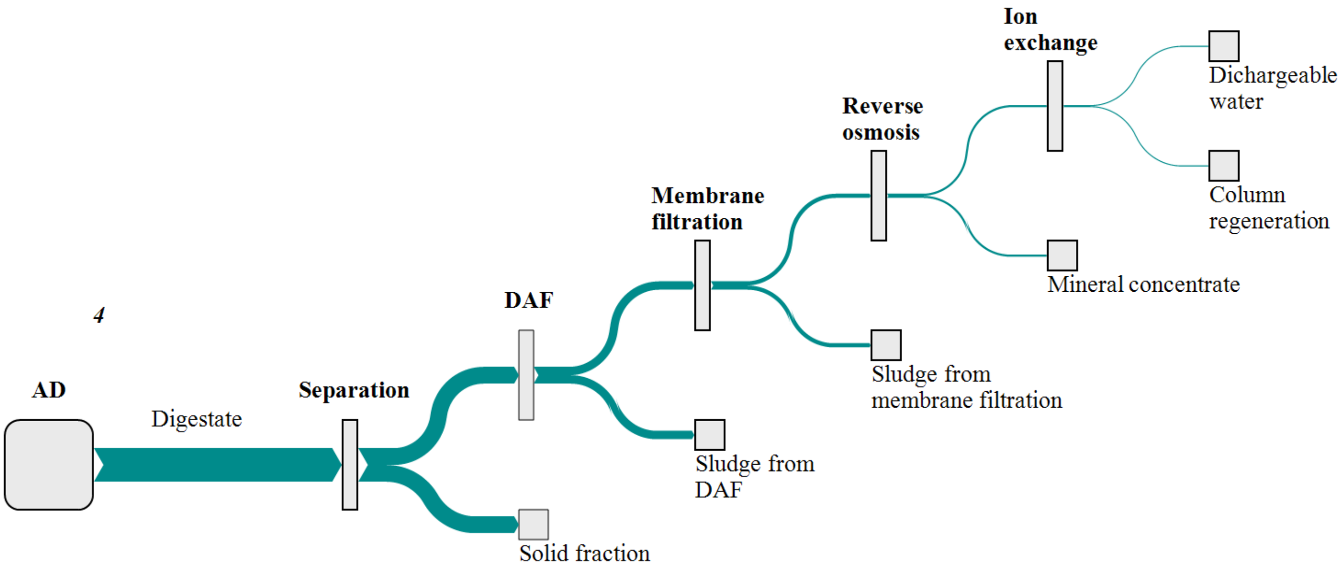


Figure I-4 Cascade 4

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

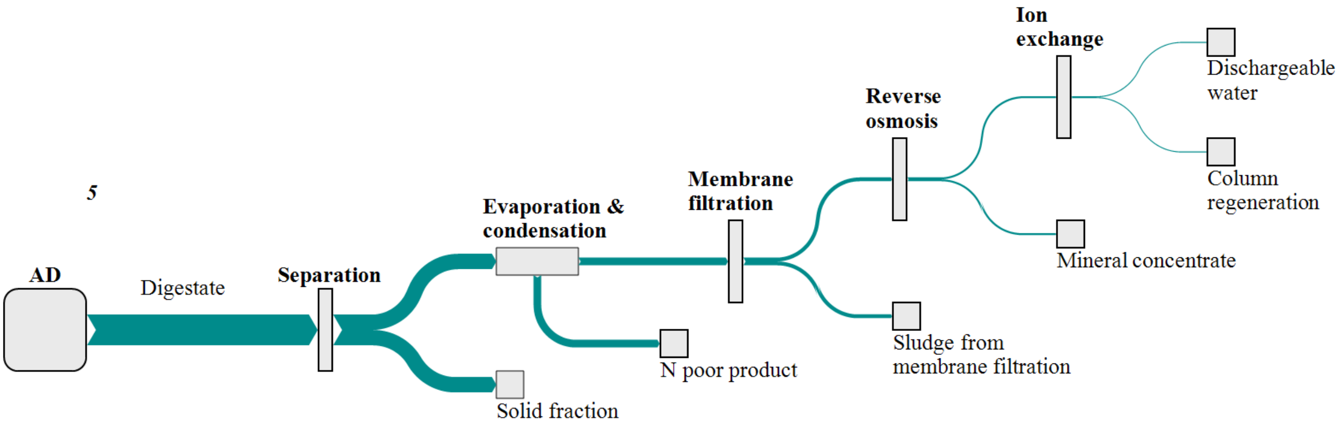


Figure I-5 Cascade 5

Demo Plant AM-Power (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).

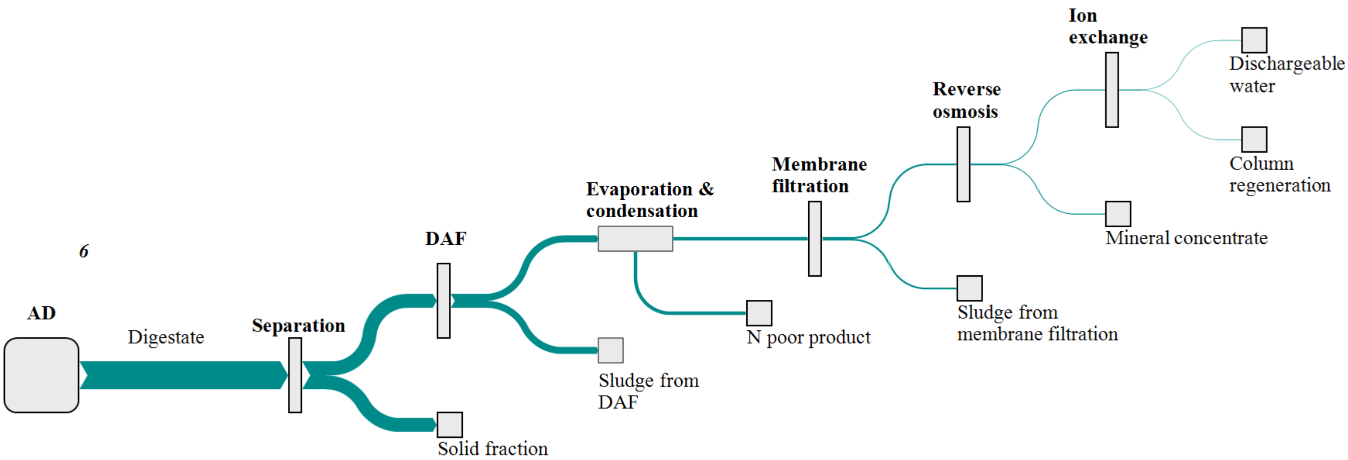


Figure I-6 Cascade 6

This cascade is a variation on Cascade 5.

7

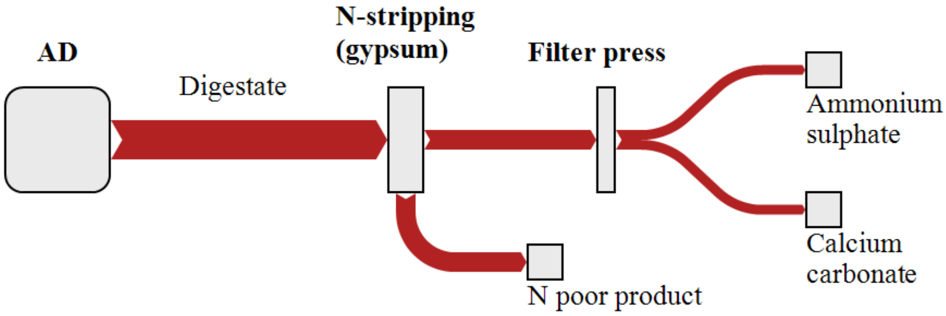


Figure I-7 Cascade 7

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

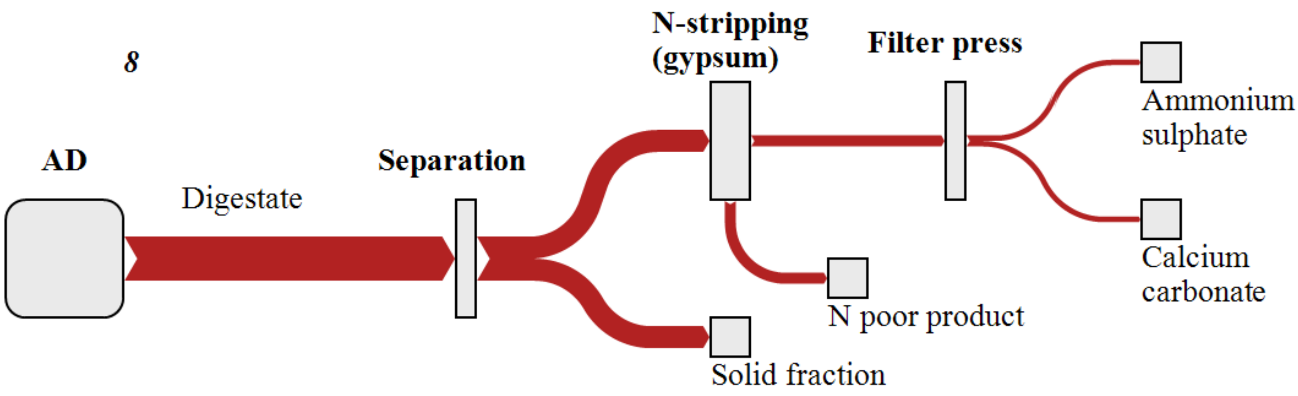


Figure I-8 Cascade 8

This cascade is a variation on Cascade 7.

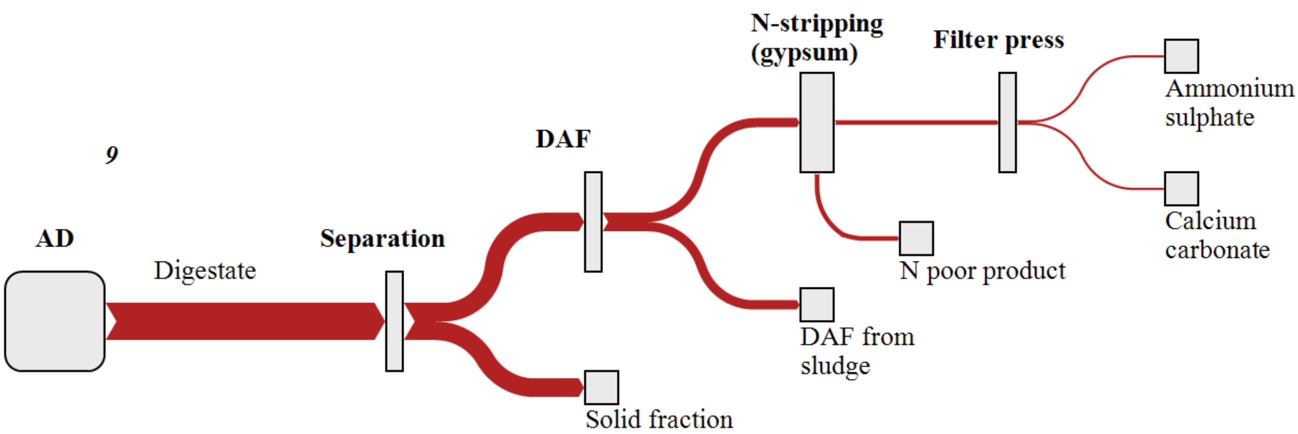


Figure I-9 Cascade 9

This cascade is a variation on Cascade 7.

10

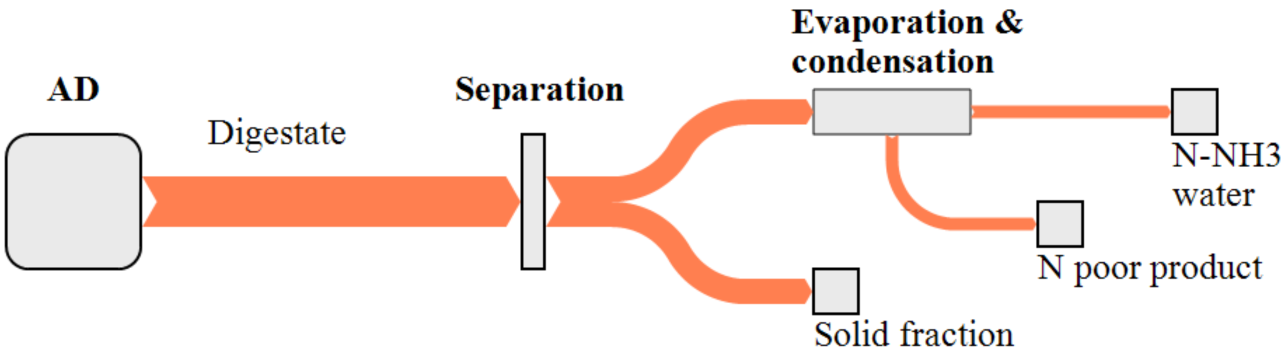


Figure I-11 Cascade 10

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.

11

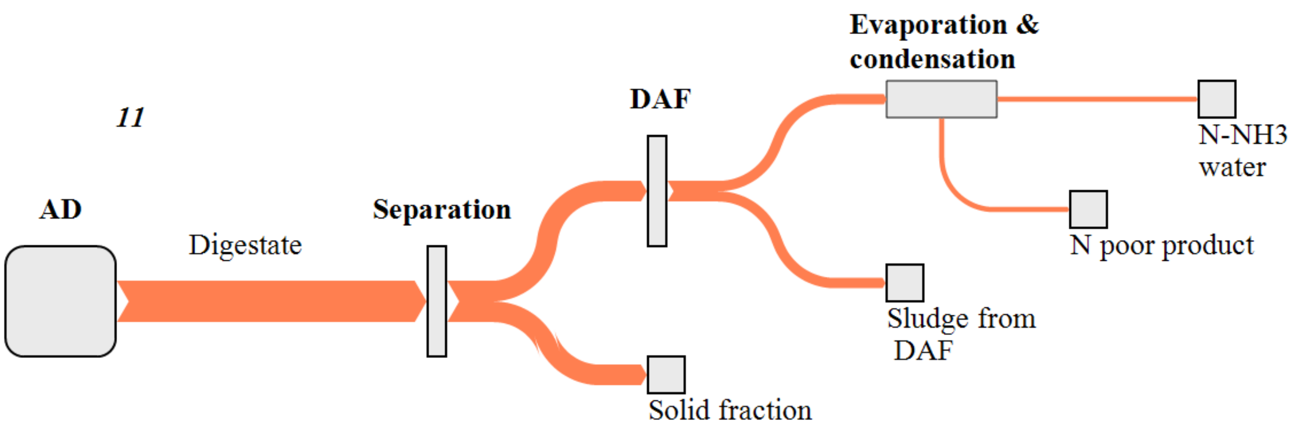


Figure I-10 Cascade 11

This cascade is a variation on Cascade 10.

12

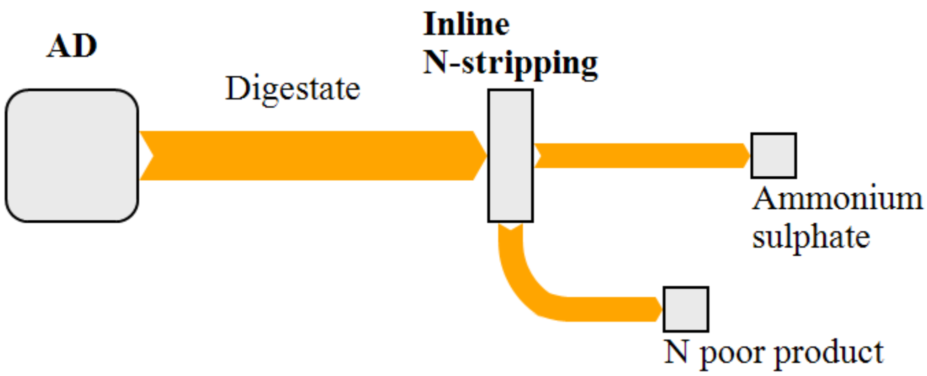


Figure I-14 Cascade 12

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

14

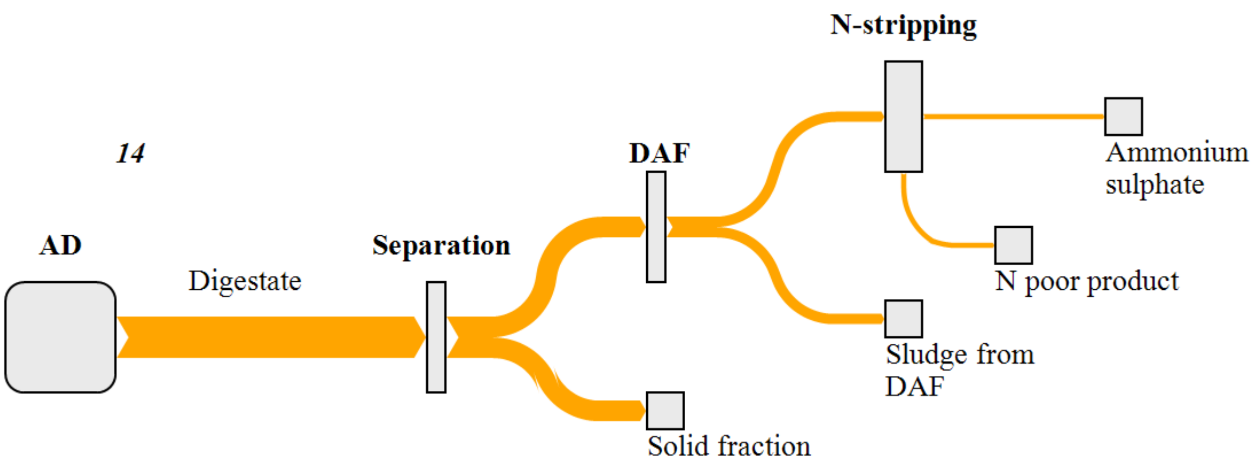


Figure I-13 Cascade 14

This cascade is a variation on Cascade 13.

13

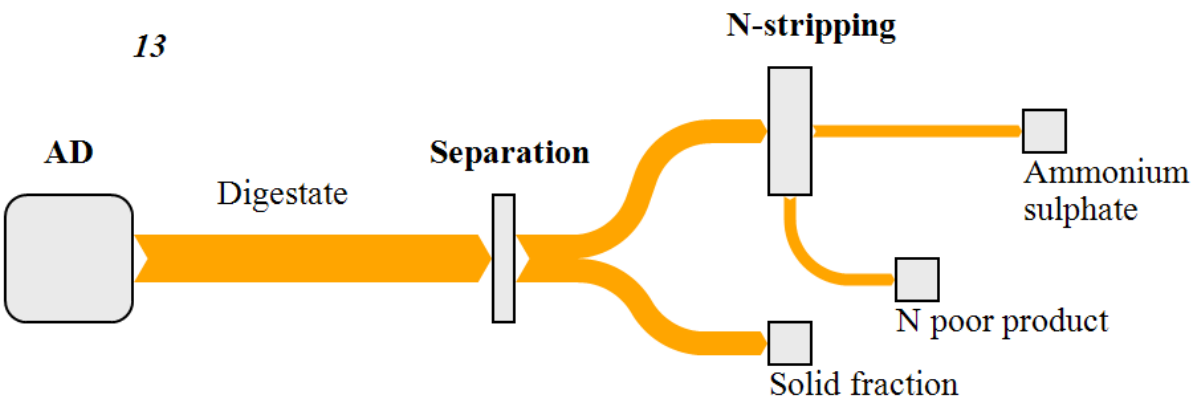


Figure I-12 Cascade 13

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.

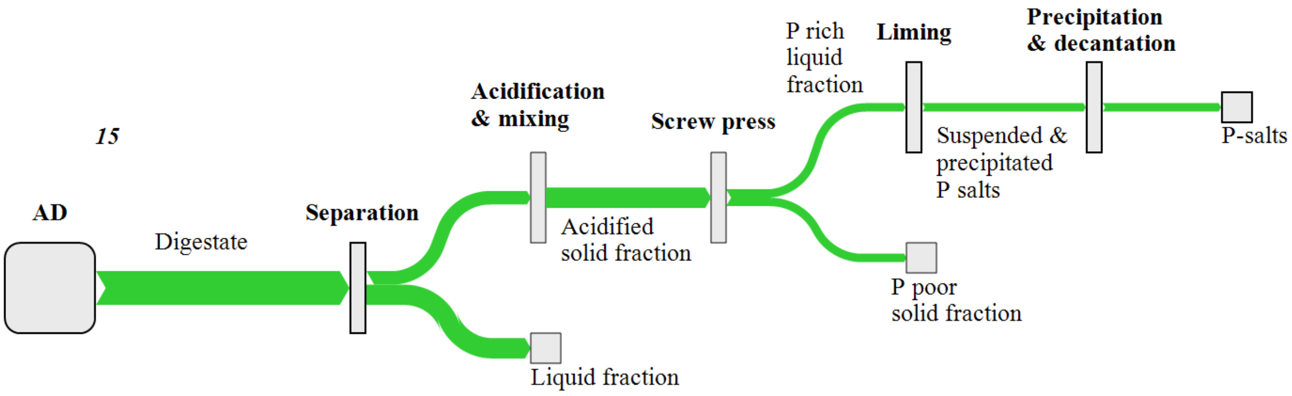


Figure I-17 Cascade 15

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

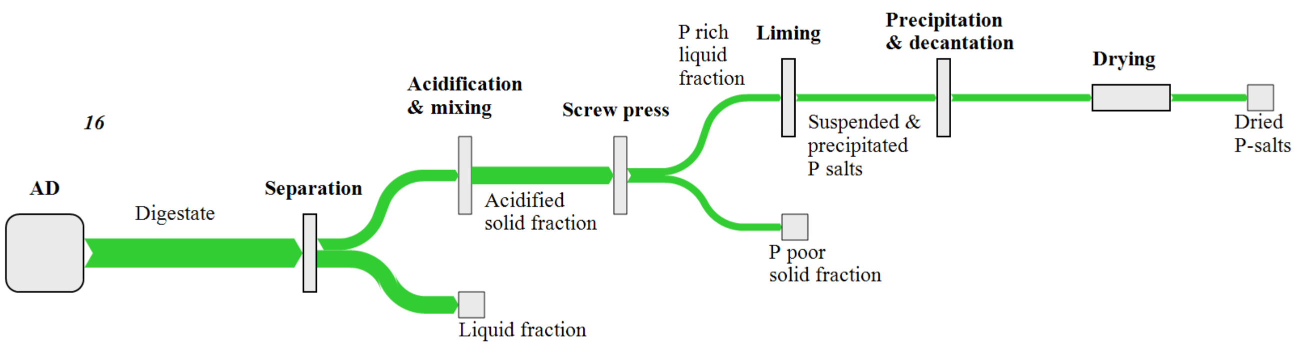


Figure I-16 Cascade 16

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

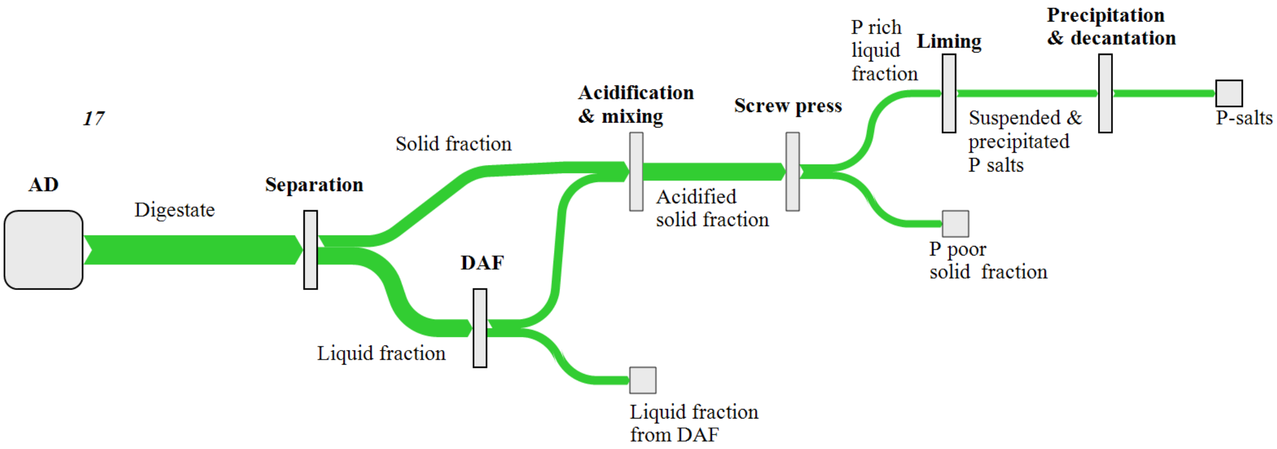


Figure I-15 Cascade 17

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

18

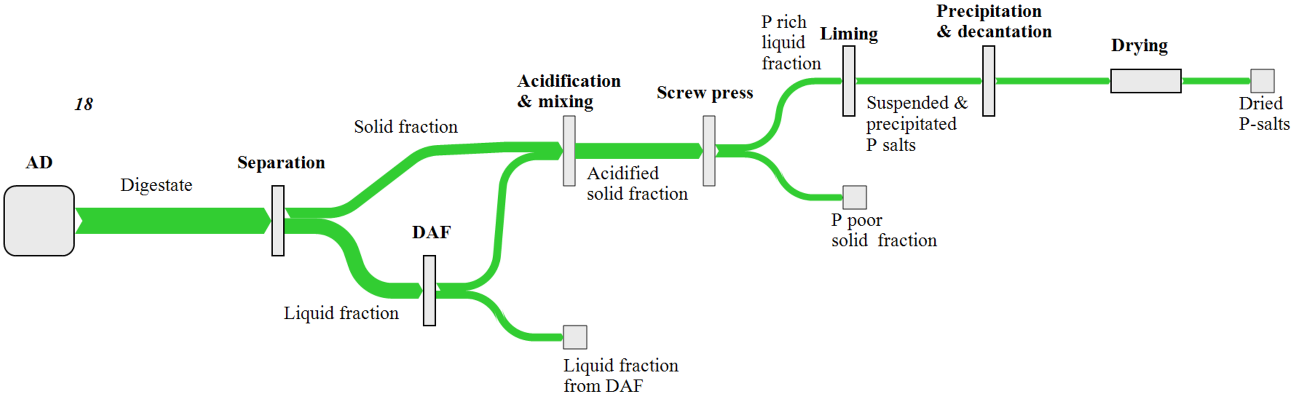


Figure I-19 Cascade 18

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

19

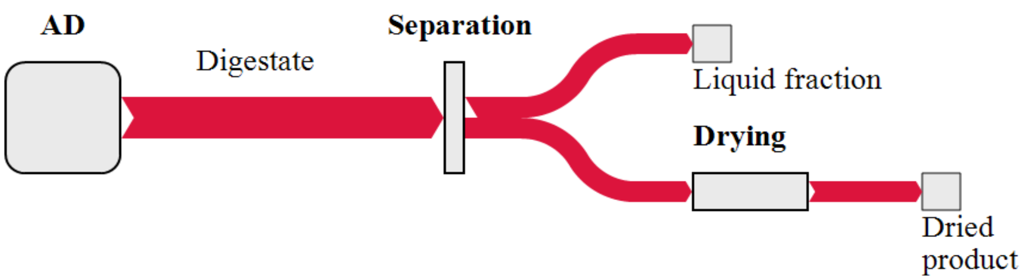


Figure I-18 Cascade 19

Outreach Location Waterleau New Energy(BE) is drying the solid fraction after centrifugation in a rotating disk 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

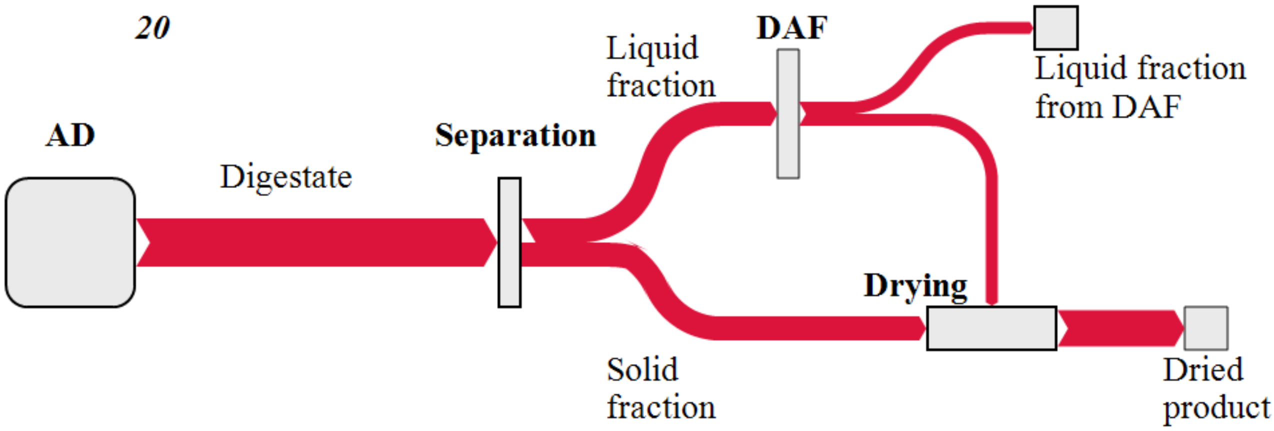


Figure I-20 Cascade 20

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

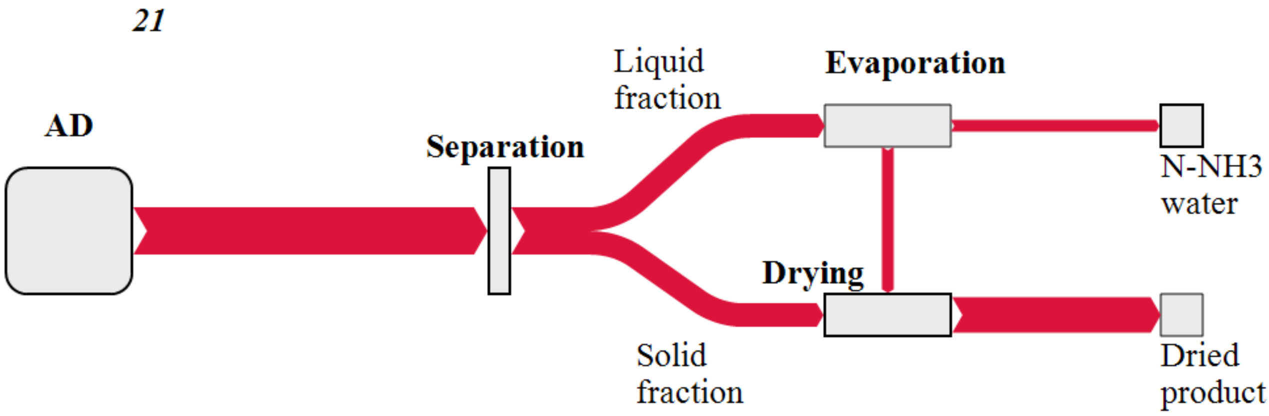


Figure I-21 Cascade 21

Demo Plant AM-Power (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.

II. Annex II

Technology fact sheets

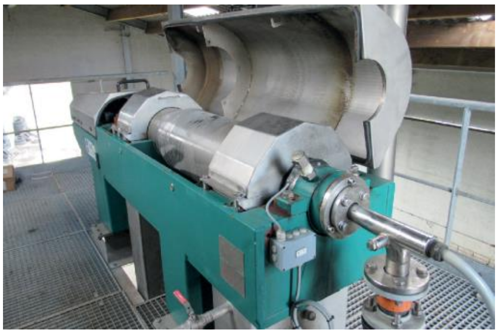
TECHNOLOGY FACT SHEET

Liquid-solid separation

Decanter Centrifuge

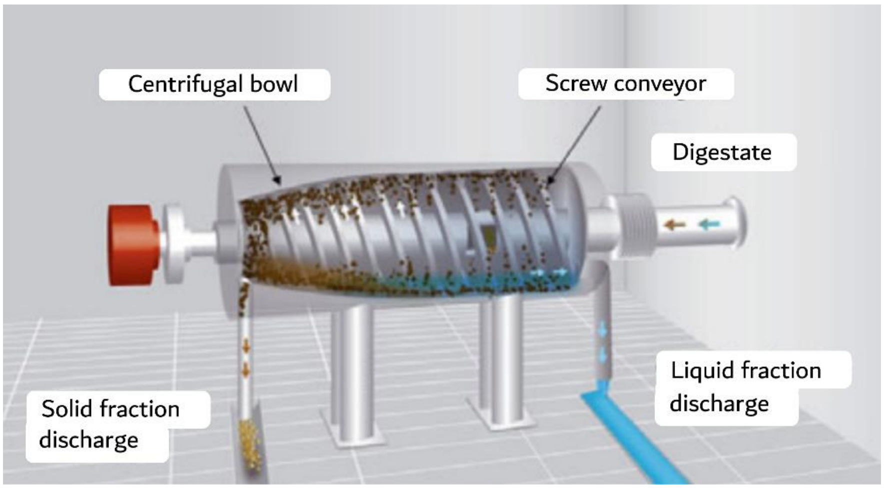
A decanter centrifuge consists of a closed cylinder that rotates. Due to centrifugal forces, the heavy, undissolved particles like colloids, organic components and salts are propelled to the outside of the spinning centrifugal bowl, where they are collected on the screw conveyor.

The liquid phase is transported to the other end of the centrifuge by rotating the cylinder at high speed and by simultaneously rotating the conveyor at a speed that differs slightly from the speed of the bowl.
The solid particles and the liquid fraction are collected at separate outlets.



Horizontal decanter centrifuge Source: (Gorissen and Snauwaert 2018)

Centrifuges are available in different capacities. The smallest centrifuges can treat around 1 m^3/h but an average centrifuge for digestate treatment is between 8-30 m^3/h. To obtain larger capacities, larger centrifuges are available (up to 90m^3/h) or multiple centrifuges can be put in parallel (Lemmens et al. 2020).



Scheme of a decanter centrifuge, source: adapted from (Hjorth et al. 2010)

Read more about the separation efficiencies, use of additives, energy requirements and costs in Chapter 2.2.1.1 of D 3.2 Final report on schemes and scenario's for nutrient recovery and Reuse.

Screw press

A screw press (or screw press filter or press auger) is a machine in which a large screw rotates withing a cylindrical screen with 0.1-1 mm holes.

The liquid fraction is physically separated from the rest of the digestate through these perforations and is collected in a container surrounding the screen. Separation is therefore based on particle size.

The screw provides a gradual increase in pressure and at the end of the axle the solid fraction will be pressed against the plate and more is liquid pressed out. The solid fraction is retained by this plate and goes out through an outlet pipe.

The separation efficiency can be adapted by the counter pressure of the outlet opening.
Typical capacities of screw presses are around 2-15 m^3/h (Lemmens et al. 2020; Postma et al. 2012).

Screw press. Source: (Gorissen and Snauwaert 2018)

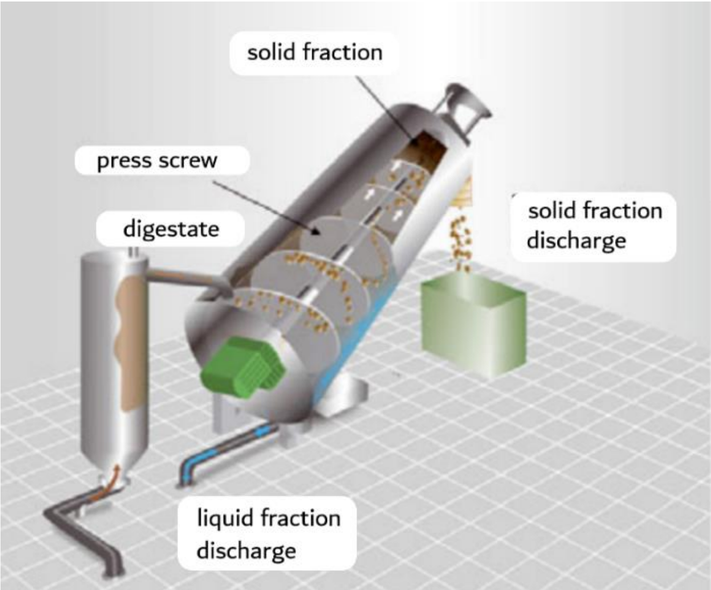


Figure II-1 Scheme of a screw press, source: adapted from (Hjorth et al. 2010)

Read more about the separation efficiencies, use of additives, energy requirements and costs in Chapter 2.2.1.2 of D 3.2 Final report on schemes and scenario's for nutrient recovery and Reuse.

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.

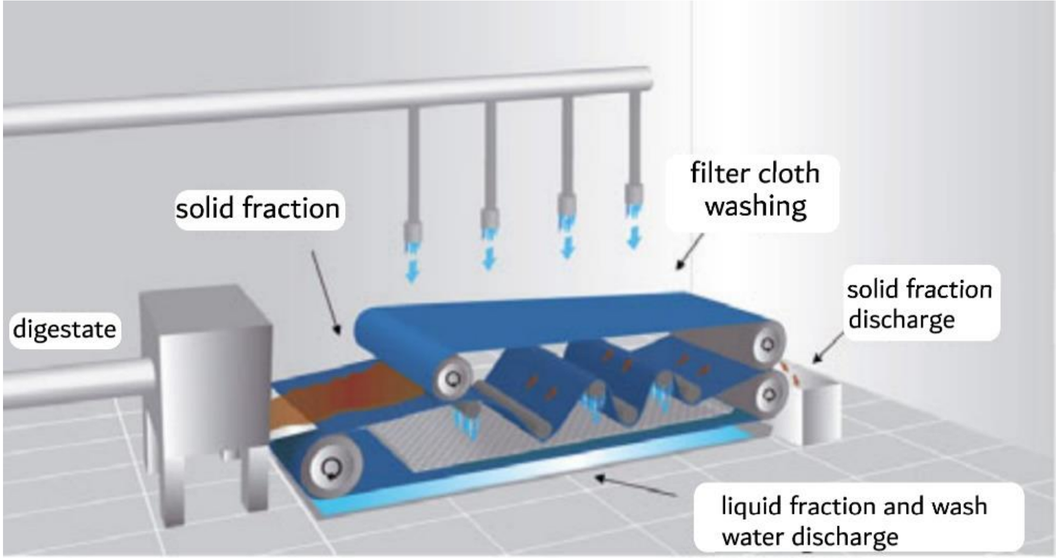
The process typically consists of three stages; gravity, low pressure and high pressure.

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.

Belt press. Source: VP-Hobe, installed at BioStorg Biogas Plant, Houthalen-Helchteren, Belgium, 2019.

Belt presses can treat on average 2-40 m³/h.(Postma et al. 2012).



Scheme of a belt press, source: adapted from (Hjorth et al. 2010)

Read more about the separation efficiencies, use of additives, energy requirements and costs in Chapter 2.2.1.2 of D 3.2 Final report on schemes and scenario's for nutrient recovery and Reuse.

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TECHNOLOGY FACT SHEET

Dissolved air flotation unit

A flotation system is mainly used as an additional separation step, to remove suspended solids, oil, fats and grease and other apolar substances from liquid fraction (Gruwez 2012).

It is a gravity separation process based on the attachment of air or gasses bubbles to solid particles, which are then carried to the liquid surface where they form a crust, which can be scraped off (Lebuf et al. 2013).

Scheme of a Dissolved air flotation (DAF), source: adapted from Nijhuis Industries.

Depending on the way the gas bubbles are generated, flotation is divided into dispersed air, dissolved air and electrolytic air.

The Dissolved Air Flotation (DAF) is the most widespread flotation system. By decompressing compressed air, very small air bubbles are created, which are released on the bottom of the tank.

In order to improve the separation efficiency, coagulating and/or flocculating agents can be added to input stream. Complexing agents like $FeCl_3$, $Fe_2(SO_4)_3$, organic coagulants, etc. are used to coagulate the solid particles, fats and grease. Polymer is added to flocculate the created complexes which can be removed at the surface.
Treatment capacity ranges from 0.1m³/h to more than 1000m³/h .

Read more about the separation efficiencies, use of additives, energy requirements and costs in Chapter 2.2.1.4 of D 3.2 [Final report on schemes and scenario's for nutrient recovery and Reuse.]

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Lebuf, V., F. Accoe, S. Van Elsacker, C. Vaneeckhaute, E. Michels, E. Meers, G. Ghekiere, and B. Ryckaert. 2013. "Inventory:Techniques for Nutrient Recovery from Digestate."

TECHNOLOGY FACT SHEET

Thermal drying

The purpose of thermal drying is to reduce the volume and mass of the digestate.
Thermal drying relies on evaporating water by heating up the product by means of heat transfer from another medium (e.g. air, steam, heated oil). Preferably the heat is residual heat from the CHP.
When a drying step is added, the dry matter content can be increased to 95-95% and during drying, a germ-count reduction also occurs. Every type of digestate has specific drying characteristics. Also air velocity, pressure and temperature will have an influence on the drying process (de Vogeleer 2009).

There are many drying digestate systems on biogas plants in Europe and the predominant systems used are: belt dryers, fluidized bed dryers and indirect dryers (Bamelis 2016; Buckwell et al. 2014; Drosg et al. 2015).
One type of classification can be made based on the contact between the heated medium and the product:

Direct dryers (a.k.a. convection dryers) directly use the evaporation energy of the heat medium, which can be heated air or even flue gasses. During and after drying, the heated air/gasses will contain many volatile components (like ammonia) and dust originating from the drying of the product.

Indirect dryer (a.k.a. conduction dryers) dry the product by transfer of heat through a surface (i.e. a heat exchanger), meaning that the heat medium does not come into direct contact with the product (Bamelis 2016). The heat medium can be a hot liquid (e.g. thermal oil, hot water) or gas (e.g. steam).

Depending on the chosen medium, there may or may not be a need for the extension of the contact surface. Each type of medium has its own advantages and disadvantages (personal communication Waterleau, 2016):

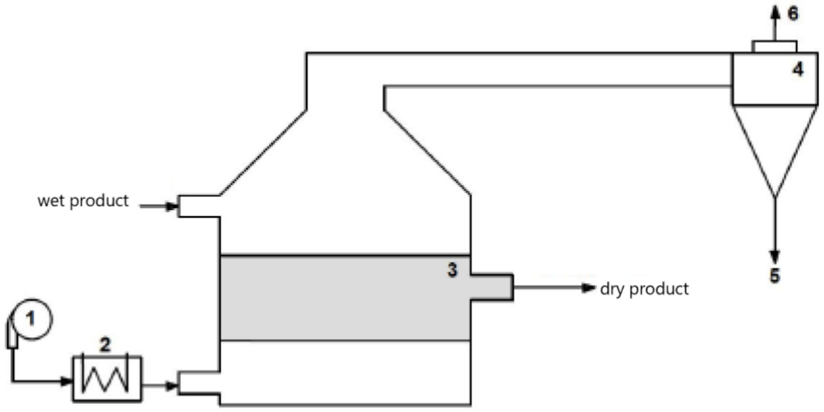
Hot water is often immediately available from cooling or production processes. Because of the lower temperature, a larger contact surface is required and a high flow. The heat exchange is about 20 ° C.

Steam ensures that a high temperature heat exchange is possible, limiting the required contact surface and flow. However, this medium places some restrictions on construction because of the higher pressures involved.

Thermal oil combines a high temperature and heat exchange at relatively low pressure. Like steam, a smaller contact is surface required, yet it requires a higher mass flow compared to steam.

The main advantages of working with an indirect dryer (such as the Hydrogone®) are that due to the lack of direct contact between hot gases and dry dust, a safer process is created. The dryer is airtight, so that work can be carried out below the explosion limit. In addition, the systems are characterized by a high evaporation rate (large contact surface) and a high efficiency (both thermal and electrical). Maintenance of this type of installations is also limited, because there are few moving parts. The investment cost is a disadvantage. Moreover, this type of dryer can only be used profitably from a certain scale size.

Fluidized bed dryer



Scheme of a fluidized bed dryer. 1) fan 2) air heater, 3) drying chamber, 4) cyclone, 5) dust, 6) exhaust air. Source: (de Vogeleer 2009)

In a fluidized bed dryer, the product to be dried is placed on a perforated, gas distributor plate (the "bed") in a vertical cylinder shaped drying chamber, through which the heat medium (air of flue gasses) is sent (0.2-3 m/s) from below.

Pressure drop across the bed increases as the fluidizing gas velocity is increased. At a certain gas velocity, the bed is fluidized when the gas stream totally supports the weight of the whole bed. This increases the contact surface with the heat medium.
The temperature in the dryer can range from 100-800°C (Bamelis 2016; Ceulemans and Schiettecatte 2013).

Advantage of this type of dryer include low residence time (a few minutes), high rate of moisture removal, high thermal efficiency (70-85%), easy material transport inside dryer and ease of control.

Limitations include high pressure drop, poor fluidization quality of some particulate products, nonuniform product quality for certain types of fluidized bed dryers, erosion of pipes and vessels, entrainment of fine particles, attrition or pulverization of particles, and agglomeration of fine particles (Law and Mujumdar 2015).

Belt dryer/tunnel dryer

The belt dryer or tunnel dryer is a continuous dryer where the product is placed on a perforated band or grid, through which a fan blows hot air in counter current or vertically at air velocities of 0.3-2.5m/s.

This dries the product in the tunnel. It is important that the product is spread evenly on the belt, to prevent uneven drying and fire hazard.

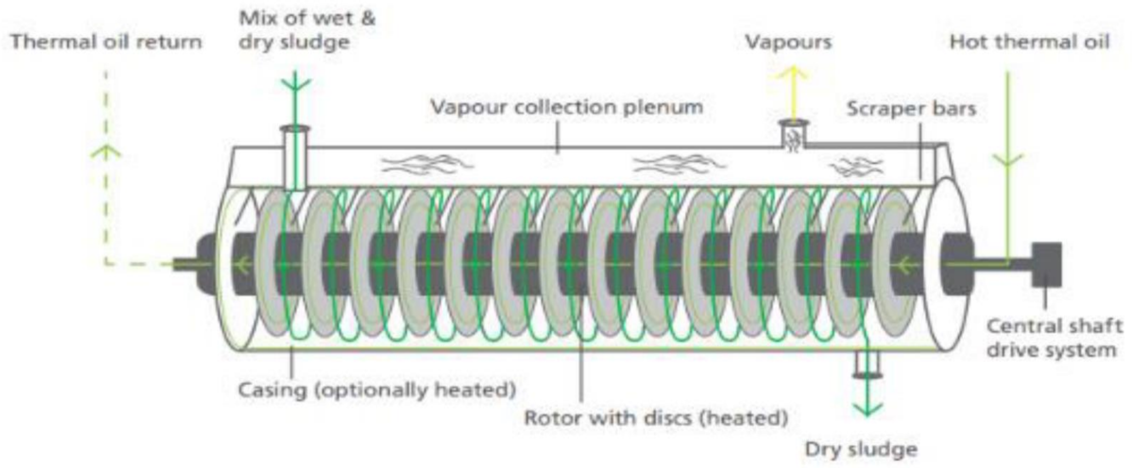

Belt dryer. Source: Spiessens.be

The residence time depends on the size of the particles, the air velocity and the temperature and moisture content of the heat medium. The higher residence times (10-60 minutes) the product quality can easily be finetuned (de Vogeleer 2009).

Advantages of the belt dryer are the possibility to also work on lower temperatures (30-400°C), meaning that other heat sources can also be used (radiation heat, heat from the cooling circuit of the heat exchanger, etc.)

Limitations are the lower thermal efficiency compared to the fluidized bed dryer (55-75%) and a higher air flow, because of lower temperatures.

Rotating disk dryer



Scheme of a Hydrogone® rotating disk dryer from Waterleau Engineering.

The rotating disk dryer is a continuous dryer that consists of a rotor on which discs are attached. Both the rotor and the discs are heated by means of steam, hot water or thermal oil.
The housing (jacket) around the rotor can also be heated (optionally). The product to be dried is mixed with dried product prior to entering the dryer to avoid sticking to the rotors.

Once introduced, the product is slowly propelled through the dryer by the combined movement of the rotating discs, the "swords" on the discs and the partitions in the dryer, with optimum heat transfer (Bamelis 2016).

Read more about the recovery efficiencies, energy requirements and costs in Chapter 2.2.5 of D 3.2 Final report on schemes and scenario's for nutrient recovery and Reuse.

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TECHNOLOGY FACT SHEET

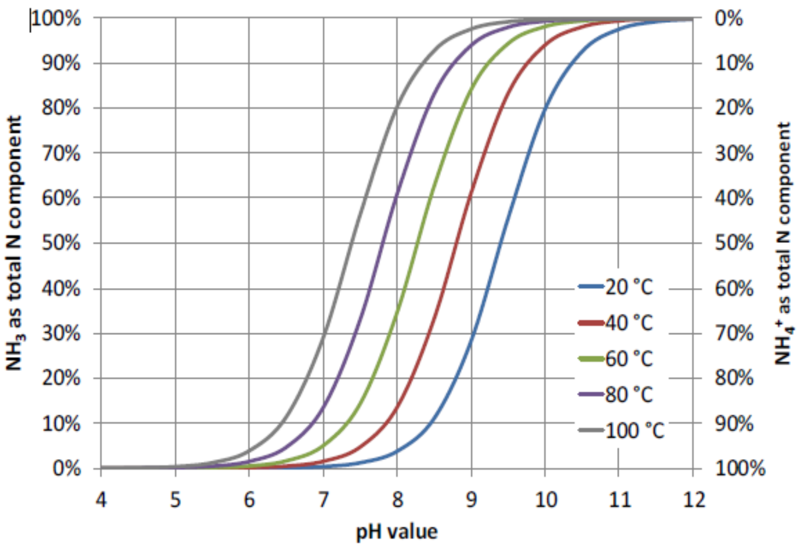
Evaporation

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

The liquid is heated to vaporize the water, which will reduce the volume of the initial product, often up to 80% (personal communication SYSTEMIC biogas plants, 2020). Some other components in the liquid also have a tendency to "escape" the liquid based on their vapour pressure. When evaporating (liquid fraction of) digestate, this will mainly be volatile organics (e.g. volatile fatty acids, CO_2 from carbonates) and ammonia.

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 [2].

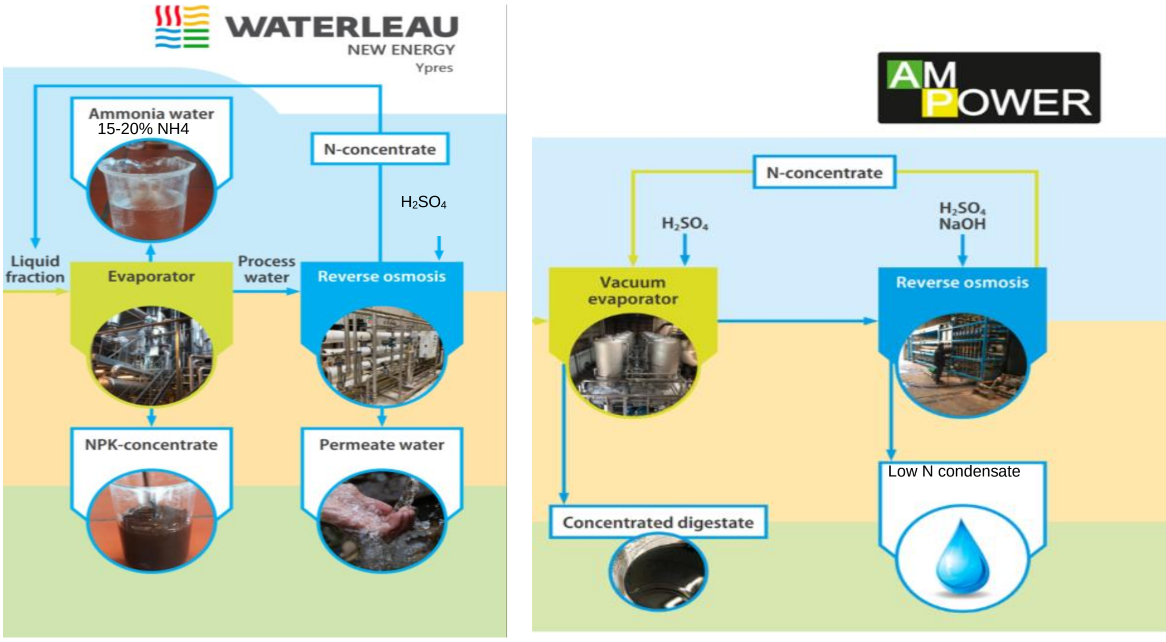
Increasing pH and/or temperature pushes the equilibrium from soluble ammonium (NH_4^+) towards gaseous strippable ammonia. The partial pressure of NH_3 will also rise with the falling pressure (when working under vacuum conditions).
During evaporation, dissolved ammonium in the (liquid fraction of) digestate will transfer to the gas phase as ammonia (NH_3).



Equilibrium of NH_3 and NH_4^+ in water at different pH and different temperatures

[2] The base ionization constant is Kb = $1.8\times10{-}5$ 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.

After evaporation, the water vapour containing volatile components is recovered by cooling it down. The result is a condensate or distillate containing a solution of ammonia that is salt-free with pH of >9 (Scheme Waterleau New Energy).



Evaporation cascade at Waterleau New Energy (left) without acidification, and AM-Power(right) with acidification.

To prevent volatilisation of ammonia during the evaporation step, the pH of the influent of the evaporator can be adjusted to <6,5 by adding acid. This approach will cause only the water (and some volatile components) to evaporate and create a more concentrated digestate which still includes the ammonia (Scheme AM-Power). However, acidification can cause foaming due to the release of carbon acid.

The produced concentrate remains fluid or slurry-like and contains all non-volatile components (e.g. organic matter, nutrients and salts).

Unlike ammonia stripping, the goal of evaporation is usually not to strip ammonium out but to reduce the volume of the digestate hereby concentrating the nutrients in it. Therefore, the evaporation process does not usually include a pH increase step by means of CO_2 stripping or alkali addition.

Configurations

Different configurations of the evaporator determine the amount of heat that can be re-used from the evaporation (Gruwez 2012).

Operating the evaporator at negative pressure (i.e. vacuum evaporation) will reduce the boiling temperature of the liquid. This way, low energy, recovered heat (e.g. from a CHP) can also be used to heat up the evaporator.

Another way to reduce the heat input is by using an evaporator that works in multiple steps. In each subsequent step, part of the heat from the previous step is re-used.
Next to the configuration for energy recovery, there are also different types of evaporators possible based on the mode of heat transfer and viscosity. For evaporation of (liquid fraction of) digestate mostly long vertical tube evaporators with falling film, spray-film or forced circulation evaporators with external heat exchangers are used because they have proven to be more suitable for viscous and heat-sensitive liquids (Vondra, Máša, and Bobák 2017).

Falling film evaporators work best on flows with low to medium viscosity. Other systems, working with a heat exchanger in the boiling chamber are also applicable for evaporating digestate. (Automated) cleaning of the heat elements needs to be taken into account here.

Read more about the recovery efficiencies, use of additives, energy requirements and costs in Chapter 2.2.4 of D 3.2 Final report on schemes and scenario's for nutrient recovery and Reuse.

References

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Vondra, Marek, Vítězslav Máša, and Petr Bobák. 2017. “The Energy Performance of Vacuum Evaporators for Liquid Digestate Treatment in Biogas Plants.” *Energy*.

TECHNOLOGY FACT SHEET

Membrane filtration and reverse osmosis

Membrane technology is mostly used on a pre-treated (liquid fraction of) digestate stream, meaning that most of the solids have been removed.

The input stream is forced through the membrane's pores by means of pressure. The pore size of the membrane determines which molecules go through and the pressure to be used

Characteristics of different membrane filtration types. Source: Lenntech.com. TM= transmembrane

Type of membrane	Pore size[3]	pressure	Membrane material	retaines
Microfiltration	0.1-1µm	1-3 bar	Organic materials, e.g. polymer based membranes Inorganic materials,e.g. ceramic or stainless steel	Suspended particles, bacteria
Ultra-filtration	200nm-10nm	2-10 bar	Polymer materials, e.g. polysulfone, polyethersulfone, polyvinylideenfluoride, polypropylene, cellulose acetate, polylactic acid Ceramic membranes for high temperature applications.	+ viruses
Nano filtration	10nm-1nm	8-40 bar	Organic, thin-film composite membranes	+some multi-valent ions
Reverse osmosis	<1nm	10-100 bar	Semi-permeable, thin film composite membranes: -Polyester support web -Microporous polysulfone interlayer - Ultra think polyamide barrier layer	+multivalent ions +monovalent Ions

Micro filtration (MF) and/or ultra-filtration (UF) separate all remaining suspended solids and colloidal dispersed fraction (MF), macromolecules (UF) into a "concentrate".

Waeger et al. (2010) recommended ceramic ultrafiltration membranes with pore sizes of 20–50 nm for biogas digestate filtration applications.

The water with dissolved compounds like ammonium is not retained by these membranes and this stream is called the "permeate".

In order to further purify the permeate, nanofiltration and reverse osmosis (RO) can be applied.

Unlike RO membranes, which reject almost all solutes (low molecular, neutral molecules like CO_2 and NH_3 will pass), NF membranes will reject most multi-valent ions but a significant amount of mono-valent ions will pass.

RO can also be used on a pre-processed digestate stream, such as the condensate of the evaporator, liquid fraction from DAF, pre-treated with a paper filter. When using RO as a

[3] NF and RO membranes technically don't have pores, their separation ability is not based on particle size but on differences in diffusion velocity of ions and particles. The pore size indicated here give an indication on the size of the particles that can be retained by these membranes.

final separation step, also nutrients (i.e. ions) can be separated in the concentrate stream, however the concentrations are not as high as in synthetic mineral fertilisers. The permeate stream generated from RO contains low concentrations of nutrients and can be discharged to sewer or surface water, if necessary after a 'polishing' step, 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).

Read more about the recovery efficiencies, fouling and scaling, use of additives, energy requirements and costs in Chapter 2.2.3 of D 3.2 Final report on schemes and scenario's for nutrient recovery and Reuse.

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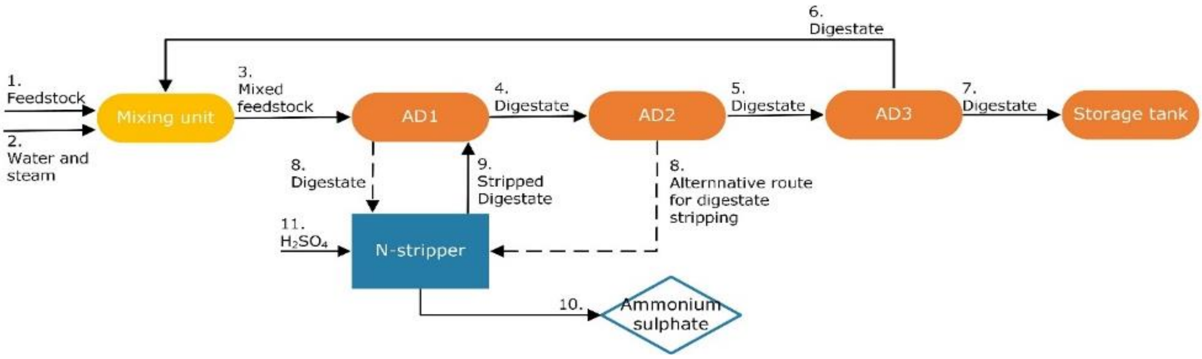
TECHNOLOGY FACT SHEET

Ammonia stripping-scrubbing

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 (Ghyselbrecht et al. 2017).
Within the SYSTEMIC project, Acqua & Sole (Italy) has implemented an inline N-stripper to reduce the NH_3 concentration in the digester during the digestion process.



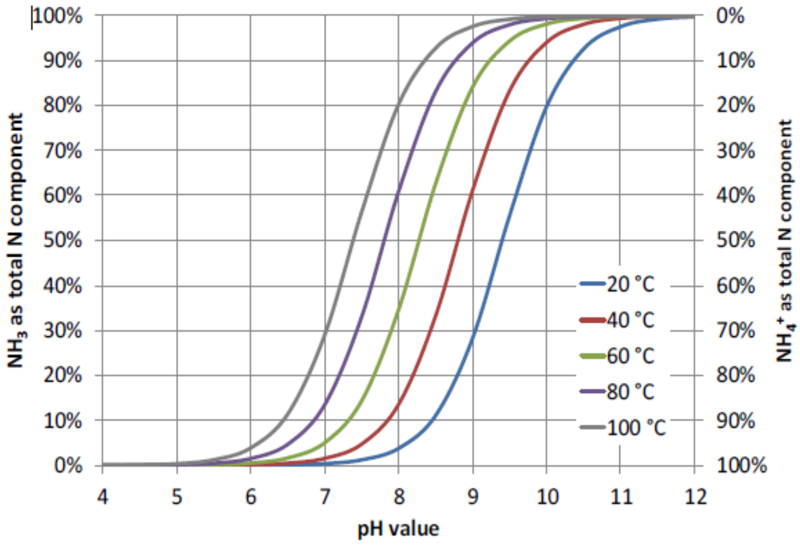
Scheme inline ammonia stripping-scrubbing from digestate at Acqua e Sole (Italy).

The ammonia stripping-scrubbing technique can be applied on a nitrogen (N) rich waste stream, such as (liquid fraction) of digestate.

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 [[4]].

Increasing pH and/or temperature pushes the equilibrium from soluble ammonium (NH_4^+) towards gaseous strippable ammonia. The partial pressure of NH_3 will also rise with the falling pressure (when working under vacuum conditions).

[4]The base ionization constant is $Kb = 1.8\times10{-}5$ 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.



Equilibrium of NH_3 and NH_4^+ in water at different pH and different temperatures

pH increase and temperature increase

In the first step, the liquid fraction is manipulated to ensure that more nitrogen becomes available in the form of ammoniacal nitrogen (NH_3-N) as only this form of gaseous nitrogen can be recovered. This can be done either by increasing the pH with caustic lime ($Ca(OH)_2$) or by sodium hydroxide (NaOH).

NaOH consumption can be decreased or avoided when the excess carbonate buffer capacity in the input is removed. This can be achieved by stripping CO_2 from the input, which will also prevent the formation of $CaCO_3$ precipitates in the N stripper (Vaneeckhaute 2015).

Ammonia stripping

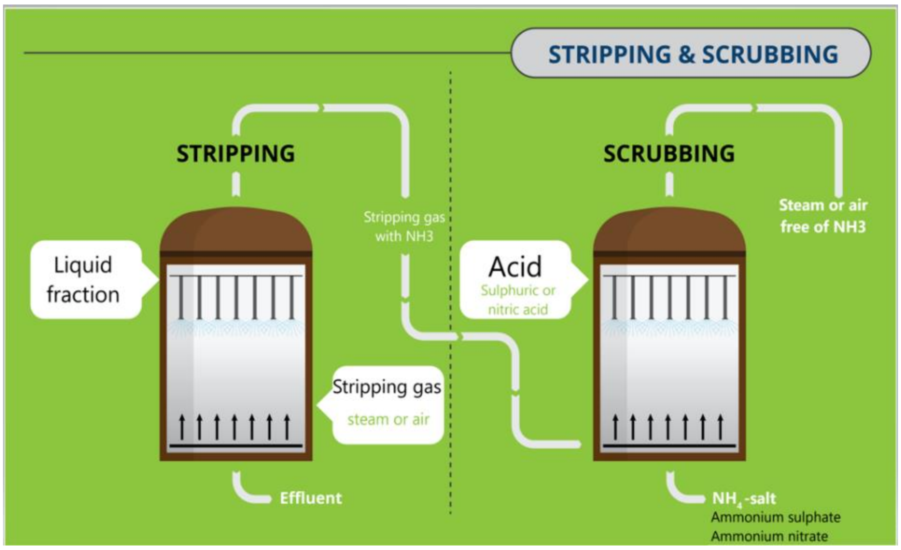
Next, the liquid fraction enters on top of the system, where it is sprayed over a packing material to increase the contact surface of liquid and air. These packed towers are most commonly used, because they have a low surface footprint.
However, they are easily fouled when input steam contains a lot of suspended solids or fibres. Total suspended solid levels (TSS) > 2 % must usually be removed using a solid-liquid phase separation unit prior to stripping to prevent a decreased stripping performance.
Nonetheless, it is unavoidable that the packing material will have to be cleaned periodically (Vaneeckhaute 2015).

The stripping gas enters usually from the bottom. In this way ammonia is transferred from the liquid to the gaseous phase in a counter current system. 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).

Ammonia scrubbing

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 scrubber water, is an ammonium salt solution of ammonium sulphate or ammonium nitrate, which can be used as an alternative crop fertiliser (see D 3.4 Market research in Europe).

$2\ NH_3 + H_2SO_4 = (NH_4)_2SO_4$



Scheme of N stripping-scrubbing. Adapted from: Intereg Flanders-the Netherlands project NITROMAN.www.nitroman.be

The stripping gas from which the ammonia is removed can be recirculated to the stripping tower.
As stripping and scrubbing of ammonia occurs in a closed system, emissions are generally low. Obviously, non-volatile components, like organic-bound N, phosphorus, potassium, metals, solids etc. will not be transferred to the ammonium sulphate/nitrate solution, but will stay in the stripper effluent.

If the concentration of the ammonium sulphate solution rises above 40%, crystals can form which can cause blockage of the spraying system in the scrubber. Therefore, the ammonium sulphate solution needs to be diluted with water to avoid reaching these concentrations in the reactor.

Ammonia stripping-scrubbing can also be useful before or after biological treatment (nitrification-denitrification), when focussing on lowering and recovering the nitrogen of the digestate for marketing reasons (f.e. low N fertilising application limits in nitrate vulnerable zones).

Read more about the separation efficiencies, use of additives, energy requirements and costs in Chapter 2.2.2 of D 3.2 Final report on schemes and scenario's for nutrient recovery and Reuse.

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TECHNOLOGY FACT SHEET

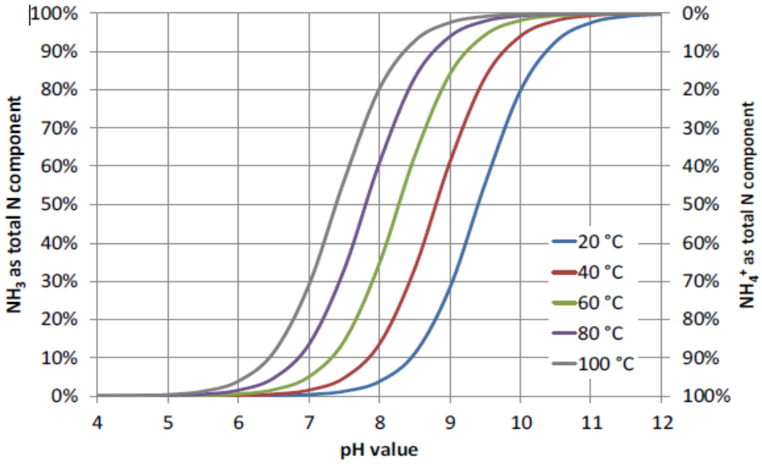
Ammonia stripping-scrubbing

FiberPlus

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 (methane producing bateria) and lower biogas production (Krakat et al. 2017; SYSTEMIC et al. 2018).

The ammonia stripping-scrubbing technique can be applied on a nitrogen (N) rich waste stream, such as (liquid fraction) of digestate.
Recirculation of N-depleted digestate after N stripping to the anaerobic digestion has proven to be effective in diluting ammonia concentrations within the digester (Ghyselbrecht et al. 2017).

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 [[5]].



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 strippable ammonia. The partial pressure of NH_3 will also rise with the falling pressure (when working under vacuum conditions).
Within the SYSTEMIC project, Benas (Germany) has implemented the FiberPlus ammonia stripping-scrubbing system (formerly known as ANAStrip), designed by GNS.

pH increase and temperature increase

[5]The base ionization constant is Kb = 1.8×10^{-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 the first step, the liquid fraction is manipulated to ensure that more nitrogen becomes available in the form of ammoniacal nitrogen (NH_3-N) as only this form of gaseous nitrogen can be recovered.

This isachieved by stripping CO_2 from the input, which will also prevent the formation of $CaCO_3$ precipitates in the N stripper (Vaneeckhaute 2015).

Ammonia stripping

Next, the liquid fraction enters on top of the system, where it is diffused by nozzles to increase the contact surface of liquid and air. The stripping gas enters usually from the bottom. In this way ammonia is transferred from the liquid to the gaseous phase in a counter current system. These liquid spraying systems would be capable of handling liquid flows containing up to 8-9 % total suspended solids (TSS), without addition of any chemicals. However, they require multiple vessels with diffuser systems in series to reach a maximal ammonia mass transfer area (communication with technology providers, 2020; Barampouti et al. 2020).

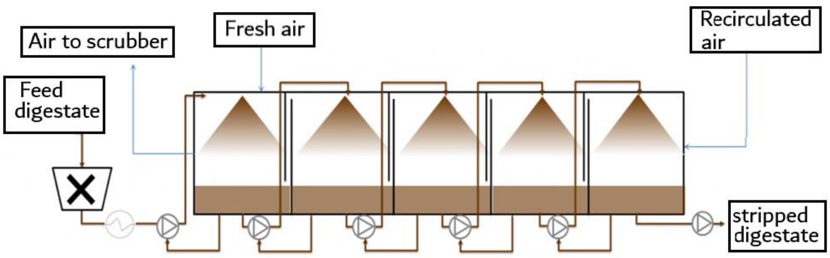


Figure II-2 Configuration of NH_3 stripping-scrubbing on manure or digestate without packing tower. Source: AMFER, Colsen.

Ammonia scrubbing

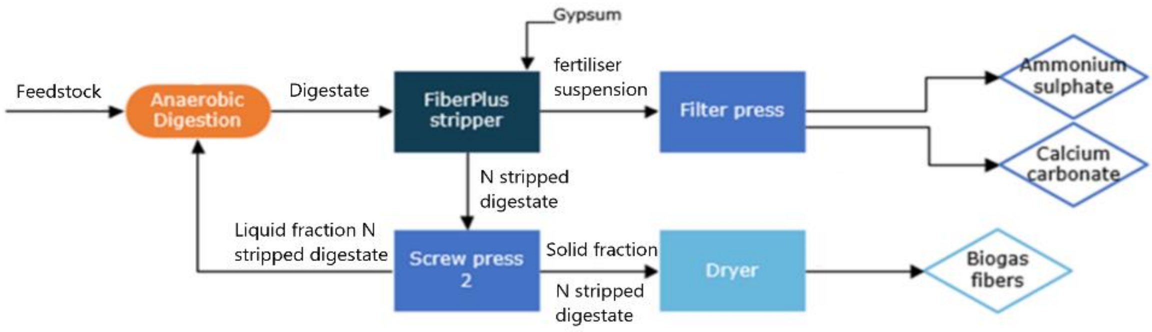
The stripping gas, charged with ammonia, CO_2 and H_2O is brought into contact with wet gypsum ($CaSO_4.2H_2O$), a by-product of flue gas desulphurisation. This reacts with ammonia in the stripping gas to produce a suspension of ammonium sulphate and a liming product containing $CaCO_3$.

$2\ NH_3 + CO_2 + H_2O + CaSO_4 = CaCO_3 + (NH_4)_2SO_4$
These two are separated by means of a chamber filter press.

The stripping gas from which the ammonia is removed, can be recirculated to the stripping tower.

As stripping and scrubbing of ammonia occurs in a closed system, emissions are generally low. 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.

If the concentration of the ammonium sulphate solution rises above 40%, crystals can form which can cause blockage of the spraying system in the scrubber. Therefore, the ammonium sulphate solution needs to be diluted with water to avoid reaching these concentrations in the reactor.



Scheme of ammonia stripping-scrubbing from digestate at Benas (Fiberplus system, GNS).

Read more about the separation efficiencies, use of additives, energy requirements and costs in Chapter 2.2.2 of D 3.2 Final report on schemes and scenario's for nutrient recovery and Reuse.

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TECHNOLOGY FACT SHEET

Phosphorus solubilisation and precipitation: RePeat

The RePeat (Recovery of P to eat) process is an acid-alkaline approach to separate solid fraction of digestate into a low-P soil improver and precipitated phosphate salts. The concept has been developed by Wageningen University and Research (Wageningen, The Netherlands) and Nijhuis Industries (Doetinchem, The Netherlands).

The Repeat installation consist of the following units:

- Acidification tank were solid fraction is mixed with process water and sulphuric acid
- Screw press 1 – leaching step 1
- Screw press 2 – leaching step 2
- Lamella clarifier to remove fines from the acid liquid fraction
- Precipitation reactor
- Settling tank to separate the precipitated P

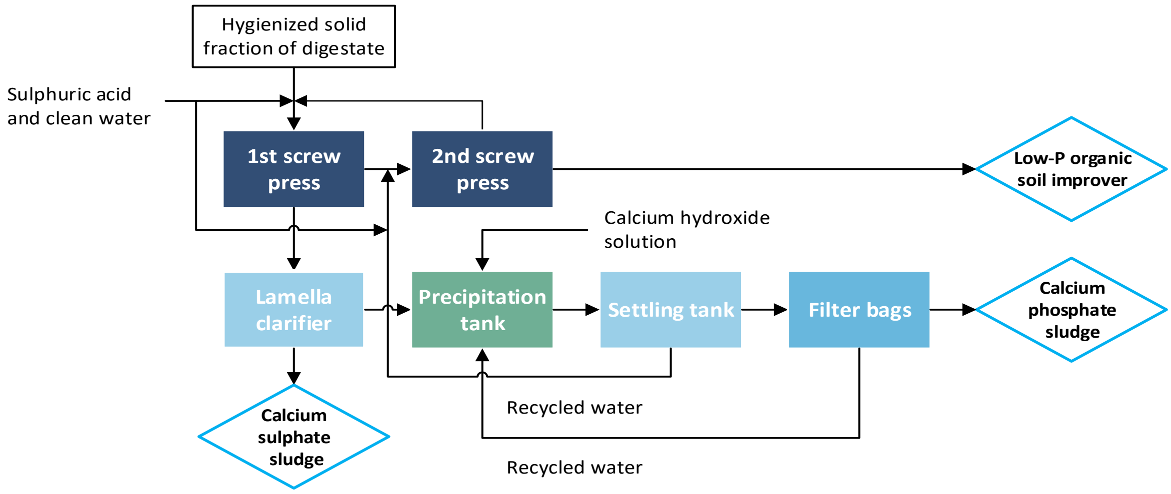


Figure II-3 Process scheme of the RePeat installation at GZV (as configured in May 2020) (Brienza et al. 2020)

The solid fraction of co-digested pig manure after decanter centrifuge is diluted with process water that remains after the after the second leaching step (screw press 2). This way the solid fraction is liquid enough to be pumped to the acidification tank.

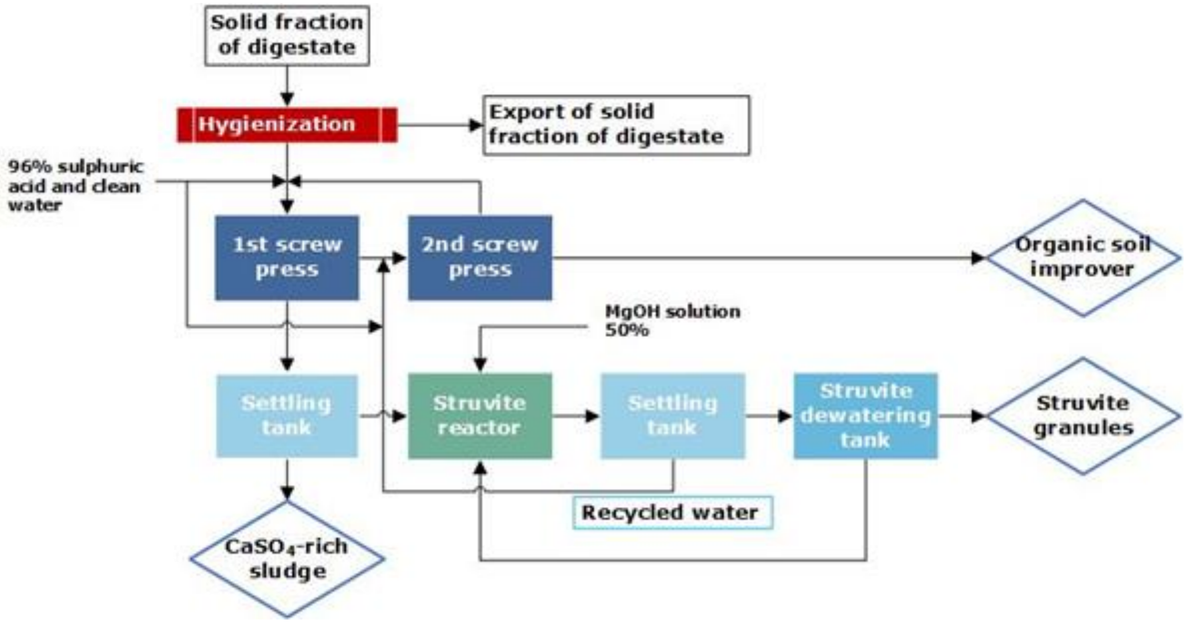
There the pH of the slurry is lowered to pH 5.5 through addition of 98% H_2SO_4 and the slurry is thereafter separated into a solid fraction and a liquid fraction by means of the first screw press.

The solid fraction is thereafter again mixed with process water (with a low P content), acidified to pH 5.5 and dewatered in the second screw press. This second leaching step removes residual P from the solid matrix, ensuring a high P removal efficiency.
The liquid fraction after screw press 1 contains about 3000 mg/L of P mostly as ortho-phosphate ($P\text{-}PO_4$) and is treated by a lamella clarifier to remove fine organic matter prior to feeding it into the precipitation tank.

In the precipitation tank, phosphate precipitation is induced by increasing the pH to 7.0 through addition of a 45% $Ca(OH)_2$ suspension. The precipitation tank is continuously mixed by means of aeration and a screw. The volume of the precipitation tank (>30 m^3) is large enough to ensure a hydraulic retention time of five hours.

The effluent of the precipitation tank is fed into a settling tank were the precipitated P salt is separated from the liquid based on difference in density. The sludge of the settling tank has a dry matter content of about 20%. The effluent of the settling tank is poor in phosphorus and recycled back to the second screw press.

The calcium phosphate salt sludge is pumped into a storage tank. An additional treatment step to increase the dry matter content of the slurry is foreseen. An alternative route also currently under development, is investigating the feasibility of P precipitation as struvite by adding $Mg(OH)_2$ instead of $Ca(OH)_2$.



Configuration of RePeat as to commence production in January 2020

Read more about the recovery efficiencies, energy requirements and costs in Chapter 2.2.8.1 of D 3.2 Final report on schemes and scenario's for nutrient recovery and Reuse.

References

Brienza, Claudio, Inge Regelink, Micol van Puffelen, Jasper Dedeyne, Henk Giordano, Andrea Schepis, Harry Hoskyns Abrahall, Thomas Meier, and Ute Bauermeister. 2020. *D 1.4 Third Annual Updated Report on Mass and Energy Balances, Product Composition and Quality and Overall Technical Performance of the Demonstration Plants (Year 3)*. Vol. 5.

III. Annex III
Terminology

SYSTEMIC
Circular solutions for biowaste

Horizon 2020

The SYSTEMIC project has received funding from the European Union's Horizon 2020 Framework Programme for Research and Innovation under Grant Agreement no. 730400

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

Consortium

Wageningen University and Research (NL)
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)

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