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Technical performance and mass- and energy balances of five large-scale anearobic digesters applying nutrient recovery and reuse

A report within the H2020 project SYSTEMIC

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A full list of all end products is available at www.systemicproject.eu. The SYSTEMIC project was coordinated by Oscar Schoumans (oscar.schoumans@wur.nl) and Inge Regelink (inge.regelink@wur.nl) from Wageningen Environmental Research.

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Photo cover: Groot Zevert Vergisting, The Netherlands

Content

Preface

This study was carried out as part of the European demonstration project SYSTEMIC funded by the H2020 programme (project number 730400). At the heart of the SYSTEMIC project are five large-scale biogas plants at which innovative nutrient recovery and reuse (NRR) processing technologies were implemented and which were monitored by the SYSTEMIC project team on their overall technical, economic and environmental performance. One of the tasks within the project is the monitoring of the demonstration plants including mass- and energy balances and consumption of additives. This is the final and public version of the annually updated report on 'mass and energy balances, product composition and quality and overall technical performance of the demonstration plants' which was submitted to the European Comissions as Deliverable D1.5 'Final report on mass and energy balances, product composition and quality and overall technical performance of the demonstration plants'. It is based on the monitoring results obtained over the period 2017–2021. This report focusses on the technical performance of the installed NRR processing technologies and the benefits they provide in terms of product quality, reduced transport distances and other cost savings. The report also discusses to which extent the envisaged separation efficiencies were realised and to what cost. The data shown in this report was subsequently used to quantify the resulting environmental benefits of the implemented NRR systems by means of a life cycle assessment (Hermans et al, 2022) and an environmental impact assessment (Schoumans et al. 2022).

The authors

Summary

Chapter 2 gives the technical and operational performance of the demonstration plant Groot Zevert Vergisting. A first section is dedicated to the anaerobic digestion plant. Next, both the NRR systems GENIUS and RePeat are described in detail and their achieved separation efficiencies and mass balances are dealt with. The consumption of chemicals and the energy generation and consumption of the plant are described. The chapter concludes with the measured composition of the end products over time.

Chapter 3 gives the technical and operational performance of the demonstration plant Am-Power. A first section is dedicated to the anaerobic digestion plant. Next, the previous and the current NRR systems are described in detail and their separation efficiencies and mass balances are dealt with. More specifically, separation efficiencies and mass balance were derived for the period October 2020 – April 2021, a period in which the newly installed acidification tank and vacuum evaporator were operational. The consumption of chemicals and the energy generation and consumption of the plant are described. The chapter concludes with the measured composition of the digestate, dried solid fraction of digestate and evaporator concentrate over time and with a comparison of the previous and current NRR systems in terms of benefits to Am-Power.

Chapter 4 gives the technical and operational performance of the demonstration plant Waterleau NewEnergy. The plant joined the SYSTEMIC project with their fully implemented and operational NRR system. The first section is dedicated to the anaerobic digestion plant. Next the NRR system is described in detail and its achieved separation efficiencies and mass balances are dealt with. The consumption of chemicals and the energy generation and consumption of the plant are described. The chapter concludes with the measured composition of the digestate, dried solid fraction of digestate and evaporator concentrate over time and with a comparison of the digestate handling and transportation costs with and without the implemented NRR system.

Chapter 5 gives the technical and operational performance of the demonstration plant Acqua & Sole. A first section is dedicated to the anaerobic digestion plant. Next, the NRR system with the previous ammonia stripping unit and the NRR system with the current ammonia stripping unit, are described in detail and their separation efficiencies and mass balances are dealt with. The consumption of chemicals and the energy generation and consumption of the plant are described. The chapter concludes with the measured composition of the digestate and ammonium sulphate solution over time and with a comparison of the previous and the current NRR system.

Chapter 6 gives the technical and operational performance of the demonstration plant BENAS. A first section is dedicated to the anaerobic digestion plant. Next the NRR system, with a strong focus on the N-stripper, is described in detail and its achieved separation efficiencies and mass balances are dealt with.
Specifically, the results of a short monitoring campaign, during which the N-stripped digestate was separated into a solid and liquid fraction of digestate to produce low-nitrogen fibres, are included. The consumption of chemicals and the energy generation and consumption of the plant are described. The chapter concludes with the measured composition of the digestate and ammonium sulphate solution over time and with a comparison of the previous and the current NRR system.

Chapter 7 is dedicated to the comparison of the demonstration plants before and after the implementation of NRR technologies, including the main achievements in this during the SYSTEMIC project. At the time of writing, the implemented NRR systems of Groot Zevert Vergisting and Acqua & Sole for the processing of digestate are fully operational. Am-Power is at the time of writing still implementing and optimizing the new reverse osmosis installation to achieve the for discharge required purification of the condensate produced by the evaporator. The NRR systems of BENAS and WNE were already operational before the start of the project. Over the course of the project BENAS has improved its NRR system to produce materials (i.e. mulch mats, plant pots and paper rolls) from the fibres present in the digestate.

List of abbreviations

AD: Anaerobic digestion
AmP: Am-Power
AS: Ammonium sulphate
ASW: Air scrubber water
A&S: Acqua & Sole
BOD: Biochemical oxygen demand
CaP: Calcium phosphate
CC: Calcium carbonate
CHP: Combined heat and power
DAF: Dissolved air flotation
DM: Dry matter
EC: Electrical conductivity
FTE: Full time equivalent
FW: Fresh weight
GZV: Groot Zevert Vergisting
HSAD: High solid anaerobic digestion
IX: Ion exchanger
KPI: Key performance indicator
kt: Kilo tonne
LF: Liquid fraction
NRR: Nutrient recovery and reuse
NUE: Nitrogen use efficiency
NVZ: Nitrate vulnerable zone
OM: Organic matter
PLC: Programmable logic controller
RENURE: REcovered Nitrogen from manURE
RO: Reverse osmosis
SF: Solid fraction
SSFW: Source segregated food waste
t: Tonne
TOC: Total organic carbon
WNE: Waterleau NewEnergy
WWTP: Wastewater treatment plant

List of definitions

Term	Definition
Digestate	Solid material remaining after the anaerobic digestion of a biodegradable feedstock.
Liquid fraction (LF) of digestate	LF of digestate after separation of digestate by a decanter centrifuge or screw press.
Solid fraction (SF) of digestate	SF of digestate after separation of digestate by a decanter centrifuge or screw press.
Reverse osmosis (RO) concentrate	Concentrate remaining after removal of water from a liquid stream (e.g. LF of digestate or condensed water) by RO.
Permeate water	Permeate after reverse osmosis, which needs further purification by means of ionic exchange prior to discharge to surface water.
Purified water	Water recovered from digestate by means of RO and IO (ionic exchange), purified to be used as process water or to be discharged to surface water.
Low phosphorus (P) soil improver	Solid fraction of the digestate after flushing with water and sulphuric acid to remove most of the P.
Precipitated phosphate salts	Precipitated phosphate salts, obtained by precipitation of phosphate (PO_4) with calcium, and which are recovered as a sludge.
Dried SF of digestate	SF of digestate after a thermal drying process.
Evaporator concentrate	LF of digestate, after evaporation of water and volatile components including ammonia.
Ammonium sulphate (AS) solution	Solution of AS obtained after ammonia stripping followed by recovery of gaseous ammonia in sulphuric acid (Acqua&Sole) or with gypsum (FibrePlus at BENAS).
Condensed ammonia water	Condensate after evaporation of LF of digestate with a high content of ammonium and high pH, and treated by RO to reduce the water content.
Condensed water	Condensate after evaporation of LF of digestate which contains water and volatile compounds including ammonia, bicarbonate and volatile organic acids.
Low nitrogen (N) organic fibres	SF of digestate obtained by a screw press from digestate after N stripping-scrubbing in the FibrePlus system and used for production of fibre.
Organic fibres	GZV: Organic fibres with a low N and P content, recovered from digestate by means of a screw press after two or three washing steps to remove P, salts and fine particles. BENAS: SF obtained by a screw press from digestate after N stripping-scrubbing in the FibrePlus system and used for production of fibre.
Calcium carbonate sludge	Precipitate of calcium and carbonate produced as a side product of the FibrePlus N stripping unit at BENAS by the reaction of striped gas containing ammonia and carbon dioxide with gypsum ($CaSO_4$) leading to the formation of ammonium sulphate and calcium carbonate precipitate.
Micro-filtration (MF) concentrate	Concentrate after treatment of LF of digestate by means of micro filtration (MF concentrate).

1 Introduction

The current European policy strongly focuses on the transition from a linear economy towards a circular economy (EC, 2015). The main goal is 'economic sustainable growth by increasing the value of products, materials and raw materials as long as possible in the economy'. The three main strategies are (a) reduce waste to a minimum, (b) promote reuse and recycling of materials and products and (c) create value: from waste to valuable raw material. The European Commission proposes a large package of measures to set product requirements regarding reparability, sustainability and recyclability mainly to prevent the production of waste. One of these measures is the recycling of waste materials and by-products as fertilising product.

Currently, the economy in Western Europe is a linear economy in which natural finite raw materials are often used for the production of food and feed. Agricultural production is highly dependent on the availability of (fresh) water, macronutrients, nitrogen (N), phosphorus (P) and potassium (K), and a healthy soil. Besides the application of mineral fertiliser in agriculture, also organic biomass (like manure, digestate and compost and in some countries also sewage sludge) is used as source of organic matter (OM) to improve the soil quality and as sources of macro (N, P and K), secondary (Ca, Mg and S) and micro (B, Cu, Fe, Mn, Mo, Zn, etc.) nutrients. Furthermore, there is a tendency to create more value out of organic biomass 'waste' streams e.g. by producing biogas as substitute for natural gas and by recovering nutrients as substitute for the 'synthetic produced' mineral fertilisers.

The SYSTEMIC project aims to reach a break-through in reuse of nutrients recovered from biowaste (manure, sewage sludge as well as food, feed and agricultural waste) in the agricultural production cycle. SYSTEMIC is doing this by demonstrating circular economy solutions for biowaste management with an effective combination of anaerobic digestion (AD) and novel nutrient recovery and re-use (NRR) technologies at five full-scale biogas demonstration plants located in Belgium, Germany, the Netherlands and Italy. SYSTEMIC aims to validate the technical and economic viability of the presented integrated approach at the demonstration sites and focus on practical information transfer and business development to other (biogas) outreach locations in order to demonstrate business opportunities elsewhere in Europe, and to strengthen the position of the European biogas sector by offering them innovative NRR technologies.

In order to ensure the market uptake and replication of the biobased fertilisers promoted by SYSTEMIC, the operational performance of NRR technologies must ensure high stability and overall quality. The main aim of this study (D1.5) is to give an overview of the monitoring activities of the five SYSTEMIC demonstration plants in the third year of SYSTEMIC project. The assessment of mass, nutrients and energy balances was extended to prove the good operational working on NRR technologies. The implementation of enhanced NRR processes (TRL 7-8) to overcome imbalances in nutrient supply is validated at five large-scale demonstration plants. Mass and energy balances are used as a tool to verify the feasibility of nutrient recuperation from organic wastes into mineral products, or their up-concentration in organic and organo-mineral fertilisers, by reducing the volumes to be transported towards nutrient depleted regions.

To achieve a high level of detail in the information gathered in this report, the demonstration plants were closely involved in the collection of data. More precisely, every anaerobic digestion (AD) plant provided information on the operational performances of the AD plant, including an overview of the digester feedstock and the produced end products. The chemical consumption and energy production of the plants were also provided where possible. To draft mass balances of the NRR systems, if collection on site was not possible, samples were shipped to the academic partners or accredited laboratories to characterise them. Moreover, each demonstration plant was asked to provide flows of intermediate and end products. Finally, when available, the energy requirements of each unit step were also communicated to SYSTEMIC consortium. All these information is fed to Dbase that consists of five excel files – one for each demonstration plant – containing all the data that have been collected throughout the timespan of the project.

This includes data on:

- Data on monitoring of inputs, intermediate flows and outputs of the NRR systems including at least the following parameters (available for specific monitoring periods):
    - DM and OM content
    - TN, $N-NH_4$, TP, TK, S, Ca, Mg, Fe content
    - Zn, Cu, Co, Cr, Fe, Mn, Ni content
    - pH, EC
- Calculated or measured flows and mass balances (available for specific monitoring periods, however, information on chemicals consumption is available on yearly basis)
- Data on energy consumption and biogas production (available on yearly basis, and in some cases also available for specific monitoring periods on monthly basis)
- Data on additional analyses in relation to product quality (e.g. organic micro-pollutants)

The five large scale demonstration plants are located in Belgium (Am-Power, Pittem & Waterleau NewEnergy, Ypres), Germany (BENAS, Ottersberg), Italy (Acqua & Sole, Vellezzo Bellini) and the Netherlands (Groot Zevert Vergisting, Beltrum). Table 1-1 gives an overview of the feedstock and produced products of the demonstration plants.

Table 1-1 Overview of the feedstock and produced biobased fertilisers (and other end products) of the five demonstration plants.

Name	**Location**	**Feedstock quantity (2020)**	**Feedstock**	**Biobased fertilisers and other end-products**
Groot Zevert Vergisting	Beltrum (NL)	115 kt/y	Pig slurry, Biowaste from agro-industry	• RO concentrate • MF concentrate • SF of digestate • Low-P soil improver • Precipitated P salt • Purified water
Am-Power	Pittem (BE)	134 kt/y	Biowaste from agro-food industry	• Evaporator concentrate • Dried SF of digestate • Condensed water
Acqua & Sole	Vellezzo Bellini (IT)	77 kt/y	Sewage sludge, Biowaste	• AS solution • Digestate
BENAS	Ottersberg (DE)	87 kt/y	Corn silage, Poultry manure	• AS solution • Calcium carbonate sludge • LF of digestate • SF of digestate
Waterleau NewEnergy	Ypres (BE)	60 kt/y	Pig slurry Biowaste Sewage sludge	• Condensed ammonia water • Evaporator concentrate • Dried SF of digestate • Purified water

2 Groot Zevert Vergisting (the Netherlands)

2.1 General description of the plant

2.1.1 Introduction

Groot Zevert Vergisting (GZV) is located in Beltrum (Achterhoek region of the Province Gelderland) in the Netherlands. GZV is a daughter company of Groot Zevert Loon- en Grondverzetbedrijf. It is a family business in agricultural services, biogas production, manure- and soil transport, demolition and road construction. In 2020, six full time equivalent (FTE) were working at GZV and five FTE were working at Groot Zevert Loon- en Grondverzetbedrijf for manure- and digestate transport. In 2004, the first biogas production activities started with digestion of animal manure. In the years thereafter, GZV extended and it is now, in terms of feedstock mass, one of the largest AD plants in the Netherlands (Figure 2-1). GZV is a front-runner in the application of manure processing techniques in the Netherlands.

Figure 2-1 Aerial photo of the biogas plant of Groot Zevert Vergisting in Beltrum, the Netherlands.

2.1.2 Technical description of the biogas plant

GZV has a co-digestion capacity of about 120 kt total feedstock per year. Some general characteristics of the AD plant are shown in Table 2-1. The effective volume of the digesters is roughly 12,000 m^3, which is 80% of the total volume of the digesters. The digesters are operated at mesophilic conditions (38–42°C) and the average retention time in the system of connected digesters amounts to 50 days.

Until 2018, digestate was disposed of after hygienisation without further separation or processing. In November 2018, the GENIUS system was commissioned. The GENIUS system separates the produced digestate into a SF, RO concentrate, purified water and a residual stream (MF concentrate). In 2020, engineering of the RePeat system was completed, which is designed to separate the SF of digestate into a low-P soil improver and precipitated P salts. More detailed information about the GENIUS and RePeat systems is given in section 2.3.

Table 2-1 Technical information of the biogas plant of Groot Zevert Vergisting.

Date of construction	2004
Maximum electric power[a]	1000 kWe
Volume of the digesters	15,000 m^3
Effective volume of the digesters	12,000 m^3
Digestion process	Mesophilic digestion
Commissioning GENIUS system for production of SF of digestate, RO concentrate and purified water	November 2018
Commissioning RePeat system for production of low-P soil improver and precipitated P salts	January 2020

[a] Two biogas engines (combined heat and power installations) with a maximum electric power of 500 kW each. GZV sells the majority of its biogas.

2.1.3 Feedstock and hygienisation

The digesters are, on a mass basis, fed for roughly 80% with animal manure and for roughly 20% with co-substrates from the agro-industry. The animal manure consists mostly of pig slurry with smaller contributions of paunch manure[1] and dairy cattle slurry. The co-substrates include a variety of residues including potato shields, cereal grain chaff, rejected cereal flour, coffee grounds, rejected milk powder and other residues of dairy processing etc. The added co-substrates are responsible for roughly 77% of the biogas production. Digestate is hygienised in the post-digester by increasing the temperature to at least 52 °C for at least six hours.

Table 2-2 gives an overview of the digester feedstock for the period 2017–2020 during which the amounts and origin of the feedstock were fairly constant. Only the intake of pig slurry decreased in 2020 due to a decrease in the total number of livestock animals in the Netherlands initiated by the Dutch government and a simultaneous increase in the total manure processing capacity of the Netherlands.

Table 2-2 Origin of anaerobic digestion feedstock of the demonstration plant Groot Zevert Vergisting, expressed in kilotonnes of substrate per year for the period 2017–2020.

Category	Feedstock	2017	2018	2019	2020
Manure	Pig slurry	65	74	75	60
	Dairy cattle slurry	2	5	5	2
	Paunch manure	12	12	10	9
Co-substrates	Residues from agro- and food industry	20	21	18	19
	Glycerine	3	3	4	3
Total		102	115	112	93

2.1.4 Biogas production and energy generation

During the monitoring period (2017–2020), total biogas production increased from 6.5 to 9.7 million Nm^3 biogas per year (Table 2-3) due to a larger intake of co-substrates with a high biogas production per tonne. The last years GZV has deliberately steered towards a higher biogas production while keeping the methane content of the biogas roughly similar. In 2020, the average biogas production per tonne of feedstock increased due to the lower intake of animal manure, which has a lower biogas production per tonne than

[1] Paunch manure: the partially digested contents of the stomach of a ruminant, especially including the first chamber of said stomach (the rumen) during the time period immediately before and after the animal is slaughtered for meat and other by-products.

the co-substrates. It is assumed that the pig slurry digested at GZV produces at maximum 25 Nm^3 biogas (14 Nm^3 CH_4) per tonne.

Table 2-3 Biogas production and average biogas composition before purification by the demonstration plant Groot Zevert Vergisting for the period 2017–2020.

Parameter[b]	**Unit**	**2017**	**2018**	**2019**	**2020**
CH_4	vol%	58.0	56.0	55.0	55.0
CO_2	vol%	40.2	42.2	43.0	43.0
H_2S (before desulphurisation)	ppm	2000–3000	2000–3000	1000–2 000	1000–2000
H_2S (after desulphurisation)	ppm	<2	<2	<2	<2
O_2	vol%	0.2	0.2	0.2	0.2
Density	kg Nm^{-3}	-	1.2	-	-
Total biogas production	MNm^3	6.5	9.0	8.7	9.7
Calculated biogas weight[a]		7.8	10.8	10.4	11.6
Specific biogas production	Nm^3 t^{-1} feedstock	64	78	78	104
Total CH_4 production	MNm^3	3.8	5.0	4.8	5.6
Specific CH_4 production	Nm^3 CH_4 t^{-1} feedstock	40	42	43	60

[a] Based on the measured biogas density of 1.2 kg/Nm^3 for the year 2018.

[b] CH_4: methane, CO_2: carbon dioxide, H_2S: hydrogen sulphide, O_2: oxygen.

GZV deliberately does not add any iron salts to the digester which however results in high hydrogen sulphide (H_2S) concentrations, 1000–2000 ppm for the year 2020, in the biogas. Desulphurisation by GZV lowers this to < 100 ppm H_2S for the biogas going to the combined heat and power (CHP) installations of GZV and to < 2 ppm H_2S for the biogas sold to a nearby dairy processing factory. The removed H_2S is recovered in the form of elemental sulphur. In 2020 GZV sold 6.95 million Nm^3 (72%) of its biogas (55 vol.-% CH_4) to the dairy factory where it is mixed with natural gas prior to use (Table 2-4). Direct use of biogas is — both in terms of CO_2 footprint and revenues — the most beneficial way to valorise biogas since it prevents energy losses that would occur if biogas is converted to green gas or electricity. There is a 5-km pipeline from the biogas plant to the dairy processing factory to transport the biogas. The remaining circa 28% of the biogas was converted on-site into about 5,597 MWh electricity and 3,623 MWh useable thermal energy by the CHP installation (data for the year 2020). On top of that, some biogas is combusted in a biogas boiler to supply heat during cold periods. In 2020, this amounted to only 31 MWh due to the mild average winter temperatures in 2020. The produced thermal energy is used on-site for heating of the digesters, hygienisation of digestate in the post-digester, desulphurisation of the biogas and heating of the buildings. The produced electricity is partly used on-site and partly sold to the grid. Digestate production in 2020 was lower than in 2018 and 2019. Although there were still plentiful farmers that wanted to get rid of their manure via GZV in 2020, it was hard for GZV to find manure for a price that allowed sufficient profit for GZV. In 2020, on a mass basis, 12% of the ingoing feedstock was converted into biogas and 88% into digestate.

Table 2-4 Digestate, electrical energy and thermal energy production by the anaerobic digestion plant at Groot Zevert Vergisting for the period 2018–2020. Total production and per tonne of digestate (kWh t^{-1})

Year	Digestate	Biogas to end-user			Electrical energy production[c]			Thermal energy production		
	kt y^{-1}	MNm^3	MWh[a]	kWh t^{-1}	kW[b]	MWh	kWh t^{-1}	MWh (CHP)[c]	MWh (boiler)[d]	kWh t^{-1}
2018	103	6.50	36,254	311	522	4,575	44	3,350	653	59
2019	101	5.95	32,594	279	623	5,461	54	3,822	903	72
2020	81	6.95	38,072	414	639	5,597	69	3,623	31	45

[a] Based on the average biogas methane content of 56 vol.-% in 2018 and 55 vol.-% in 2019 and 2020 as reported by Groot Zevert Vergisting and the lower heating value (LHV) of methane (9.96 kWh/Nm^3). LHV of methane was calculated based on: LHV = 50.1 MJ/kg CH_4; molar volume of 22.41 mol CH_4/m^3 at 273.15 K; molar mass of 16.043 g CH_4/mole.

[b] Average over 365 days.

[c] Used part of the total heat produced by the CHP's.

[d] Used part of the total heat produced by the biogas boiler. Calculated as total thermal energy consumption by the anaerobic digestion plant and the NRR systems minus the used part of the thermal energy produced by the combined heat and power installations.

2.1.5 Other information

Implementation of the NRR systems has led to an increase in the number of employees working at GZV. Process operators have been hired to operate the RePeat system (0.5 fte) and the GENIUS system (1.0 fte) in addition to the 4.5 fte that were already employed by the biogas plant. This is excluding personnel for transport of manure, digestate and recovered fertilisers since this work is outsourced.

The storage capacity of GZV in terms of volume of end products is given in Table 2-5. Outside the premises of the biogas plant roughly 8,000 m^3 of storage capacity is available. This is sufficient to store all RO concentrate that is being produced outside the season in which field application of RO concentrate is allowed. For the other end products, the available storage capacity within the premises of the plant is minimal since those products are transported to the end-user on a daily basis.

Table 2-5 Storage capacity available to Groot Zevert Vergisting for their end products.

End product	Storage capacity	Comments
Solid fraction of digestate	100 m^3	Product is transported to end user within 1–2 days.
Purified water	-	No storage needed due to discharge to surface water.
Microfiltration concentrate and solid fraction of the 2nd decanter centrifuge	500 m^3	Products are mixed and stored together.
RO concentrate	≈8,000 m^3	RO produced in December till February is stored in external storage facilities until the start of the growing season.
Low-P soil improver	≈100 m^3	Minimal storage capacity needed because end product is transported to end user within 1–2 days.
Precipitated P salts	≈20 m^3	

2.2 Drivers for nutrient recycling

2.2.1 Motivation for nutrient recycling

GZV operates a co-digestion plant in the eastern part of the Netherlands, a region with intensive livestock farming. The digesters are, on a mass basis, fed for roughly 80% with animal manure and for roughly 20% with co-substrates from the agro-industry. GZV has two core-businesses: (i) production of renewable energy, which is mostly driven by the type and the amount of added co-substrates and (ii) handling and disposal of the produced digestate and the nutrients it contains which originate dominantly from the animal manure. All digestate produced via co-digestion is considered 'animal manure' and application rate limits for P and N apply when applying this digestate on agricultural land. There is no market for digestate in the region of the plant due to the surplus of animal manure (in terms of N and P) in the region and in the Netherlands as a whole.

In the Netherlands, intensive livestock farming has led to accumulation of P in agricultural soils and leaching of P and N to ground- and surface waters. To prevent further accumulation of P in soil, the government has set application rate limits for P fertilisers. The application rate limit for P depends on the soil-P status and is equal to the crop uptake of P for soils with a neutral P-status (so called equilibrium fertilisation). Furthermore, in line with the Nitrates Directive, the yearly application of N from animal manure is limited to 170 kg N per hectare or 240/250 kg N per ha on dairy farms with a derogation. Additionally, the total amount of N applied, the sum of applied manure and applied synthetic fertilisers, is limited by the N-application rate limit[2].

Since pig farmers usually do not have their own land to dispose of their manure, 85% of the animal manure processed by GZV, on a mass basis, is pig slurry. In the Netherlands, livestock animals (cows, pigs and chickens) excrete in total about 31% more P and 20% more N than can be applied within the application rate limits for P and N from animal manure. Hence, the surplus of manure is primarily a surplus of P and secondarily a surplus of N. Until the start of the SYSTEMIC project, GZV disposed of their digestate by exporting it over a distance of 250 km to the Eiffel region in Germany. Though there is a demand for digestate as an organic N-P fertiliser in this part of Germany, this disposal route was costly (€20,- per tonne) and not environmental friendly because of the long transport distances. Moreover, except for P, there is a demand for each of the nutrients present in the digestate within the region of GZV or within the Netherlands. This offers opportunities for the separation of digestate into fertilising products that meet this demand of local growers and farmers.

GZV first invested in the GENIUS system for the production of a solid fraction (SF) of digestate (produced by the first of two sequential decanter centrifuges), reverse osmosis (RO) concentrate, and purified water. By exporting only the SF of digestate, roughly 65% of the TP is transported in only about 15% of the initial digestate mass. The RO concentrate meets the by the Joint Research Centre proposed criteria for RENURE fertilisers, amongst others ($N\text{-}NH_4$ + $N\text{-}NO_3$)/TN > 90%. GZV initiated a pilot project called 'Biobased fertilisers Achterhoek' and received permission from the Dutch ministry of agriculture to use RO concentrate as an alternative for synthetic N fertiliser on a limited number of farms. As part of the pilot project, GZV is obliged to perform field tests – which are being monitored by WUR – to provide information about the agronomic and environmental effects to the ministry. The pilot is temporarily and its end date has recently been extended to the end of 2022 awaiting implementation of RENURE criteria by the EC. Due to this exemption, GZV could dispose of the produced RO concentrate to farmers within 25 km of their plant. Those farmers use the RO concentrate as an alternative for synthetic N fertiliser, hence on top of the application rate limit for N from animal manure but within the N-application rate limit. GZV blends RO concentrate with other N fertilisers such as urea, and ammonium sulphate solution into a tailor-made-

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[2] For organic fertilisers, the amount of N taken into account under the N-application limit is calculated as the N content times the nitrogen fertiliser replacement value (NFRV) of that fertilising product. For mineral fertilisers, the NFRV is by definition 100%.

fertiliser (TMF) with N/K/S ratios that match the need of the crop. As a side product, a microfiltration (MF) concentrate is produced which is blended with the SF of digestate produced by the second of the two sequential decanter centrifuges. This SF of digestate has a lower DM and TP content than the SF of digestate produced by the first decanter centrifuge. The blend of MF concentrate and SF of the second decanter centrifuge is sold to farmers in the Netherlands as an organic N fertiliser (with the status of manure). Averaged over 2020, roughly 15% of the mass of ingoing digestate is discharged to surface water in the form of purified water, thereby reducing the mass of digestate (or its end products) that need to be transported. Periodically, higher percentages for this, up to 18%, have been achieved.

GZV also invested in the development and construction of a process to separate the SF of digestate, from the first decanter centrifuge, into precipitated P salts and a low-P soil improver. This process, called RePeat (**Re**covery of **P** to **eat**) was developed by Wageningen Environmental Research (WENR) in collaboration with Nijhuis Industries. The RePeat system was commissioned in 2020 and produces precipitated P salts in the form of a sludge rich in calcium phosphate to be used as P fertiliser or as feedstock for the production of granular organic fertilisers. The low-P soil improver is currently applied on local arable land, however the aim is to use it as resource for potting soil or as substrate for the growing of mushrooms, thereby replacing fossil peat.

2.2.2 Sustainability goals of Groot Zevert Vergisting

- To produce **biogas** from animal manure and residues from the agro-industry and simultaneously offer a sustainable disposal solution for the surplus of animal manure in the region.
- To **reduce long-distance transport** of digestate by separating digestate into:
    - (i) purified water,
    - (ii) fertilising products that can be used within the region of the plant (e.g. RO concentrate, low-P soil improver) and
    - (iii) fertilising products with a high DM content (SF of digestate and precipitated P salts).
- To further reduce the **CO_2 footprint** of the plant.
- To **replace synthetic N fertiliser** in the region of the plant by a blend containing RO concentrate.
- To **replace peat** in potting soil or in substrate for the growing of mushrooms by the low-P soil improver.

2.2.3 Economic benefits

An analysis of the overall business case of the biogas plant including the economic benefits of the production of renewable energy was published earlier (Hermann et al., 2022). Revenues from the sale of biogas (including subsidies) are the core of the business case whereas the implementation of digestate processing only creates minor or no benefits as compared to disposal of untreated digestate. In this paragraph, costs are given for digestate treatment and product disposl without considering the benefits from biogas production. The economic benefits from the NRR systems for the separation of digestate (GENIUS, Table 2.2.1) and the separation of the SF of digestate (RePeat, Table 2.2.2) are discussed separately.

Without separation of digestate, costs for digestate disposal amount to € 20,00 per tonne (price level 2021) including transport of the digestate to Germany over a distance of about 250 km. Table 2-6 gives the costs for treatment of digestate with the GENIUS system which separates digestate into purified water and three fertilising products. Disposal costs for the SF of digestate amount to about € 18,00 per tonne including transport over distances of 300–400 km to the eastern part of Germany where farmers pay to receive the SF. The RO concentrate is blended with other N-fertilisers into a TMF and sold as a RENURE fertiliser to farmers in the region of plant (<25 km), thereby locally replacing synthetic N fertiliser. Disposal and handling costs for the RO concentrate include storage outside the growing season, sampling (obliged), transport and field application of the fertiliser via low-emission injection resulting in a nett cost of € 8,00 per ton of RO concentrate As a side product, sludge of the MF unit and the second decanter is being produced. This sludge has a low P but high N content and is trucked to Northern provinces of the Netherlands were it is applied under the application limit for animal manure. This is a cost item of € 19,00 per tonne of sludge. Other costs include depreciation and interest, use of chemicals and personnel. In total, costs for disposal and handling of digestate amount to € 22.63 for the mass balance and price levels in the first six months of 2021. Hence, separation of digestate does not yet give an economic benefit as compared to disposal of raw digestate to Germany. T. GZV is therefore still working on improvement of the mass balance of the installation in order to reduce to the volume of sludge (side stream) and increase the volume of purified water and RO concentrate. In addition, they aim to increase revenues from their end-products in particular for RO concentrate that is being sold as an alternative for synthetic N fertiliser.

In general, the business case of GZV is highly depended on the price for disposal of animal manure which in turn is depended on trends in the number of livestock animals and regulations on the application of animal manure on agricultural land. In recent years, the total number of livestock animals in the Netherlands has decreased which in turn leads to a decrease in the gate fee for animal manure which GZV receives. A further decrease in the number of livestock animals is expected and the future business case of GZV therefore depends on whether the government will tighten obligations to process manure.

After implementation of the GENIUS system, GZV implemented the RePeat(Recovery of P to eat) system to produce a low-P soil improver which can be applied on fields in the region of the plant. In contrast to the SF of digestate (which is rich in P), this product is expected to have a positive market value. The precipitated P salts can be used as raw material for the production of fertilisers for the market outside The Netherlands. The business case for the RePeat system is given in Table 2.2.2. The business case of RePeat has changed over the course of the SYSTEMIC project due to a decrease in disposal costs for the SF of digestate. In 2017, when the initial business case for the RePeat system was drawn, disposal costs for the SF of digestate amounted to € 25,00 per tonne but this has since then decreased to € 18,00 in 2020. Costs for processing the SF of digestate into a low-P soil improver and precipitated P-salts amounted to € 22,63 in 2020. For GZV, this means that the original plan in which the low-P soil improver is used as a soil improver on fields in the nearby region does not generate a profit compared to disposal of the untreated SF of digestate. This shows the economic risks that are associated with investment in NRR. However, the system is still under development and options for cost reduction are ample. For example, improving the dewaterability of the precipitated P salts (a sludge) would open new markets including the production of granular organic fertilisers. The market value of the low-P soil improver can also be increased through creation of new markets such as the use as peat replacer in potting soil or substrate for the growing of mushrooms.

Table 2-6 Costs related to processing of ***digestate*** *with the* ***GENIUS*** *system and disposal of its end-products by Groot Zevert Vergisting.*

Product disposal costs

End products	**Tonne product per tonne of digestate**	**€/tonne product**	**€/tonne digestate**	**Explanation**
Solid fraction of digestate	0.150	€ -18.00	-€ 2.70	Export to Germany
RO concentrate	0.250	€ -8.00	-€ 2.00	Use within the region as alternative for synthetic N fertiliser (RENURE)
Microfiltration concentrate & solid fraction of the second decanter centrifuge	0.450	€ -19.00	-€ 8.55	Use within the Netherlands, applied on agricultural land
Purified water	0.150	€ 0.00	€ 0.00	Discharged to surface water

Fixed costs

Cost item	**€/tonne digestate**	**Explanation**
Depreciation (5 years), interest (3%)	-€ 3.41	€ 2 million investment, capacity of 135 kt digestate/year
Maintenance	-€ 1.85	€ 250,000/year
Personnel	-€ 0.37	1 fte process engineer (on top of employees at the AD plant)
Electricity	-€ 1.75	25 kWh/tonne and € 0,07/kWh
Additives[3]	-€ 2.00	Sulphuric acid, polymer flocculant, magnesium chloride solution, cleaning agents etc.
Total costs – digestate handling and disposal	**€ -22.63**	
Without GENIUS: Total costs digestate disposal without NRR	€ -20.00	Price level 2021

[1] *Mass balance and price levels according to realisation in January – June 2021. The total investment costs for the GENIUS system is estimated at € 2 million for an installation with a processing capacity of 125–150 kt digestate per year, including air washers and excluding construction of buildings. Costs for personnel, energy consumption and consumption of chemicals are solely for the GENIUS system hence excluding cost to process the AD plant. ,*

*Table 2-7 Costs related to processing of the **solid fraction** of digestate with the **RePeat** system and disposal of its end products by Groot Zevert Vergisting.*[a]

	Mass of product	**Realised 2021**	**Envisaged business case**	**Explanation**
	(m/m)	(€/tonne SF)	(€/tonne SF)	
Low-P soil improver	0.75	+ € 3.75	+ € 22.5	2021: Soil improver, revenues € 5.00 per tonne Envisaged reveneus € 30.00 per tonne (€ 15.00 per m³) as ingredient for potting soil or mushroom substrate
Precipitated P salts	0.5	€ 9.50	€ 9.50	Currently recovered as a sludge leading to high disposal costs (€ 19.00 per tonne). In dried form, P salts have a positive market value but additional costs for dewatering and drying are yet unknown. Hence, same disposal costs are used under 'envisaged BC'.
Sludge of the lamellae clarifier (side product)	0.3	€ 4.50	€ 4.50	Disposed as animal manure: € 15.00 per tonne of sludge
Electricity		€ 1.00	€ 1.00	5 ct per kWh, assuming 8 working hours per day
Sulphuric acid		€ 4.70	€ 2.80	Consumption is 46 kg 98% sulphuric acid per ton SF. Price of sulphuric acid is 10 ct per kg. Objective is to reduce acid consumption by 40% through shifting from low-P soil improver to production of organic fibres for industry with medium P content.
Lime		€ 3.60	€ 2.20	Consumption of lime is 28 kg per ton SF. Price of lime is 13 ct per kg. A reduction in consumption of lime with 40% is foreseen due to lower sulphuric acid consumption see above.
Personnel		€ 2.20	€ 2.20	0.5 fte (15.000 euro/year) and running for 8 hours per day (capacity: 7000 tonne per year). This costs could be halved by running the installation for 24 h a day (full capacity, 15 000 tonne of SF per year, which is max amount of SF available).
Depreciation		€ 7.15	€ 7.15	Investment of € 500 000 excl. buildings and air washers and excl. development/engineering costs. Capacity 7000 tonne/year. Costs could be halved when running for 24 h a day (15 000 tonne per year).
Total costs per tonne of solid fraction		€ 28.90	€ 6.85	

[a] Total investment estimated at 2 mln euro's for an installation with an capacity of 125-150 kt per year including air washers excluding construction of buildings.

2.3 The nutrient recovery installation

2.3.1 Technical description of the installations

GZV implemented two NRR systems, the GENIUS system and the RePeat system. The GENIUS system separates digestate into an SF of digestate (of the first decanter centrifuge), RO concentrate, purified water and a blend of the SF of the second decanter centrifuge with MF concentrate. The ingoing digestate is first processed by two sequential decanter centrifuges. The second decanter centrifuge processes the LF of the first decanter centrifuge. The LF of the second decanter centrifuge is further processed into an RO concentrate and purified water through a combination of MF, RO and ion exchange. The RePeat system further separates the SF of the first decanter centrifuge, which is rich in P, into precipitated P salts and a low-P soil improver. The RePeat system was funded with subsidy from the H2020 SYSTEMIC project whereas the GENIUS system was installed without funding from the SYSTEMIC project. Both systems were monitored as part of the SYSTEMIC project.

The GENIUS system consists of the following process units:

- First decanter centrifuge
- Second decanter centrifuge
- Microfiltration unit
- Reverse osmosis unit
- Ion exchanger

The GENIUS system is a continuous process and is therefore operational 24 hours per day and seven days per week. $MgCl_2$ solution is added to the ingoing digestate to precipitate P in the form of magnesium phosphates to enhance the separation of P to the SF of the first decanter centrifuge. To the LF of the first decanter centrifuge a polymeric flocculant solution is added to improve the separation of solids to the SF of the second decanter centrifuge. The LF of the second decanter centrifuge is further treated by the MF unit to remove fine particles that need to be removed to allow further processing of the resulting MF permeate by the RO units. The RO installation consists of two RO units that are placed in series. To the influent of the first RO unit, sulphuric acid and antiscalant are added to prevent scaling of calcium carbonates, calcium phosphates and silica salts. Above pH 8 and especially above pH 9 the solubility of silica in water decreases exponentially, addition of sulphuric acid prevents these pH values from occurring. Sulphuric acid is also added to improve the retention of ammoniacal nitrogen by the RO units by shifting the equilibrium from NH_3 towards NH_4^+, the latter is due to its charge being blocked by the RO membrane. The concentrate from the first RO unit is the RO concentrate end product that GZV produces. The permeate of the first RO unit is subsequently processed by the second RO unit. The majority of the total amount of added sulphuric acid is added to the permeate of the first RO unit. This addition also has the goal of preventing scaling and improving retention of ammoniacal nitrogen by the RO membrane. The concentrate of the second RO unit is looped back to the influent of the first RO unit. The permeate of the second RO unit flows over a degassing tower to, amongst other reasons, add oxygen to the water. The effluent of the degassing tower is polished by two sequential ion exchangers, a cation exchanger followed by an anion exchanger. Main goal of the cation exchanger is removal of residual ammoniacal nitrogen. The resulting purified water is partly discharged to surface water and partly reused within the GENIUS and RePeat systems. The RO concentrate produced by the first RO unit is blended with Urea, ammonium nitrate solution and/or ammonium sulphate solution into the 'Green Meadow Fertiliser'. The SF of the second decanter centrifuge and the MF concentrate are blended as well. Figure 2-2 shows the simplified process flow diagram of the GENIUS system including locations of chemical addition and the major return flows.

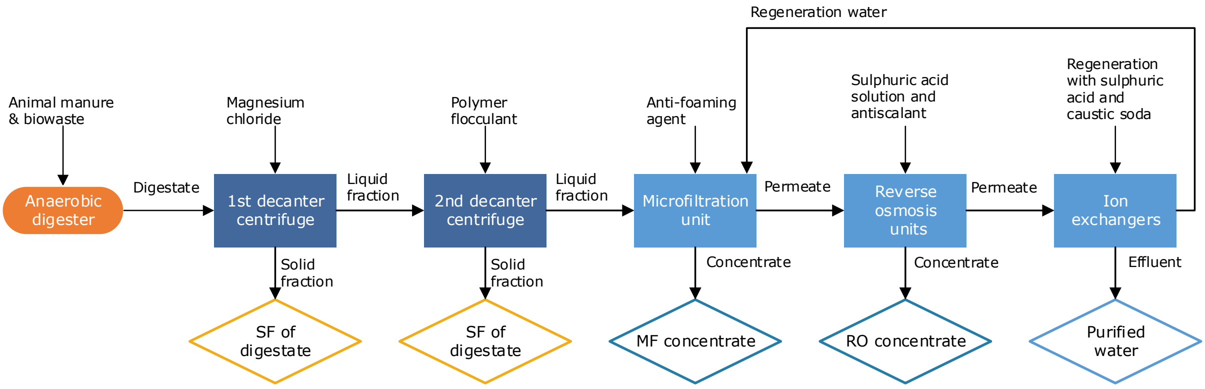

Figure 2-2 Simplified process flow diagram of the GENIUS system at the demonstration plant Groot Zevert Vergisting including locations of chemical addition and the major return flows (as configured in October 2021).

The Repeat system consists of the following units:

- Acidification tank
- First screw press – leaching step 1
- Second screw press – leaching step 2
- Lamella clarifier – removal of fines from the acidified liquid fraction
- Precipitation tank
- Settling tank – separation of the precipitated P salts from the process water

The RePeat system is designed and constructed to be operated in a continuous mode with some individual process steps of it operating batch wise. The processing capacity amounts to two tonnes of SF of digestate per hour. The SF from the first decanter centrifuge of the GENIUS system is mixed with process water and pumped to the acidification tank where the mixture is homogenised and its pH is lowered to roughly pH 5.5 through addition of 98% sulphuric acid which solubilizes inorganic P. The acidified mixture is separated into an SF and LF by the first screw press. The resulting SF is thereafter mixed with process water and sulphuric acid to allow removal of residual P in the second screw press. The SF of the second screw press is the low-P soil improver, with a TP content of on average 1.9 g TP/kg.

The LF of the first screw press, with a TP content of 2-3 g/L, is treated by a lamella clarifier to remove fine organic matter. The effluent of the lamella clarifier is fed to the precipitation tank where the pH is kept at about 7.5 through addition of $Ca(OH)_2$. The already present Ca and Mg and extra added Ca precipitate with the P into calcium phosphates and magnesium phosphates. The precipitation tank is continuously mixed by means of aeration, a screw and by intermittently pumping part of its bottom content to the top of the tank. The volume of the precipitation tank (>30 m^3) is large enough to achieve a hydraulic retention time of five hours. The content of the precipitation tank flows to the settling tank where the precipitated P is separated from the process water based on density. At the bottom a sludge of precipitated P salts forms. Part of this sludge is intermittently pumped back to the precipitation tank with the goal of providing existing precipitated particles to the precipitation tank that can there grow further. The remainder of the sludge is intermittently pumped to the closed storage tank for precipitated P salts. The effluent of the settling tank is fed back into the RePeat system and used as process water. The sludge produced by the lamella clarifier is via various storage tanks ultimately mixed with the MF concentrate produced by the GENIUS system.
Operation of the RePeat system has been causing emissions of the toxic H_2S gas after commissioning. These emissions have afterwards been decreased to a large extent by installing continuous aeration in all major tanks of the RePeat system and by installing vapour suction tubes on all process units of the Repeat system that are in some extent open to the air. The vapours are treated by air washers (acid and base) followed by a biobed. It is not known what the effect of the aeration is on the degradation of organic matter in the RePeat system.

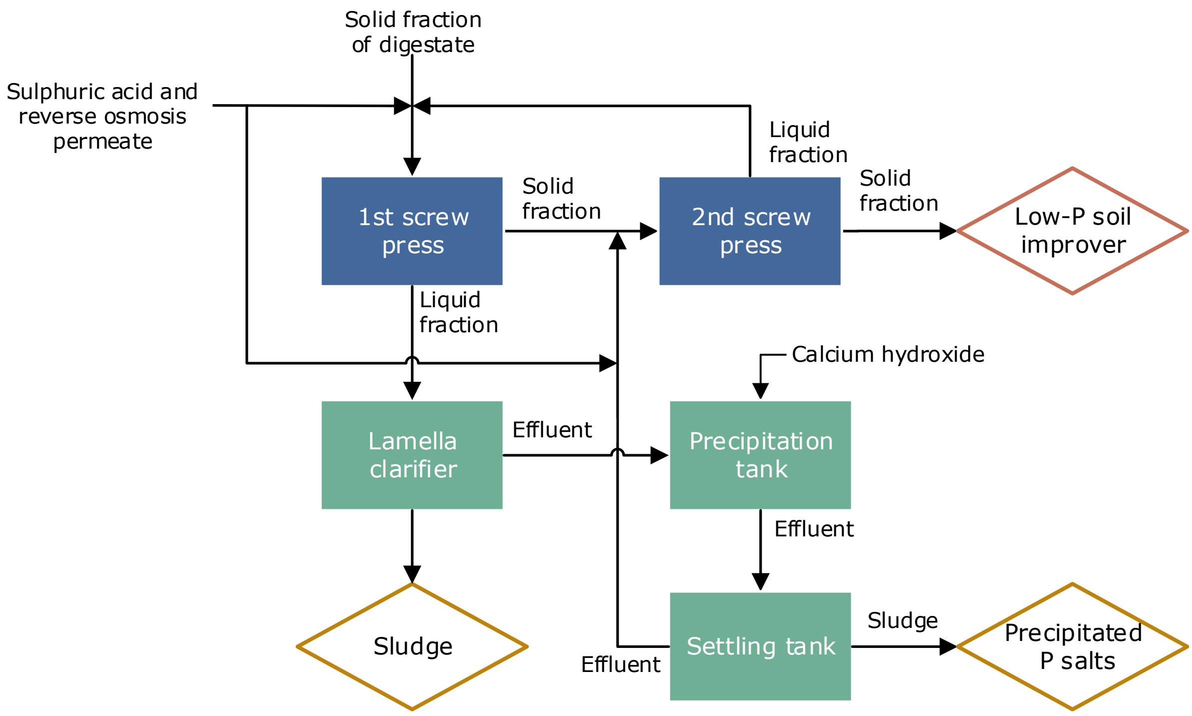

Figure 2-3 Simplified process flow diagram of the RePeat system at the demonstration plant Groot Zevert Vergisting including locations of chemical addition and the major return flows (as configured in October 2021).

2.3.2 Total production of digestate and other products

Table 2-8 gives the amounts of digestate and end product of the GENIUS and RePeat systems produced per year. In 2017 and 2018, prior to the construction of the NRR systems, hygienised digestate was exported to Germany without further separation. Only a small part was separated into an SF and LF of digestate.

In 2019, the GENIUS system was commissioned and production of SF of digestate doubled and the production of RO concentrate started. Production of purified water was still far below anticipated amounts but it doubled from 4 kt in 2019 to 8 kt in 2020. As a side product GZV produces a blend containing the MF concentrate and the SF of the second decanter centrifuge. This product is grouped in Table 2-8 with (unseparated) digestate since both are sold as manure to farmers. In 2020, production of RO concentrate and purified water increased but it was still lower than anticipated in the initial process designs. At the start of the SYSTEMIC project, it was expected that 40% of the ingoing volume of digestate would be converted into purified water. In 2020, production of purified water corresponded to 10% of the ingoing digestate mass though periodically higher percentages have been realised.

The RePeat system has been operational since January 2020. Though it has a processing capacity of nearly 10 kt of SF of digestate per year, the installation has so far only been used for a limited number of hours per day. This was because (i) the process needed further testing and optimisation and (ii) there is no market yet for the end products, hence it was yet cheaper to dispose of the SF of digestate without further processing by the RePeat system.

Table 2-8 Production of digestate and end products at Groot Zevert Vergisting for the period 2017–2020 expressed in kilotonnes per year.

		2017	**2018**	**2019**	**2020**[a]
Total digestate produced		101[c]	103	101	81
Products	**Estimated average trucking distance (km)**				
Digestate (unseparated)	<30 (regional)	5	5	0	0
Digestate (unseparated), solid fraction of second decanter centrifuge and microfiltration concentrate	150 (The Netherlands)	20[b]	11	20	13
Digestate (unseparated), solid fraction of second decanter centrifuge and microfiltration concentrate (hygienised)	300 (Germany)	65[b]	65	56	30
Solid fraction of digestate (hygienised)	300 (Germany)	1[b]	5	11	10
Liquid fraction of digestate	150 (The Netherlands)	10[b]	15	0	5
RO concentrate (in region, on top of limit for N from manure)	<30 (regional)			9	15
Precipitated P salts					<1
Low-P soil improver					<1
Purified water (discharged to surface water)	-			4	8

[a] Production of precipitated P salts and low-P soil improver was still low; only produced upon request of farmers in the region.

[b] Includes small unknown amounts of hygienised undigested manure.

[c] Total digestate produced for the year 2017 includes an unknown amount, roughly 10 kt, of hygienised undigested manure. This number is therefore nearly equal to the 102 kt of total anaerobic digester feedstock for the year 2017.

2.4 Mass balances before NRR implementation

2.4.1 Monitoring and sampling

In 2018, GZV had not yet commissioned the GENIUS and RePeat systems and disposed of its (unseparated) digestate in Germany or The Netherlands, most of it unseparated. Part of the digestate was separated into SF and LF of digestate. This section shows the yearly average concentration of TN, TP and TK in the digestate and the SF and LF of digestate for the year 2018. This is used as the reference situation.

One day per month in 2018, on the 15th, 16th or 17th of each month, a digestate sample was taken by GZV from every truck that left the plant that day transporting unseparated digestate or SF or LF of digestate. In total this resulted in 9 to 20 trucks per day being sampled of which the majority transported unseparated digestate. Only a few of these sampled trucks transported SF or LF of digestate. The TN, TP and TK contents of the samples were analyzed. According to GZV, all used samples from the SF and LF of digestate came from digestate that was separated by a decanter centrifuge without addition of polymer flocculants or other chemicals. The data is limited to the nutrients N, P and K since GZV was not obliged to analyse other parameters before the Systemic project started which would otherwise have resulted in higher analysis costs.

2.4.2 Chemical characterisation of digestate and end products

Table 2-9 shows the average concentration of TN, TP and TK in the unseparated digestate and the SF and LF of digestate from the decanter centrifuge in 2018 (prior to implementation of the GENIUS system). In terms of TN and TP, the SF of digestate is a more concentrated product than the unseparated digestate. The LF of digestate is compared to the unseparated digestate a diluted product in terms of TP but not for TN. Processing by the decanter centrifuge does not result in clear concentration differences compared to the ingoing unseparated digestate.

Table 2-9 Average concentrations (in fresh weight) of total nitrogen (TN), total phosphorus (TP) and total potassium (TK) in the unseparated digestate and the solid and liquid fractions of digestate at the demonstration plant Groot Zevert Vergisting for the year 2018, prior to the implementation of NRR systems; values ±1 standard deviation.[a]

Parameter	Unit	Digestate (unseparated)	Liquid fraction of digestate	Solid fraction of digestate
TN	g kg^{-1}	6.99 ± 0.62	6.26 ± 0.70	10.28 ± 1.73
TP	g kg^{-1}	1.76 ± 0.20	0.77 ± 0.14	6.85 ± 1.11
TK	g kg^{-1}	4.59 ± 0.47	4.18 ± 1.68	4.76 ± 0.43

[a] *For digestate (unseparated) n=126; for liquid fraction of digestate n=22; for solid fraction of digestate n=6.*

2.4.3 Separation and nutrient recovery efficiencies of process units

From the average concentrations shown in Table 2-9 the separation efficiencies of the decanter centrifuge for the parameters total mass, TN, TP and TK were calculated. These calculated separation efficiencies are shown in Table 2-10. On average 83% of the ingoing total mass of digestate ended up in the LF of digestate and 17% in the SF of digestate. The SF of digestate contains respectively 26% and 64% of the ingoing mass of TN and TP. This is, especially for TP, a relatively large amount as the total mass of this stream is only 17% of the ingoing digestate mass. From the amount of TN in the unseparated digestate 74% ended up in the LF of digestate. This indicates that the majority of TN in the unseparated digestate was either present in dissolved form or present in small particles.

Table 2-10 Calculated separation efficiencies of the decanter centrifuge at the demonstration plant Groot Zevert Vergisting for total mass, total nitrogen (TN), total phosphorus (TP) and total potassium (TK) for the year 2018, prior to implementation of NRR systems.

	Total mass **%**	**TN** **%**	**TP** **%**	**TK** **%**
Liquid fraction of digestate	83	74	36	81
Solid fraction of digestate	17	26	64	19

2.5 Mass flows and balances after NRR implementation (GENIUS)

2.5.1 Monitoring and sampling

Monitoring of the GENIUS system started in April 2019, this section shows the monitoring outcomes specifically for the period September 2020 – February 2021. The following aspects were included in the standard monitoring programme of the GENIUS system:

- Sampling of the ingoing digestate, internal flows and end-products is done every one or two months if the installation is running without problems. Samples are sent to a commercial lab and at least analysed for:
    - DM and OM content
    - TN, $N\text{-}NH_4$, TP, TK and S content
    - Ca, Mg, Fe, Zn and Cu content
    - pH, EC
- Measurement of the in- and outgoing and internal flows. Flowmeters are placed upstream and downstream of each of the individual process steps that are shown in Figure 2-3. In case an individual process step consists of separate cascaded process units, a flowmeter is also placed in between those units. This is, amongst others, the case for the RO installation which consists of two sequential RO units.
- For process streams where flowmeters cannot be placed, for example because the stream is not a pumpable liquid, the flow was calculated from the known flows and concentrations upstream and downstream of it. Flow rates are automatically measured and recorded, and daily averaged values were sent to WENR for data processing. Mass balances for the system as a whole and its individual process steps were calculated with the measured flows and concentrations in MS Excel.
- Total consumption of chemicals, amongst others of magnesium chloride solution, sulphuric acid, polymer flocculant solution and anti-scalant were determined on a half year basis based on procurement.
- Chemical consumption rate was tracked automatically by monitoring of the pumping speed in combination with the used concentration and, if applicable the dilution ratio before injection into the process.
- Electricity consumption of the AD plant, including the NRR systems, was monitored on a yearly basis. The electricity consumption over 24 hours was measured for clusters of process units in 2021.

Next to the standard monitoring programme the following parameters are monitored less frequently and not for all process flows:

- Heavy metals: Pb, Cd, Cr, Ni, As, Co,
- Density, sodium and total organic carbon (TOC)
- End-products are analysed on residues of herbicides, pesticides and pharmaceuticals (two times)

Since April 2019 there have been several large adjustments of the GENIUS system which are not dealt with here. The configuration of the GENIUS system as in October 2021 is described in this section.

2.5.2 Chemical characterisation of digestate and end products

Table 2-11 shows the average composition of the ingoing digestate and the end products of the GENIUS system for the period September 2020 – February 2021. The SF of the first decanter centrifuge has a higher DM and TP content compared to the unseparated digestate. The SF of the second decanter centrifuge has a lower DM content, 196 g/kg, compared to the SF of the first decanter centrifuge (313 g/kg). Also the TP content of the SF of the second decanter centrifuge is roughly half the TP content of the SF of the first decanter centrifuge.

Interestingly the TN content of the SFs of the first and second decanter centrifuge is higher than that of the ingoing digestate. The NH_4-N concentrations are however quite similar in these streams, the higher TN content of the SF of both decanter centrifuges is therefore the result of higher organic N concentrations. Concentrations of TK are similar in all streams except for the RO concentrate, which has a roughly two times higher TK concentration, and in the purified water, in which TK is present in concentrations below the LOQ. Concentrations of heavy metals are highest in the SF of the first and second decanter centrifuge.

Table 2-11 Average composition (in fresh weight) of the ingoing digestate and end products of the GENIUS system at the demonstration plant Groot Zevert Vergisting for the period September 2020 – February 2021; values ±1 standard deviation.[a,b]

Parameter	Unit	Digestate (unseparated)	SF of first centrifuge[c]	SF of second centrifuge[d]	MF concentrate	RO concentrate	Purified water[e]
Density							
pH		8.2 ± 0.13	8.8 ± 0.15	8.5 ± 0.27	8.4 ± 0.13	8.4 ± 0.17	5.3 ± 1.1
EC	mS cm^{-1}	47 ± 3.5	n.a.	n.a.	43 ± 3.3	89 ± 6.3	0.045 ± 0.090
DM	g kg^{-1}	81 ± 3.8	313 ± 2.8	196 ± 10	49 ± 2.8	37 ± 4.8	n.a.
OM	g kg^{-1}	59 ± 3.3	242 ± 4.6	146 ± 10	35 ± 1.9	14 ± 4.3	n.a.
TN	g kg^{-1}	7.3 ± 0.66	12 ± 0.35	15 ± 0.40	7.1 ± 0.48	8.1 ± 0.80	0.00028 ± 0.000078
NH_4-N	g kg^{-1}	5.0 ± 0.33	6.6 ± 0.33	5.1 ± 0.28	4.2 ± 0.29	8.0 ± 0.77	0.00020 ± 0.000095
TP	g kg^{-1}	1.7 ± 0.10	8.9 ± 0.80	4.6 ± 0.58	0.42 ± 0.052	0.15 ± 0.13	<0.00010
TK	g kg^{-1}	4.5 ± 0.20	4.6 ± 0.34	4.5 ± 0.27	4.1 ± 0.21	7.9 ± 0.38	<0.00040
TS	g kg^{-1}	0.67 ± 0.039	1.9 ± 0.11	2.5 ± 0.30	0.63 ± 0.28	1.5 ± 0.51	0.0029 ± 0.0033
Ca	g kg^{-1}	1.7 ± 0.064	7.7 ± 0.61	8.5 ± 0.87	0.38 ± 0.059	0.059 ± 0.013	<0.0012
Mg	g kg^{-1}	1.0 ± 0.054	6.4 ± 0.49	2.0 ± 0.68	0.11 ± 0.039	0.040 ± 0.036	<0.00015
Na	g kg^{-1}	1.6 ± 0.21	1.5 ± 0.15	1.6 ± 0.13	1.6 ± 0.22	3.1 ± 0.44	<0.00030
Al	mg kg^{-1}	53 ± 9.2	280 ± 85	365 ± 35	10 ± 1.4	0.70 ± 0.30	<0.03
Co	mg kg^{-1}	0.12 ± 0.0078	<0.32	0.35 ± 0.054	0.15 ±0.0085	<0.035	0.0000090 ± 0.0000057
Cr	mg kg^{-1}	1.2 ± 0.87	3.2 ± 0.15	2.9 ± 0.16	<0.25	<0.18	0.000065 ± 0.000030
Cu	mg kg^{-1}	15 ± 0.93	28 ± 4.9	136 ± 25	5.0 ± 1.2	<1	<0.01
Fe	mg kg^{-1}	184 ± 26	690 ± 83	2100 ± 2300	105 ± 115	<10	<0.01
Mn	mg kg^{-1}	38 ± 2.1	170 ± 0.0	180 ± 14	8.5 ± 2.1	<1	<0.01
Ni	mg kg^{-1}	1.2 ± 0.56	3.4 ± 1.6	4.0 ± 1.7	1.2 ± 0.29	0.50 ± 0.26	0.00038 ± 0.00039
Zn	mg kg^{-1}	54 ± 1.2	118 ± 9.2	434 ± 53	17 ± 3.5	<5	0.025 ± 0.016

[a] For the heavy metals n=2, for all other parameters n=5.

[b] n.a. = not analysed

[c] Solid fraction of digestate produced by the first decanter centrifuge

[d] Solid fraction of digestate produced by the second decanter centrifuge

[e] For zinc (Zn) some of the values were above and some were below the LOQ (limit of detection) of 0.02 mg/l. Values below LOQ were treated as having the value LOQ/(√2) for calculation of the average and standard deviation.

2.5.3 Mass flow analyses of macronutrients, micronutrients and heavy metals

Figure 2-4 shows the calculated total mass flows of the GENIUS system based on the monitoring and Figure 2-5 shows the calculated TN, TP and TK flows of the GENIUS system based on the monitoring for the period September 2020 – February 2021. Ingoing and outgoing streams for the whole GENIUS system as well as for individual process units are not always equal. This is a.o. thought to be caused by the error margin of the flow meters and the small temporal deviations in composition of the steams. In the period September 2020 – February 2021 part of the MF concentrate was fed back to the post-digester. This is at the time of writing not the case anymore, all MF concentrate is nowadays blended with the SF of digestate produced by the second decanter centrifuge.

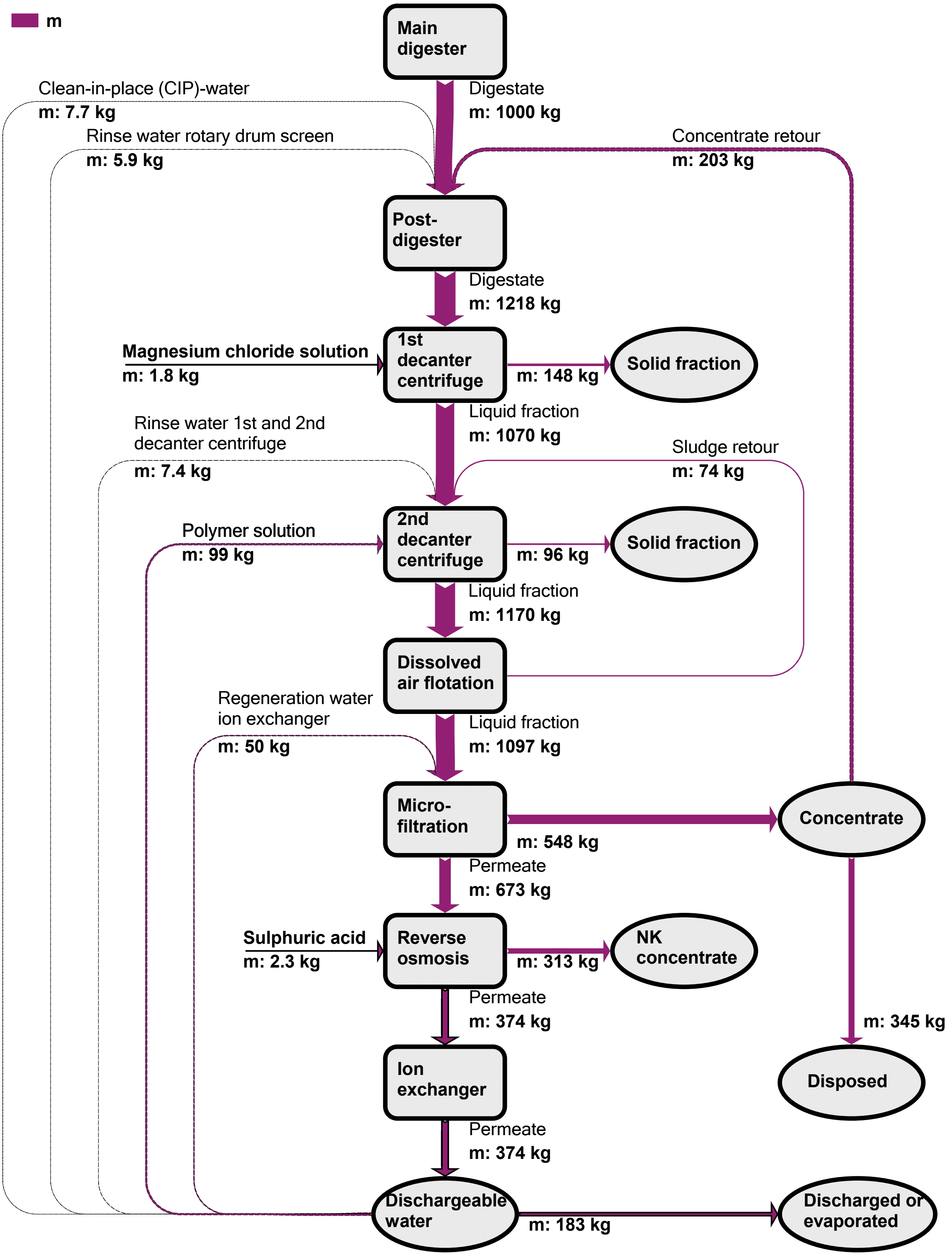

Figure 2-4 Total mass (m) flows of the GENIUS system at the demonstration plant Groot Zevert Vergisting in kg per 1000 kg of ingoing digestate for the period September 2020 – February 2021.

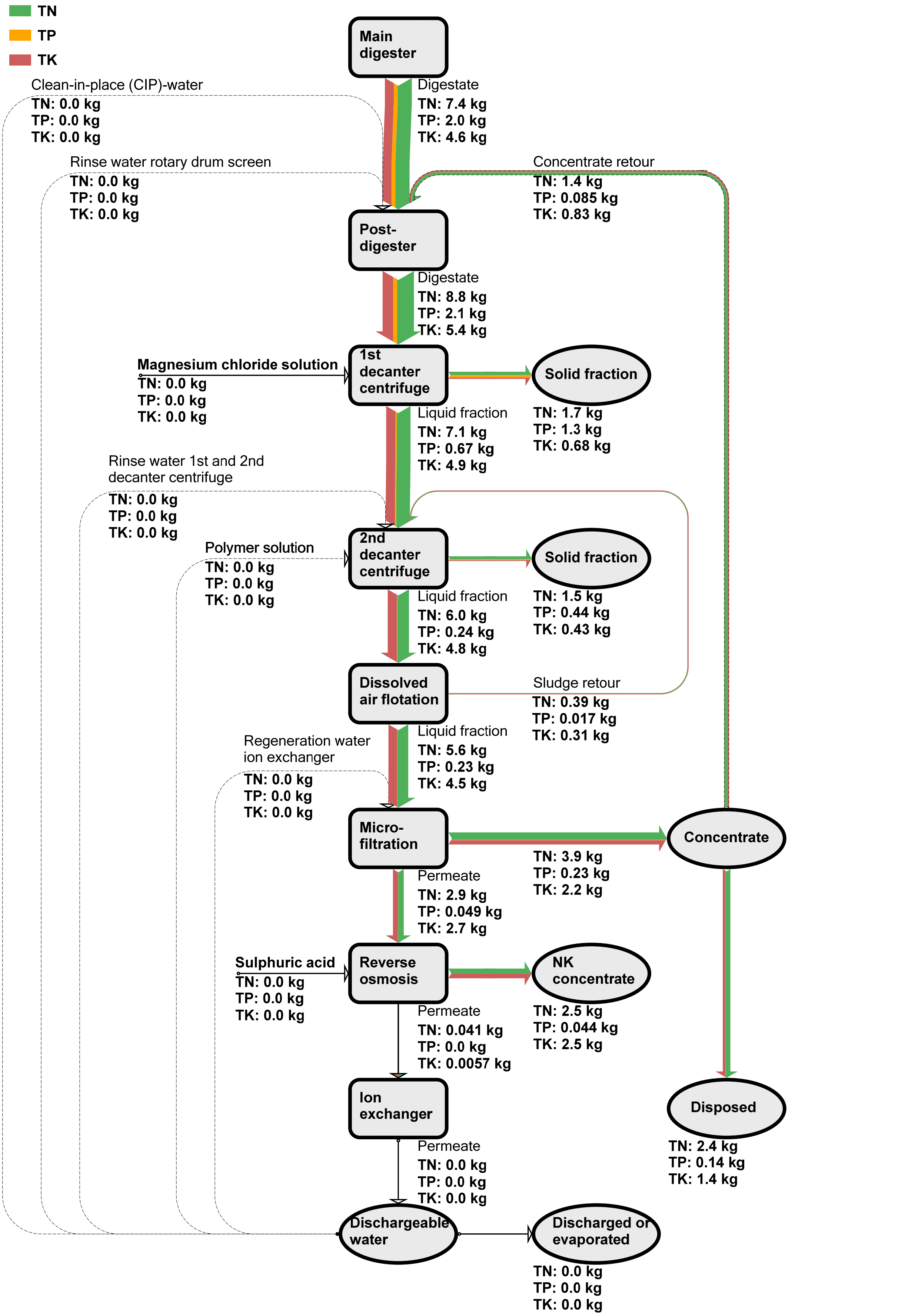

Figure 2-5 Total nitrogen (TN), total phosphorus (TP) and total potassium (TK) flows of the GENIUS system at the demonstration plant Groot Zevert Vergisting in kg per 1000 kg of ingoing digestate for the period September 2020 – February 2021.

2.5.4 Separation and nutrient recovery efficiencies of process units

Table 2-12 shows the calculated separation efficiencies of the individual GENIUS process units as a percentage of the ingoing mass of each component. The separation efficiencies for many of the components do not exactly add up to 100%. This is a.o. thought to be caused by the heterogeneous nature of the streams whilst the taken samples only result in concentration data for a specific moment. For the first decanter centrifuge the majority of the heavy metals go, on a mass basis, to the SF of digestate. Interestingly, for the second decanter centrifuge this depends on the specific metal observed.

Small volatile S compounds are passing the membranes of the RO units of GZV resulting in S concentrations of 1.5 g/kg in the RO permeate. This concentration is lowered to a very large extent by the following degassing tower. To be able to pass the RO membranes, these S compounds need to be small and uncharged. Therefore it is expected that they consist of either H_2S and/or small organic S compounds like mercaptanes. Further research should however shed more light on this. As GZV does not add any iron salts (nor to the digester nor to the GENIUS process), any formed H_2S in the digesters is not captured by iron and might very well be still present in the influent of the RO units.

Table 2-12 Separation efficiencies of the GENIUS process units at the demonstration plant Groot Zevert Vergisting for the period September 2020 – February 2021 for the following parameters: total mass, moisture (H_2O), dry matter (DM), organic matter (OM), nutrients and heavy metals.[a]

	Total mass	**H_2O**	**DM**	**OM**	**TN**	**NH_4-N**	**TP**	**TK**	**TS**	**Ca**	**Mg**
	%	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
First decanter centrifuge											
LF of digestate	88	91	53	48	81	83	32	91	66	48	24
SF of digestate	12	9.1	47	50	20	16	63	13	34	53	84
Second decanter centrifuge											
LF of digestate	92	94	66	59	79	92	34	92	60	19	26
SF of digestate	7.6	6.4	34	39	19	9.2	63	8.2	36	78	72
Microfiltration unit											
Permeate	55	56	31	20	47	53	18	55	41	8.7	12
Concentrate	45	44	72	86	63	46	86	45	64	92	78
Reverse osmosis unit											
Permeate	55	n.a.	n.a.	n.a.							
Concentrate	47	n.a.	n.a.	n.a.							
Ion exchanger											
Effluent		n.a.	n.a.	n.a.							
Removed		n.a.	n.a.	n.a.	99.7	99.8		>97.4	99.8		

	Na	**Cu**	**Zn**	**Al**	**Fe**	**Cd**	**Co**	**Pb**	**Cr**	**Ni**	**Mn**
	%	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
First decanter centrifuge											
LF of digestate	93	81	78		58						
SF of digestate	6.9	22	27		46						
Second decanter centrifuge											
LF of digestate	92	83	15		18						
SF of digestate	8.3	14	80		72						
Microfiltration unit											
Permeate	54				0						
Concentrate	45	103	100		112						
Reverse osmosis unit											
Permeate	55										
Concentrate	47										
Ion exchanger											
Effluent	100	100	n.a.	n.a.							
Removed	0	0	n.a.	n.a.							

[a] *n.a. = not analysed*

2.6 Mass flows and balances after NRR implementation (RePeat)

2.6.1 Monitoring and sampling

The following aspects are included in the standard monitoring programme of the RePeat system:

- Sampling of the ingoing, internal and outgoing flows (Figure 2-3) occurs on a monthly basis unless the system is not running. Sampling locations have been chosen as such that a mass balance can be made for each process step. Samples are sent to a commercial lab and at least analysed for:
    - Dry matter (DM) and organic matter (OM) content
    - TN, NH_4-N, TP, TK and S content
    - Ca, Mg, Fe, Zn and Cu content
    - pH, electrical conductivity (EC)
- Measurement of the in- and outgoing and internal flows. In total, eight flowmeters are placed upstream and downstream of the individual process steps. Weight of the end-products, the precipitated P salts and low-P soil improver, are recorded per truck that leaves the plant.
- Electricity consumption of the RePeat system is automatically measured in the following three power groups:

  Group 1: conveyer belt for SF of digestate, pumps and mixer for addition of process water and the mixer of the first acidification tank

  Group 2: screw presses, pumps before screw presses, mixer in between screw presses, dosing pumps for sulphuric acid and the pump for the sludge of the lamella clarifier

  Group 3: pumps for the phosphate reactor and settling tank, mixers of the phosphate reactor and base storage tank, base dosing pump and the aeration of the phosphate reactor
- Chemical consumption rate, for sulphuric acid and base, is tracked automatically

Next to the standard monitoring programme, the following parameters are monitored less frequently and not for all process flows:

- Heavy metals (Pb, Cd, Cr, Ni, As, Hg)
- Density
- End-products are analysed on residues of organic micro pollutants (herbicides, pesticides and pharmaceuticals) (two times in 2020/2021)

2.6.2 Chemical characterisation of digestate and end products

Table 2-13 shows the average composition of the ingoing digestate and the end products of the RePeat system for the period April 2020 – July 2021. The ingoing SF of digestate had an average TP content of 9.0 g/kg and an alkaline pH. The produced low-P soil improver had a 4.5 times lower TP content (1.9 g TP/kg) than the ingoing SF of digestate. Also it had a lower pH value of 6.2 and a 2.9 times higher S content of 5.8 g/kg due to the use of sulphuric acid to leach P. The TK, TN and NH_4-N content of the low-P soil improver were low compared to the SF of digestate since soluble K, N and NH_4-N components were co-extracted during the leaching steps. The precipitated P salts were produced in the form of a slurry with a low DM content of 159 g/kg. Further dewatering or drying of this sludge is needed in order to enable long-distance transport. Roughly 48% of the DM of the precipitated P salts is made up of OM implying that the precipitated P salts are an organic fertiliser instead of a mineral fertiliser. At the time of writing, the precipitated P salts are disposed of as P-rich animal manure to farmers in the Netherlands or Germany. The S content of the precipitated P salts (11.6 g/kg) is 5.8 times higher than the S content of the ingoing

SF of digestate (2.0 g/kg) due to the addition of sulphuric acid, to extract P, which leads to the formation of calcium sulphates.

Table 2-13 Average composition (in fresh weight) of the ingoing solid fraction of digestate and end products of the RePeat system at the demonstration plant Groot Zevert Vergisting for the period April 2020 – July 2021; values ±1 standard deviation.[a,b]

Parameter	**Unit**	**Solid fraction of digestate**	**Low-P soil improver**	**Precipitated P salts**[c]	**Sludge of lamella clarifier**
pH	-	8.8 ± 0.3	6.2 ± 0.6	7.2 ± 0.2	5.7 ± 0.5
EC	mS cm^{-1}	n.a.	n.a.	2.1 ± 2.3	2.1 ± 2.5
DM	g kg^{-1}	319.8 ± 10.2	284.1 ± 68.5	158.8 ± 61.8	109.8 ± 31.5
OM	g kg^{-1}	246.2 ± 9	252.2 ± 65.4	73.3 ± 23.4	71.3 ± 26.6
TN	g kg^{-1}	12.2 ± 0.4	5.9 ± 0.9	6.9 ± 2.3	4.6 ± 0.5
NH_4-N	g kg^{-1}	6.3 ± 0.3	1.9 ± 0.7	4.6 ± 1.8	2.8 ± 0.7
TP	g kg^{-1}	9.0 ± 1.0	1.9 ± 1.0	8.8 ± 4.5	3.3 ± 0.3
TK	g kg^{-1}	4.6 ± 0.4	1.8 ± 0.8	2.3 ± 0.7	2.4 ± 0.8
Ca	g kg^{-1}	8.4 ± 0.9	4.5 ± 1.6	14.2 ± 6.9	4.4 ± 1.3
Mg	g kg^{-1}	6.2 ± 0.7	1.4 ± 0.6	4.9 ± 1.8	2.3 ± 0.3
S	g kg^{-1}	2 ± 0.2	5.8 ± 1.5	11.6 ± 5.2	8 ± 2.3
Cu	mg kg^{-1}	40	21	30	20
Zn	mg kg^{-1}	145	79	101	72
Cd	mg kg^{-1}	<0.1	<0.1	<0.05	<0.05
Ni	mg kg^{-1}	2.1	1.7	3.8	1.2
Pb	mg kg^{-1}	0.6	0.2	0.3	0.29
Cr	mg kg^{-1}	2.7	1.7	5.3	1.8
Hg	mg kg^{-1}	<0.01	<0.01	<0.005	<0.005
As	mg kg^{-1}	<0.3	<0.3	<0.1	<0.1

[a] *For Cd, Ni, Pb, Cr, Hg and As n=2, for all other parameters n=8.*

[b] *n.a. = not analysed.*

[c] *Precipitated P salts were sampled in the outlet of the settling tank.*

2.6.3 Mass flow analyses of macronutrients, micronutrients and heavy metals

Figure 2-6 shows the calculated total mass flows of the RePeat system based on the monitoring and Figure 2-7 shows the calculated TN, TP and TK flows of the RePeat system based on the monitoring for the period September 2020 – February 2021. Figure shows 2-8 the calculated Ca, Mg and S flows of the RePeat system based on the monitoring for the period September 2020 – February 2021. For all three figures the ingoing and outgoing flows of the individual process units and the RePeat system as a whole have been calculated, via iteration, to exactly match. In the calculations it has been assumed that all sulphuric acid has been added on the first screw press instead of being split between the first and second screw press. This has been done because it was not possible to measure the added amount of sulphuric acid at the second screw press and calculation of the added amount of sulphuric acid there was not possible due to multiple streams with unknown S mass coming together there.

The total mass of reverse osmosis permeate added per 1000 kg of ingoing solid fraction of digestate is large, 1230 kg. This results in a large total mass of the sludge of the lamella clarifier (512 kg) and precipitated P salts (793 kg). The sludge of the lamella clarifier is ultimately mixed with the MF concentrate and the SF of the second decanter centrifuge of the GENIUS system. The mixture is applied as manure fertiliser in the North of the Netherlands. The added reverse osmosis permeate is needed to provide more solution in which the solubilized P from the ingoing solid fraction can dissolve. The added chemicals, sulphuric acid and calcium hydroxide solution, do not contribute much to the total mass of the end products, only 44 kg in total. The total mass of produced low-P soil improver is practically equal to the total mass of ingoing solid fraction of digestate.

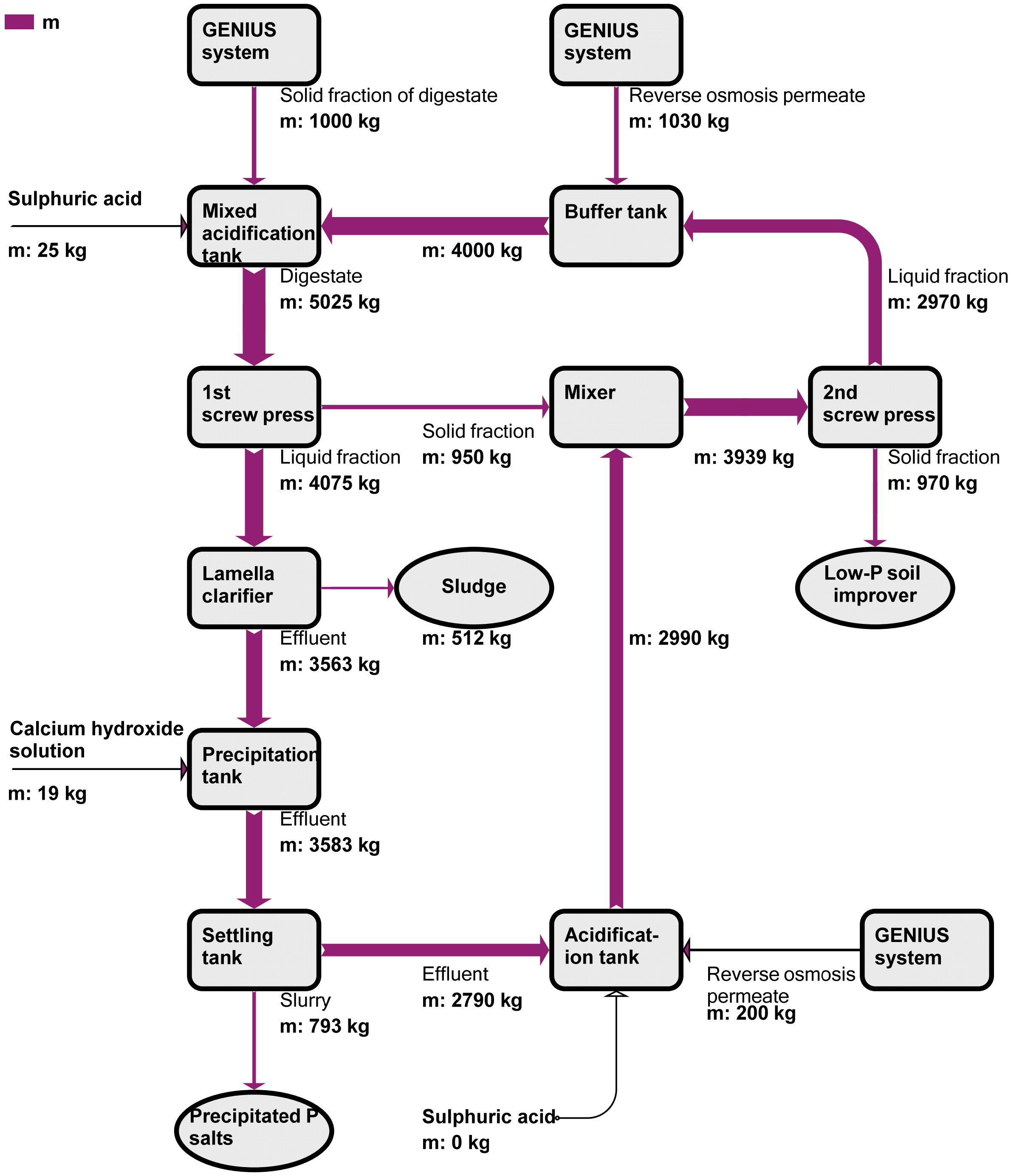

Figure 2-6 Total mass (m) flows of the RePeat system at the demonstration plant Groot Zevert Vergisting in kg per 1000 kg of ingoing digestate for the period September 2020 – July 2021.

From the 8.8 kg TP in the ingoing solid fraction of digestate 6.2 kg ends up in the precipitated P salts and only 1.2 and 1.4 kg end up in respectively the sludge of the lamella clarifier and the low-P soil improver. The removal of TP from the ingoing SF of digestate is thus successful as only 16% of it end up in the produced low-P soil improver. Of the ingoing TK, 27% and 43%, end up respectively in the sludge of the lamella clarifier and the low-P soil improver. For TK and TN there is no clear separation, as was already shown in Table 2-13. The TK and TN concentrations in the end products do not differ that much from each other.

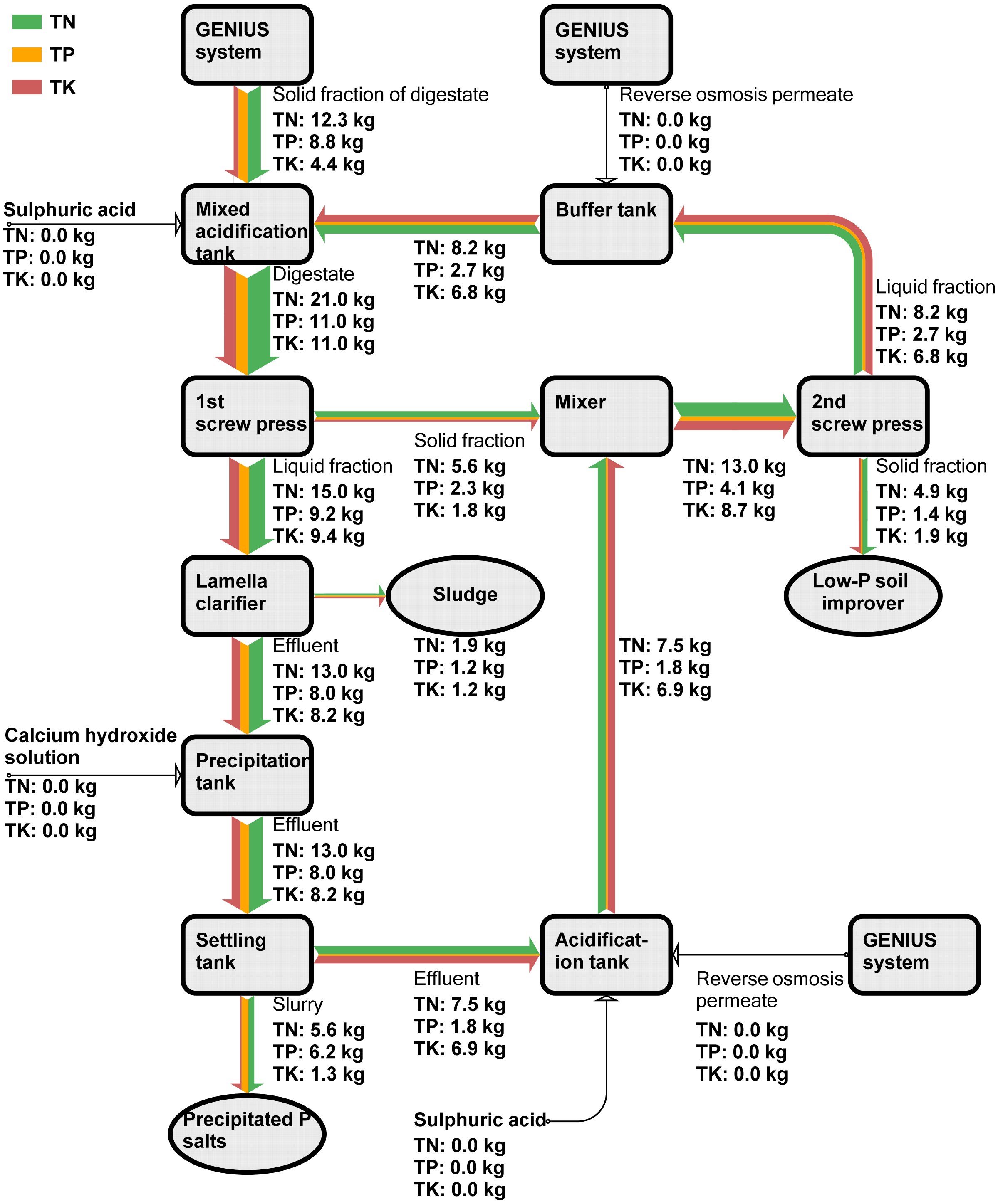

Figure 2-6 Total nitrogen (TN), total phosphorus (TP) and total potassium (TK) flows of the RePeat system at the demonstration plant Groot Zevert Vergisting in kg per 1000 kg of ingoing solid fraction of digestate for the period September 2020 – July 2021.

For every ingoing 2.0 kg of S, 14.7 kg of S are added via sulphuric acid addition. The total amount of S in the end products in thereby increased by a factor 8 compared to the S in the ingoing SF of digestate. As could be seen based on the concentrations in Table 2-13, relatively much of the S ends up in the precipitated P salts and to a lesser extent in the sludge of the lamella clarifier. From the ingoing S, from SF of digestate and sulphuric acid, 41% ends up in the precipitated P salts and 24% in the sludge of the lamella clarifier. It is expected that part of this is as gypsum ($CaSO_4 \cdot 2H_2O$).

For Mg relatively much, 55%, ends up in the precipitated P salts, as also seen from the concentrations in Table 2-13. This is expected to be struvite precipitation. It seems that not all magnesium salts dissolve as still roughly 20% of the Mg that enters the first screw press goes to the SF. For the second screw press this percentage is even 30%. However, compared the ingoing SF of digestate, only 27 % of Mg ends up in the low-P soil improver.

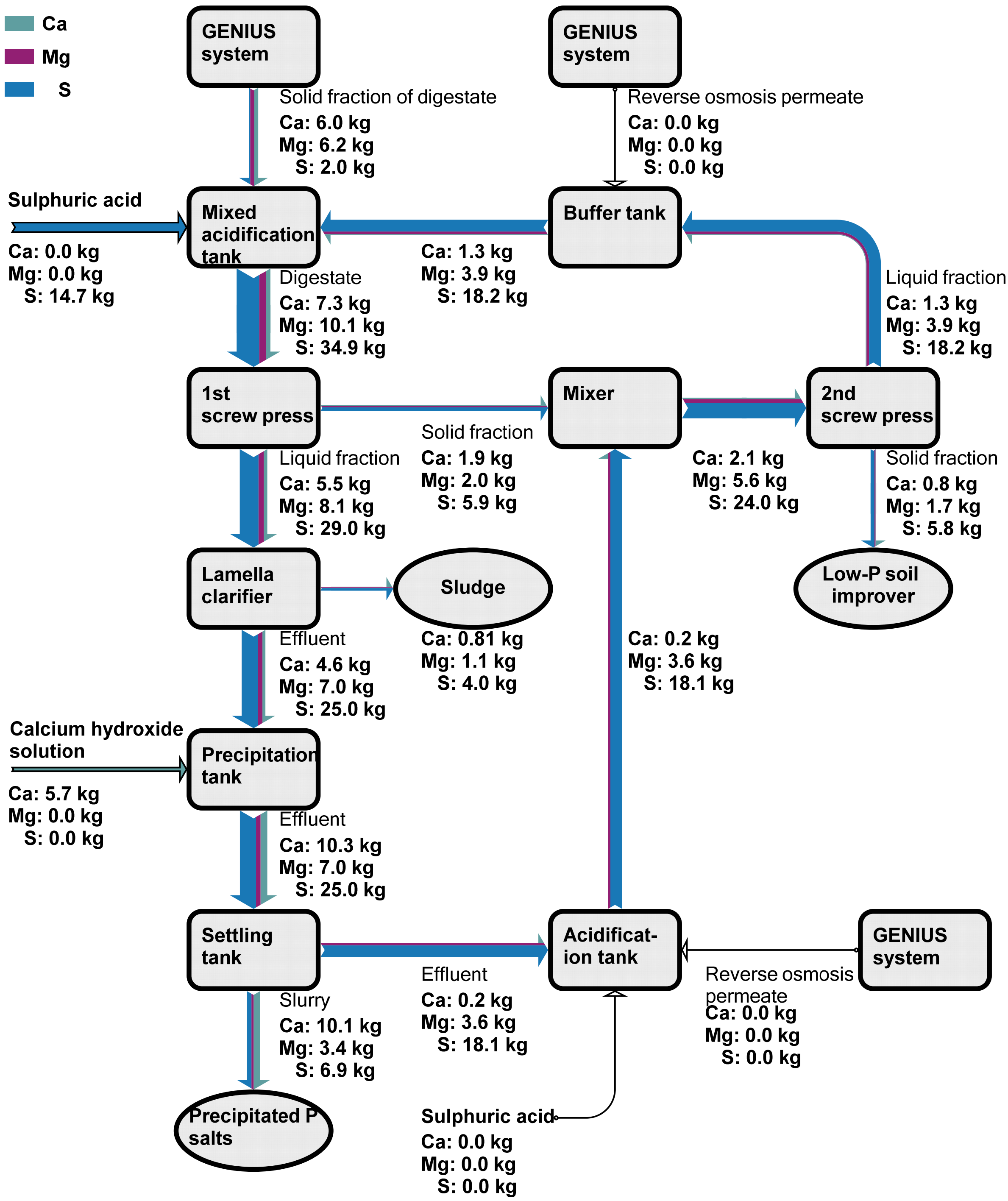

Figure 2-7 Calcium (Ca), magnesium (Mg) and sulphur (S) flows of the RePeat system at the demonstration plant Groot Zevert Vergisting in kg per 1000 kg of ingoing solid fraction of digestate for the period September 2020 – July 2021.

2.6.4 Separation and nutrient recovery efficiencies of process units

Table 2-14 shows the calculated separation efficiencies of the individual RePeat process units as a percentage of the ingoing mass of each component. The separation efficiencies exactly add up to 100%.
Separation efficiencies could not be calculated for all process units as for some process units the samples taken were most likely not representative for one or more of the ingoing or outgoing streams. This then resulted in separation efficiencies of over 100% which are not shown here. For the process units for which reliable separation efficiencies could be calculated, the calculated efficiencies differed a lot depending on which component was used to calculate it (high uncertainty).

Table 2-14 Separation efficiencies of the RePeat process units at the demonstration plant Groot Zevert Vergisting for the period September 2020 – February 2021 for the following parameters: total mass, moisture (H_2O), dry matter (DM), organic matter (OM), nutrients and heavy metals.[a,b,c]

	Total mass %	**H_2O %**	**DM %**	**OM %**	**TN %**	**NH_4-N %**	**TP %**	**TK %**	**S %**	**Ca %**	**Mg %**
LF first screw press	81	90	55	47	73	81	80	84	83	75	80
SF first screw press	19	10	45	53	27	19	20	16	17	25	20
LF second screw press	74	93	40	32	61	76	65	77	74	62	69
SF second screw press	26	7	60	68	39	24	35	23	26	38	31
LF lamella clarifier	87	91	88	88	88	87	87	87	86	85	87
SF lamella clarifier	13	9	12	12	12	13	13	13	14	15	13
LF settling tank	81	91	59	68	62	71	31	87	76	0	57
SF settling tank	19	9	41	32	38	29	69	13	24	100	43
	Na %	**Cu %**	**Zn %**	**Al %**	**Fe %**	**Cd %**	**Co %**	**Pb %**	**Cr %**	**Ni %**	**Mn %**
LF first screw press		74	61		68						
SF first screw press		26	39		32						
LF second screw press		71	49		49						
SF second screw press		29	51		51						
LF lamella clarifier		87	86		85						
SF lamella clarifier		13	14		15						
LF settling tank		32	14		21						
SF settling tank		68	86		79						

[a] *For Cd, Ni, Pb, Cr, Hg and As n=2, for all other parameters n=5.*

[b] *n.a. = not analysed.*

[c] *Third screw press was not in use in the period September 2020 – February 2021.*

2.7 Energy balance

2.7.1 Energy production

For details on the biogas and electricity production by GZV see Table 2-3 and Table 2-4 in section 2.1. In 2020 approximately 72% of the produced biogas was transported through a 5-km pipeline to a nearby dairy processing factory. The majority of the remaining biogas was fed to the plant's own combined heat and power (CHP) installation. This produced 80-°C water, all of which was used by the plant itself, and electric power: 4.6 GWh in 2018, 5.5 GWh in 2019 and 5.6 GWh in 2020. Based on the lower heating value of the biogas, the CHP installation had a conversion efficiency to electric power of approximately 38%. In 2020, approximately 0.052 MNm^3 of the biogas was fed to the plant's biogas boiler to produce heat in times that the useable heat produced by the CHP installation was lower than the heat demand of the plant. From the produced electric power 68% was used to operate the AD plant and its NRR systems and 32% was sold to the grid.

2.7.2 Energy consumption

Table 2-15 shows the estimated electricity and residual heat consumption by the installations of the AD plant and the NRR systems of GZV. Reported values are a combination of by GZV estimated and measured values. These estimated values are based on power ratings of o.a. pumps and on differences in total electricity consumption before and after implementation of the NRR systems. For the RePeat system the electricity consumption for the year 2020 has been measured.

Interestingly, the amount of heat required for heating of the anaerobic digesters differs quite a bit from year to year. This might be caused by differences in average yearly temperature as the winter of 2019–2020 was a warm winter (average temperature of 6.4 °C compared to the 30-year average of 3.4 °C). Another cause could be differences in heat production by the digester itself due to differences in the feedstock composition. Total electricity consumption of the plant has increased from roughly 2.0 GWh per year before implementation of the NRR systems to roughly 3.8 GWh per year after implementation of the GENIUS and RePeat systems. Only part of the individual process units of the RePeat system were continuously operational in 2020. The electricity consumption will be higher when, as designed, all individual process units of the RePeat system are continuously operational. Total heat consumption of the plant has remained quite similar over the period 2018 – 2020 as no additional heat consuming installations have been added to the plant.

Table 2-15 Estimated electricity and residual heat consumption in MWh per year by the installations of the demonstration plant Groot Zevert Vergisting before (2018) and after (2019 and 2020) implementation of nutrient recovery and reuse systems.[a]

	2018		**2019**		**2020**	
	Electricity	**Heat**	**Electricity**	**Heat**	**Electricity**	**Heat**
Anaerobic digesters	700	2,402	700	2,835	700	1,546
Hygienisation of digestate in post-digester	100	1,001	100	1,180	-	1,200
Hygienisation (infrared) of the solid fraction of digestate	-	-	-	-	-	-
Heating buildings	-	600	-	710	-	908
Drying of products	-	-	-	-	-	-
Two decanter centrifuges	300	-	300	-	300	-
Biogas desulphurisation and biogas processing	700	-	700	-	700	-
Construction of GENIUS system	172	-	-	-	-	-
Operation of GENIUS system[b]	Not yet commissioned		2,172	-	1,379[c]	-
Operation of RePeat system	Not yet commissioned		Not yet commissioned		709[d]	-
Total[e]	*1,972*	*4,003*	*3,972*	*4,725*	*3,783*	*3,654*

[a] Values include both measured and estimated values by Groot Zevert Vergisting.

[b] Excluding the two decanter centrifuges which are part of the GENIUS system and are listed separately.

[c] Value is based on a 24-hour electricity consumption measurement of the GENIUS system multiplied with 365 days (1.679 MWh) minus the estimated electricity consumption of the two decanter centrifuges.

[d] Value calculated as total electricity consumption minus the electricity consumption of the anaerobic digesters, biogas desulphurization and biogas processing, two decanter centrifuges and operation of the rest of the GENIUS system.

[e] Values are based on the electricity metering.

2.7.3 Energy balance

Figure 2-6 shows the energy production and consumption by GZV for the year 2020. The energy content of the biogas from manure (not paunch manure) was calculated assuming a biogas production of 23 m^3 (55 vol.-% CH_4) per tonne manure and the remaining biogas production was attributed to the co-products.

From the total amount of biogas produced, 7,673 MWh, (14%) comes from the manure (excluding paunch manure) and in total 45,469 MWh (86%) comes from the co-substrates and paunch manure. Lost heat in the CHP installation is roughly 38% of the energy content of the biogas fed to the CHP installation.

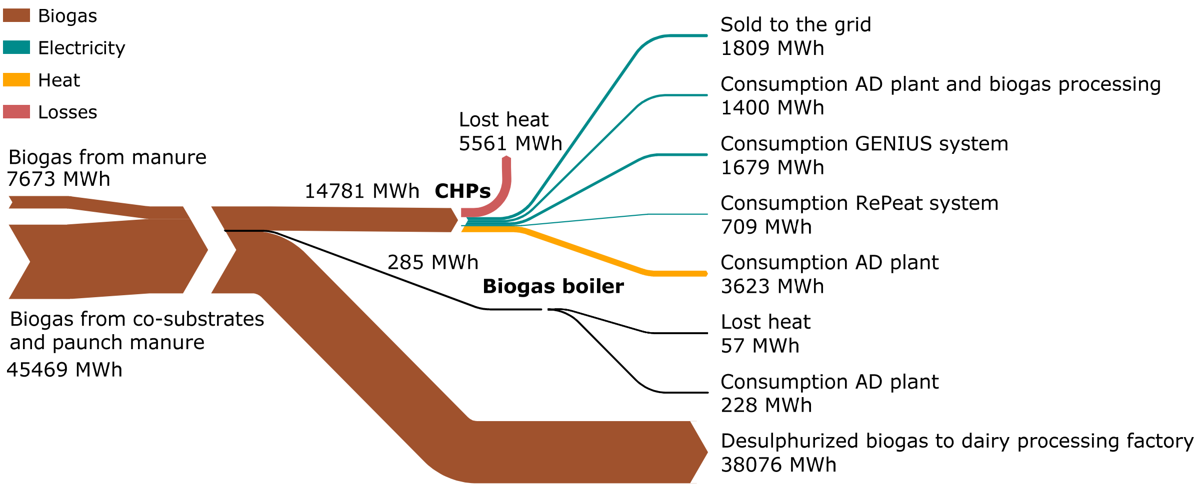

Figure 2-6 Energy production and consumption at Groot Zevert Vergisting for the year 2020. Biogas from manure (not paunch manure) was calculated with 23 m^3 biogas (55 vol.-% CH_4) per tonne and the lower heating value (LHV) of methane of 9.96 kWh/Nm^3. LHV of methane was calculated based on: LHV = 50.1 MJ/kg CH_4 ; molar volume of 22.41 mol CH_4/m^3 at 273.15 K; molar mass of 16.043 g CH_4/mole.

2.8 Temporal variation in product composition

2.8.1 End products of the GENIUS system

Figure 2-7 shows the composition of the SF of digestate, produced by the first decanter centrifuge, over the period April 2019 – July 2021. Concentrations of DM, OM and TS remained similar throughout this period. Concentrations of TP, TN and N-NH_4 have shown some variation but without a clear trend.

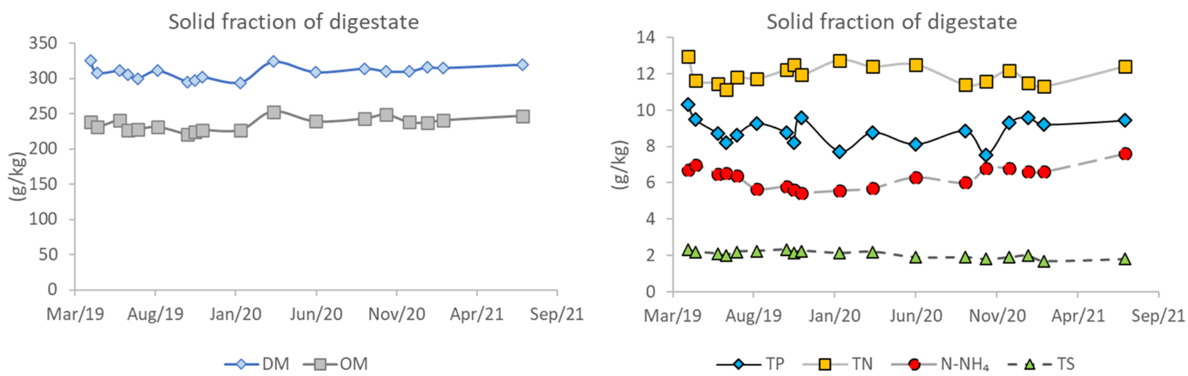

Figure 2-7 Composition (in fresh weight) over time of the solid fraction of digestate produced by the GENIUS system at the demonstration plant Groot Zevert Vergisting for the period April 2019 – July 2021: dry matter (DM); organic matter (OM); total phosphorus (TP); total nitrogen (TN); ammoniacal nitrogen (N-NH_4); total sulphur (TS)

Figure 2-8 shows the composition of the produced RO concentrate over the period April 2019 – July 2021. The DM and OM concentrations vary over time but without a clear trend. Increases and decreases in DM and OM content coincide. The changes in DM content over time are therefore most likely caused by changes in OM content. TS concentrations decrease from 6.6 g/kg in May 2019 to between 1.0 and 2.3 g/kg from October 2019 onward. This is the result of GZV deliberately lowering the sulphuric acid addition on both RO units with the goal of lowering the S content of the RO concentrate. GZV clearly succeeded in this.

Concentrations of TP are rather stable over time. Concentrations of TN and $N\text{-}NH_4$ vary over time but without a clear trend.

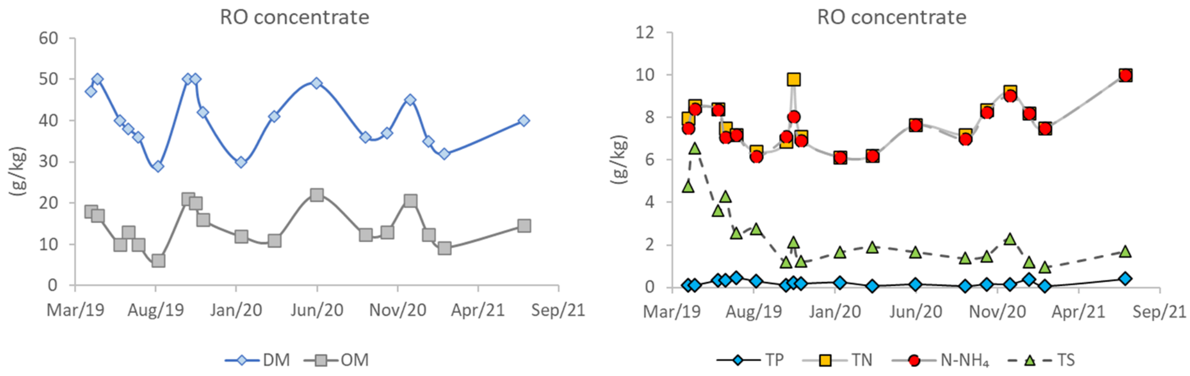

Figure 2-8 Composition (in fresh weight) over time of the reverse osmosis (RO) concentrate produced by the GENIUS system at the demonstration plant Groot Zevert Vergisting for the period April 2019 – July 2021: dry matter (DM); organic matter (OM); total phosphorus (TP); total nitrogen (TN); ammoniacal nitrogen ($N\text{-}NH_4$); total sulphur (TS)

2.8.2 End products of the RePeat system

The RePeat system has been monitored since April 2020. Figure 2-9 shows the composition of the produced Low-P soil improver over the period April 2020 – July 2021. The composition is not yet constant over time for all shown parameters. Both the DM and OM content decreased from respectively 409 g/kg and 365 g/kg in April 2020 to on average 252 g/kg and 222 g/kg from September 2020 onwards. This decrease was unintentional. To reduce the amount of salts and nutrients on DM basis, GZV should strive to achieve a quality similar as was achieved in early 2020. Because of the higher OM content of the soil improver in April 2020, the salts and nutrient concentrations were lower on a DM basis.
Fluctuations in TP and TS concentrations can be explained by settling issues in the precipitation tank and settling tank where precipitated P and S should settle leading to a settling tank effluent with a low S content and which is free of P. This effluent is used to flush the SF of the first screw press. High TP or TS concentrations in the effluent therefore lead to elevated levels of TP and TS in the produced low-P soil improver. Nevertheless, the P content of the soil improver has been at any time substantially lower than the TP content of the ingoing SF of digestate (8.8 g/kg). The cause of the fluctuations in TN and $N\text{-}NH_4$ content of the low-P soil improver is unclear.

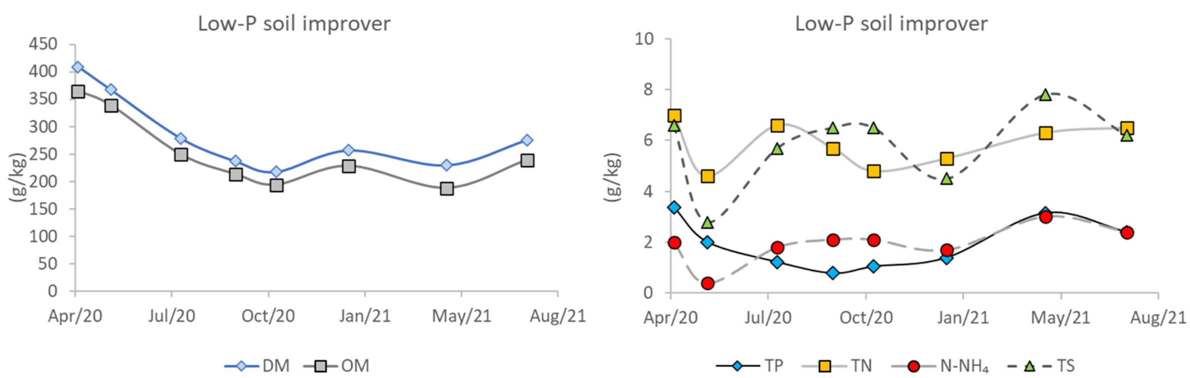

Figure 2-9 Composition (in fresh weight) over time of the low-P soil improver produced by the RePeat system at the demonstration plant Groot Zevert Vergisting for the period April 2020 – July 2021: dry matter (DM); organic matter (OM); total phosphorus (TP); total nitrogen (TN); ammoniacal nitrogen ($N\text{-}NH_4$); total sulphur (TS)

Figure 2-10 shows the composition of the precipitated P salts over the period April 2020 – July 2021. The DM content fluctuates over time whilst the OM content is relatively stable over time. The sample taken in July 2021 was, as visually observed, a more thick sludge than the samples taken until then. This was most likely the result of the installation not being operational the day before the sampling which will have allowed to form a thicker sludge through longer settling. The sample had a higher DM and OM content but it is considered not representative for continuous operation of the RePeat system.

Though GZV aimed to increase the DM content of the precipitated P salts, they did not yet succeed in this. Increasing the DM content of the P salts would either require an additional dewatering step or the addition of $Mg(OH)_2$ in the precipitation tank instead of $Ca(OH)_2$ in order to produce struvite which is known for its tendency to form crystals rather than a sludge. So far, GZV has chosen to add $Ca(OH)_2$ because it is cheaper than $Mg(OH)_2$ and because of fear for damage to the installations due to struvite scaling when adding $Mg(OH)_2$.

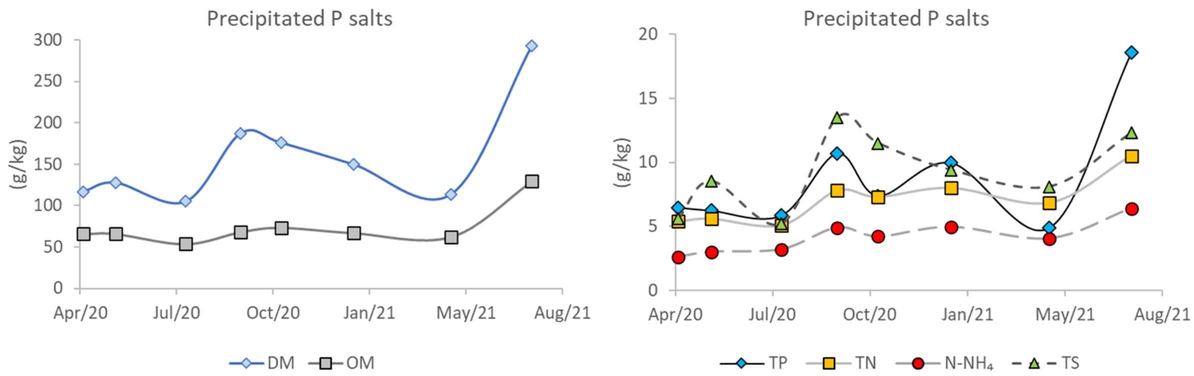

Figure 2-10 Composition (in fresh weight) over time of the precipitated P salts produced by the RePeat system at the demonstration plant Groot Zevert Vergisting for the period April 2020 – July 2021: dry matter (DM); organic matter (OM); total phosphorus (TP); total nitrogen (TN); ammoniacal nitrogen (N-NH_4); total sulphur (TS).

2.9 Overall performance of the NRR system

GZV operates in a region where intensive husbandry has resulted in a surplus of manure as compared to the amount of manure that can be applied on agricultural land within the application rate limits for animal manure. Until the start of the SYSTEMIC project, GZV exported unseparated digestate over distances of about 250 km to regions in Germany with a demand for organic fertilisers. Over the course of the SYSTEMIC project, GZV installed two NRR systems to reduce transport by processing digestate into RO concentrate and low-P soil improver, to be used within the region of the plant, SF of digestate and an organic P fertiliser (precipitated P salts), to be transported over long distances, and purified water, to be discharged on local surface water.

GZV produces from the digestate, without adding iron salts or polymer flocculants, a high-grade SF of digestate. These additives are commonly used to improve solid-liquid separation but polymers are of environmental concern and addition of iron salts reduces the percentage of P that is directly available for plant uptake in the SF of digestate. GZV therefore avoided these additives despite the fact that they improve separation efficiencies for P and OM. The SF of digestate is sold in Germany where farmers are willing to pay for this fertiliser though the revenues do not outweigh the transportation costs. Only exporting the SF of digestate results in only having to export roughly 15% of the mass compared to when unseparated digestate was exported before the SYSTEMIC project. Total transport for digestate and its end products, calculated as distance * mass, has been reduced by 52% compared to the situation without digestate separation.

Nitrogen from animal manure is available in excess in de area were GZV operates. The by GZV produced RO concentrate meets the, by the Joint Research Centre, proposed RENURE criteria and its composition is constant over time. Over the course of the project, GZV decreased the sulphuric acid dosage on the RO units which resulted in a lower TS content of the RO concentrate. The TN:TS ratio of the RO concentrate therefore better matches the nutrient uptake demand of the crops grown in the region. Also GZV deliberately does not dose iron sulphates in the digestate processing, something which is regularly done in the industry, because this would also increase the TS content of the RO concentrate. The RO concentrate is blended with other N fertilising products to increase the TN content and to adjust the N:K:S ratio to meet crop demands even better. About 48% of N-NH_4 from the ingoing digestate is recovered in the RO concentrate which is less than anticipated at the start of the project.

Despite improvements during the project, the percentage of digestate mass that is converted into purified water is still low (average in 2021; 15%) compared to what was envisaged at the start of the project (50%). This is mostly due to the unwanted large amount of produced MF concentrate and to a lesser extent also due to the amount of SF of digestate produced by the second decanter centrifuge. The amount of fine particles that pass the decanter centrifuges and that therefore enter the MF unit was underestimated and this contributes to the large amount of produced MF concentrate. This concentrate has a relatively low TP:TN ratio (0.059 kg/kg) compared to the ingoing digestate (0.23 kg/kg) and is therefore suitable as organic N fertiliser on arable land. However, this concentrate does not meet the proposed RENURE criteria of (N-NH_4 + N-NO_3)/TN ≥ 90% meaning that the N-application rate limit for animal manure (170 kg N/ha) applies. As a consequence, it is trucked to the Northern provinces of the Netherlands over a distance of about 125 km. The decanter centrifuges are however effective at removing P as together they remove 88% of the TP present in the ingoing digestate. This is important as in the Netherlands it is mostly the TP content of the manure which limits manure application and only to a lesser extent the TN content.

Over the course of the SYSTEMIC project, the supply of manure to the AD plant has decreased due to a decrease in the number of pigs in The Netherlands. A further decrease in the number of livestock animals is expected because the government has to take actions to decrease ammonia emissions from agriculture due to legally binding limits for nitrogen deposition in nature areas. This has consequences for co-digestion and manure processing plants including a drop in gate fees which shows the uncertainty and financial risks that plant owners have to deal with. Due to this decline in the manure surplus, disposal costs for the SF of digestate (and SF of manure as well) has decreased in the last years. This has decreased the necessity for GZV to operate the RePeat system as it became more economically attractive to dispose of the SF of digestate to farmers in Germany. Also the form in which the precipitated P salts are produced (a slurry) is still an undesirable form as it is costly to transport due to its DM content of only 16%. It is expected that demand for the precipitated P salts will be higher if it were dewatered as this makes handling by the buyers much easier. On a DM basis the precipitated P salts contain 46% OM which was not envisaged during the design of the process.

3 Am-Power (Belgium)

3.1 General description of the plant

3.1.1 Introduction

Am-Power (AmP) is located in the western part of Flanders (Pittem, Belgium), a region characterised by a surplus of animal manure, in terms of nutrients that are allowed to be applied on agricultural land, and yet a high market demand for synthetic N fertiliser. The demonstration plant is the largest biogas plant in Belgium (Figure 3-1) and converts source-separated organic waste from the agro-industry and households into biogas and biobased fertilisers. At the start of the SYSTEMIC project, the NRR system consisted of solid-liquid separation of digestate followed by drying of the SF of digestate and processing of the LF of digestate by means of an RO installation. The dried SF of digestate was exported to French regions with a high demand for P fertilising products. The RO installation produced an NK-rich RO concentrate, however, AmP faced difficulties in disposal of this concentrate because of the low demand for it in the region of the plant.

In the SYSTEMIC project, AmP has implemented an NRR system consisting of solid-liquid separation followed by drying of the SF of digestate and processing of the LF of digestate by means of a vacuum evaporator and RO installation. In the current NRR system, the previous DAF unit and RO installation were replaced by an acidification tank and a triple effect vacuum evaporator. The aim was to convert digestateinto a dried SF of digestate, evaporator concentrate and, via polishing of the evaporator concentrate, permeate water. This reduces the amount of water in the end products and, in turn, the costs for transport to France. However, during the project, the last treatment step to treat condensed water from the evaporator to clean water was not yet operational due to fouling issues with the RO installation. The goal for the near future is however to achieve production of permeate water of a high quality to meet discharge limits.

Figure 3-1 Aerial photo of the demonstration plant Am-Power, Pittem, Belgium.

3.1.2 Technical description of the biogas plant

AmP performs thermophilic AD in four digesters and a storage tank with a volume of 5,000 m^3 each. The average retention time in the system of digesters and storage tank is 45 days and the total co-digestion capacity is 180 kt of organic substrate per year (Table 3-1). AmP has two AD lines which are operated separately; one for biowaste (no manure) and one for animal manure. Digestate from biowaste (no manure) is processed in the NRR system which was monitored as part of the SYSTEMIC project whereas the digested manure was disposed of without further separation.

Table 3-1 Technical information of the demonstration plant Am-Power.

Characteristics	
Year of construction	2011
Maximum electric power	7.5 MWe
Volume of the digesters	20 000 m^3
Digestion process	Thermophilic
Commissioning evaporator	June 2019 (start first part)
Finalisation acidification tank	October 2019
Commissioning new reverse osmosis installation	September 2020

3.1.3 Feedstock and hygienisation

In 2017, the co-digestion plant processed about 167 kt of feedstock, out of which 72% was organic waste from the food industry and source segregated food waste (SSFW). Added co-substrates include maize silage, glycerine and fat-rich substrates. The years thereafter the amounts of processed feedstock decreased. In 2018 and 2019 the amounts of processed feedstock were respectively 138 kt and 161 kt; nonetheless the share of organic waste increased to 80% of the feedstock (Table 3-2). In the last monitoring year of the SYSTEMIC project, the plant processed approximately 153 kt of substrate, together food waste and SSFW contributed for 53% to this amount.

Manure and SF of manure are digested in a separate digester and the resulting digestate from this line is not further processed, but stored and subsequently applied on agricultural land. However, the biogas produced by both the non-manure and manure digesters is measured by AmP together (Table 3-3).

Table 3-2 Origin of anaerobic digestion feedstock of the demonstration plant Am-Power, expressed in kt of substrate per year for the period 2017–2020.

Feedstock	**2017**	**2018**	**2019**	**2020**
Digester - 1 (non-manure)				
Food waste and SSFW	107.5	94	111	80
Food industry sludge	13	17.5	18	21
Glycerine and fatty substrates	4.5	11	9.1	15
Other substrates	21	3	6.3	15
Corn	0.1	0.1		0.027
Digester – 2 (manure)				
Manure (slurry)	15	12	12	19
SF of manure	6		4.9	2.4
Total	167.1	137.6	161.3	152.9

Digestate hygienisation is achieved through the thermophilic digestion process and additionally, digestate is retained for one hour at 70°C to ensure complete hygienisation. After this, the digestate of the non-manure line is sent to the NRR system.

3.1.4 Biogas production and energy generation

The highest production of biogas and CH_4 (including digesters and post-digesters) was achieved in 2017, 18 Mm^3 biogas and 9.9 Mm^3 CH_4 (Table 3-3), together with the highest specific biogas production (108 Nm^3 t^{-1} feedstock). The produced biogas is converted into electrical and thermal energy by a combined heat and power (CHP) installation.

Table 3-3 Production and average composition of biogas before purification at Am-Power for the period 2017–2020. Abbreviations: methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and oxygen (O_2).

Parameter	Unit	2017	2018	2019	2020
CH_4	%	55−57	55	55	57
CO_2	%	46	45	45	44
H_2S	ppm	83	83	83	89
O_2	%	0.1	0.1	0.1	0.1
Total biogas production	MNm^3	18	14	17	15
Specific biogas production	$Nm^3\ t^{-1}$ feedstock	108	100	104	95
Total CH_4 production	MNm^3	9.9	7.6	9.2	8.0
Specific CH_4 production	$Nm^3\ CH_4\ t^{-1}$ feedstock	59	55	57	52

3.1.5 Other information

Labour

AmP employs 12 FTE, of which 2.5 are specifically dedicated to the NRR system.

Buildings and storage capacity

The plant has several storage tanks with the following storage capacity for intermediate and end products:

- Digestate: 5 000 m^3
- LF of digestate: 5 000 m^3
- Dried SF of digestate: 500 m^3
- Evaporator concentrate: 100 m^3
- Condensed water (water for cleaning): 75 m^3

3.2 Drivers for nutrient recycling

3.2.1 Motivation for nutrient recycling

AmP has a history of experimenting with and investing in nutrient recovery innovations. Several years ago AmP already envisaged the importance and benefits of moving towards a circular economy because disposal of the digestate is an important part of the costs for biowaste processing plants. On top of this, the agro food industry in Flanders realises that their waste streams are valuable and thus demand a gate fee to biogas plants for intake of their biowaste.

Competition between biogas plants makes it difficult to achieve a cash flow above the breakeven point. AmP believes that nutrient recovery can be a way to achieve this. AmP produces about 160 kt of digestate per year and strives to process it in a cost effective, efficient and relatively simple way, without losing the nutrients. The plant has developed and implemented a process for the recovery of nutrients in the form of valuable fertilisers which is currently being optimised.

3.2.2 Sustainability goals

AmP is committed to reaching the following targets:

- Reduce CO_2 emissions related to digestate transport by reducing the water content and hence volume of the liquid NK fertiliser (evaporator concentrate).
- Reduce the use of additives and chemicals: reduction of polymer dosage and elimination of addition of iron sulphate ($FeSO_4$) and iron chloride ($FeCl_3$)
- Increase the production of purified water suitable for reuse and discharge to surface water

3.2.3 Economic benefits

The economic advantages of the current, improved, NRR system of AmP compared to the previous one are:

- By improving the RO efficiency, AmP has estimated that approximately an additional 160 m^3 of water per day will become available for discharge (after polishing) or for use on site. This amount of water does not have to be transported, and;
- By replacing the DAF by an evaporator, the costs for additives will be drastically reduced as polymer flocculant was dosed on the DAF and the use of iron salts becomes redundant.

3.3 The nutrient recovery installation

3.3.1 Technical description of the installation

Organic waste is collected and homogenised in a mixing unit to a substance with a DM content of approximately 20%. The homogenised feedstock is thereafter hydrolysed in a separate tank (with a retention time of three days) and fed to the digesters (with a retention time of about 45 days). Digestate from each of the digesters is pumped to a post-digester where it is retained for 10 days. Digestate derived from animal manure (digester 2) amounts to approximately 20 kt/year. Digestate is applied on 600 ha of agricultural fields without separation. In summer it is applied locally (within 15 km), whereas in winter it is transported up to 250 km far. Digestate derived from biowaste (digester 1) is further processed in the NRR system.

Description of the previous NRR system (2019)

Figure 3-2 gives an overview of the sequential NRR stages that were operational at the plant until December 2019. Digestate was sent to a decanter centrifuge for solid-liquid separation, where coagulation, flocculation and P removal were favoured by the addition of 40 % $Fe_2(SO_4)_3$ solution and 0.35% polymer flocculant solution, respectively 100 and 8.5 l per m^3 of digestate. The SF of digestate, which contains 90–95% of TP of the digestate, was dried producing a P-rich SF of digestate with a DM content of about 90%. Since the SF produced by the decanter centrifuge was too wet (25% DM) to be processed in the fluidised bed dryer by itself, it was first mixed with a part of previously dried SF of digestate (90% DM) in order to obtain a dust-free product with a DM content of about 62%. This mixture was then dried to the final DM content of 90%. Exhaust air from the fluidised bed dryer was treated by an air scrubber to remove the NH_3 that vaporised during drying, thereby producing air scrubber water (ASW). Part of the LF of digestate was recirculated to the decanter centrifuge and mixed with the ingoing digestate in a volume ratio of 6:4 (digestate:LF of digestate). The remaining part of the LF of digestate was sent to a 5,000 m^3 storage tank where it was mixed with several other process streams (i.e. cleaning and process water, ASW and rainwater) which led to dilution, resulting in lower nutrient concentrations. The diluted LF of digestate was processed by a DAF unit to which a solution of 40% $FeCl_3$ and polymer flocculant solution were added, respectively in dosages of 3.5 and 46 l per m^3 of digestate. The DAF unit removed remaining particulate matter that could otherwise clog the RO membranes. The sludge produced by the DAF unit was circulated back to the influent of the decanter centrifuge, whilst the effluent of the DAF unit was further processed in an RO unit. Processing by RO required the addition of sulphuric acid (96% H_2SO_4, 2.7 kg per m^3 of digestate) to the influent to ensure a high separation efficiency for NH_4. Periodic cleaning of the membranes was done by adding sulphuric acid (37% H_2SO_4) and caustic soda (29% NaOH) respectively in dosages of 2 kg and 0.7 kg per m^3 of digestate. The concentrate produced by the RO was rich in N, K and S, and was used as fertiliser on local agricultural land.

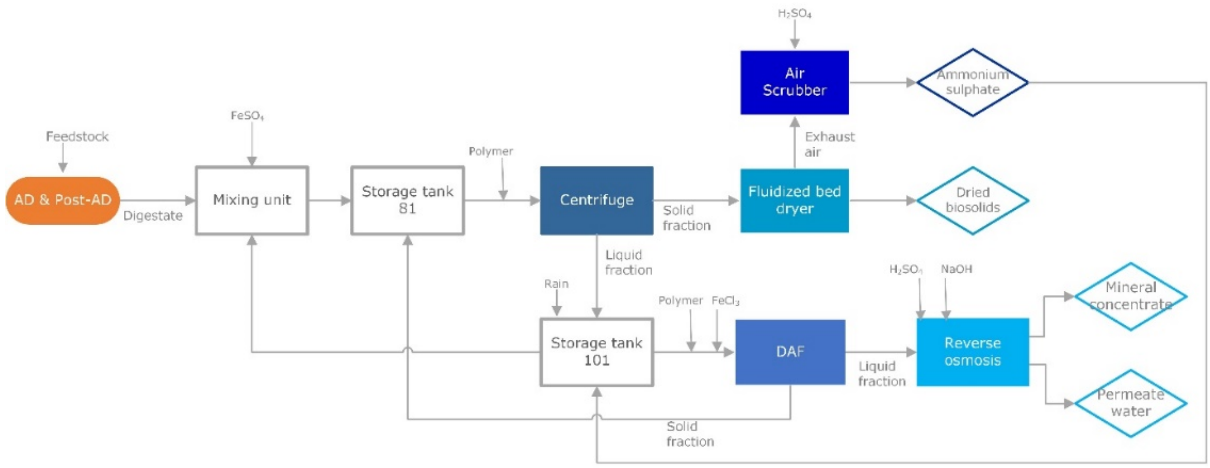

Figure 3-2. Simplified process flow diagram of the previous NRR system at the demonstration plant Am-Power including locations of chemical addition and the major return flows (as configured in 2019).

Description of the current NRR system (2021)

The process now in operation at Am-Power is depicted in Figure 3-3 and includes a continuous multiple-effect vacuum evaporator prior the RO, thus increasing the removal of water from the LF of digestate. In the current system, the ingoing digestate is still separated via the decanter centrifuge. Differently than in the previous system, the raw digestate is not mixed with the LF of digestate prior to mechanical separation, thus increasing the treatment capacity of the decanter centrifuge. The SF of digestate is still, as previously, dried to a DM content of 90% DM, while the LF of digestate is sent to the evaporator. An advantage of treatment by the evaporator instead of the RO is that pre-treatment by DAF becomes redundant and hence, addition of iron chloride and polymer on the DAF is avoided.. Prior to the evaporator, the LF of digestate is acidified to a pH of roughly 6.8, to prevent ammonia from evaporating in the evaporator. The aim is that most of the ammoniacal nitrogen in the LF of digestate ends up as ammonium in the evaporator concentrate. If AmP would not add sulphuric acid to the LF of digestate, ammonia would vaporise and the composition of the condensed water could be similar to condensed ammonia water as produced by the demonstration plant WNE. The vapour, which contains part of the ingoing ammonia, of the evaporator of AmP is condensed as condensed water and subsequently pumped to the RO unit for separation into an N-rich evaporator concentrate and permeate water. During the course of the SYSTEMIC project, the RO membranes had continuous fouling problems. This was not expected beforehand because the ingoing condensed water is free of divalent cations and phosphate which typically cause fouling of RO membranes (Zhang *et al.*, 2020). The operators however suspect that the condensed water contains volatile fatty acids which cause the membrane fouling. As a consequence, the RO installation was taken out of operation. For the time being, the condensed water is used to make the polymer flocculant solution and anti-foaming agent solution, to clean the evaporator plates and to dilute the feedstock of the digesters. This is, however, a temporary situation as AmP will invest in a new RO installation to improve the produced permeate water such that it meets the criteria for discharge into surface water. The evaporator concentrate will be mixed with SF of digestate and traded as an organic NPK fertiliser in France. AmP is building a mixing unit to mix evaporator concentrate with the dried SF of digestate, in order to produce a fertilising product with a lower DM content than the current dried SF of digestate. Once the RO unit is fully operational again, the permeate water will be discharged to surface water and the RO concentrate will be either fed back somewhere in the NRR system or disposed as an NS fertiliser. The investment costs for the evaporator and adaptation costs of the process amounted to € 2 million in total.

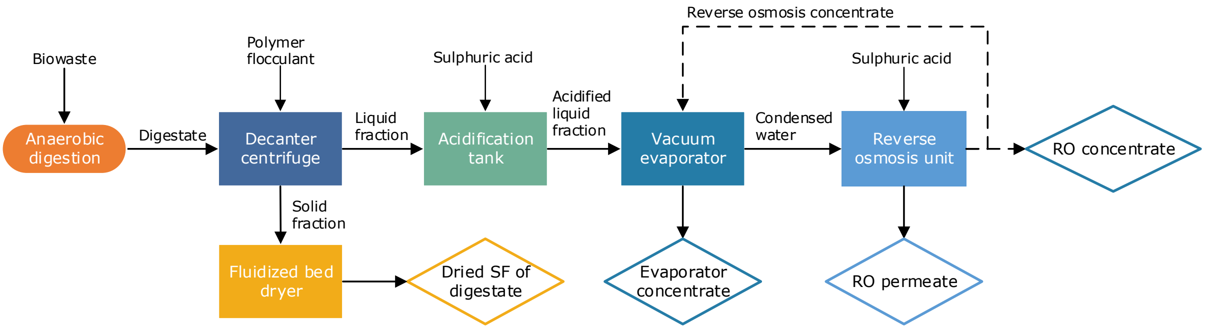

Figure 3-3 Simplified process flow diagram of the current NRR system at the demonstration plant Am-Power including locations of chemical addition and the major return flows (as configured in October 2021).

On a mass basis, the evaporator currently processes the LF of digestate into 73% condensed water and 27% evaporator concentrate, thereby separating roughly 65–70% of the water in the LF of digestate to the condensed water. The technical specifications of the evaporator are summarised in Table 3-4.

Table 3-4 Technical specifications of the evaporator at the demonstration plant Am-Power.

Technical specification	**Amount**
Processing capacity of LF of digestate	3.5–4.5 $m^3\ h^{-1}$
DM content of LF of digestate	40 $g\ kg^{-1}$
Water removal percentage	65–70 %
Production capacity of condensed water	2.5–3 $m^3\ h^{-1}$
Production capacity of evaporator concentrate	1–1.5 $m^3\ h^{-1}$

Compared to the previous NRR system, the current one does not require addition of iron salts for solid-liquid separation (addition of iron salts were needed to remove phosphate from the liquid fraction which would otherwise cause scaling on RO membranes) and hence the consumption of 982 tonnes of iron sulphate and 378 tonnes of iron chloride are now being avoided. Also, consumption of polymer has decreased from 63 tonnes per year to 38 tonnes per year because the DAF is not operational any more. However, the addition of sulphuric increased compared to the previous system due to the necessity of acidifying the influent of the evaporator. Additionally, to prevent foam formation in the evaporators, a considerable amount of anti-foaming agent is currently added (Table 3-5).

Table 3-5 Chemical consumption of the NRR systems and the anaerobic digestion of the demonstration plant Am-Power in tonnes per year (based on purchasing) for processing of about 165 kt digestate per year.

Substance	**Concentration (% m/m)**	**Function**	**Estimated consumption ($t\ y^{-1}$)**
Previous NRR system (before 2019)			
Polymer flocculant powder	100	Flocculant	63
Iron sulphate ($Fe_2(SO_4)_3$) solution	40	Coagulant	982
Iron chloride ($FeCl_3$) solution	40	Coagulant	378
Sulphuric acid (H_2SO_4)	96	Acid for RO operation	200
Sulphuric acid (H_2SO_4)	37	Acid for RO cleaning	15.6
Caustic soda (NaOH)	29	Base for RO cleaning	15.6
Current NRR system (since 2021)			
Polymer flocculant powder	100	Flocculant	38
Anti-foaming agent	n.a.	Antifoaming agent for decanter centrifuge	5.3
Anti-foaming agent	n.a.	Antifoaming agent for vacuum evaporator	76
Sulphuric acid (H_2SO_4)	96	Acid for acidification of LF of digestate	682
Anaerobic digester and biogas desulphurisation			
		Coolant for dew point reduction	0.000045

3.3.2 Total production of digestate and other products

Over the course of the SYSTEMIC project, digestate production at AmP fluctuated between 152 and 170 kt per year. Until 2019 (before construction of the evaporator), the majority of the digestate mass was converted into RO concentrate and RO permeate, the latter two almost in a ratio of 1:1. The produced RO permeate was reused on site for dilution of internal streams, polymer solution preparation and cleaning. In 2020, the evaporator was in operation, however not at full capacity. Moreover, the acidification tank was only completed in the second half of 2020. Despite 2020 being a year full of process adjustments and trouble-shooting, the amount of produced water that could potentially have been discharged (i.e. condensed water) was twice the amount of produced evaporator concentrate (Table 3-6).

Table 3-6 Total production of digestate and end products in tonnes per year at the demonstration plant Am-Power for the period 2017–2020.

Digestate and end products	Unit	2017	2018	2019	2020
Digestate	t y^{-1}	170 590	134 420	161 280	152 330
RO concentrate	t y^{-1}	≈ 65 000	≈ 65 000	≈ 65 000	-
Permeate water	t y^{-1}	≈ 55 000	≈ 55 000	≈ 60 000	-
Dried SF of digestate	t y^{-1}	7 868	4 492	≈ 4 000	≈ 4 000
Condensed water	t y^{-1}	-	-	-	19 1433
Evaporator concentrate	t y^{-1}	-	-	-	9 150
Digestate not separated	t y^{-1}				74 923
LF not processed in the evaporator	t y^{-1}				38 797

3.4 Mass flows and balances of the previous NRR system

3.4.1 Monitoring and sampling

Before the implementation of the evaporator, AmP processed the digestate via a cascade of separators (decanter centrifuge, DAF unit and RO units), the reference situation. In this section the monthly average composition of the produced digestate, end products and intermediate process streams for the year 2018 are dealt with. An attempt was made to calculate a mass balance of the previous NRR system for the period September–October 2018. In November 2018 the digestate processing cascade was stopped to be able to install the evaporator, thereby interrupting the monitoring campaign. Samples of the different process stream were collected twice by Ghent University during September-October 2018 and average values of macronutrients were measured (Table 3-7). Only those parameters that have been measured in every process stream, and are thus relevant for the mass balance, are shown. The full characterisation of the produced digestate and end products is available in deliverable 1.13.

Since none of the mass flows at AmP were measured via flowmeters, ingoing and outgoing mass flows of the process units, where possible, were calculated based on their DM and K contents. Mass flows were calculated by multiplying volume flows with the measured density and concentrations of the process streams. Mass flows for the outgoing streams of the fluidised bed dryer were calculated assuming that all K in the SF of digestate ended up in the dried SF of digestate and none in the evaporated water. K was used for this calculation because it is non-volatile which makes it safe to assume that all K in the SF of digestate ended up in the dried SF of digestate. Two recirculation loops of unknown mass caused difficulties in calculation of the overall mass balance. Therefore it was assumed that the cleaning and process water, ASW and rainwater fed to the storage tank of the LF of digestate (storage tank 102) had a DM content of 0%, even though the measured DM content of the ASW was 0.048%. This assumption resulted in only one unknown recirculation loop in the system (sludge from the DAF unit to storage tank 81), that was assessed more easily, based on DM content. However, a better estimation of the process stream fed back to storage tank 102 is needed. Moreover, full chemical characterization of the added polymer flocculant solution needs to be carried out.

3.4.2 Chemical characterisation of digestate and end products

The average composition of the different process streams for the period September-October 2018 is shown in Table 3-7.

Table 3-7 Chemical characterisation (in fresh weight) of the ingoing digestate, intermediate process streams and end products of the NRR system at the demonstration plant Am-Power for the period September–October 2018. Averages of four samples ± standard deviation.

Parameter	**Unit**	**Digestate**	**LF of decanter centrifuge**	**SF of decanter centrifuge**	**Influent DAF unit**	**Dried SF of digestate**
pH		8.7 ± 0.84	8.0 ± 0.67	8.8 ± 1.3	8.1 ± 0.093	7.5 ± 0.54
EC	mS cm^{-1}	30	31	2.2	30	4.8
DM	g kg^{-1}	59 ± 0.84	23 ± 0.28	239 ± 0.35	14 ± 0.82	912 ± 4.9
OM	g kg^{-1}	32 ± 5.5	7.1 ± 3.2	129 ± 12		523 ± 0.11
TN	g kg^{-1}	5.5 ± 0.07	3.2 ± 0.076	12 ± 0.0066	2.6 ± 0.028	31 ± 0.03
NH_4-N	g kg^{-1}	2.9 ± 0.11	2.5 ± 0.067	2.6 ± 0.015	2.3 ± 0.069	0.88 ± 0.047
TP	g kg^{-1}	1.4 ± 0.021	0.19 ± 0.082	6.5 ± 0.13	0.037 ± 0.014	21 ± 3.3
TK	g kg^{-1}	3.3 ± 0.28	2.5 ± 0.14	2.8 ± 0.023	2.1 ± 0.043	11 ± 0.14
Ca	g kg^{-1}	1.7 ± 0.049	0.31 ± 0.013	7.4 ± 0.19	0.094 ± 0.025	26 ± 0.042
Mg	g kg^{-1}	0.41 ± 0.0042	0.14 ± 0.0064	0.90 ± 0.0024	0.12 ± 0.0067	4.4 ± 0.058
Parameter	**Unit**	**Effluent of DAF unit**	**Sludge of DAF unit**	**Air scrubber water**	**RO concentrate**	**RO permeate**
pH		8.1 ± 2.3	8.0 ± 0.51	4.5 ± 1.8	7.7 ± 0.25	6.8 ± 0.91
EC	mS cm^{-1}	28 ± 3.1	27	6.9	57	
DM	g kg^{-1}	12 ± 0.073	32 ± 0.80	4.8 ± 0.078	43 ± 0.45	-
OM	g kg^{-1}	2.3 ± 2.4	11 ± 9.6	4.1 ± 0.75	18 ± 5.0	-
TN	g kg^{-1}	2.4 ± 0.027	3.6 ± 0.00041	0.75 ± 0.043	5.3 ± 0.0015	<0.16
NH_4-N	g kg^{-1}	2.2 ± 0.017	2.4 ± 0.064	0.69 ± 0.063	4.2 ± 0.043	0.019 ± 0.0047
TP	g kg^{-1}	0.090 ± 0.0000036	0.032 ± 0.036	0.0075 ± 0.00024	0.011 ± 0.00061	<0.0076
TK	g kg^{-1}	1.7 ± 0.016	2.0 ± 0.096	0.093 ± 0.0008	4.3 ± 0.10	<0.0095
Ca	g kg^{-1}	0.061 ± 0.0013	0.093 ± 0.0034	0.10 ± 0.0027	0.13 ± 0.0029	<0.019
Mg	g kg^{-1}	0.12 ± 0.00093	0.12 ± 0.0062	0.020 ± 0.00014	0.23 ± 0.00066	<0.019

3.4.3 Mass flow analyses of macronutrients, micronutrients and heavy metals

The calculated total mass flows of the NRR system of AmP are depicted in Figure 3-4. Every 1000 kg of ingoing digestate was mixed with 667 kg LF of digestate from storage tank 102.To this mixture 570 kg of sludge of the DAF unit, 21 kg of $Fe_2(SO_4)_3$ solution and 226 kg of polymer flocculant solution were added prior to the decanter centrifuge. Solid-liquid separation by the decanter centrifuge resulted in 220 kg of SF of digestate and 2263 kg of LF of digestate. From this LF of digestate 667 kg was recirculated to the influent of the decanter centrifuge, whilst the remaining 2917 kg was sent to the DAF unit.

The 220 kg of SF of the decanter centrifuge were dried in a fluidised bed dryer to produce 59 kg of dried SF of digestate and 161 kg of water vapour. Ammonia present in the water vapour was recovered by an air scrubber in the form of 1059 kg of ASW (0.69 g NH_4-N kg^{-1}). Of the LF of digestate in storage tank 102, 2917 kg were processed in a DAF unit after addition of 134 kg of polymer flocculant solution and 10 kg of 43% $FeCl_3$ solution, which resulted in 570 kg of DAF sludge and 2492 kg of effluent of the DAF unit. Finally, the effluent of the DAF unit was processed via RO into 961 kg of RO concentrate and 1545 of permeate water. To the RO step 4.5 kg of 37% sulphuric acid, 6.7 kg of 96% sulphuric acid and 1.7 kg of 29% caustic soda were added per 1000 kg of initial ingoing digestate.

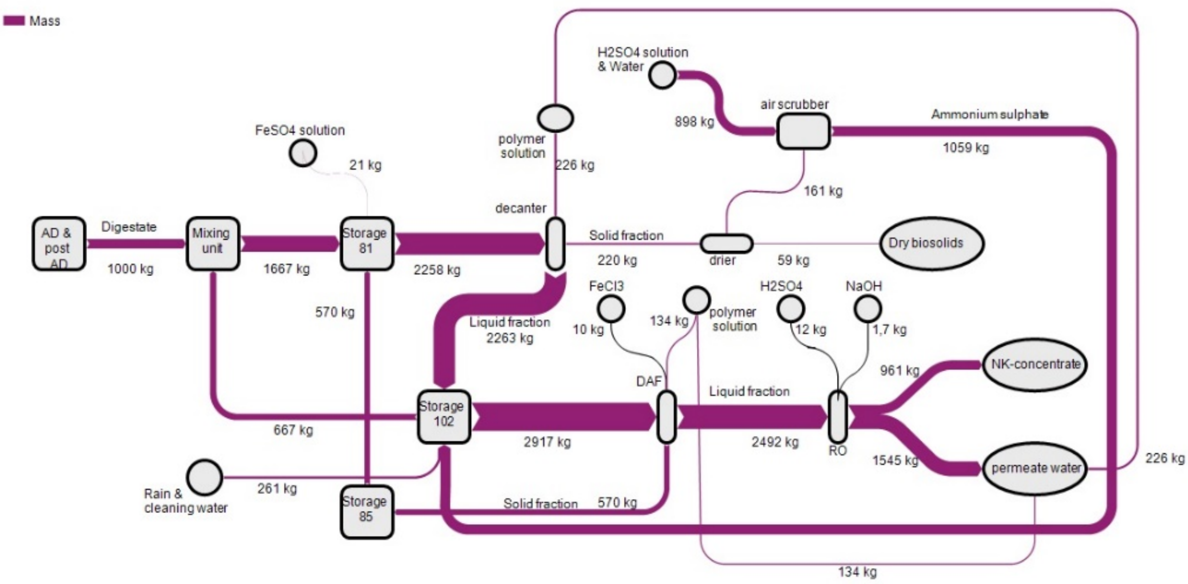

Figure 3-4 Total mass flows of the NRR system at the demonstration plant Am-Power in kg per 1000 kg of ingoing digestate for the period September–October 2018.

Figure 3-5 shows the calculated TN flows of the NRR system at AmP. The NRR system was fed with 5.5 kg of TN per 1000 kg of ingoing digestate. Of this, 1.9 kg of TN ended up in the dried SF of digestate and 4.8 kg of TN ended up in the RO concentrate. The sum of the calculated TN amounts in the end products is together 26% more than the amount of TN in the ingoing digestate. Additional nitrogen is of course not created in the NRR system. This deviation is therefore thought to be caused by uncertainties in...

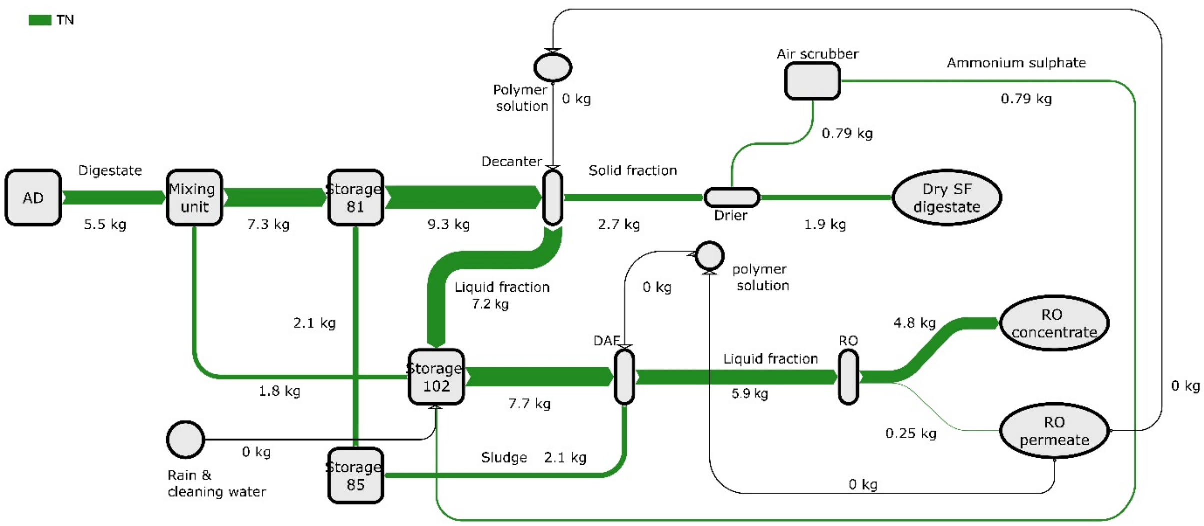

Figure 3-5 Total nitrogen (TN) flows of the NRR system at the demonstration plant Am-Power in kg per 1000 kg of ingoing digestate for the period September–October 2018.

Figure 3-6 shows the calculated TP flows of the NRR system at AmP. The NRR system was fed with 1.4 kg of TP per 1000 kg of ingoing digestate. Of this, 1.1 kg of TP ended up in the dried SF of digestate and 0.011 kg of TP ended up in the RO concentrate. The sum of the calculated TP amounts in the end products is together 11% less than the amount of TP in the ingoing digestate.

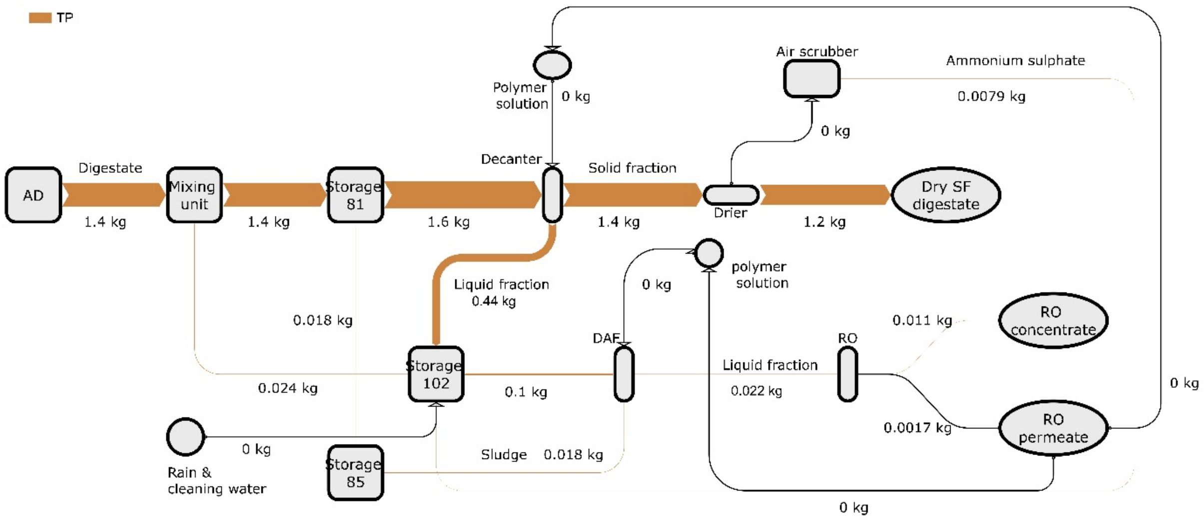

Figure 3-6 Total phosphorus (TP) flows of the NRR system at the demonstration plant Am-Power in kg per 1000 kg of ingoing digestate for the period September–October 2018.

Figure 3-7 shows the TK flows of the NRR system at AmP. The NRR system was fed with 3.3 kg of TK per 1000 kg of ingoing digestate. Of this, 0.63 kg of TK ended up in the dried SF of digestate and 4.1 kg of TK ended up in the RO concentrate. The sum of the calculated TK amounts in the end products is 44% more than the amount of TK in the ingoing digestate.

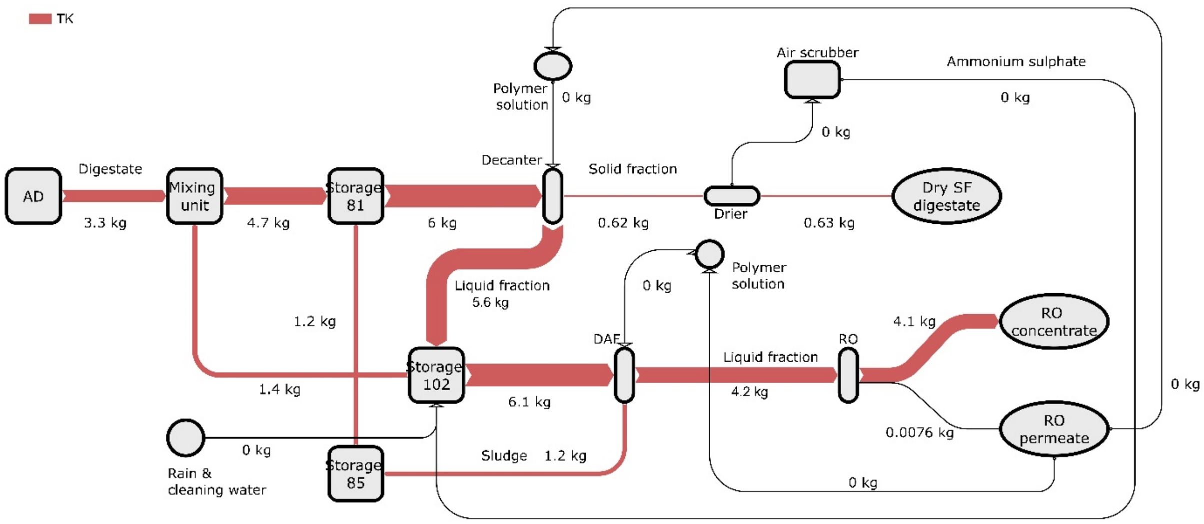

Figure 3-7 Total potassium (TK) flows of the NRR system at the demonstration plant Am-Power in kg per 1000 kg of ingoing digestate for the period September–October 2018.

Figure 3-8 shows the Ca flows of the NRR system at AmP. The NRR system was fed with 1.7 kg of Ca per 1000 kg of ingoing digestate. Of this, 1.5 kg of Ca ended up in the dried SF of digestate and 0.13 kg of Ca ended up in the RO concentrate. The mass balance for Ca is therefore trustworthy with a gap of only <10% between the ingoing and outgoing a mounts of Ca.

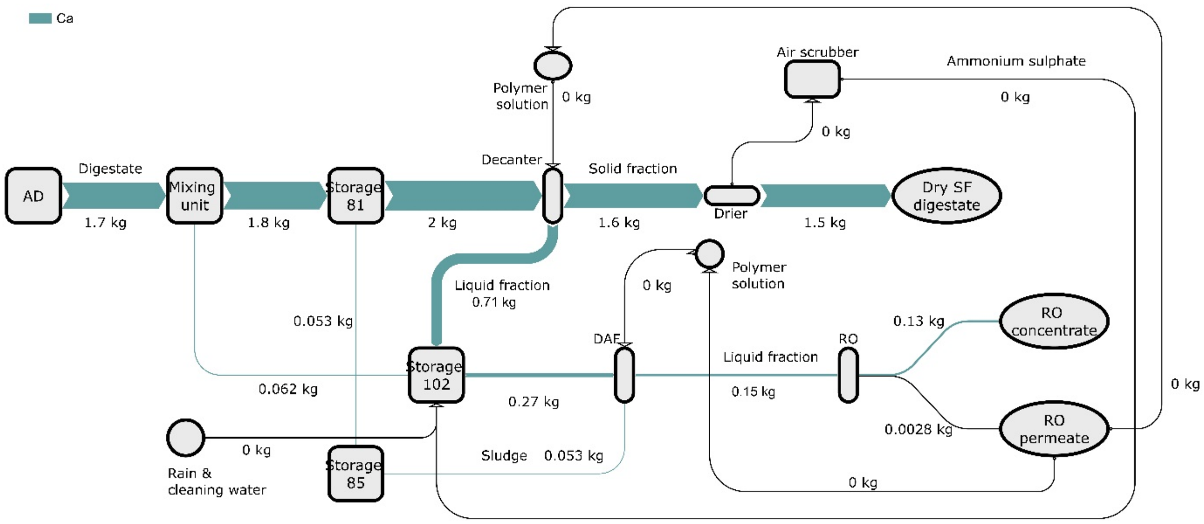

Figure 3-8 Calcium (Ca) flows of the NRR system at the demonstration plant Am-Power in kg per 1000 kg of ingoing digestate for the period September–October 2018.

Figure 3-9 shows the Mg flows of the NRR system at AmP. The NRR system was fed with 0.41 kg of Mg per 1000 kg of ingoing digestate. Of this, 0.26 kg of Mg ended up in the dried SF of digestate and 0.22 kg of Mg ended up in the RO concentrate. The sum of the calculated Mg amounts in the end products is 20% more than the amount of Mg in the ingoing digestate.

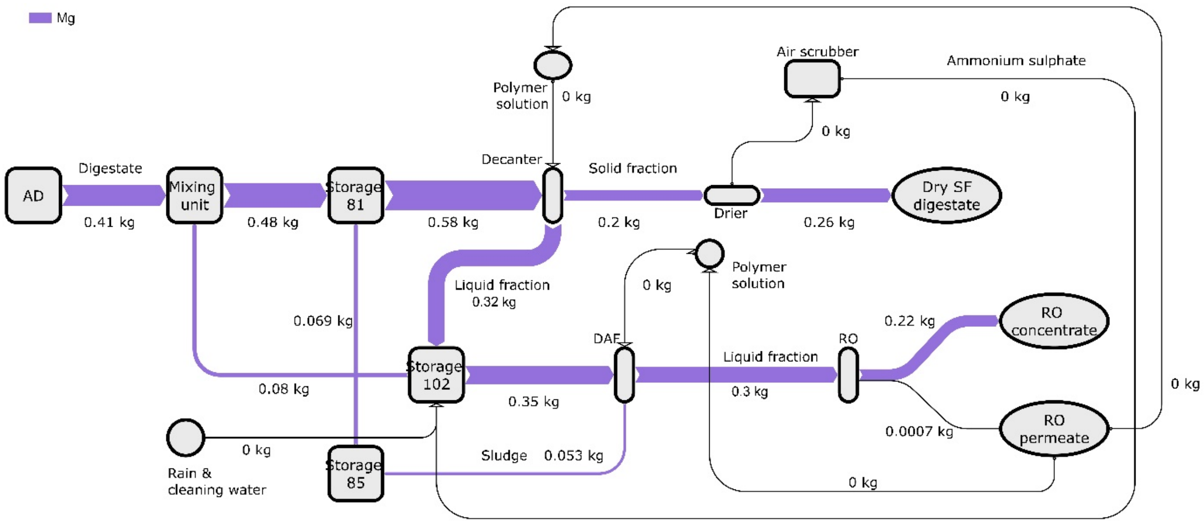

Figure 3-9 Magnesium (Mg) flows of the NRR system at the demonstration plant Am-Power in kg per 1000 kg of ingoing digestate for the period September–October 2018.

3.4.4 Separation and nutrient recovery efficiencies of process units

Large differences characterised ingoing and outgoing stream flows, hindering the assessment of separation efficiencies of each process unit. Also, the calculated mass balance has a high uncertainty due to the following:

- Total mass flows for each process unit were calculated based on contents of DM and TK in the ingoing and outgoing process streams. DM content of each of the process streams was however only measured twice over the period of two months. The measured DM contents may therefore not be representative for the period of two months, leading to inaccurate total mass flows.
- The dosage, DM content and density of the added chemicals, were in many cases assumed or not known as in the case of the polymer flocculant solution dosed on the decanter centrifuge.

- Storage tank 102 has a capacity of 5000 m^3, therefore the LF of digestate is diluted with cleaning and process water, ASW from the air scrubber and rainwater before it both enters the mixing unit and the DAF unit. Moreover, storage tank 102 was not mixed, leading to sedimentation of solids and possibly inhomogeneous conditions.
- It is unlikely that per 1000 kg of processed digestate, 1059 kg of ASW were produced. Most likely, this high calculated amount of ASW is a measurement artefact caused by the ASW being stored together with the other streams flowing to storage tank 102.

Every 1000 kg of digestate fed to the NRR system contained 5.5 kg of TN. The TN in the RO concentrate and dried SF of digestate amounted respectively to 4.8 kg (88% of TN in the ingoing digestate) and 1.9 kg (34% of TN in the ingoing digestate). Of the TP in the ingoing digestate, 88% ended up in the dried SF of digestate. Less than 1% of the TP in the ingoing digestate ended up in the outgoing process streams of the RO installation. For TN, TK and Mg the sum of the amounts in the end products exceeds the amount in the ingoing digestate. Only for Ca was this gap between the ingoing and outgoing amounts less than 10%.

3.5 Mass flows and balances of the current NRR system

3.5.1 Monitoring and sampling

The current, NRR system, implemented during the SYSTEMIC project, at AmP includes a cascade of multiple steps for the processing of the LF of digestate: acidification, evaporation and membrane filtration (RO). A short monitoring campaign to assess the performance of the vacuum evaporator without acidification of its influent was carried out for the period January–February 2020. It was however interrupted by the outbreak of the COVID-19 pandemic.

In this section the monthly average composition of the digestate, end products and intermediate process streams from October 2020 to April 2021 are dealt with. During this period the influent of the vacuum evaporator was acidified in the acidification unit. An RO unit was supposed to improve the quality of the condensed water prior to discharge. The RO unit however never worked in a stable and continuous way due to continuous fouling of its membranes. As a consequence, the RO unit is not included in the calculated separation efficiencies and mass balances. Similarly as for the previous NRR system, the SF of digestate was dried. Samples of the different process stream were collected every month (once or twice) by Ghent University and their contents of macronutrients, micronutrients and heavy metals were measured (Table 3-8). Only those parameters that have been measured in every process stream, and thus are relevant for the mass balance, are shown. The full characterisation of the digestate and end products is available in deliverable D1.13.

Total mass flows of the ingoing and outgoing process streams of the vacuum evaporator were measured via flowmeters, whereas the total mass flows of the ingoing and outgoing streams of the decanter centrifuge were calculated based on their DM content. Similarly as for the previous NRR system, the produced amount of dried SF of digestate was not measured, but calculated based on the TK content of the ingoing and outgoing streams of the fluidised bed dryer. Mass flows for the NRR system were calculated in the same way as for the previous NRR system with the exception that in this case the mass flows of the ingoing and outgoing streams of the evaporator were measured instead of calculated. Chemical consumption rates for sulphuric acid, polymer flocculant solution and anti-foaming agent solution were tracked by AmP and communicated to Ghent University.

3.5.2 Chemical characterisation of digestate and end products

The average composition of the ingoing digestate, intermediate process streams and end products of the NRR system at AmP for the period October 2020 – April 2021 are shown in Table 3-8.

Table 3-8 Chemical characterisation (in fresh weight) of the ingoing digestate, intermediate process streams and end products of the NRR system at the demonstration plant Am-Power for the period October 2020 – April 2021. Average of ten samples ± one standard deviation.

Parameter	Unit	Digestate	LF of digestate	SF of digestate	Dried SF of digestate	Evaporator influent
pH		8.1 ± 0.12	8.3 ± 0.12	8.3 ± 0.35	8.1 ± 0.25	6.8 ± 0.55
EC	mS cm^{-1}	26 ± 0.82	30 ± 3.1	4.6 ± 0.48	6.3 ± 1.5	32 ± 3.8
DM	g kg^{-1}	81 ± 4.5	26 ± 5.0	261 ± 16	823 ± 70	33 ± 6.6
OM	g kg^{-1}	50 ± 3.1	14 ± 5.0	171 ± 9.2	529 ± 29	16 ± 5.4
TN	g kg^{-1}	4.9 ± 0.29	4.0 ± 0.62	8.4 ± 1.1	23 ± 2.9	3.7 ± 0.60
NH_4-N	g kg^{-1}	2.3 ± 0.52	2.4 ± 0.78	2.3 ± 0.67	1.3 ± 0.59	2.2 ± 0.53
TP	g kg^{-1}	1.4 ± 0.19	0.21 ± 0.061	5.4 ± 0.41	19 ± 3.2	0.22 ± 0.05
TK	g kg^{-1}	3.3 ± 0.31	3.1 ± 0.39	4.0 ± 0.77	14 ± 1.7	2.9 ± 0.53
TS	g kg^{-1}	1 ± 0.13	0.21 ± 0.092	3.5 ± 0.75	11 ± 1.8	3.1 ± 1.1
Ca	g kg^{-1}	1.6 ± 0.15	0.18 ± 0.10	6.5 ± 0.42	23 ± 3.6	0.20 ± 0.065
Mg	g kg^{-1}	0.38 ± 0.062	0.031 ± 0.014	1.5 ± 0.15	5.5 ± 1.2	0.034 ± 0.015
Na	g kg^{-1}	2.4 ± 0.27	2.1 ± 0.27	2.4 ± 0.43	8.6 ± 1.7	2 ± 0.37
Al	mg kg^{-1}	405 ± 28	8.4 ± 5.1	1850 ± 219	5960 ± 857	59 ± 26
Co	mg kg^{-1}	0.18 ± 0.039	0.1 ± 0.015	0.36 ± 0.068	1.1 ± 0.27	0.1 ± 0.017
Cr	mg kg^{-1}	1.7 ± 0.16	<0.27	5.5 ± 0.75	20 ± 3.2	0.28 ± 0.093
Cu	mg kg^{-1}	6.0 ± 0.77	0.65 ± 0.26	22 ± 1.3	70 ± 12	1.1 ± 0.34
Fe	mg kg^{-1}	1588 ± 133	42 ± 26	7050 ± 737	22680 ± 3249	393 ± 93
Mn	mg kg^{-1}	20 ± 1.1	2 ± 0.24	80 ± 3.8	256 ± 8.7	3.2 ± 0.51
Ni	mg kg^{-1}	1.2 ± 0.15	0.48 ± 0.058	3.6 ± 0.57	12 ± 2.1	0.54 ± 0.1
Zn	mg kg^{-1}	27 ± 4.1	2.5 ± 0.83	100 ± 4.6	321 ± 55	4.1 ± 1.7
Parameter	**Unit**	**Condensed water**	**Evaporator concentrate**	**Polymer flocculant solution**	**Anti-foaming agent for decanter centrifuge**	**Anti-foaming agent for evaporator**
pH		9.6 ± 0.2	6.2 ± 0.26	5.6 ± 1.8	9.4 ± 0.16	6.5 ± 0.32
EC	mS cm^{-1}	1678 ± 814	74 ± 6.3	9.5 ± 2.0	-	-
DM	g kg^{-1}	-	115 ± 23	12 ± 1.5	537 ± 82	942 ± 30
OM	g kg^{-1}	-	63 ± 14	-	-	-
TN	g kg^{-1}	1.0 ± 0.30	9.9 ± 1.8	1.2 ± 0.24	1.2 ± 0.52	14 ± 1.1
NH_4-N	g kg^{-1}	0.87 ± 0.58	5.3 ± 0.62	0.79 ± 0.22	-	-
TP	g kg^{-1}	<0.00027	0.92 ± 0.26	0.004 ± 0.00072	-	-
TK	g kg^{-1}	<0.00027	10 ± 0.82	<0.00027	-	-
TS	g kg^{-1}	0.029 ± 0.0053	12 ± 1.6	0.93 ± 0.25	-	-
Ca	g kg^{-1}	<0.00027	0.73 ± 0.34	0.001 ± 0.00043	-	-
Mg	g kg^{-1}	<0.00027	0.13 ± 0.074	<0.00027	-	-
Na	g kg^{-1}	0.0011 ± 0.00066	7.0 ± 1.2	0.0078 ± 0.0025	-	-
Al	mg kg^{-1}	<0.27	220 ± 102	<0.27	-	-
Co	mg kg^{-1}	<0.27	0.38 ± 0.16	<0.27	-	-
Cr	mg kg^{-1}	<0.27	1 ± 0.59	<0.27	-	-
Cu	mg kg^{-1}	<0.27	4.3 ± 2.5	<0.27	-	-
Fe	mg kg^{-1}	<0.27	648 ± 321	<0.27	-	-
Mn	mg kg^{-1}	<0.27	12 ± 4.2	<0.27	-	-
Ni	mg kg^{-1}	<0.27	1.9 ± 0.82	<0.27	-	-
Zn	mg kg^{-1}	<0.27	15 ± 8.1	<0.27	-	-

3.5.3 Mass flow analyses of macronutrients, micronutrients and heavy metals

Figure 3-10 shows the DM and water flows of the NRR system at AmP. Flows were either measured (liquid streams) by flowmeters or calculated (SF of digestate and dried SF of digestate).

On average, 267 t d^{-1} of digestate were produced by the AD of biowaste. Digestate was separated by the decanter centrifuge into 212 t d^{-1} of LF of digestate and 63 t d^{-1} of SF of digestate. To the influent of the decanter centrifuge, 8.8 t d^{-1} of polymer flocculant solution were added, to improve solid-liquid separation, and 0.028 t d^{-1} of anti-foaming agent were added. Drying of the SF of digestate resulted in 18 t d^{-1} of dried SF of digestate. The amount of DM lost due to drying was assumed to be equal to the amount of NH_4-N that vaporised during drying.

Of the produced LF of digestate, 25% was stored (53 t d^{-1}) for application on agricultural land, whereas the remaining 75% (158 t d^{-1}) was further processed. This LF of digestate was pumped to an acidification tank (500 m^3) where about 1.5 t d^{-1} of 96% sulphuric acid were added to lower the pH from 8.3 to about 6.8, thereby reducing the amount of NH_3 that evaporates in the vacuum evaporator. The acidified LF of digestate (160 t d^{-1}) was processed in the vacuum evaporation after addition of 0.22 t d^{-1} of anti-foaming agent and 8.6 t d^{-1} of cleaning water. This resulted in the production of condensed water (126 t d^{-1}) and evaporator concentrate (43 t d^{-1}). The condensed water was used on-site for dilution of the digester feedstock, preparation of polymer flocculant solution and anti-foaming agent solution and cleaning of the evaporator. Part of it was stored for land application mixed with the LF of digestate.

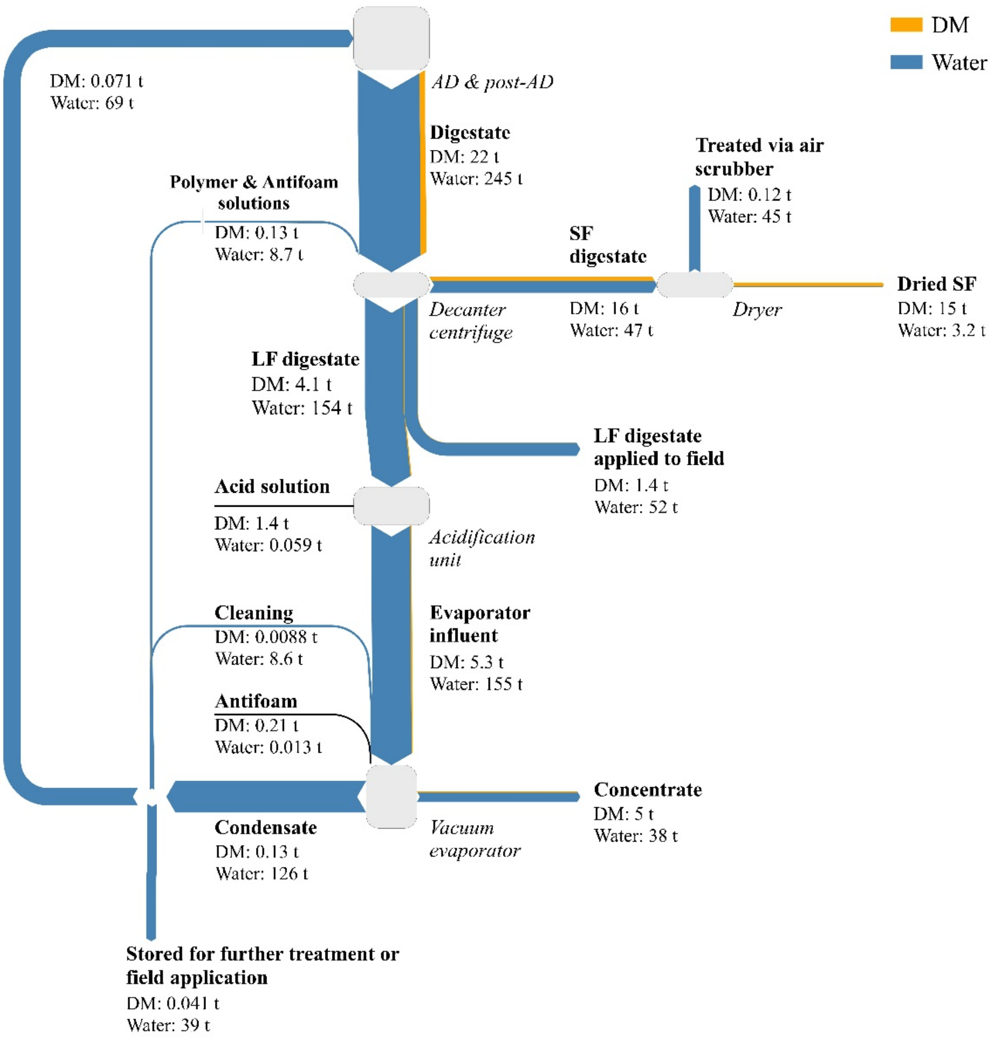

Figure 3-10 Dry matter (DM) and water flows of the NRR system at the demonstration plant Am-Power in tonnes per day for the period October 2020 – April 2021. Process streams: liquid fraction of digestate (LF digestate), solid fraction of digestate (SF digestate) and dried solid fraction of digestate (Dried SF).

Figure 3-11 shows the flows of organic nitrogen and ammoniacal nitrogen of the NRR system at AmP. On average, 1315 kg TN d^{-1} (708 kg d^{-1} of organic nitrogen and 607 kg d^{-1} of ammoniacal nitrogen) were produced in the form of digestate by the AD of biowaste. The solid-liquid separation step (decanter centrifuge with polymeric flocculant addition) applied by AmP effectively separates OM, TP and TS to the SF of digestate, whereas water, NH_4-N and TK mainly end up in the LF of digestate. The NH_4-N:TN ratios of the LF digestate and the acidified LF of digestate were similar, roughly 0.58. The ingoing acidified LF of digestate contained 591 kg TN d^{-1} whereas the outgoing evaporator streams together contain 538 kg TN d^{-1}. This calculated loss of 9% over the evaporator is likely caused by small deviations in the measured flows by the flowmeters and/or by temporal fluctuations in the concentrations of the process streams that cannot be captured by the performed discontinuous sampling. About 110 kg d^{-1} of NH_4-N ended up in the condensed water which has an NH_4-N content of 0.87 ± 0.58 g kg^{-1}.

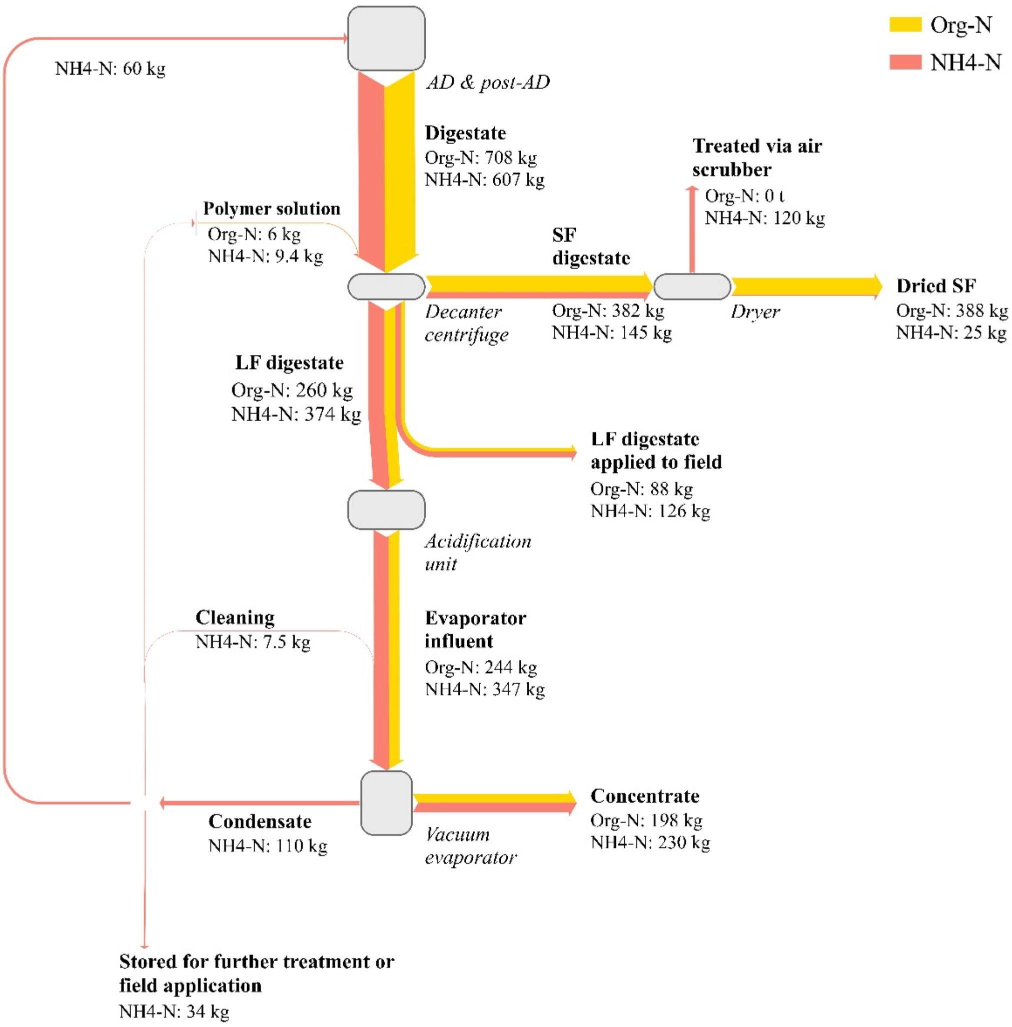

Figure 3-11 Organic nitrogen (Org-N) and ammoniacal nitrogen (NH_4-N) flows of the NRR system at the demonstration plant Am-Power in kg per day for the period October 2020 – April 2021. Process flows: liquid fraction of digestate (LF digestate), solid fraction of digestate (SF digestate) and dried solid fraction of digestate (Dried SF).

Figure 3-12 shows the flows of TP and TK of the NRR system at AmP. On average, 368 kg d^{-1} of TP and 892 kg d^{-1} of TK were produced in the form of digestate by the AD of biowaste. Flows of TP show the same trend as those of DM and OM. About 93% of the TP in the ingoing digestate ended up in the dried SF of digestate. As TK in the digestate was mainly present in the form of solubilised cations (K^+): 72% of it was separated to the LF of digestate.
Overall, the NRR system at AmP effectively separated TP to the dried SF of digestate. It also effectively separated NH_4-N and TK to the evaporator concentrate.

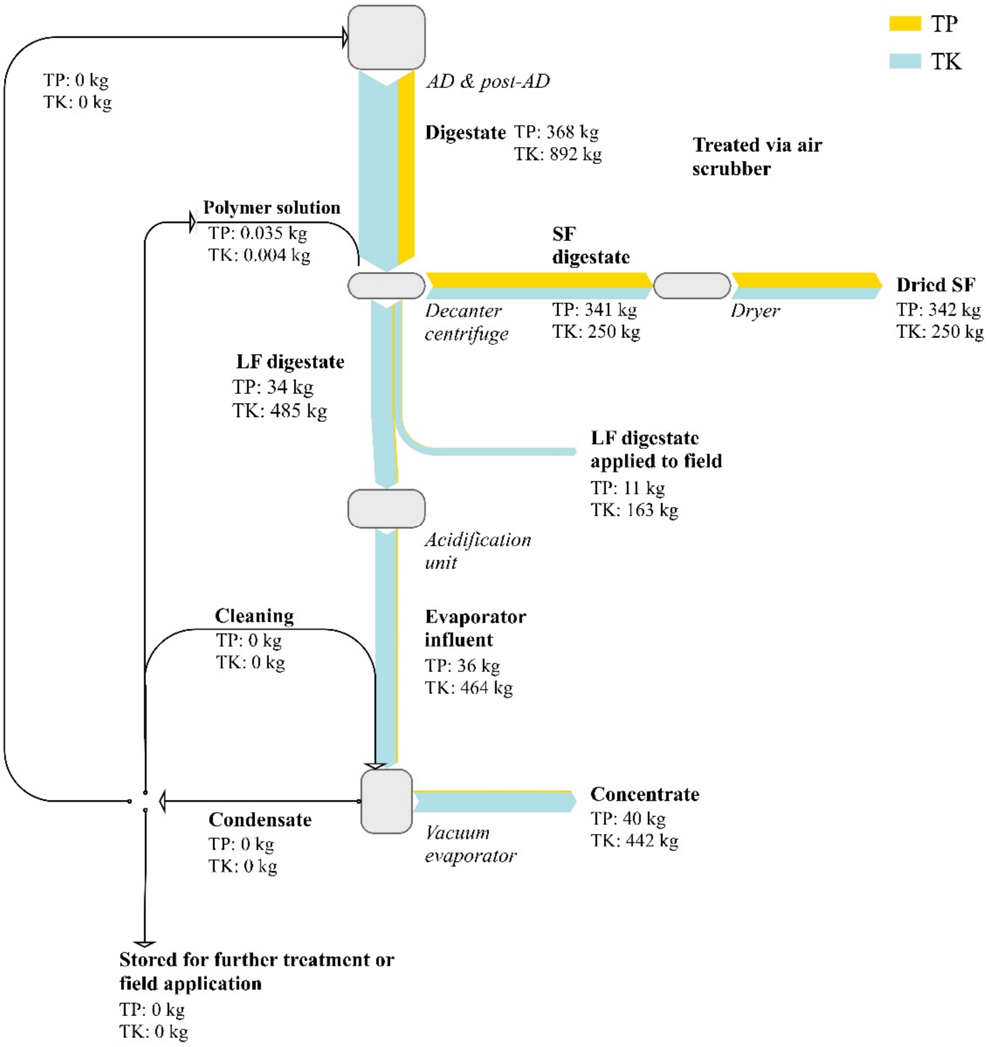

Figure 3-12 Total phosphorus (TP) and total potassium (TK) flows of the NRR system at the demonstration plant Am-Power in kg per day for the period October 2020 – April 2021. Process flows: liquid fraction of digestate (LF digestate), solid fraction of digestate (SF digestate) and dried solid fraction of digestate (Dried SF).

3.5.4 Separation and nutrient recovery efficiencies of process units

Table 3-9 shows the calculated separation efficiencies of the individual process units of the NRR system at AmP as a percentage of the ingoing amount of each parameter. On average, 79% of the total mass of ingoing digestate ended up in the LF of digestate and 24% in the SF of digestate. The SF of digestate contained respectively 40% and 93% of the ingoing amounts of TN and TP. Of the DM and NH_4-N in the influent of the evaporator respectively 90% and 66% ended up in the evaporator concentrate. Also the majority of TP and TK in the influent of the evaporator ended up in the evaporator concentrate. It was assumed that 100% of TK in the SF of digestate ended up in the dried SF of digestate.

Table 3-9 Separation efficiencies of the process units of the NRR system at Am-Power for the period October 2020 – April 2021 for the following parameters: total mass, moisture (H_2O), dry matter (DM), organic matter (OM), nutrients and heavy metals. Condensed water is here indicated as Condensate.

	Total mass %	H_2O %	DM %	OM %	TN %	NH_4-N %	TP %	TK %	TS %	Ca %	Mg %
Decanter centrifuge											
LF of digestate	79	82	25	22	64	81	12	72	16	9.3	6.5
SF of digestate	24	18	75	80	40	24	93	28	79	97	94
Vacuum evaporator											
Concentrate	26	25	94	108	72	66	110	95	102	100	105
Condensate	74	81	2.4	-	22	32	-	-	0.73	-	-
Fluidised bed dryer											
Dried SF of digestate	29	7.0	91	90	78	17	93	100	92	102	105
Water vapour	71	96	0.73	-	-	83	-	0	-	-	-
	Na %	**Cu %**	**Zn %**	**Al %**	**Fe %**	**Cd %**	**Co %**	**Pb %**	**Cr %**	**Ni %**	**Mn %**
Decanter centrifuge											
LF of digestate	72	8.5	7.4	108	2.1	n.a.	45	n.a.	-	31	8.3
SF of digestate	24	85	88	1.7	105	n.a.	46	n.a.	105	70	97
Vacuum evaporator											
Concentrate	92	107	98	101	91	n.a.	102	n.a.	99	93	102
Condensate	0.042	-	-	-	-	n.a.	-	n.a.	-	-	-
Fluidised bed dryer											
Dried SF of digestate	103	94	93	94	93	n.a.	91	n.a.	103	93	93
Water vapour	-	-	-	-	-	n.a.	-	n.a.	-	-	-

Table 3-10 shows the calculated recovery efficiencies to the end products of the NRR system at Am-Power. Roughly 75% of the produced LF of digestate was processed by the evaporator because its processing capacity was not yet sufficient to treat all produced LF of digestate. The remaining 25% of the LF of digestate was applied as fertiliser to fields without further processing. Overall, 38% of NH_4-N and 11% of TP in the ingoing digestate were recovered as evaporator concentrate. Still 18% of NH_4-N in the ingoing digestate was recovered in the condensed water. Once the RO unit is operational, AmP plans to recover also the NH_4-N from the condensed water in the form of RO concentrate, thereby producing purified water as well. Thanks to the effective solid-liquid separation step, 93% of TP in the ingoing digestate was recovered in the form of dried SF of digestate. Of the TK in the ingoing digestate, 50% ended up in the evaporator concentrate.

Table 3-10 Recovery efficiencies to the end products of the NRR system at Am-Power for the period October 2020 – April 2021 for total nitrogen (TN), ammoniacal nitrogen (NH_4-N), total phosphorus (TP) and total potassium (TK) as percentage of the amounts in the ingoing digestate.

End product	**TN** %	**NH_4-N** %	**TP** %	**TK** %
Dried SF of digestate	31	4.1	93	28
Air scrubber water*	8.7	20	-	-
LF of digestate to the field	16	21	3.1	18
Evaporator concentrate	33	38	11	50
Condensed water	10	18	-	-
Total	99	101	107	96

*Calculated

3.6 Energy balance

3.6.1 Energy production

The amount of electrical energy produced by AmP decreased from 39 910 MWh_e in 2017 to 32 166 MWh_e in 2020 (Table 3-11). Consequently, the thermal energy production followed the same trend, decreasing from 44 256 MWh_{th} in 2017 to 29 727 MWh_{th} in 2020.

Table 3-11 Digestate, electrical energy and thermal energy production by the anaerobic digestion plant at Am-Power for the period 2017–2020.

	Digestate production (t y^{-1})	Working days	Electrical energy generation		Thermal energy generation	
			MWh	kWh t^{-1} digestate	MWh	kWh t^{-1} digestate
2017	170 590	365	39 910	234	44 256	259
2018	134 420	365	29 094	216	31 694	236
2019	161 280	365	35 295	219	37 730	234
2020	152 330	365	32 166	211	29 727	195

3.6.2 Energy consumption

The amount of electrical energy sold via the grid in the period 2017–2020 was >87% of the total amount of electrical energy generated on-site. The amount of thermal energy valorised by the plant was above 90% of the thermal energy generated by the CHP installation for all monitored years (Table 3-12). The valorised thermal energy includes the thermal energy consumption of the AD, NRR system and the offices. Only for 2017 was information on the amount of heat valorised on-site not available.

Table 3-12 Consumption of electrical energy and thermal energy by the anaerobic digestion plant and NRR system at Am-Power for the period 2017–2020.

	Digestate production (t y^{-1})	Working Days	Electrical energy consumption		Thermal energy consumption	
			MWh	kWh t^{-1} digestate	MWh	kWh t^{-1} digestate
2017	170 590	365	5 264	31	n.a.	n.a.
2018	134 420	365	3 641	27	30 439	226
2019	161 280	365	3 092	19	35 327	219
2020	152 330	365	4 220	28	28 283	186

An estimation of the energy (electrical and thermal) consumption of the NRR system is shown in Table 3-13. The electrical energy consumption of the current NRR system amounts to approximately 20% of the electrical energy generated in 2020. The estimated thermal energy consumption slightly exceeds the thermal energy generated by the AD plant at AmP. Detailed calculations and measurements are necessary to assess how much thermal energy is in practice used, especially for the evaporator. Nevertheless, AmP relies entirely on the thermal energy generated by the CHP installations and does not use any external source of natural gas.

Table 3-13 Consumption of electrical energy and thermal energy by the NRR system at Am-Power.

	Electrical energy consumption	Thermal energy consumption
	kWh_e t^{-1} digestate	kWh_{th} t^{-1} digestate
Decanter centrifuge	5.8	0
Fluidised bed dryer	18	199
Vacuum evaporator	14	124
Total	38	323

3.6.3 Energy balance

Based on the energy input and output of AmP, an energy balance was drafted for the year 2020 (Figure 3-13). For this it was assumed that 1 m^3 of CH_4 from biogas corresponds to 8.89 kWh of energy.

In 2020, 13% of the electricity generated was consumed by the AD plant and the NRR system of AmP. The heat generated, was largely valorised (95%) and reused on-site.

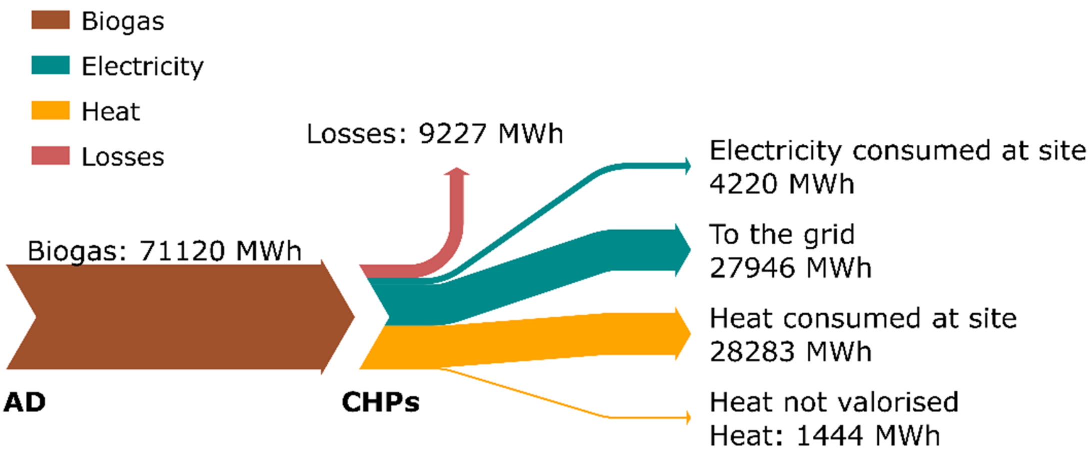

Figure 3-13 Energy production and consumption at Am-Power for the year 2020.

3.7 Temporal variation in product composition

Since start-up of the evaporator, the composition of digestate, intermediate process streams and end products has been monitored. This paragraph gives the composition of the ingoing digestate and the outgoing dried SF of digestate and evaporator concentrate over time.

For the digestate, OM and TOC content, pH and EC were quite constant over time (Figure 3-14a and c). Similarly, the DM content was rather stable as well, ranging between 75 and 91 g kg^{-1} FW. Fluctuations in TN and NH_4-N content show similar trends (Figure 3-14e). A decrease in TK and Na content was observed (Figure 3-14b and d). More insights in the causes of the temporal variation in digestate composition may be gathered from the temporal variation in the composition of the digester feedstock.

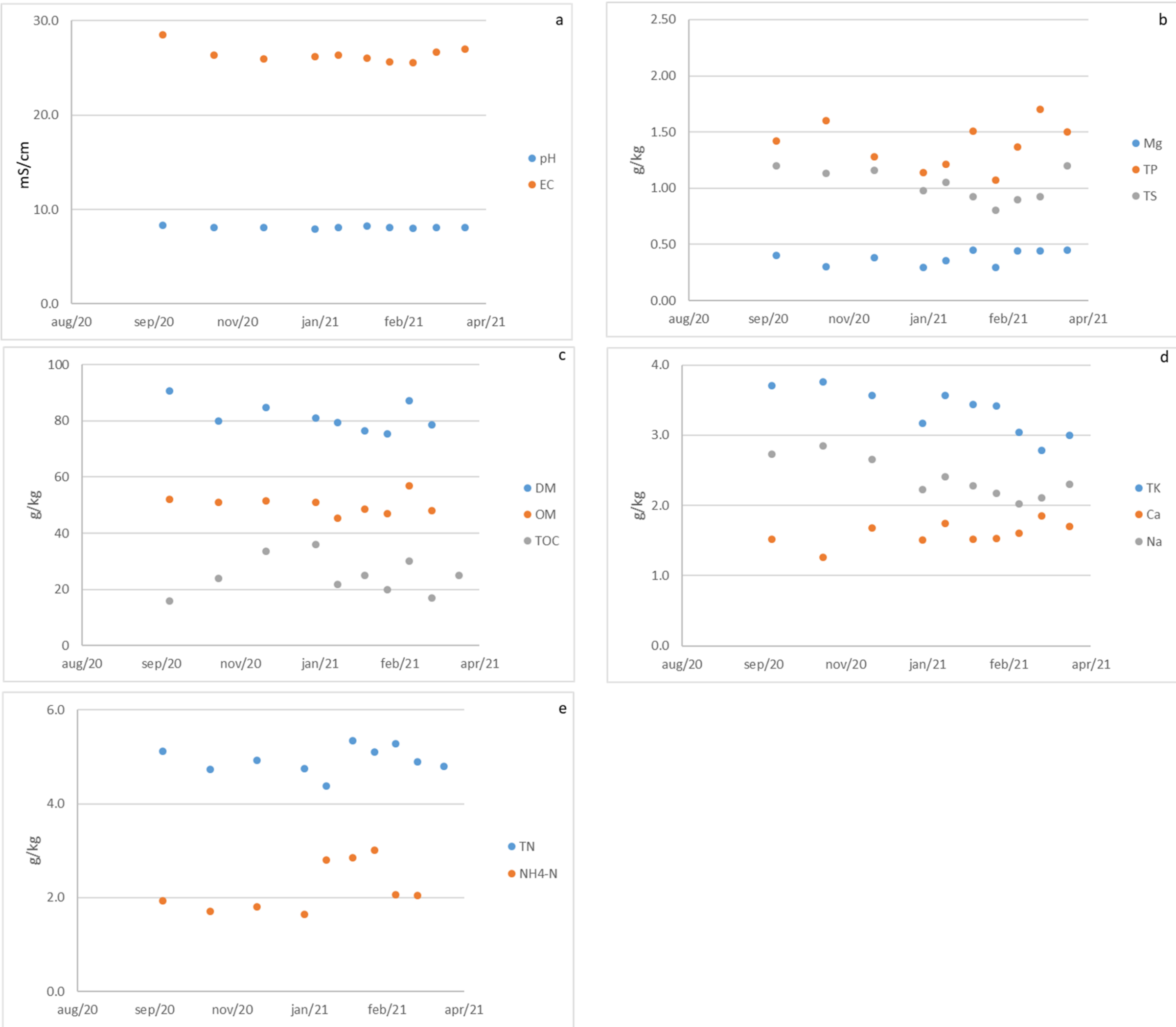

Figure 3-14 Composition (in fresh weight) over time of the digestate produced at Am-Power for the period October 2020 – April 2021: a) pH and electrical conductivity (EC); b) magnesium (Mg), total phosphorus (TP) and total sulphur (TS); c) dry matter (DM), organic matter (OM) and total organic carbon (TOC); d) total potassium (TK), calcium (Ca) and sodium (Na); e) total nitrogen (TN) and ammoniacal nitrogen (NH_4-N).

The composition of the dried SF of digestate fluctuated over time. Given the high content of TP (16–24 g kg^{-1}) and low content of N-NH_4 (<2.7 g kg^{-1}), this product is primarily a P fertiliser (Figure 3-15 c). The fraction of NH_4-N in TN was low (about 6.1%), except for one sampling round where it was 13% (Figure 3-15e) due to evaporation of N-NH_4 during drying.

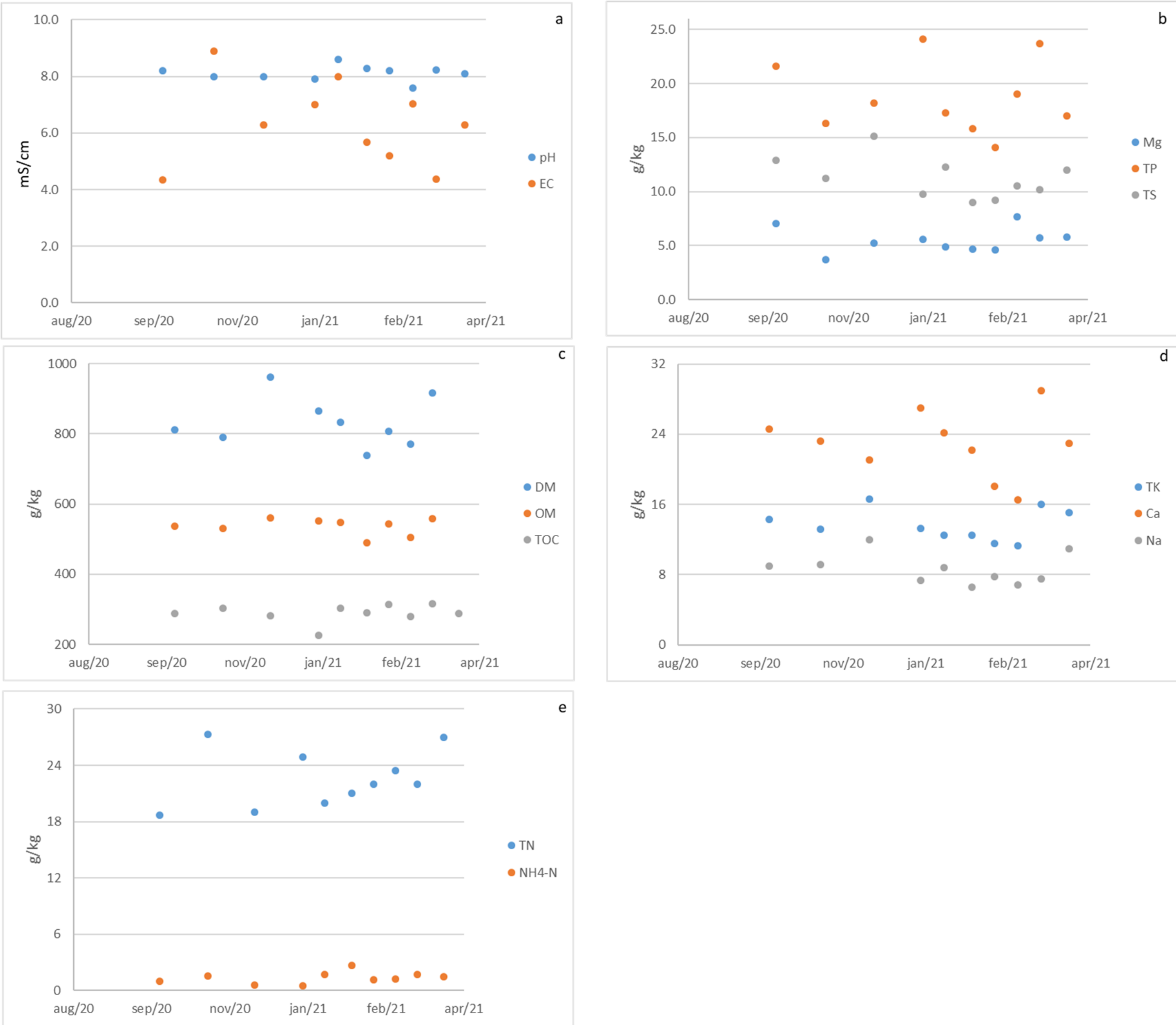

Figure 3-15 Composition (in fresh weight) over time of dried solid fraction of digestate produced at Am-Power for the period October 2020 – April 2021: a) pH and electrical conductivity (EC); b) magnesium (Mg), total phosphorus (TP) and total sulphur (TS); c) dry matter (DM), organic matter (OM) and total organic carbon (TOC); d) total potassium (TK), calcium (Ca) and sodium (Na); e) total nitrogen (TN) and ammoniacal nitrogen (NH_4-N).

Figure 3-16 shows an increase in DM, OM and TOC content of the evaporator concentrate for the sampling rounds from February 2021 onwards (Figure 3-16c). This is due to an increase in the evaporation capacity of the evaporator, resulting in higher concentrations of the non-evaporating components. This trend was only partially followed by NH_4-N as its concentration only increased slightly over time. This suggests that the acidification step prior to evaporation was not sufficient to prevent all NH_4-N from evaporating (Figure 3-16e). Conversely, the increase in DM content coincides with an increase in the contents of all macronutrients except NH_4-N (Figure 3-16b and d).

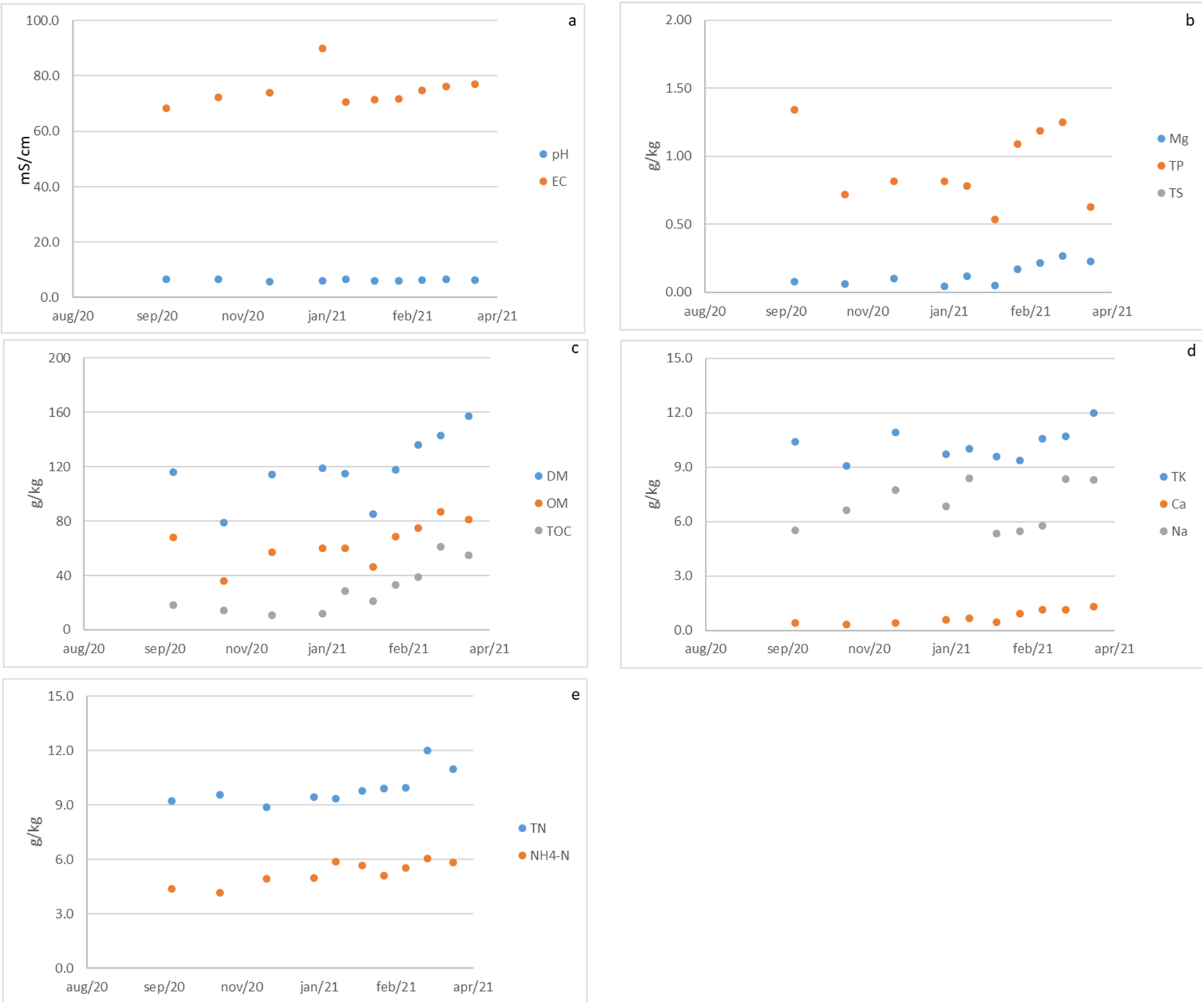

Figure 3-16 Composition (in fresh weight) over time of evaporator concentrate produced at Am-Power for the period October 2020 – April 2021: a) pH and electrical conductivity (EC); b) magnesium (Mg), total phosphorus (TP) and total sulphur (TS); c) dry matter (DM), organic matter (OM) and total organic carbon (TOC); d) total potassium (TK), calcium (Ca) and sodium (Na); e) total nitrogen (TN) and ammoniacal nitrogen (NH_4-N).

3.8 Overall performance of the NRR system

In Flanders, disposal of digestate produced from non-manure feedstocks to agriculture competes with disposal of animal manure to agricultural lands. AmP initially implemented an NRR system, that includes a DAF unit and RO installation, for the processing of LF of digestate with the main objective of reducing the total volume of digestate and its end products that have to be disposed. The SF of digestate was dried and exported to France (over about 300 km) as P-rich fertiliser. The main bottlenecks of this NRR system were:

- the high use and cost of chemicals (polymer flocculant and iron salts) required for an effective solid-liquid separation prior to membrane filtration;
- the high maintenance costs of the RO installation and;
- the low ratio of permeate water:RO concentrate (roughly 1:1) produced by the RO installation;
- the high costs for disposal of RO concentrate since there is no demand for it in nearby regions.

With the implementation of the vacuum evaporator, AmP aimed at reducing the volume of effluent by increasing the percentage of water removed. The monitoring campaign performed between October 2020 and April 2021 revealed that 75% of the water present in the LF of digestate was removed in the evaporator. The evaporator is therefore more effective in removal of water than the previous RO system was. Nevertheless, the quality of the condensed water does not yet comply with the Flemish discharge limits. AmP still investigates the best way to polish the condensed water with a smaller RO unit. The removal of the DAF unit decreased the use of polymer flocculant and iron salts for the solid-liquid separation step which will benefit the bioavailability of P in the end products. Implementation of the vacuum evaporator contributed to reaching one of SYSTEMIC's key performance targets, namely the implementation of enhanced nutrient recovery technologies (TRL 7-8).

Flanders is a P surplus region and already with the previous NRR system, the dried SF of digestate had to be transported over long distances in order to be disposed. Thanks to the higher volume reduction achieved by the current NRR system, AmP is planning to also transport the evaporator concentrate (rich in TN and TK) to France. More specifically AmP will mix the dried SF of digestate with the evaporator concentrate to obtain an NPK-rich organic fertiliser. Mixing the dried SF of digestate with evaporator concentrate also prevents dust formation during field application of the dried SF of digestate. By mixing the dried SF of digestate with the evaporator concentrate, AmP also aims to reach a DM content of 50-60%, in line with requests from French farmers. This will help to alleviate nutrient imbalances between nutrient-rich and nutrient-poor regions (a SYSTEMIC key performance target). Nevertheless, regulations for exporting products made from digestate from Flanders to France are complex. The easiest administrative framework for export of the mixture of dried SF of digestate and evaporator concentrate is the French NFU 44-051. It is applicable to hygienised and composted digestate with a DM content >30% and an NPK content <7%. Furthermore, compliance of the product with the NFU 44-051 norm should be checked by a French laboratory. The required minimal DM and maximal NPK content of the mixture can be achieved by blending the evaporator concentrate with the dried SF to increase DM and nutrient content. Moreover, the fertiliser must be sold at prices not compromising the French market. Products not covered by an NFU norm can be exported under the "specifications" decree developed for French digesters. Use of this decree is not recommended for AmP as Flemish digestate usually does not meet the decree requirements. Export to France is also possible via 'mutual recognition', i.e. a simplified certification procedure, via certification of the product in Belgium or via a homologation procedure to certify a new fertiliser in France. However, both the required procedures for the NFU norm and the mutual recognition take at least one year to complete. It therefore might be more efficient to aim for export of the mixture under the Fertilising Product Regulation (EU) 2019/1009, which will come into force in 2022.

4 Waterleau NewEnergy (Belgium)

4.1 General description of the plant

4.1.1 Introduction

Waterleau NewEnergy (WNE) is an environmental services company in the field of water, air and waste treatment. WNE runs an AD plant in Ypres (West-Flanders, Belgium; Figure 4-1) which occupies an area of 10 000 m^2. The plant is operational since 2012 and can digest roughly 120 kt feedstock at mesophilic conditions, including manure, agricultural waste and sludge from the agro-food industry. The produced digestate is processed in an NRR system that includes solid-liquid separation via a decanter centrifuge, drying of the SF of digestate, treatment of the LF of digestate in an aerated aerobic treatment tank for lowering the biochemical oxygen demand (BOD), up-concentration of the LF of digestate by an evaporator and effluent polishing by membrane filtration. Processing by the evaporator, in which both water and NH_3 evaporate, results in three outgoing process streams: evaporator concentrate, condensed ammonia water (NH_4-N > 10%) and process water (<0.1% NH_4-N). The evaporator concentrate has a DM content of circa 17%. Part of the process water is directly reused on-site, the other part is processed by two RO units placed in series. The permeate from the first RO unit is used for the preparation of the polymer flocculant solution. The permeate from the second RO unit, purified water, is discharged to surface water.

Figure 4-1 Aerial photo of the demonstration plant Waterleau NewEnergy, Ypres, Belgium.

4.1.2 Technical description of the biogas plant

The biogas plant of WNE was built in 2008 and has a maximum electric power generation of about 3.2 MWe (Table 4-1). It consists of two mesophilic digesters (4 000 m^3 each) and two post-digesters (2 200 m^3 each), operating respectively at 38–42 °C and 25–30 °C. In 2013, Waterleau environmental engineering bought the plant and subsequently implemented the NRR system.

Table 4-1 Technical information of the demonstration plant Waterleau NewEnergy.

Characteristics	
Year of construction	2008
Maximal electric power	3.2 MWe
Volume of the digesters	12 400 m^3
Digestion process	Mesophilic
Commissioning aerobic treatment system	End 2012
Commissioning evaporator and stripper	2013
Commissioning reverse osmosis installation	2013
Heat recovery (heat exchangers and heat re-use operational)	2013

4.1.3 Feedstock and hygienisation

The biogas plant processes about 70 kt of feedstock annually, including pig manure from local farms, sludge from wastewater treatment plants (WWTPs) that treat industrial wastewater (no sewage) and agro-food by-products. Pig manure and SF of pig manure constituted roughly 38% (for 2019) and 30% (for 2020) of the digester feedstock (Table 4-2). The added co-substrates are organic waste streams (e.g. potato waste, grain residues) and liquid products with a high energy content (e.g. molasses, glycerine).

The AD feedstock is pre-heated to 40 °C and mixed to an optimal DM content before being pumped to the anaerobic digesters. The residence time is around 30 days in the digester and an additional 10 days in the post-digester. The produced digestate is hygienised by heating it to 70 °C for one hour in a hygienisation tank. WNE has six hygienisation tanks, each with a volume of 10 m^3.

Table 4-2 Origin of anaerobic digestion feedstock of Waterleau NewEnergy, expressed in kilotonnes per year for the period 2019–2020.

Feedstock	**2019**	**2020**
Manure and SF of manure	25.2	21
Glycerine and molasses,	1.2	1.8
Other biowastes: grain residues, potato waste, sludge from industrial WWTPs	39.8	47.8
Total	66	71

4.1.4 Biogas production and energy generation

The biogas produced by WNE is desulphurised and converted into electricity and heat by the CHP installations. Annual production of biogas and methane were similar in 2019 and 2020. The biogas composition is shown in Table 4-3.

Table 4-3 Production and average composition of biogas before purification for the period 2019–2020 at Waterleau NewEnergy. Abbreviations: methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and oxygen (O_2).

Parameter	**Unit**	**2019**	**2020**
CH_4	%	56	55
CO_2	%	44	45
H_2S	ppm	<200	<200
O_2	%	<1	<1
Total biogas production	MNm^3	9.9	10.3
Specific biogas production	Nm^3 t^{-1} feedstock	129	150
Total CH_4 production	MNm^3	5.5	5.7
Specific CH_4 production	Nm^3 CH_4 t^{-1} feedstock	72.2	82.5

4.1.5 Other information

Labour
One plant manager, one administrative employee, two senior process engineers and eight operators working in shifts.

Waste production
- General waste (packaging, paper etc.): 50 t y^{-1} transported over 30 km for disposal
- Oil waste: 25 t y^{-1} transported over 45 km for disposal

Buildings and storage capacity
WNE includes the following buildings:
- Reception and offices: 120 m^2;
- Warehouse and mixing/heating modules: 324 m^2;
- NRR system: 864 m^2;
- Operational room and laboratory: 40 m^2.

WNE has the following storage capacity:
- AD feedstock
  - Manure: 800 m^3;
  - Dry substrates: 800 m^3;
  - Sludge from industrial WWTP's: 800 t;
  - Liquid products with a high energy content: 100 t;
- Sulphuric acid: 20 m^3;
- End products
  - Dried SF of digestate: 75 m^3;
  - Evaporator concentrate: 600 m^3;
  - Condensed ammonia water: 20 m^3;
  - Purified water: 30 m^3;

4.2 Drivers for nutrient recycling

4.2.1 Motivation for nutrient recycling

Since 2012, WNE has focussed on the implementation of nutrient and water recovery technologies. The produced digestate cannot be used on agricultural land in the region because of its 'animal manure' status. Costs for long distance transport (export) of the digestate would be too high due to the large volume and low nutrient content of the digestate. External biological nitrification-denitrification treatment would also be costly to WNE, costing about 15–20 € per tonne. WNE therefore has focussed on on-site technologies to remove water from the digestate and to concentrate the nutrients it contains resulting in the implemented NRR system. An alternative market for the ammoniacal nitrogen in the digestate was found in the period 2012–2015. This market is use of condensed ammonia water as an alternative for urea in DeNOx (selective non-catalytic reduction) systems for treatment of the flue gasses of incineration plants. Processing of the digestate into concentrated end products (evaporator concentrate and SF of digestate), removal of water and mixing of the end products to reach more desired NPK ratios can all reduce disposal costs and thereby increase the small profit margins for export to France. Also the NRR system provides a means to maximise the use of residual heat of the CHP installation, which provides WNE subsidies in the form of 'Heat certificates'.

4.2.2 Sustainability goals

WNE is currently redesigning their process as a whole, including optimization of the feedstock to increase the biogas production, which will also optimize the performance of some of the installed technologies. Also, the production of solid ammonium sulphate, as a dried product or mixed with composted SF of digestate

with nutrient ratios tailored to the need of the crop, is being investigated to further improve the use of the residual heat and to improve the marketability of the end products.
WNE is also aware that optimizing their technologies (with regard to efficiency and energy consumption) and producing end products with a lower CO_2 footprint, will ultimately also translate into economic benefits.

More specifically, WNE has the following goals:

- Reduction of the volume of the evaporator concentrate: reduce the volume of evaporator concentrate that needs to be transported over long distances.
- Cooperation with other local manure processors for synergetic use of process installations (i.e. biological nitrification-denitrification and evaporator/N-stripper, RO units) to reduce transport of liquid streams.
- Optimising the plant's electricity and heat generation and (re-)use.
- Discharging purified water or in the future even storing it as irrigation water for the surrounding agriculture.

4.2.3 Economic benefits

In Flanders, land application of digestate suffers from competition with animal manure. The cost for disposal of raw digestate fluctuate between 15 and 20 € per tonne. This includes transport of the digestate and biological treatment via nitrification-denitrification. With its NRR system, WNE currently has the following disposal costs. Of the produced evaporator concentrate, 70% is exported to the Netherlands at a cost of 40 € t^{-1} (including transport costs, storage costs, field application costs and the profit margin for the trader/contractor). The remaining 30% is blended with all the dried SF of digestate and revenues for this mixed product cover its transport costs. Disposal costs for the condensed ammonia water currently amount to 10–17 € t^{-1}. Overall, per tonne of produced and processed digestate, between 11–16 € are saved by the current NRR system compared to conventional disposal.
Yet, a more thorough analysis of the digestate processing costs is needed to evaluate the economic feasibility of the NRR system in more detail.

4.3 The nutrient recovery installation

4.3.1 Technical description of the installation

Digestate is separated into an SF of digestate and an LF of digestate by a decanter centrifuge, with addition of polymer flocculant solution (DM content <0.2%) to improve the solid-liquid separation. The SF of digestate is dried in a rotating disc dryer (Hydrogone®), which can evaporate 1–1.8 t of water per hour. The dried SF of digestate is thereafter composted externally. The air from the dryer is treated by an air scrubber which produces ASW. The LF of digestate, together with the evaporated water and the ASW flow to an aerated aerobic treatment tank for lowering of the mixture's BOD. Part of the effluent of the aerobic treatment tank is fed back to the anaerobic digester. The remainder of the effluent flows to a falling film evaporator that operates at temperatures of 50–60 °C and can operate at temperatures up to 75 °C. The produced evaporator concentrate (rich in N, P and K), with a DM content of circa 17%, is partly exported as organic fertiliser and partly mixed with the dried SF of digestate. In the evaporator, NH_3 and water evaporate which after condensation of the vapours forms condensed ammonia water. The condensed ammonia water has an NH_4-N content of around 10%, it is used in the DeNOx system of a local incineration plant for treatment of the plant's flue gasses. The evaporator also produces condensed water with a low N content (<0.1%), called process water. The process water is reused, mostly for the recovery of heat in the cooling towers, the dilution of the LF of digestate in the aerobic treatment tank and for daily cleaning operations. A biofilter prevents emissions to air of volatile components, other than water, from the cooling tower. Alternatively, the process water can be polished in an RO installation consisting of two RO units. The permeate water produced by the first RO unit is usually used for the preparation of polymer flocculant solution. Alternatively the permeate water of the first RO unit can be further polished in a second RO unit, producing dischargeable purified water. The concentrates produced by the RO units are fed back to the aerobic treatment tank (Figure 4-2). Table 4-5 provides an overview of the chemical consumption of the NRR system and the anaerobic digestion plant of WNE.

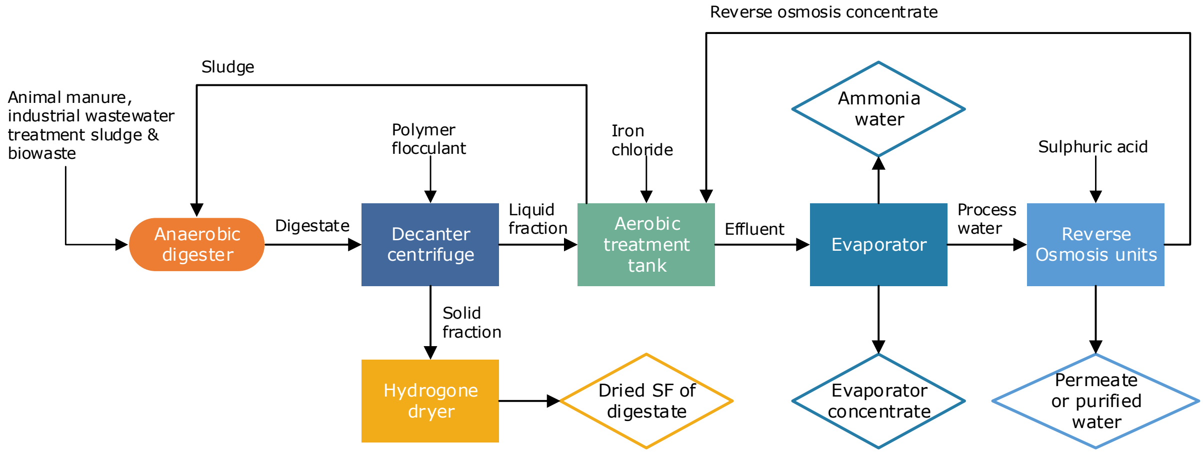

Figure 4-1 Simplified process flow diagram of the NRR system at the demonstration plant Waterleau NewEnergy including locations of chemical addition and the major return flows (as configured in October 2021).

Table 4-5 Chemical consumption of the NRR system and the anaerobic digestion plant of Waterleau NewEnergy in tonnes per year (based on purchasing) for processing of about 65 kilotonnes digestate per year.

Substance	**Concentration (% m/m)**	**Function**	**Estimated use ($t\ y^{-1}$)**
Polymer flocculant	100% powder	Flocculant	12
Iron chloride ($FeCl_3$) solution	40%	Coagulant	5–6
Sulphuric acid (H_2SO_4)	96%	Acid for RO operation	273
Antifoaming agent 1	100%	Antifoaming agent for the evaporator	38.2
Antifoaming agent 2	100%	Antifoaming agent for the decanter centrifuge	14

4.3.2 Total production of digestate and other products

Table 4-6 shows the amount of ingoing digestate and outgoing end products at WNE for the years 2019 and 2020. Currently, all dried SF of digestate (about 3 000 t per year) is mixed with part of the evaporator concentrate (about 2 500 t per year) and thereafter composted at an external facility. The composted product is exported over a distance of up to 100 km to northern France. The remaining part of the evaporator concentrate (about 5833 t per year), which represents 70% of the total production is exported to Zeeland, a province in the south of the Netherlands over a distance of 120 km. The condensed ammonia water (724 t per year) is transported to an incineration plant over a distance of 58 km where it is used as DeNOx agent. Finally, all RO permeate of the first RO unit is reused on-site and only 3.66 t per year of purified water, produced by the second RO unit, is discharged.

Table 4-6 Total production of digestate and end products at Waterleau NewEnergy in tonnes per year for the period 2019–2020.

Digestate and end products	**Unit**	**2019**	**2020**
Digestate	$t\ y^{-1}$	60 000	65 000
Dried SF digestate	$t\ y^{-1}$	3 200	≈ 3 000
Evaporator concentrate	$t\ y^{-1}$	12 000	8 333
Condensed ammonia water	$t\ y^{-1}$	550	724
RO concentrate	$t\ y^{-1}$	10 000	3 803
RO permeate	$t\ y^{-1}$	30 000	22 655

Purified water	t y^{-1}	-	3.66

4.4 Mass flows and balances of the current NRR system

4.4.1 Monitoring and sampling

Samples of the ingoing and outgoing process streams of the individual process units were collected and chemically analysed every month by Ghent University for the period June 2020 – October 2020. Table 4-7 shows the average content of macronutrients, micronutrients and heavy metals of those process streams. Only those parameters that have been measured in every process stream, and are thus relevant for the mass balance, are shown. The full characterisation of the produced digestate and end products is available in deliverable 1.13.

The RO installation however only operated in a stable way in November and December 2020. Over these two months, samples of the ingoing and outgoing process flows of both RO units were taken. The chemical characterisation of the produced purified water is included in deliverable D1.13.

Ingoing and outgoing volume flow rates of the evaporator and decanter centrifuge were measured via flowmeters, except for the flow of SF of digestate, which was tracked in terms of produced total mass of SF of digestate by WNE. Mass flows for the dried SF of digestate were subsequently calculated based on the K contents of the SF of digestate and the dried SF of digestate. Nutrient mass flows were calculated by multiplying the volume flow rates with the measured concentrations for each of the process streams.

4.4.2 Chemical characterisation of digestate and end products

The average composition of the ingoing digestate, intermediate process streams and end products of the NRR system at Waterleau NewEnergy for the period June – October 2020 are shown in Table 4-7.

The produced dried SF of digestate can be used as a P-rich soil improver due to its high TP content of up to 30 g kg^{-1} FW. Nevertheless, with 16% of TN present in the form of NH_4-N, appropriate handling and field application of this product are required to prevent NH_3 losses to the air.
The low NH_4-N:TN ratio of on average 0.48 does not make the evaporator concentrate a suitable replacement for synthetic N fertilisers. In contrast, the high TK content (above 14 g kg^{-1} FW) makes the evaporator concentrate an interesting organic K-rich fertiliser. At the time of writing WNE mixed part of the evaporator concentrate with the dried SF of digestate to obtain a PK-rich soil improver for the French market.

The produced ASW can be used as replacement for mineral-N fertiliser. In a 3-year field trial, Vaneeckhaute *et al*. (2013) reported limited improvements on maize yield on the one hand, but significant ecological and economic advantages when digestate derived products (e.g. ASW) were used as replacement for animal manure in combination with synthetic fertilisers. Also, results from a greenhouse experiment on lettuce with a duration of <1 year, reported similar fresh yields and post-harvest NO_3-N levels in soils for the application of ASW compared to conventional fertilisation. Moreover, the use of ASW resulted in a higher Nitrogen Use Efficiency (NUE) when used as mineral-N fertiliser compared to conventional fertilisation (Sigurnjak *et al*. 2016).

Table 4-7 Chemical characterisation (in fresh weight) of the ingoing digestate, intermediate process streams and end products of the NRR system at the demonstration plant Waterleau NewEnergy for the period June–October 2020. Average of four samples ± one standard deviation.

Parameter	**Unit**	**Digestate**	**LF of digestate**	**SF of digestate**	**Dried SF of digestate**	**Air scrubber water**
pH		8.6 ± 0.26	8.8 ± 0.26	8.6 ± 0.10	8.2 ± 0.25	3.7 ± 0.29

EC	mS cm^{-1}	36 ± 1.1	33 ± 0.61	6.1 ± 1.7	8.4 ± 0.26	55 ± 16
DM	g kg^{-1}	54 ± 8.2	27 ± 2.3	234 ± 12	943 ± 29	56 ± 7.4
OM	g kg^{-1}	31 ± 5.1	13 ± 2.7	161 ± 5.2	642 ± 28	-
TN	g kg^{-1}	6.5 ± 0.21	5.8 ± 0.29	8.8 ± 0.22	27 ± 4.4	12 ± 2.6
NH_4-N	g kg^{-1}	3.9 ± 0.59	3.9 ± 0.33	3.9 ± 0.49	5.0 ± 1.2	12 ± 1.3
TP	g kg^{-1}	0.91 ± 0.31	0.25 ± 0.079	5.5 ± 1.2	24 ± 3.8	0.0029 ± 0.0037
TK	g kg^{-1}	4.0 ± 0.68	3.4 ± 0.69	3.8 ± 0.65	16 ± 1.7	0.018 ± 0.020
TS	g kg^{-1}	0.90 ± 0.11	0.55 ± 0.12	2.5 ± 0.20	10 ± 0.58	13 ± 0.90
Ca	g kg^{-1}	1.2 ± 0.51	0.18 ± 0.062	8.3 ± 2.2	36 ± 10	0.013 ± 0.022
Mg	g kg^{-1}	0.30 ± 0.057	0.030 ± 0.0025	2.1 ± 0.29	9.4 ± 0.31	0.0041 ± 0.0071
Na	g kg^{-1}	2.2 ± 0.40	2.0 ± 0.39	2.2 ± 0.22	8.5 ± 0.58	0.012 ± 0.015
Parameter	**Unit**	**Aerobic treatment effluent**	**Evaporator influent**	**Evaporator concentrate**	**Process water**	**Condensed ammonia water**
pH		9.2 ± 0.22	9.3 ± 0.17	8.9 ± 0.81	10 ± 0.10	11 ± 0.21
EC	mS cm^{-1}	28 ± 0.58	29 ± 1.5	90 ± 10	3.6 ± 0.78	118 ± 7.2
DM	g kg^{-1}	21 ± 1.5	22 ± 0.50	174 ± 22	-	-
OM	g kg^{-1}	10 ± 1.6	10 ± 2.3	81 ± 15	-	-
TN	g kg^{-1}	4.6 ± 0.41	4.6 ± 0.43	12 ± 2.6	1.6 ± 0.088	105 ± 4.3
NH_4-N	g kg^{-1}	3.2 ± 0.80	3.1 ± 0.74	1.5 ± 0.87	1.5 ± 0.091	102 ± 4.4
TP	g kg^{-1}	0.19 ± 0.061	0.21 ± 0.094	1.6 ± 0.36	0.00055 ± 0.00049	0.00039 ± 0.00070
TK	g kg^{-1}	2.9 ± 0.30	3.0 ± 0.58	24 ± 4.6	0.0010 ± 0.0012	0.00011 ± 0.00075
TS	g kg^{-1}	0.66 ± 0.038	0.76 ± 0.042	6.5 ± 0.57	0.014 ± 0.011	0.58 ± 0.58
Ca	g kg^{-1}	0.14 ± 0.042	0.15 ± 0.041	1.2 ± 0.30	0.00079 ± 0.00081	0.00010 ± 0.00012
Mg	g kg^{-1}	0.024 ± 0.010	0.029 ± 0.015	0.24 ± 0.044	0.00011 ± 0.00012	0.000052 ± 0.0000032
Na	g kg^{-1}	1.7 ± 0.067	1.6 ± 0.046	13 ± 0.98	0.00018 ± 0.000068	0.0011 ± 0.0014

4.4.3 Mass flow analyses of macronutrients, micronutrients and heavy metals

Figure 4-3 shows the calculated mass flows for DM and water of the NRR system at WNE. Mass flows were either measured (liquid streams) by flowmeters or calculated (SF of digestate and dried SF of digestate) as previously described.

On average, 244 t d^{-1} of digestate were produced by the AD of animal manure, agro-food waste and sludge from industrial WWTPs. Digestate was separated by the decanter centrifuge into 242 t d^{-1} of LF of digestate and 30 t d^{-1} of SF of digestate. To the influent of the decanter centrifuge, 28 t d^{-1} of 0.060% polymer flocculant solution were added, to improve solid-liquid separation. Drying of the SF of digestate resulted in 7.1 t d^{-1} of dried SF of digestate. The vapours of the dryer are processed by an air scrubber, thereby recovering evaporated NH_3. Over the monitoring period, the air scrubber produced 6 t d^{-1} of ASW and 17 t d^{-1} of condensed water and consumed 0.25 t d^{-1} of 96% sulphuric acid. The ASW and the condensed water were, together with the LF of digestate and part of the process water from the evaporator (60 t d^{-1}), sent to the aerobic treatment tank. Of the effluent of the aerobic treatment tank, 73 t d^{-1} were fed back to the anaerobic digester and 251 t d^{-1} were stored and subsequently processed in the evaporator. The evaporator produced evaporator concentrate (30 t d^{-1}), condensed ammonia water (3.9 t d^{-1}) and process water (217 t d^{-1}). The latter was used to dilute the LF of digestate in the aerobic treatment tank (60 t d^{-1}), processed by the first RO unit to produce RO permeate for the preparation of polymer flocculant solution (28 t d^{-1}) and used as cleaning water (25 t d^{-1}). Finally, about 105 t d^{-1} evaporated as cooling water in the cooling towers.

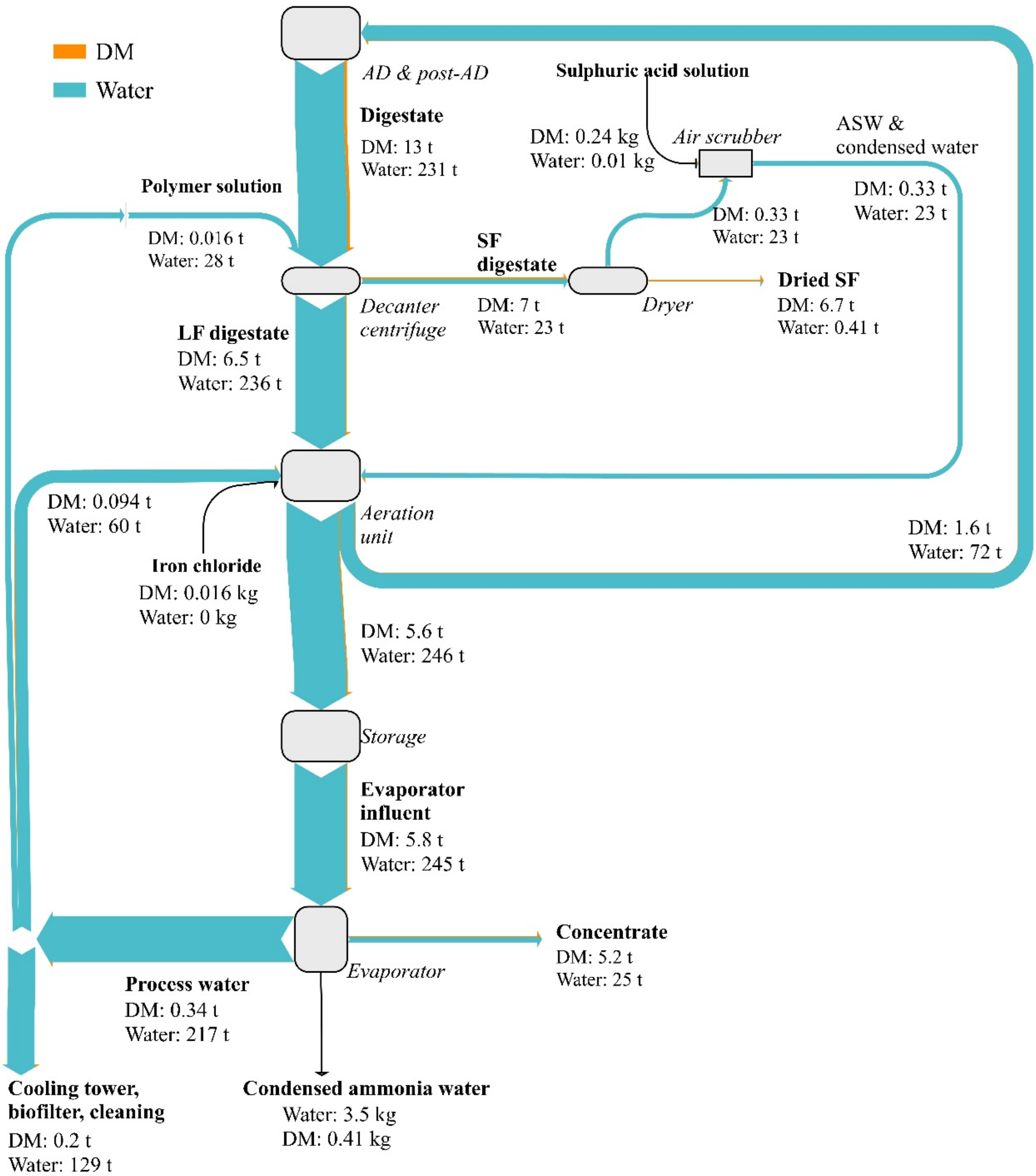

Figure 4-3 Dry matter (DM) and water mass flows of the NRR system at the demonstration plant Waterleau NewEnergy in tonnes per day for the period June – October 2020. Process streams: liquid fraction of digestate (LF digestate), solid fraction of digestate (SF digestate), dried solid fraction of digestate (Dried SF) and air scrubber water (ASW).

Figure 4-4 shows the flows of organic nitrogen and ammoniacal nitrogen of the NRR system at WNE. On average, 1601 kg TN (634 kg d^{-1} of organic nitrogen and 967 kg d^{-1} of ammoniacal nitrogen) were produced in the form of digestate by the AD of biowaste. The solid-liquid separation step (decanter centrifuge with polymeric flocculant addition) applied by WNE effectively separates OM, TP and TS to the SF of digestate, whereas water, NH_4-N and TK mainly end up in the LF of digestate. About 396 kg d^{-1} of NH_4-N ended up in the condensed ammonia water. By drying, the NH_4-N:TN ratio decreased from 0.44 in the SF of digestate to 0.17 in the dried SF of digestate. Of the evaporated NH_4-N in the dryer, 70 kg d^{-1} was recovered as air scrubber water. The influent of the evaporator contained 1144 kg TN d^{-1} whereas the outgoing evaporator streams together contain 1048 kg TN d^{-1}. In contrast the influent of the evaporator contained 856 kg NH_4-N d^{-1} whereas the outgoing evaporator streams together contain 895 kg NH_4-N d^{-1}. These calculated small imbalances over the evaporator are likely caused by small deviations in the measured flows by the flowmeters and/or by temporal fluctuations in the concentrations of the process streams that cannot be captured by the performed discontinuous sampling.

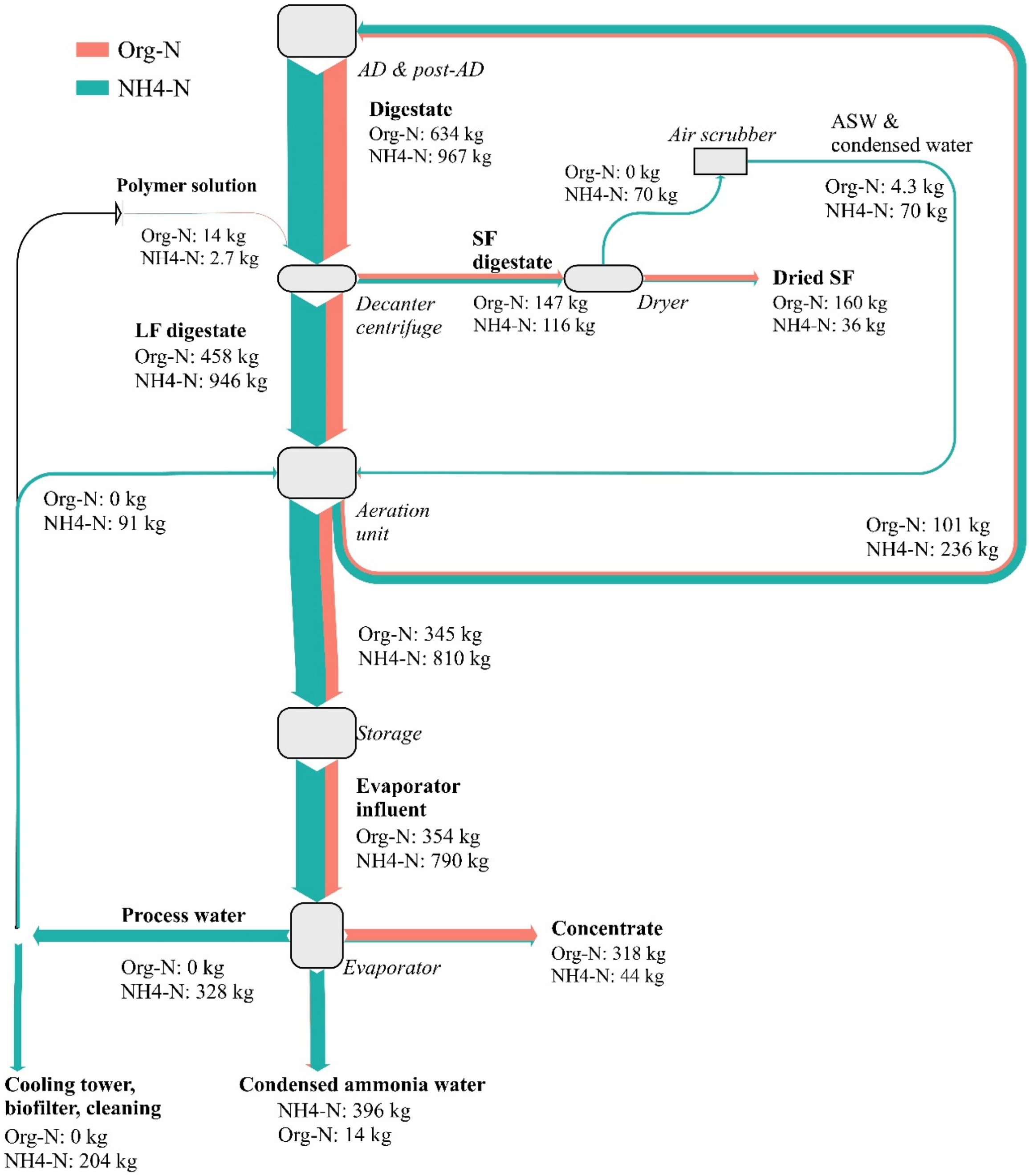

Figure 4-4 Organic nitrogen (Org-N) and ammoniacal nitrogen (NH_4-N) flows of the NRR system at the demonstration plant Waterleau NewEnergy in kg per day for the period June – October 2020. Process flows: liquid fraction of digestate (LF digestate), solid fraction of digestate (SF digestate), dried solid fraction of digestate (Dried SF) and air scrubber water (ASW).

Figure 4-5 shows the flows of TP and TK of the NRR system of WNE. On average, 223 kg d^{-1} of TP and 984 kg d^{-1} of TK were produced in the form of digestate by the AD. This includes retour flows (14 kg d^{-1} of TP and 215 kg d^{-1} of TK) to the AD. Flows of TP show the same trend as those of DM and OM. About 78% of the TP in the ingoing digestate ended up in the dried SF of digestate. As TK in the digestate was mainly present in the form of solubilised cations (K^+): 85% of it ended up in the LF of digestate

A slight accumulation of TP (about 6%) was calculated in the dried SF of digestate. Conversely, a loss of 7% of TP was found during the evaporation step. A slight accumulation of TK was registered in the aeration tank (10%), whereas it was roughly in equilibrium in both decanter and evaporator. TK is mainly present in its ionic form in digestate (K^+), it was found to follow the LF pathway. Overall, the NRR system at WNE effectively separated TP to the dried SF of digestate. It also effectively separated NH_4-N and TK to the evaporator concentrate.

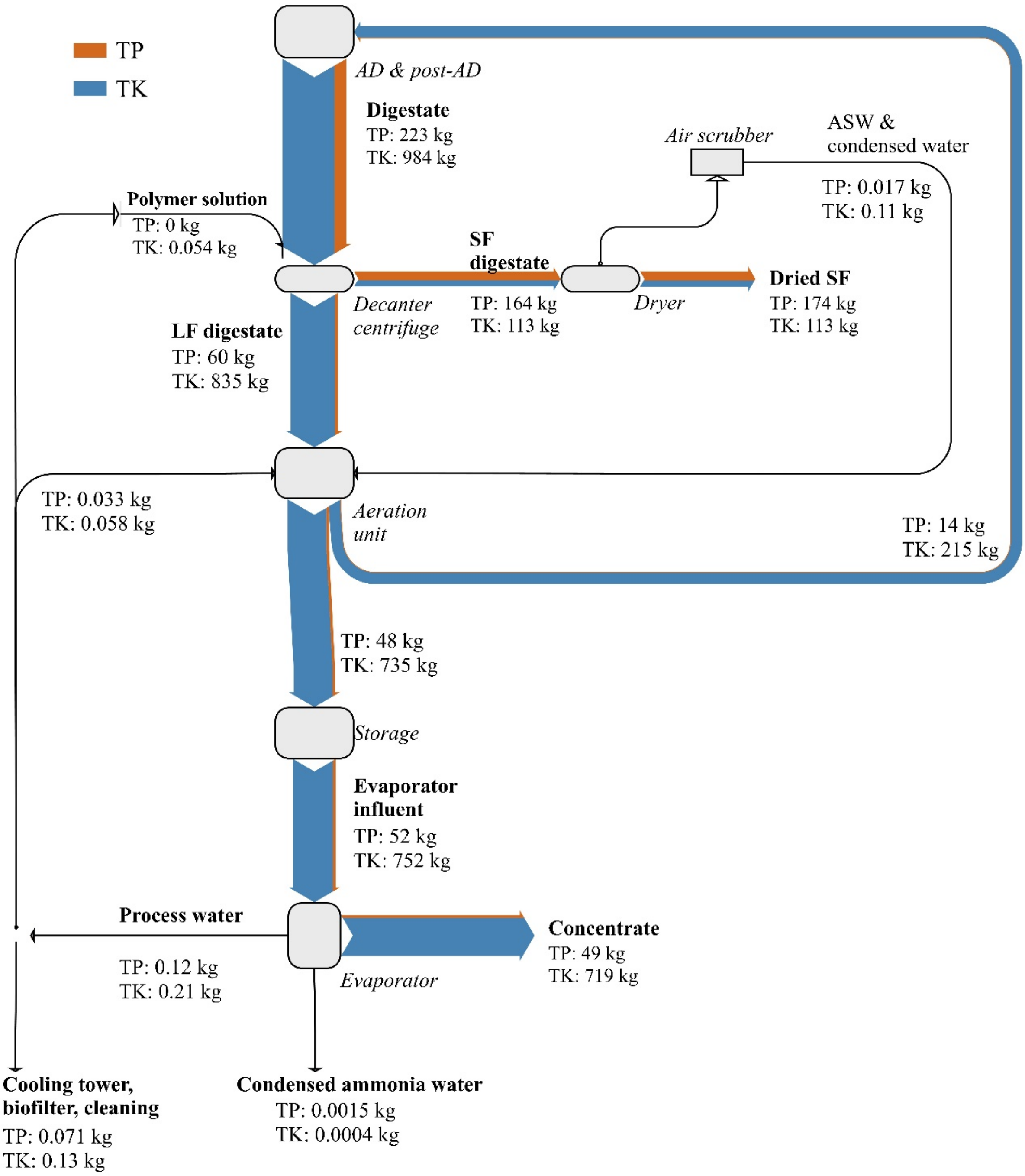

Figure 4-5 Total phosphorus (TP) and total potassium (TK) flows of the NRR system at the demonstration plant Waterleau NewEnergy in kg per day for the period June – October 2020. Process flows: liquid fraction of digestate (LF digestate), solid fraction of digestate (SF digestate), dried solid fraction of digestate (Dried SF) and air scrubber water (ASW).

4.4.4 Separation and nutrient recovery efficiencies of process units

Table 4-8 shows the calculated separation efficiencies of the individual process units of the NRR system at WNE as a percentage of the ingoing amount of each parameter. On average, 89% of the total mass of ingoing digestate ended up in the LF of digestate and 11% in the SF of digestate. The SF of digestate contained respectively 16% and 73% of the ingoing amounts of TN and TP. The evaporator effectively concentrated 93% of the ingoing DM in a relatively small volume as the evaporator concentrate only constitutes 12% of the ingoing total mass. Similarly, the majority of TP and TK in the evaporator influent ended up in the evaporator concentrate. It was assumed that 100% of TK in the SF of digestate ended up in the dried SF of digestate.

Table 4-8 Separation efficiencies of the process units of the NRR system at Waterleau NewEnergy for the period June–October 2020 for the following parameters: total mass, moisture (H_2O), dry matter (DM), organic matter (OM) and macronutrients.

	Total mass %	**H_2O %**	**DM %**	**OM %**	**TN %**	**NH_4-N %**
Decanter centrifuge						
LF of digestate	89	91	49	41	87	98
SF of digestate	11	8.8	53	63	16	11
Evaporator						
Evaporator concentrate	12	1.4	93	96	32	5.5
Condensed ammonia water	1.6	10	7.4		36	50
Process water	86	88	6.1	-	30	42
Dryer						
Dried SF	24	99	97	96	75	33
Air scrubber water		1.8			28	64
	TP %	**TK %**	**TS %**	**Ca %**	**Mg %**	**Na %**
Decanter centrifuge						
LF of digestate	27	85	60	16	10	89
SF of digestate	73	12	33	87	86	12
Evaporator						
Evaporator concentrate	93	96	102	102	100	100
Condensed ammonia water	0.0029	0.00006	1.2	0.0011	0.0028	0.0011
Process water	0.23	0.028	1.6	0.47	0.34	0.1
Dryer						
Dried SF	106	100	95	105	108	94
Air scrubber water	0.011	-	-	-	-	-

Table 4-9 shows the calculated recovery efficiencies to the end products of the NRR system at WNE based on four months of monitoring. Of the TN in the ingoing digestate, 12% ended up in the dried SF of digestate, for the majority in the form of organic N. Overall, 18% of NH_4-N, 22% of TP and 73% of TK in the ingoing digestate were recovered as evaporator concentrate. Still 13% of TN in the ingoing digestate is not valorised because it ends up as process water in the cooling towers where the majority of it is subsequently, after evaporation, converted to N_2 by a biofilter. From June until October 2020, the RO installation was not operational. When it is operational, N is recovered from the process water in the form of RO concentrate and recirculated to the influent of the evaporator. The majority of NH_4-N in the RO concentrate is present as dissolved ammonium sulphate due to the addition of sulphuric acid on the RO installation. This leads to enrichment of the evaporator concentrate with sulphur. Thanks to the efficient solid-liquid separation, 78% of TP was recovered in the form of dried SF of digestate and 73% of TK as evaporator concentrate. For NH_4-N, TP and TK the sum of the recovery efficiencies to the end products is close to 100%. The <10% deviations from 100% are most likely caused by small deviations in the measured volume flows by the flowmeters and/or by temporal fluctuations in the concentrations of the process streams that cannot be captured by the performed discontinuous sampling. Part of the TN and NH_4-N will be converted to N_2 in the aerobic treatment tank which might explain why the sum of their recoveries is below 100% whilst those for TP and TK are above 100%. Additionally, a portion of TN, NH_4-N, TP and TK will end up in the biological activated sludge produced by the aerobic treatment tank.

Table 4-9 Recovery efficiencies to the end products of the NRR system at Waterleau NewEnergy for the period June–October 2020 for total nitrogen (TN), ammoniacal nitrogen (NH_4-N), total phosphorus (TP) and total potassium (TK) as percentage of the amounts in the ingoing digestate.

End product	TN %	NH_4-N %	TP %	TK %
Dried solid fraction of digestate	12	3.7	78	12
Evaporator concentrate	23	4.5	22	73
Condensed ammonia water	26	41	0.001	<0.0001
Effluent aerobic treatment tank[a]	21	24	6.3	22
Process water eliminated	13	20	0.032	0.013
Total	83	93	106	107

[a] the part of the effluent of the aerobic treatment tank that is fed back to the anaerobic digester.

4.5 Energy balance

4.5.1 Energy production

In 2020, 71 kt of feedstock was digested by WNE resulting in 65 kt of digestate and 10.3 MNm^3 of biogas. The latter was used to generate 21 313 MWh of electricity and 22 800 MWh of thermal energy (Table 4-10).

Table 4-10 Electricity and heat generation by the anaerobic digestion plant at Waterleau NewEnergy for the year 2020.

	Digestate production ($t\ y^{-1}$)	Working days	Electricity generation		Thermal energy generation	
			MWh	$kWh\ t^{-1}$ digestate	MWh	$kWh\ t^{-1}$ digestate
2020	65 000	350	21 313	327.9	22 800	350

4.5.2 Energy consumption

Table 4-11 shown the estimation of the energy (electricity and thermal energy) consumption of the AD plant and NRR system. The energy consumption of the digester and post-digester is however not known. The process units of the NRR system of WNE that are most energy demanding are the evaporator (45 $kWh_e\ t^{-1}$ digestate), followed by the dryer (32 $kWh_e\ t^{-1}$ digestate) and the aerobic treatment tank (19 $kWh_e\ t^{-1}$ digestate, respectively). The evaporator and dryer also have the highest heat consumptions of the process units, respectively 196 and 112 $kWh_{th}\ t^{-1}$ digestate.

Table 4-11 Electricity and heat consumption of the anaerobic digestion plant and NRR system at Waterleau NewEnergy for the year 2020.

	Digestate production (t y^{-1})	Electricity consumption		Thermal energy consumption	
		MWh_e	kWh_e t^{-1} digestate	MWh_{th}	kWh_{th} t^{-1} digestate
2020					
Digester & post-digester	65 000	Not known	Not known	Not known	Not known
Hygienisation tanks	65 000	198	3.0	2 840	44
Decanter centrifuge(s)	65 000	248	3.8	0	0
Aerobic treatment tank	65 000	1 242	19	0	0
Evaporator	65 000	2 900	45	12 740	196
RO installation	65 000	86	1.3	0	0
External buildings	0	0	0	Not known	Not known
Rotating disc dryer	65 000	2 070	32	7 308	112
Total	65 000	6 744	104	22 888	352

4.5.3 Energy balance

Based on the energy input and output of WNE, an energy balance was drafted for the year 2020 (Figure 4-6). For this it was assumed that 1 m^3 of CH_4 from biogas corresponds to 8.89 kWh of energy. The energy consumption of the AD plant and external buildings are not included as that information was not available.

In 2020, 32% of the electricity generated was consumed by the NRR system. More specifically, 14% by the evaporator, 10% by the dryer, 5.8% by the aerobic treatment tank, 1.2% by the decanter centrifuges, 0.93% by the hygienisation tanks and 0.4% by the RO installation. The generated heat was entirely valorised and reused on-site by the hygienisation tanks (12%), dryer (31%) and evaporator (56%).

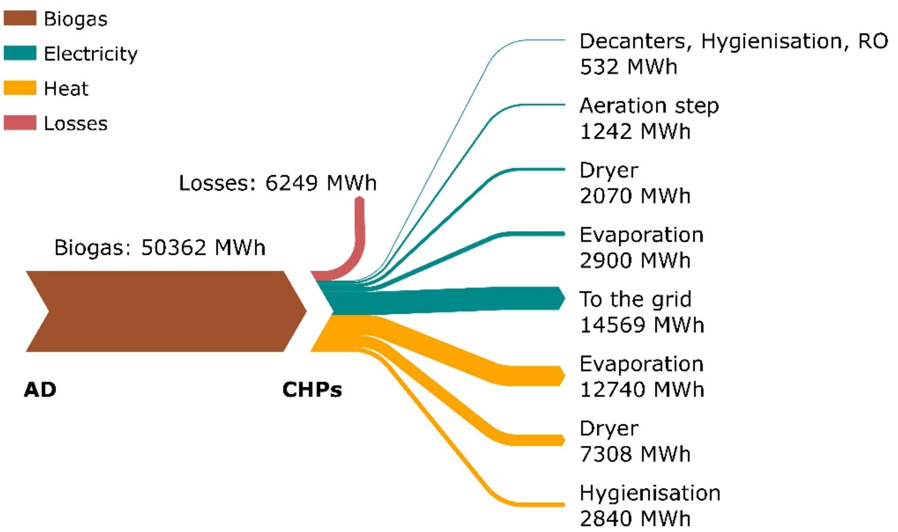

Figure 4-6 Energy production and consumption at Waterleau NewEnergy for the year 2020.

4.6 Temporal variation in product composition

Since the end of 2019, the composition of digestate, intermediate process streams and end products has been monitored. This paragraph gives the composition of the ingoing digestate and the outgoing dried SF of digestate and evaporator concentrate over time.

For the digestate, pH and EC did not vary much over time (Figure 4-7a), whereas the contents of OM and TOC (and consequently the content of DM as well) varied over time. DM content ranged between 44 and 72 g kg^{-1} FW). TN was fairly stable over time whereas NH_4-N showed more variation over time (Figure 4-7e). Contents of Mg, TP and TS (Figure 4-7b) and Ca showed large variability over time (Figure 4-7d). Contents of TK and Na varied less, however with a large high content outlier around May 2020. Not only the temporal variation in the feedstock of the digester can have been the cause of these variations but also variations in the volume flow and content of the effluent of the aerobic treatment tank that is fed back to the AD can have been a cause for this.

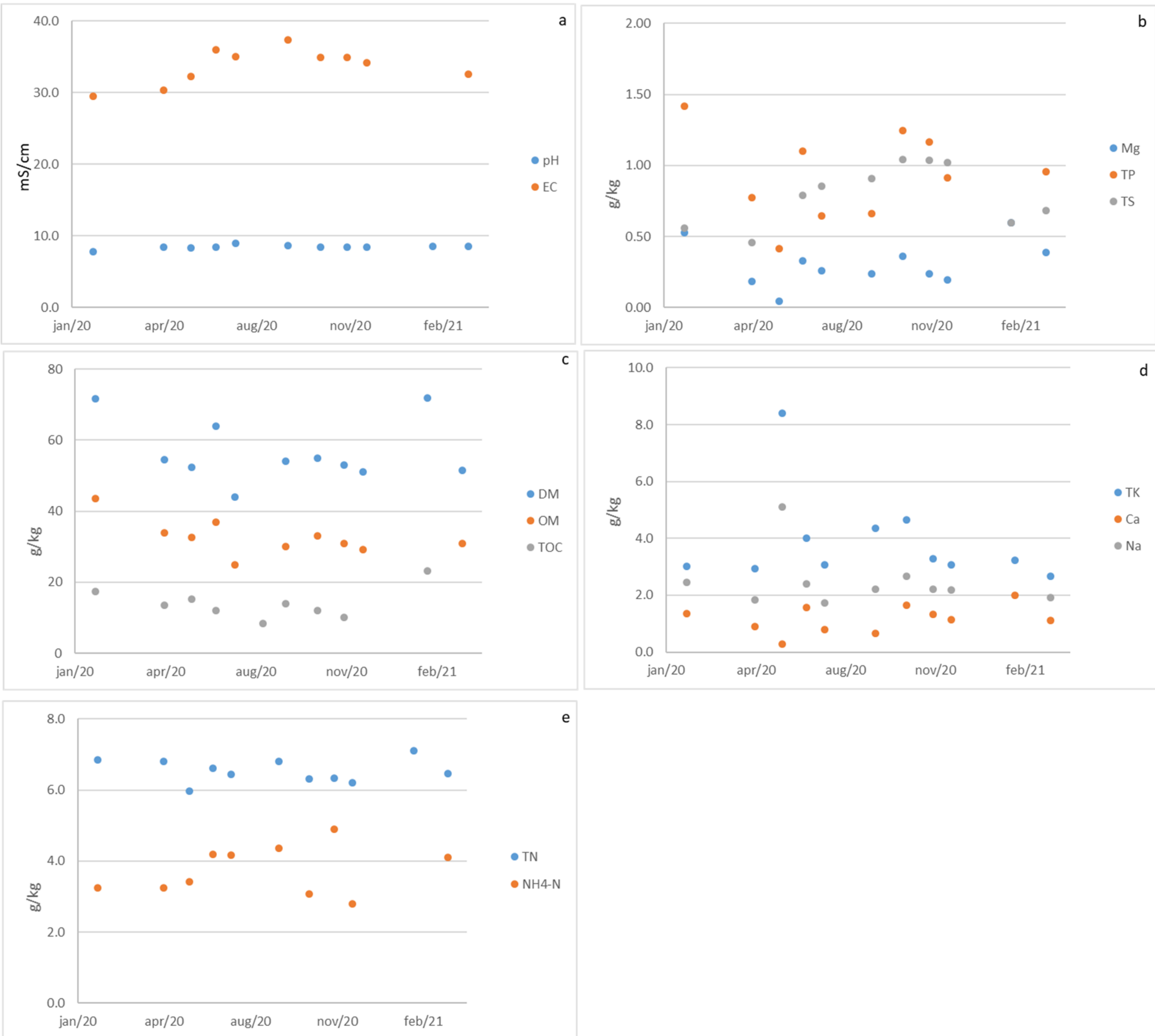

Figure 4-7 Composition (in fresh weight) over time of the digestate produced at Waterleau NewEnergy for the period February 2020 – March 2021: a) pH and electrical conductivity (EC); b) magnesium (Mg), b) total phosphorus (TP) and total sulphur (TS); c) dry matter (DM), organic matter (OM) and total organic carbon (TOC); d) total potassium (TK), calcium (Ca) and sodium (Na); e) total nitrogen (TN) and ammoniacal nitrogen (NH_4-N).

The content of DM, OM and TOC in the dried SF of digestate was fairly stable over time (Figure 4-8c). This in contrast to the contents of TN, NH_4-N (Figure 4-8e) and Ca (Figure 4-8d) which varied strongly over time. Interestingly, TN and NH_4-N contents do not show the same trend. Contents of TK and TP also fluctuated over time although to a lesser extent than Ca (Figure 4-8d). In contrast, the contents of TS, Mg and Na were relatively stable over time.

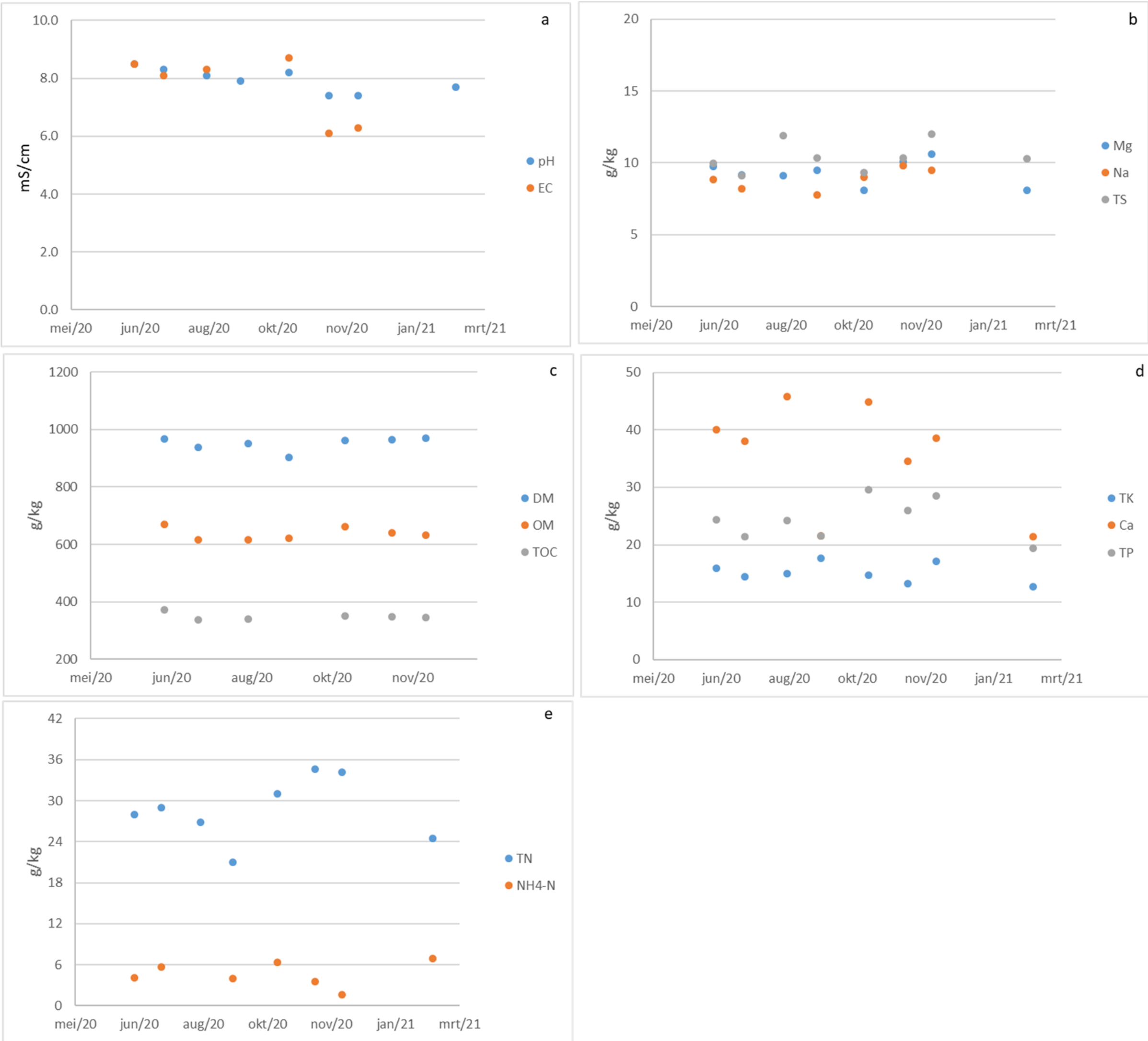

Figure 4-8 Composition (in fresh weight) over time of dried solid fraction of digestate produced at Waterleau NewEnergy for the period June 2020 – March 2021: a) pH and electrical conductivity (EC); b) magnesium (Mg), b) total phosphorus (TP) and total sulphur (TS); c) dry matter (DM), organic matter (OM) and total organic carbon (TOC); d) total potassium (TK), calcium (Ca) and sodium (Na); e) total nitrogen (TN) and ammoniacal nitrogen (NH_4-N).

Figure 4-9 shows large variation over time in the content of all nutrients, especially for TN, TP, TS and Ca, of the evaporator concentrate (Figure 4-9b and e). Higher contents of NH_4-N seem to coincide with higher contents of TS and vice versa.

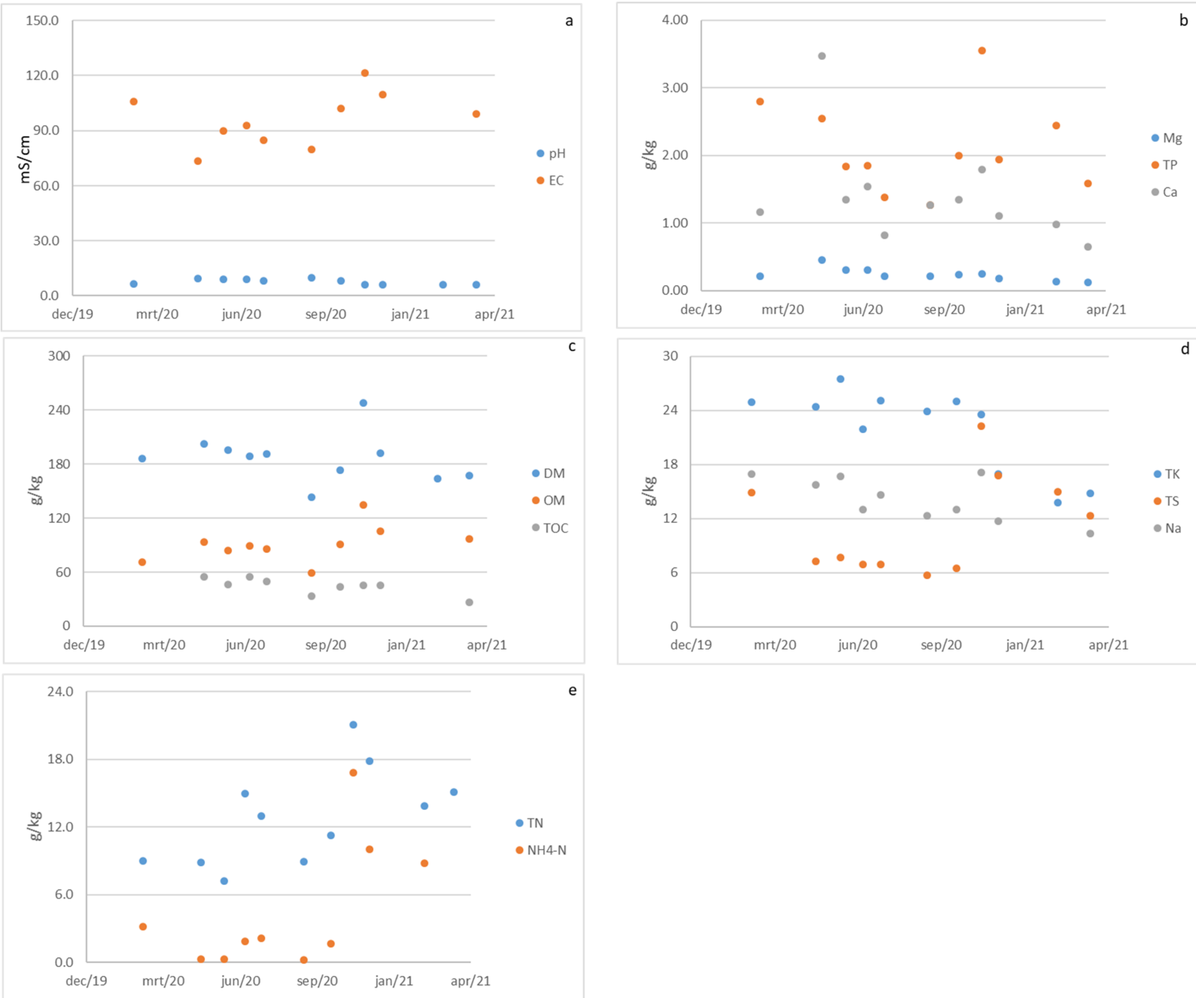

Figure 4-9 Composition (in fresh weight) over time of evaporator concentrate produced at Waterleau NewEnergy for the period February 2020 – March 2021: a) pH and electrical conductivity (EC); b) magnesium (Mg), b) total phosphorus (TP) and total sulphur (TS); c) dry matter (DM), organic matter (OM) and total organic carbon (TOC); d) total potassium (TK), calcium (Ca) and sodium (Na); e) total nitrogen (TN) and ammoniacal nitrogen (NH_4-N).

4.7 Overall performance of the NRR system

To preserve ground and surface waters in nitrate vulnerable zones (NVZs) in Belgium, the application of N from animal manure and digested animal manure in is generally limited to 170 kg ha^{-1} in accordance with the EU Nitrate Directive. As a result, biogas plants face high costs to dispose of their digestate due to the required transport from livestock intensive regions to nutrient demanding regions. On a total mass basis, almost 50% of the digester feedstock of WNE is animal manure. Without its NRR system, the biogas plant would have to transport the digestate over long distances at a cost of about 15–20 € t^{-1}. Paradoxically, farmers require synthetic mineral fertiliser to meet crop nutrient demands. To overcome this paradox, WNE implemented an NRR system with the goal of up-concentrating and separating the nutrients from the digestate into several end products with reduced water contents, to lower transport costs.

The implemented enhanced NRR technologies (TRL 7-8) (a SYSTEMIC key performance target of the SYSTEMIC PROJECT) at WNE were monitored. The calculated mass flows show that up to 90% of the water from the ingoing digestate is either discharged to surface water or reused on-site. As a result, the end products only contain around 10% of water that was present in the ingoing digestate. Moreover, the NRR system can operate on the electricity and thermal energy generated by the AD. Overall, in 2020 the average disposal costs for the end products (i.e. dried SF of digestate, evaporator concentrate and condensed ammonia water) amounted to 3.9 € t^{-1} of ingoing digestate, which is about 4–5 times lower than the costs for disposal of unseparated digestate. This is in line with one of SYSTEMIC's key performance targets that aims at changing the current practice for manure disposal by 20%. Moreover, transport of the mixture of dried SF of digestate with evaporator concentrate to France, helps to overcome imbalances in the supply of nutrient between intensive and extensive agriculture regions, which is another SYSTEMIC key performance target. From a market perspective, the dried SF of digestate is a soil improver rich in OM, TOC and P, whereas the evaporator concentrate finds application as additional source of N, P, K and S to tailor the nutrient content of this dried SF of digestate by blending. However, the evaporator concentrate cannot be used as fertiliser on itself because of the high temporal variation in TN and NH_4-N contents and high salt content. Condensed ammonia water could be a very interesting mineral N fertilising product, as all TN it contains is present in mineral form. However its high pH (>11) is a serious risk for crop growth and ammonia volatilisation. Transforming it to a more stable form (e.g. ammonium sulphate) could largely remove or lower those risks. The condensed ammonia water is at the time of writing used locally as DeNOx agent for treatment of the flue gasses of an incineration plant. At the beginning of 2022, WNE started upgrading its NRR system to replace the production of condensed ammonia water with AS solution (40%), which will be destined to the agricultural market. WNE estimated that the production of 40% AS solution will cost about 150 € t^{-1}, and pricing negotiations are still ongoing.

5 Acqua & Sole (Italy)

5.1 General description of the plant

5.1.1 Introduction

The AD plant of Acqua & Sole (A&S) is located in Vellezzo Bellini (Northern Italy), in an area dedicated to cereal cultivation, mainly rice (Figure 5-1). A&S has as main focus the provisioning of environmental services that are required for a sustainable agriculture in peri-urban areas in the region. Sewage sludge from municipal WWTPs is the major digester feedstock and A&S aims to showcase that the use of the resulting digestate in agriculture is a safe and environmentally friendly alternative to incineration of the digestate. Recently, more and more sewage sludge is incinerated in Italy despite the fact that its field application in agriculture is allowed. A&S produces an organic pumpable fertiliser (digestate) from sewage sludge and agro-food waste. The digestate is applied on agricultural land in the region of the plant. The nutrients in the digestate function as fertiliser and the organic matter in the digestate increases the soil carbon content. Due to the thermophilic digestion process, the digestate is hygienised.
A&S focusses on NRR technologies, specifically the development of equipment for digestate application to agricultural land (direct injection into the soil). This equipment is developed in collaboration with local farmers with the aim to increase the fertiliser uptake by the crop and to reduce odour and ammonia (NH_3) emissions.

Figure 5-1 Aerial photo of Acqua & Sole.

5.1.2 Technical description of the biogas plant

AD is performed in three digesters placed in series, each with a volume of 4 500 m^3. The produced digestate is stored in a storage tank with a capacity of 53 000 m^3. A second storage tank of the same size is at the time of writing under construction. The total AD capacity of the plant is 120 kt of organic substrate per year (Table 5-1).

Table 5-1 Technical information of the demonstration plant Acqua & Sole.

Characteristics	
Year of construction	2016
Maximum electric power	1.6 MWe
Volume of the digesters	13 500 m^3

Digestion process	Thermophilic

5.1.3 Feedstock and hygienisation

The biogas plant can anaerobically digest animal manure, expired food, organic wastes, sewage sludge and waste from the agro-food industry. Table 5-2 shows the origin of the feedstock that is digested by the A&S biogas plant for the years 2017 to 2020. In 2017, 72 kt of feedstock were digested of which about 86% was sewage sludge from WWTPs and 14% was other biowaste such as digestate from anaerobically digested source-segregated food waste (SSFW), agro-food waste and liquid fraction of SSFW. In 2018, A&S operated normally from January until July. However in August and September the plant was not operational due to a legislative block. The plant was restarted in October and was again fully operational by January 2019. In 2018, approximately 44 kt of feedstock were digested of which about 89% was sewage sludge from WWTPs, 4.5% was agro-food waste, 4.5% was digestate from the anaerobically digested SSFW and 2% was liquid fraction of SSFW. In 2019, the share of sewage sludge in the feedstock decreased slightly to 85% and liquid fraction of SSFW was no longer part of the feedstock anymore. Instead, the feedstock shares of digestate from anaerobically digested SSFW and agro-food waste increased to respectively 6.6% and 8.8%. In 2020, the feedstock share of sewage sludge from WWTPs represented 85% of the total feedstock (87.5 kt) and 15% of the feedstock were other biowastes.
Hygienisation of the digestate is achieved through the thermophilic digestion process, with a minimum retention time of 20 days in the system of digesters at a temperature of 55°C.

Table 5-2 Origin of anaerobic digestion feedstock of Acqua & Sole, expressed in kilotonnes per year for the period 2017–2020.

Feedstock	**2017**	**2018**	**2019**	**2020**
Sewage sludge of WWTPs	62	39	69.2	74
Digestate from anaerobically digested SSFW	6	2	5.4	4.5
Agro-food waste	0	2	7.2	9.0
Liquid fraction of SSFW	4	1	0	0
Total	72	44	81.8	87.5

5.1.4 Biogas production and energy generation

The biogas production and composition at A&S are summarized in Table 5-3. The highest biogas production was achieved in 2017 which amounted to 4.0 MNm^3 of biogas (2.3 MNm^3 of methane).

Table 5-3 Production and average composition of biogas before purification at Acqua & Sole for the period 2017–2020. Abbreviations: methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and oxygen (O_2).

Parameter	**Unit**	**2017**	**2018**	**2019**	**2020**
CH_4	%	55–60	55–66	60–65	60–67
CO_2	%	32–37	29–38	33–36	32–36
H_2S	ppm	<50	<10	<10	<10
O_2	%	1	<2	<1	<1
Total biogas production	MNm^3	4	2.3	3.3	3.3
Specific biogas production	$Nm^3\ t^{-1}$ feedstock	56	52	40	38
Total CH_4 production	MNm^3	2.3	1.4	2.1	2.1
Specific CH_4 production	$Nm^3\ CH_4\ t^{-1}$ feedstock	32	32	26	24

All biogas produced at A&S is converted into electrical and thermal energy (Table 5-4). Over the course of the SYSTEMIC project, the electrical energy generated varied between 7 032 and 8 384 MWh_e per year, whereas the thermal energy generation ranged between about 5 700 to 8 700 MWh_{th}. Moreover, A&S changed its biogas usage strategy. From 2017 to March 2020, all biogas produced by the AD plant was converted by a CHP installation into electrical and thermal energy. The majority of generated electrical energy was consumed on-site and the remainder was sold via the national grid. In cold periods the extra heating needed for the digesters was provided by burning natural gas in a back-up boiler. In March 2020 A&S obtained an authorisation to feed biogas to a biogas boiler, thereby avoiding the usage of natural gas. Biogas was partly converted to electricity and heat in the CHP and partly burned in the biogas boiler to supply additional heat required. The distribution of biogas among the CHP and biogas boiler depended on the heat demand which in turn depend on the season.

Table 5-4 Electricity and heat generation at Acqua & Sole for the period 2017–2020.

	Digestate production ($t\ y^{-1}$)	**Working days**	**Electricity generation**		**Thermal energy generation**[a]	
			MWh	**kWh t^{-1} digestate**	**MWh**	**kWh t^{-1} digestate**
2017	91 245	365	8 384	92	6 570	72
2018	59 570	365	5 036	85	5 777	97
2019	112 322	365	7 737	69	8 070	72
2020	114 608	365	7 032	61	8 712	76

[a] sum of thermal energy generated from the biogas produced by the plant and thermal energy generated from external natural gas.

5.1.5 Other information

Labour

Acqua & Sole employs 15 FTE in total.

Waste production

In 2019, the following waste streams were produced at A&S:

- Laboratory reagents: 0.4 t;
- Packaging material: 4.31 t;
- Non-chlorinated oil waste: 2.67 t;
- Other emulsions: 1.56 t;
- Absorbents, filter materials, filters: 0.66 t;
- Spent activated carbon: 47.49 t;
- Oils and concentrated products from separation processes: 3.5 t;
- Sand and stones: 2.46 t.

Buildings and storage capacity

A&S has the following storage capacity:

- AD feedstock: 1 500 m^3;
- Digestate: 53 000 m^3, a second storage tank (53 000 m^3) is currently under construction;
- AS solution: 4 000 m^3.

5.2 Drivers for nutrient recycling

5.2.1 Motivation for nutrient recycling

Nutrient recovery from organic wastes (e.g. sewage sludge, the organic fraction of municipal solid waste and food waste) represents an interesting circular economy business model in which waste can be converted into fertilisers that can replace synthetic mineral fertilisers *(Toop et al.*, 2017). Unprocessed organic wastes are not by themselves useful as fertilisers, (bio)technology is needed to transform them into useful products (Sigurnjak *et al.*, 2019). AD has been proposed as a useful biotechnology to produce renewable energy and biobased fertilisers from digestate, to be used in agriculture as substitute for synthetic fertilisers (Riva *et al.*, 2016; Tambone *et al.*, 2019; Verdi *et al.*, 2019). Furthermore, the low carbon contents of soils is an issue in Italy and the field application of organic matter in the form of digestate is a valuable means to tackle this.

Nonetheless, the use of N-rich organic wastes as feedstock in AD may lead to high concentrations of NH_3 in digesters, resulting in inhibition of the digestion process. N-stripping allows NH_3 concentrations in the digester to be maintained below inhibiting concentrations and simultaneously recovery of NH_4-N in the form of a mineral N fertiliser. The fertilisers produced by A&S can fulfil the following functions:

- A mineral N fertiliser (ammonium sulphate solution) that can be useful for topdressing (i.e. applied on the soil surface) or fertigation (i.e. combined with irigation) and
- N-stripped digestate that can act as an organic fertiliser amendment because of its high OM content, high biological stability to further breakdown and high nutrient content.

5.2.2 Sustainability goals

A&S is committed to reaching the following targets:

- Close nutrient cycles through the use of fertilisers produced from sewage sludge and biowaste;
- Showcase that fertilisers from sewage sludge and biowaste are agronomically effective and environmentally friendly and safe;
- Increase soil quality due to the use of digestate rather than chemical fertilisers, thereby contributing to sequestration of carbon in the soil;
- Reduce NH_3, NO_3^- and N_2O emissions during digestate application;
- Eliminate unpleasant odours during field application of digestate to increase public acceptance.

5.2.3 Economic benefits

In order to valorise the nutrients in digestate, A&S made agreements with local farmers who have recognised the agronomic value of the digestate in terms of nutrients. As a result, those farmers have partially replaced the use of chemical fertilisers with the use of the biobased fertilisers produced by A&S, including the AS solution. This has a beneficial effect on the local farms and on the surrounding area, allowing the application of the circular economy principles. Furthermore, the agreement does not result in any costs for the farmers, neither for the purchase, nor for the distribution of the digestate and AS solution. The implementation of the N-absorber reduces the NH_4-N content of the digester, thereby avoiding inhibition of the AD process, and produces an AS solution. Therefore, N-stripping at A&S allows:

- a controlled High Solids Anaerobic Digestion (HSAD) process without NH_3 inhibition;
- production of a high-quality mineral fertiliser.

5.3 The nutrient recovery installation

5.3.1 Technical description of the installation

Since April 2016, the plant has been operating as follows (Figure 5-2): sewage sludge and biowaste are collected in basins located in a closed building maintained at negative pressure to prevent the release of odours. A biofilter placed on the roof of the building purifies the exhausted air. The sewage sludge and biowaste are moved to a mixer where they are homogenised and mixed with part of the digestate produced by the third digester (AD3). The mixture is subsequently heated by steam injection. Steam is also supplied to each digester to maintain them at a stable thermophilic temperature. Water is added to the feedstock mixture to lower its DM content to about 14% such that it can be pumped through the system of digesters. The feedstock mixture is then fed to the first digester. A side-stream N-stripping column is connected to the second digester (AD2). With the previous absorption unit, biogas was used as stripping agent; with the newly installed N-scrubber, biogas has been replaced by air as stripping agent. Moreover, the novel N-absorber is made of the high performance alloy 825, which allows higher process temperature and it is also more acid-resistant. After leaving the column, the stripping gas is passes through acid traps to recover NH_3. This is achieved by absorption with 50% sulphuric acid. The system does not require the addition of any chemicals for pH control and the recovered product is a circa 36% AS solution containing about 7.2% of NH_4-N. N-stripped digestate is fed back to the first digester (AD1). The digestate produced by AD1 is subsequently further digested AD2 and AD3. Both the produced digestate and the AS solution are stored in tanks. A more detailed description of the ammonia extraction unit can be found in Di Capua *et al.* (2021).

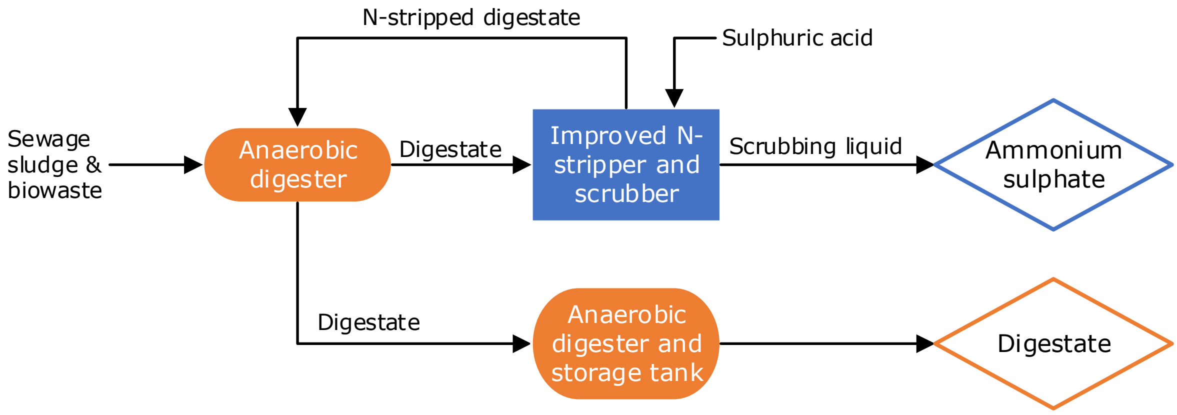

Figure 5-1 Simplified process flow diagram of the NRR system at the demonstration plant Acqua & Sole including locations of chemical addition and the major return flows (as configured in October 2021).

The technical specifications of the N-stripping system at A&S are summarised in Table 5-5. The novel N-absorber is, because it is made of alloy 825, more resistant to corrosion than the previous. Next to this does the design of the novel scrubber enable a higher gas flow rate, which in turn increases the amount of N recovered.

Table 5-5 Technical specifications of the N-stripping unit at Acqua & Sole (Di Capua et al., 2021).

Technical specification	**Previous system**	**Current system**
Processing capacity of digestate	10 $m^3\ h^{-1}$	10 $m^3\ h^{-1}$
NH_4-N stripping efficiency	15–25%	up to 35%
Consumption of 50% sulphuric acid	1–1.5 t d^{-1}	1.2–1.7 t d^{-1}
Production capacity of ammonium sulphate solution	1.1–2.0 t d^{-1}	up to 3.0 t d^{-1}
Stripping temperature	65–73 °C	65–73 °C
Consumption of electrical energy	6.3 kWh kg^{-1} N	4.5–5 kWh kg^{-1} N
Stripping agent	biogas	air
Liquid-to-gas ratio of scrubber	2.1 L/G	-
Liquid-to-gas ratio of scrubber	-	1.5–4.6 L/G

5.3.2 Total production of digestate and other products

The AS solution produced in 2017 was stored until its REACH certification was obtained in 2018. The majority of produced AS solution has been used in agriculture as a mineral fertiliser whereas a small fraction has been sold to industry. The yearly production of digestate and AS solution over the course of the SYSTEMIC project is summarised in Table 5-6. In 2020 the production of AS solution was lower than in previous years due to the following reasons:

- In 2020, production of AS solution only started in April because the construction of the new N-absorber was completed in March.
- the N-stripper was stopped for in total 27 days in November and December 2020 due to a technical issue.

Regarding 2021, from January to July about 640 t of AS solution have been produced.

Table 5-6 Total production of end products at Acqua & Sole in tonnes per year for the period 2017–2020.

End product	**Unit**	**2017**	**2018**	**2019**	**2020**
N-stripped digestate produced	t y^{-1}	91 245	59 570	112 322	114 608
AS solution produced	t y^{-1}	722	637	571	481

5.4 Mass flows and balances with the previous N-absorption unit (Period 1)

A mass balance for the previous NRR system, with the previous N-absorber, was drafted for the monitoring period January–July 2018 (196 days in total). This period is referred to as "Period 1". A second monitoring period for the previous NRR system, with the previous N-absorber, was carried out in 2019, referred to as "Period 1b". Monitoring of the current NRR system, with the current N-absorber, was performed for the period October 2020 – April 2021. This "Period 2" is described in chapter 5.5.

5.4.1 Monitoring and sampling

Monitoring was done by A&S and the collected data was, on a monthly basis, shared with Ghent University for data processing. The aim of this was evaluation of the overall performance of the plant, including the achieved N recovery efficiencies. From January until July 2018, the plant digested 33 766 t of feedstock, of which 90% was sewage sludge from WWTPs, 4.8% was agro-food waste, 2.8% was LF of SSFW and 2.4% was digestate from anaerobically digested SSFW (Table 5-7).

Table 5-7 Origin of anaerobic digestion feedstock of Acqua & Sole in kilotonnes for the period January–July 2018.

Feedstock	**kt**
Agro-food waste	1.6
Liquid fraction of SSFW	0.92
Digestate from anaerobic treatment of SSFW	0.82
Sewage sludge of WWTPs	30.4
Total	33.8

The amount of biogas produced by the AD process from January to July 2018 was around 1.9 MNm^3, of which 56% was methane (Table 5-8).

Table 5-8. Production and average composition of biogas before purification at Acqua & Sole for the period January–July 2018. Abbreviations: methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and oxygen (O_2).

Parameter	**Unit**	**Amount**
CH_4	%	56
CO_2	%	33
H_2S	ppm	<10
O_2	%	2
Total biogas production	MNm^3	1.9
Specific biogas production	$Nm^3\ t^{-1}$ feedstock	56
Total CH_4 production	MNm^3	1.1
Specific CH_4 production	$Nm^3\ t^{-1}$ feedstock	32

5.4.2 Chemical characterisation of digestate and end products

The average composition of the feedstock and end products of the NRR system at A&S for the period January–July 2018 are shown in Table 5-9. Samples were chemically analysed by either a commercial (accredited) laboratory or by the laboratory of the University of Milan. The full characterisation of the end products, with metal concentrations expressed in mg kg^{-1} DM, is available in deliverable 1.13.

The characterisation of the feedstock and of the N-stripped digestate was the responsibility of A&S, which was caried out in agreement with the Italian legislation. Therefore not all parameters were analysed for the different feedstocks and the digestate going to the storage tank. Consequently, mass balances could not be calculated for each parameter.

Table 5-9 Chemical characterisation in (fresh weight) of the feedstock and end products (N-stripped digestate to storage tank and ammonium sulphate solution) of the NRR system at Acqua & Sole for the period January–July 2018. Average value ± one standard deviation.[1]

Parameter	**Unit**	**Agro-food waste**	**Liquid fraction of SSFW**	**Digestate from SSFW**	**Sewage sludge of WWTPs**	**N-stripped digestate**	**Ammonium sulphate solution**
pH	-	7.6	4	8.3	7.3	8.7 ± 0.23	6.9 ± 0.28
EC	mS cm^{-1}						
DM	g kg^{-1}	174	212	158	195	102 ± 5	372 ± 24
OM	g kg^{-1}	125	177	104	140	62 ± 3.1	-
TN	g kg^{-1}	7.1	9.7	10	11	8 ± 0.46	73 ± 0.82
NH_4-N	g kg^{-1}					4 ± 0.038	73 ± 1.4
TP	g kg^{-1}	3.1	1.1	2.4	3.4	2.7 ± 0.42	0.013 ±0.0034
TK	g kg^{-1}	0.89	2.4	2.97	0.57	0.65 ± 0.15	0.013 ± 0.0018
TS	g kg^{-1}						92 ± 7.4
Ca	g kg^{-1}						0.068 ± 0.0054
Mg	g kg^{-1}						<0.005
Cu	mg kg^{-1}	6	4.7	17	62	46 ± 5.9	<5
Zn	mg kg^{-1}	30	14	48	133	97 ± 15	2.6 ± 0.42
Cd	mg kg^{-1}	0.25	0.042	0.11	0.23	0.083 ± 0.016	<0.16
Ni	mg kg^{-1}	4.1	0.66	4.4	7.9	6.3 ± 0.86	1 ± 0
Pb	mg kg^{-1}	0.68	2	3.3	9.2	6.5 ± 1.3	1 ± 0
Cr	mg kg^{-1}	4.6	0.95	6.3	14	11 ± 2.1	<0.62
Hg	mg kg^{-1}	0.30	0.021	0.21	0.25	0.15 ± 0.018	0.25 ± 0
As	mg kg^{-1}	0.31	0.49	0.79	1.4	1.1 ± 0.16	0.6 ± 0.57

For Agro-food waste, liquid fraction of SSFW, digestate from SSFW and sewage sludge of WWTPs n=215; for digestate to storage tank n=7; for ammonium sulphate solution n=2.

5.4.3 Mass flow analyses of macronutrients, micronutrients and heavy metals

The calculated total mass flows of the NRR system of A&S for the period January–July 2018, a period of 196 days in total, are depicted in Figure 5-3. These are based on the measured volume flows by flowmeters. On average, 172 t d^{-1} of feedstock were, via the mixing unit, fed to AD1 consisting of 155 t d^{-1} of sewage sludge, 8.1 t d^{-1} of agro-food waste, 4.7 t d^{-1} of liquid fraction of SSFW and 4.2 t d^{-1} of digestate from anaerobically digested SSFW. Of the digestate in AD1, 894 t d^{-1} were pumped to AD2. About 240 t d^{-1} of digestate from AD2 were processed in a side-stream N-stripper, to which also about 1.3 t d^{-1} of 50% sulphuric acid and 0.9 t d^{-1} of water were added. The water was added to dilute the produced AS solution to an N content of about 7%. As result, about 2.4 t d^{-1} of AS solution were produced. The resulting 240 t d^{-1} of N-stripped digestate were fed back to AD1.

From AD2, 880 t d^{-1} of digestate were pumped to AD3. Part of the digestate from AD3 was fed back to the mixing unit (655 t d^{-1}) and the remainder was pumped to the storage tank (224 t d^{-1}). Water is added to the mixing unit to make the content of the mixing unit mixable. Steam is added to each digester to keep the temperature at thermophilic conditions. How much steam was added to each digester was not measured, only the total amount of water and steam supplied to the entire AD system is known (62 t d^{-1}). For simplicity it was assumed that all 62 t d^{-1} of water and steam were supplied in the mixing unit.

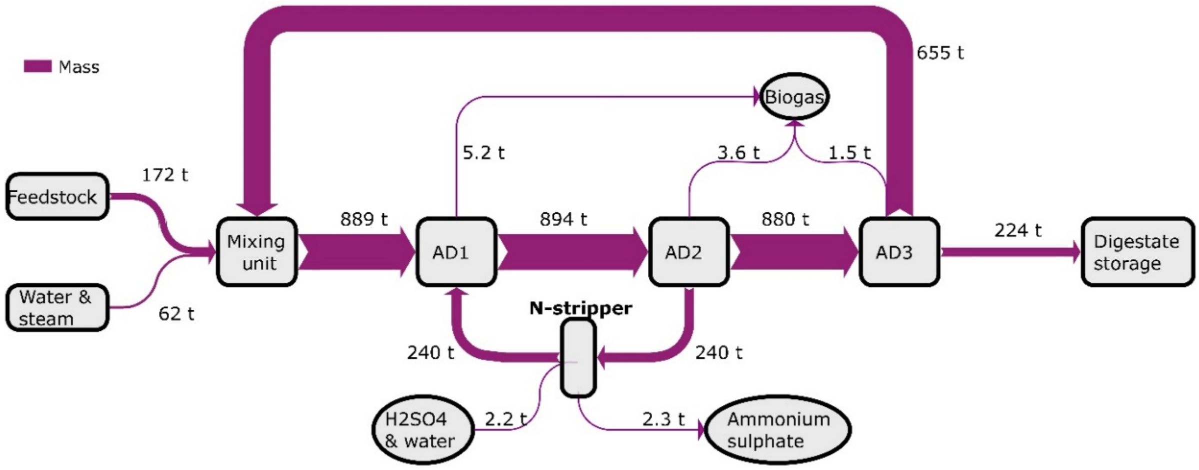

Figure 5-3 Total mass flows of the NRR system at Acqua & Sole in tonnes per day for the period January–July 2018. Abbreviations: anaerobic digestion (AD), sulphuric acid (H2SO4).

Mass flows for individual nutrients were calculated by multiplying the measured volume flows with the measured concentrations of the ingoing, intermediate and outgoing process streams. Mass flows for the feedstock streams were as monthly averages via the monthly average composition and the monthly added feedstock mass. This results in a mass balance that approximates the real situation, it still deviates from the real situation because the ingoing volume flow (the sum of the ingoing feedstock) was multiplied with the arithmetic concentration (not the weighted average concentration) of the ingoing feedstock. Figure 5-4 shows the TN, TP and TK mass flows of the NRR system of A&S for the period January–July 2018. The ingoing feedstock and the sum of the outgoing end products did not deviate much from each other for the mass flows of TN, TP and TK. Overall, 9.6% of TN was removed from digestate and recovered as AmS.

Regarding the Sankey diagrams it is important to specify that the feeding loads are a raw approximation since the calculation is performed by multiplying volume rates (evaluated as the sum on the incoming waste) and the arithmetic concentration of the incoming waste (it is not a weighted average).

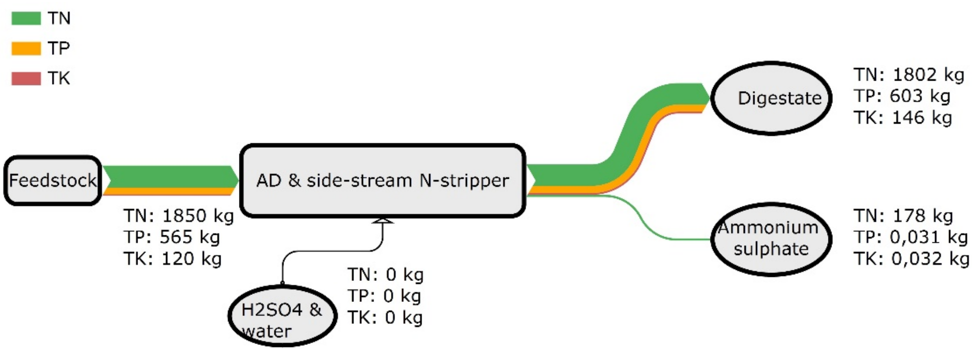

Figure 5-4 Total nitrogen (TN), total phosphorus (TP) and total potassium (TK) mass flows of the NRR system at Acqua & Sole in kg per day for the period January–July 2018. Abbreviations: anaerobic digestion (AD), sulphuric acid (H2SO4).

Figure 5-5 shows the Cu and Zn mass flows of the NRR system of A&S for the period January–July 2018. Ingoing and outgoing mass flows for Cu and Zn were similar, differing <10% (respectively 6% and 3%). These small differences are the result of the earlier explained cause.

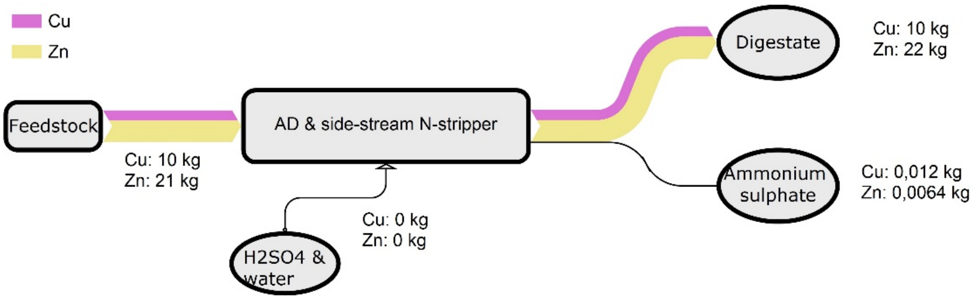

Figure 5-5 Copper (Cu) and zinc (Zn) mass flows of the NRR system at Acqua & Sole in kg per day for the period January–July 2018. Abbreviations: anaerobic digestion (AD), sulphuric acid (H2SO4).

Figure 5-6 shows the Ni, Pb and Cr mass flows of the NRR system of A&S for the period January–July 2018. Ni, Cr and Pb nearly completely end up in the digestate. Ingoing and outgoing mass flows were fairly similar. The sum of the outgoing streams was respectively 10% larger for Ni and Cr and 12% larger for Pb than the ingoing feedstock. The added sulphuric acid and water were however not chemically analysed. It was assumed that those streams do not contain any Ni, Cr and Pb which might not be the case.

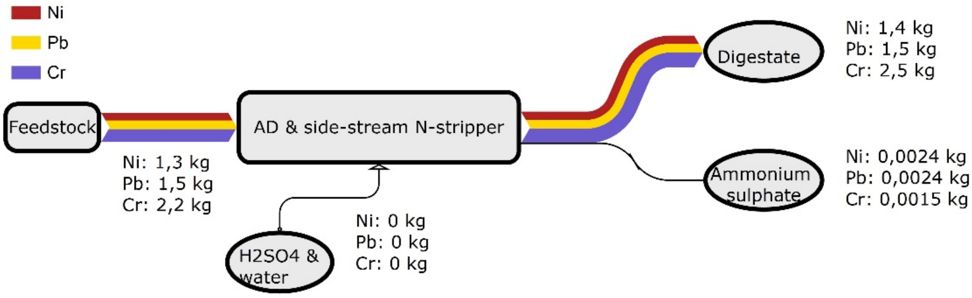

Figure 5-6 Nickel (Ni), Lead (Pb) and Chromium (Cr) mass flows of the NRR system at Acqua & Sole in kg per day for the period January–July 2018. Abbreviations: anaerobic digestion (AD), sulphuric acid (H2SO4).

5.4.4 Separation and nutrient recovery efficiencies of process units

Over the monitoring period of January–July 2018, the N-stripping system at A&S on average recovered 9.6% of the TN in the feedstock in the form of AS solution (73 ± 1.4 g NH_4-N kg^{-1}). This is equivalent to a recovery efficiency for NH_4-N of 22% (Pigoli *et al*., 2021).

5.5 Mass flows and balances after implementation of the new N-absorption unit (Period 2)

A mass balance for the current NRR system, with the new N-absorber, was drafted for the monitoring period October 2020 – April 2021 (189 days in total). This period is referred to as "Period 2". Between November and December 2020, the N-stripping unit was not operational for 27 days, resulting in a lower production of the AS solution and a lower energy consumption.

5.5.1 Monitoring and sampling

Monitoring was done by A&S and the collected data was, on a monthly basis, shared with Ghent University for data processing. The aim of this was evaluation of the overall performance of the plant, including the achieved N recovery efficiencies. From October 2020 to April 2021, the plant digested 46 200 t of feedstock, of which 80.7% was sewage sludge from WWTPs, 9.4% was digestate from anaerobically digested SSFW, 6.7% was SSFW and 3.2% was liquid biowaste. Liquid biowaste is specified as any liquid waste stream with a DM content <10%.

Table 5-10 Origin of anaerobic digestion feedstock of Acqua & Sole in kilotonnes for the period October 2020 – April 2021.

Feedstock	**kt**
Sewage sludge of WWTPs	37.3
SSFW	3.1
Digestate from anaerobically digested SSFW	4.3
Liquid biowaste	1.5
Total	46.2

The amount of biogas produced by the AD process from October 2020 to April 2021 was around 1.9 MNm^3, of 65% was methane (Table 5-11).

Table 5-11 Production and average composition of biogas before purification at Acqua & Sole for the period October 2020 – April 2021. Abbreviations: methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and oxygen (O_2).

Parameter	**Unit**	**Amount**
CH_4	%	65
CO_2	%	34
H_2S	ppm	<10
O_2	%	0.15
Total biogas production	MNm^3	1.9
Specific biogas production	Nm^3 t^{-1} feedstock	41
Total CH_4 production	MNm^3	1.2
Specific CH_4 production	Nm^3 t^{-1} feedstock	27

5.5.2 Chemical characterisation of digestate and end products

The average composition of the feedstock and end products of the NRR system at A&S for the period October 2020 – April 2021 are shown in Table 5-12. Samples were chemically analysed by either a commercial (accredited) laboratory or by the laboratory of the University of Milan. The full characterisation of the end products, with metal concentrations expressed in mg kg^{-1} DM, is available in deliverable 1.13.
The characterisation of the feedstock and of the N-stripped digestate was the responsibility of A&S, which was caried out in agreement with the Italian legislation. Therefore not all parameters were analysed for the different feedstocks and the digestate going to the storage tank. Consequently, mass balances could not be calculated for each parameter.

Table 5-12 Chemical characterisation in (fresh weight) of the feedstock and end products (N-stripped digestate to storage tank and ammonium sulphate solution) of the NRR system at Acqua & Sole for the period October 2020 – April 2021. Average value ± one standard deviation.[1]

Parameter	Unit	Agro-food waste	Digestate & liquid biowaste	Sewage sludge of WWTPs	N-stripped digestate	Ammonium sulphate solution
pH		6.4 ± 1.3	7.9 ± 0.45	7.4	8.6 ± 0.096	5.9 ± 1.0
EC	mS cm^{-1}				7.3 ± 0.2	118 ± 3.3
DM	g kg^{-1}	154 ± 73	73 ±86	196	106 ± 3.2	360 ± 12
OM	g kg^{-1}	34 ± 27	29 ± 32	110	63 ± 2.3	-
TN	g kg^{-1}	7.6 ± 2.9	4.8 ± 4.2	9.7	8.0 ± 0.31	75 ± 3.8
NH_4-N	g kg^{-1}				3.7 ± 0.074	71 ± 0.31
TP	g kg^{-1}	2.5	0.73	4.2	3.4 ± 0.4	0.012 ± 0.00035
TK	g kg^{-1}	1.5	8.5	0.67	0.59 ± 0.062	0.017 ± 0.012
TS	g kg^{-1}				1.1 ± 0.021	85 ± 6.2
Ca	g kg^{-1}				5.9 ± 0.68	0.043 ± 0.024
Mg	g kg^{-1}				0.59 ± 0.094	0.0068 ± 0.0022
Na	g kg^{-1}				0.21 ± 0.015	0.019 ± 0.01
Cu	mg kg^{-1}	4.8 ± 4.4	7.5 ± 10	55	37 ± 5.2	<5
Zn	mg kg^{-1}	20 ± 15	14 ± 19	158	113 ± 12	<8.5
Cd	mg kg^{-1}	0.1 ± 0.052	0.05 ± 0.06	0.2	0.092 ± 0.024	<0.2
Ni	mg kg^{-1}	2.0 ± 1.4	2.5 ± 3.4	6.2	5.8 ± 0.63	<1.1
Pb	mg kg^{-1}	1.0 ± 0.57	2.6 ± 3.6	10	7.4 ± 1.3	<1
Cr	mg kg^{-1}	4.5 ± 5.1	3.3 ± 4.5	9.0	7.9 ± 0.66	<0.23
Hg	mg kg^{-1}	0.23 ± 0.19	0.094 ± 0.11	0.2	<0.14	<0.25
As	mg kg^{-1}				0.82 ± 0.18	<0.98
Al	mg kg^{-1}				3580 ± 686	<0.1
Co	mg kg^{-1}				0.67 ± 0.041	<0.1
Fe	mg kg^{-1}				2016 ± 648	<9.75
Mn	mg kg^{-1}				50 ± 10	1.9 ± 0.77

For agro-food waste, digestate & liquid biowaste and sewage sludge of WWTPs n=262; for digestate to storage tank n=8; for ammonium sulphate solution n=3.

5.5.3 Mass flow analyses of macronutrients, micronutrients and heavy metals

The calculated total mass flows of the NRR system of A&S for the period October 2020 – March 2021, a period of 189 days in total, are depicted in Figure 5-7. These are based on the measured volume flows by flowmeters.

On average, 244 t d^{-1} of feedstock were, via the mixing unit, fed to AD1 consisting of 197 t d^{-1} of sewage sludge, 31 t d^{-1} of digestate and liquid biowaste and 16 t d^{-1} of agro-food waste. Of the digestate in AD1, 642 t d^{-1} were pumped to AD2. About 240 t d^{-1} of digestate from AD2 were processed in a side-stream N-stripper, to which also about 1.3 t d^{-1} of 50% sulphuric acid and 0.95 t d^{-1} of water were added. The water was added to dilute the produced AS solution to an N content of about 7%. As result, about 2.5 t d^{-1} of AS solution were produced. The resulting 240 t d^{-1} of N-stripped digestate were fed back to AD1.
From AD2, 638 t d^{-1} of digestate were pumped to AD3. Part of the digestate from AD3 was fed back to the mixing unit (324 t d^{-1}) and the remainder was pumped to the storage tank (312 t d^{-1}). Water is added to the mixing unit to make the content of the mixing unit mixable. Steam is added to each digester to keep the temperature at thermophilic conditions. How much steam was added to each digester was not measured, only the total amount of water and steam supplied to the entire AD system is known (62 t d^{-1}). For simplicity it was assumed that all 79 t d^{-1} of water and steam were supplied in the mixing unit.

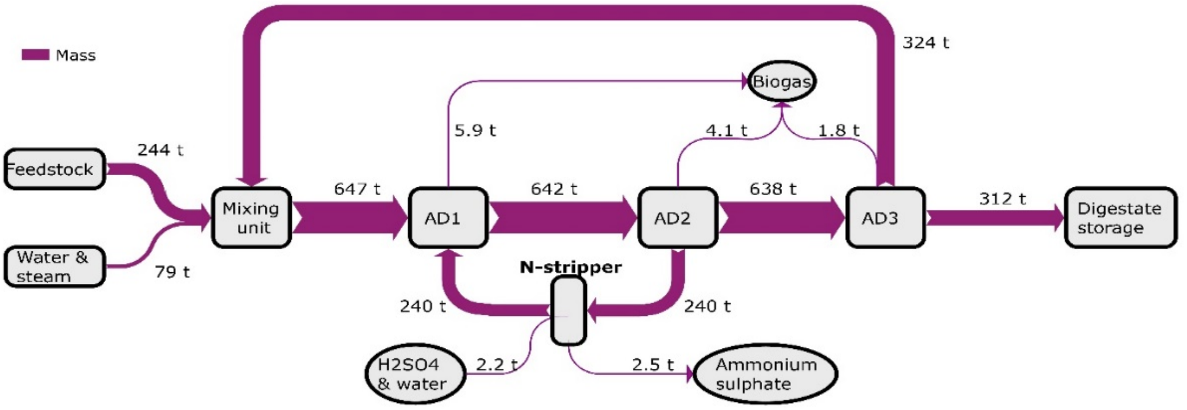

Figure 5-7 Total mass flows of the NRR system at Acqua & Sole in tonnes per day for the period October 2020 – March 2021. Abbreviations: anaerobic digestion (AD), sulphuric acid (H2SO4).

Mass flows for individual nutrients were calculated by multiplying the measured volume flows with the measured concentrations of the ingoing, intermediate and outgoing process streams. Mass flows for the feedstock streams were as monthly averages via the monthly average composition and the monthly added feedstock mass. This results in a mass balance that approximates the real situation, it still deviates from the real situation because the ingoing volume flow (the sum of the ingoing feedstock) was multiplied with the arithmetic concentration (not the weighted average concentration) of the ingoing feedstock. Figure 5-8 shows the calculated TN, TP and TK mass flows of the NRR system of A&S for the period October 2020 – March 2021. Ingoing and outgoing mass flows for TP were similar, differing only 3%. However for TN and TK the outgoing mass flows were in total respectively 14% and 13% larger than the ingoing mass flow. This is due uncertainty in the average composition of the feedstock because each truck of sewage sludge has a slightly different composition as mentioned above.

The monitoring points 8% of TN being removed from the digestate and recovered as AmS. The N stripper however treats a side stream of digestate. The N removal efficiency of the N stripper amounts to 35% of ammoniacal N as was determined earlier based on N measurements on digestate samples taken before and after the stripper (Di Capua et al., 2021). The Sankeys instead give the overall mass balance over the AD plant including the N stripper.

Figure 5-9 shows the calculated Cu and Zn mass flows of the NRR system of A&S for the period October 2020 – March 2021. Figure 5-10 shows the calculated Ni, Pb and Cr mass flows of the NRR system of A&S for the period October 2020 – March 2021.

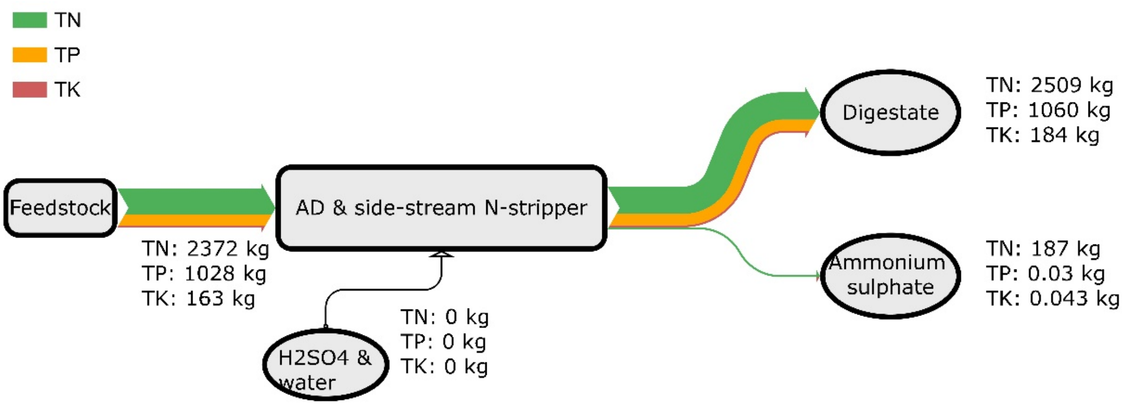

Figure 5-8 Total nitrogen (TN), total phosphorus (TP) and total potassium (TK) mass flows of the NRR system at Acqua & Sole in kg per day for the period October 2020 – March 2021. Abbreviations: anaerobic digestion (AD), sulphuric acid (H2SO4).

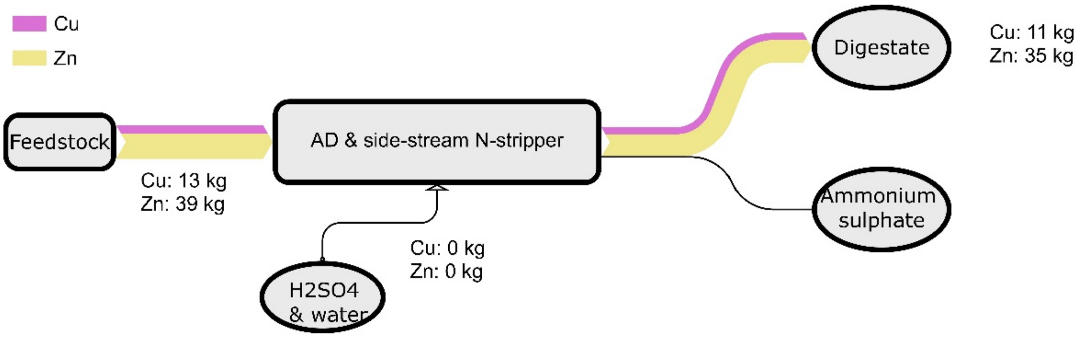

Figure 5-9 Copper (Cu) and zinc (Zn) mass flows of the NRR system at Acqua & Sole in kg per day for the period October 2020 – March 2021. Abbreviations: anaerobic digestion (AD), sulphuric acid (H2SO4).

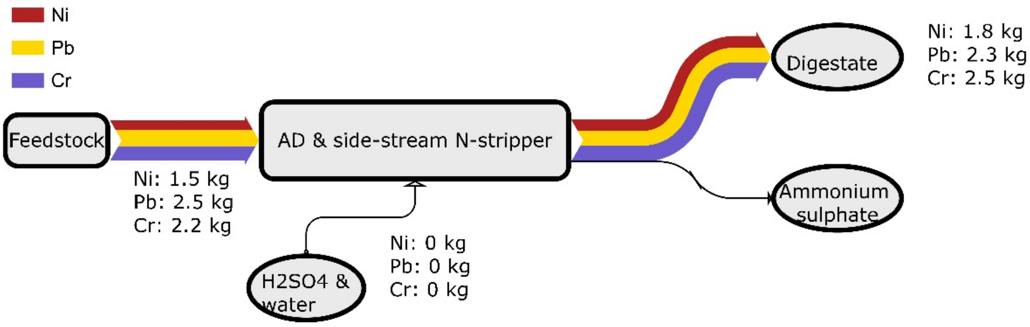

Figure 5-10 Nickel (Ni), Lead (Pb) and Chromium (Cr) mass flows of the NRR system at Acqua & Sole in kg per day for the period October 2020 – March 2021. Abbreviations: anaerobic digestion (AD), sulphuric acid (H2SO4).

5.5.4 Nutrient recovery efficiencies of the N-stripping unit

The ammonia nitrogen removal efficiency (N recovery) was evaluated in the two periods with reference to the ammonia concentration of anaerobic digesting sludge entering and leaving the stripping unit. As reported by Di Capua *et al*. (2021), the recovery of NH_4-N with the novel adsorption system reached values as high as 35%. Air flow rate was the main factor influencing ammonia removal. Nitrogen stripping is performed on a side stream of the AD plant; after stripping, digestate is recirculated to the first digester to dilute the incoming feedstocks. Overall, about 8% of TN contained in the feedstock was recovered as ammonium-sulphate.

5.6 Energy balance

5.6.1 Energy production

If all produced biogas was sent to the CHP installation, the amount of thermal energy produced would not be sufficient to support the thermophilic digestion process. For comparison of the amounts of energy produced in Period 1 and Period 2 it is therefore important to take into account that in Period 1 the produced thermal energy was the sum of thermal energy produced from biogas in the CHP installation and natural gas in the back-up boiler (in colder periods).

In 2020, the obtained authorisation allowed feeding biogas to a biogas boiler, thereby avoiding the use of natural gas in the back-up boiler. Therefore, in period 2, the required thermal energy has been produced only from biogas, avoiding the use of natural gas. The biogas use strategy is flexible. Biogas is primarily used to produce the electricity that is needed to run the plant. Part of the biogas is then fed to the biogas boiler to produce thermal energy in the periods that this is needed. Any possible still remaining biogas is fed to the CHP installation and the resulting electricity is sold via the national grid. Table 5-13 shows the production and average composition of the biogas for Periods 1 and 2.

Table 5-13 Production and average composition of biogas before purification at Acqua & Sole for the period January–July 2018 (Period 1) and for the period October 2020 – April 2021 (Period 2). Abbreviations: methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and oxygen (O_2).

Parameter	**Unit**	**Previous absorption unit (Period 1)**	**Current absorption unit (Period 2)**
CH_4	%	56	65
CO_2	%	33	34
H_2S	ppm	<10	<10
O_2	%	2	0.15
Total biogas production	MNm^3	1.9	1.9
Specific biogas production	Nm^3 t^{-1} feedstock	57	40
Total CH_4 production	MNm^3	1.1	1.2
Specific CH_4 production	Nm^3 t^{-1} feedstock	32	27

All produced biogas was converted into electrical and thermal energy (Table 5-14). The amount of electricity generated per tonne of digestate decreased from 91 kWh t^{-1} in Period 1 to 65 kWh t^{-1} in Period 2. This decrease is due to the different biogas use strategies for the two periods as reported in the paragraph 5.1.4. The amount of thermal energy produced, which is equal to the amount of thermal energy consumed, per tonne of digestate increased from 69 kWh t^{-1} in Period 1 to 87 kWh t^{-1} in Period 2. The cause for this is most likely that Period 2 covered on average a colder period, mainly winter months, than Period 1.

Table 5-14 Electricity and heat generation at Acqua & Sole for the period January–July 2018 (Period 1) and the period October 2020 – April 2021 (Period 2).

	Digestate production (t)	Working days	Electricity generation		Thermal energy generation[a]	
			MWh	kWh t^{-1} digestate	MWh	kWh t^{-1} digestate
Period 1	43 876	196	3 998	91	3 613	82
Period 2	58 920	189	3 820	65	5 348	91

[a] In Period 1, 3 613 MWh of thermal energy were generated, of which 3 021 MWh from biogas and 592 MWh from natural gas. In Period 2, 5 348 MWh of thermal energy were generated, of which 5 103 MWh from biogas and 245 MWh from natural gas.

5.6.2 Energy consumption

The electrical energy consumption of the N-stripping unit per kg N recovered as AS solution decreased from 5.9 kWh kg^{-1} N (4.7 kWh t^{-1} digestate) in Period 1 (previous scrubber) to 5.3 kWh kg^{-1} N (2.7 kWh t^{-1} digestate) in Period 2 (current scrubber), as shown in Table 5-15. This reduction was achieved thanks to the higher energy efficiency of the new scrubber. These results are in line with the electricity consumption by the demonstration plant BENAS (3.8 kWh kg^{-1} N). Moreover, the need for thermal energy from the back-up boiler decreased from 13 to 4.2 kWh t^{-1} digestate due to the production of heat by the recently installed biogas boiler.

A&S aimed at producing all required thermal energy by combustion of biogas, but due to a technical issue, the biogas boiler was not always in operation for one month in Period 2.

Table 5-15 Electricity and heat consumption at Acqua & Sole for the period January–July 2018 (Period 1) and the period October 2020–April 2021 (Period 2).

	Digestate production (t)	Working days	Electricity consumption		Thermal energy consumption (from CHP installation and biogas boiler)		Thermal energy consumption (from back-up boiler)	
			MWh	kWh t^{-1} digestate	MWh	kWh t^{-1} digestate	MWh	kWh t^{-1} digestate
Period 1								
Mixing unit & biofilter	43 876	196	240	5.5				
AD & CHP	43 876	196	502	11				
N-stripping unit	43 876	196	206	4.7				
Total	43 876		947	22	3 021	69	592	13
Period 2								
Mixing unit & biofilter	58 920	189	209	3.6				
AD & CHP	58 920	189	472	8.0				
N-stripping unit	58 920	162	160	2.7				
Total	58 920		841	14.3	5 103	87	245	4.2

5.6.3 Energy balance

Based on the energy input and output of A&S, an energy balance was drafted for Periods 1 and 2 (Figure 5-11). For this it was assumed that 1 m^3 of CH_4 from biogas corresponds to 8.89 kWh of energy.

In Period 1, 24% of the electricity generated was consumed by the plant (22 kWh t^{-1} digestate) as shown in Figure 5-11. In Period 2, 22% of the electricity generated was consumed by the plant. The percentages of generated electricity that were consumed by the N-stripping system were respectively 5.2% and 4.1% for Period 1 and Period 2.

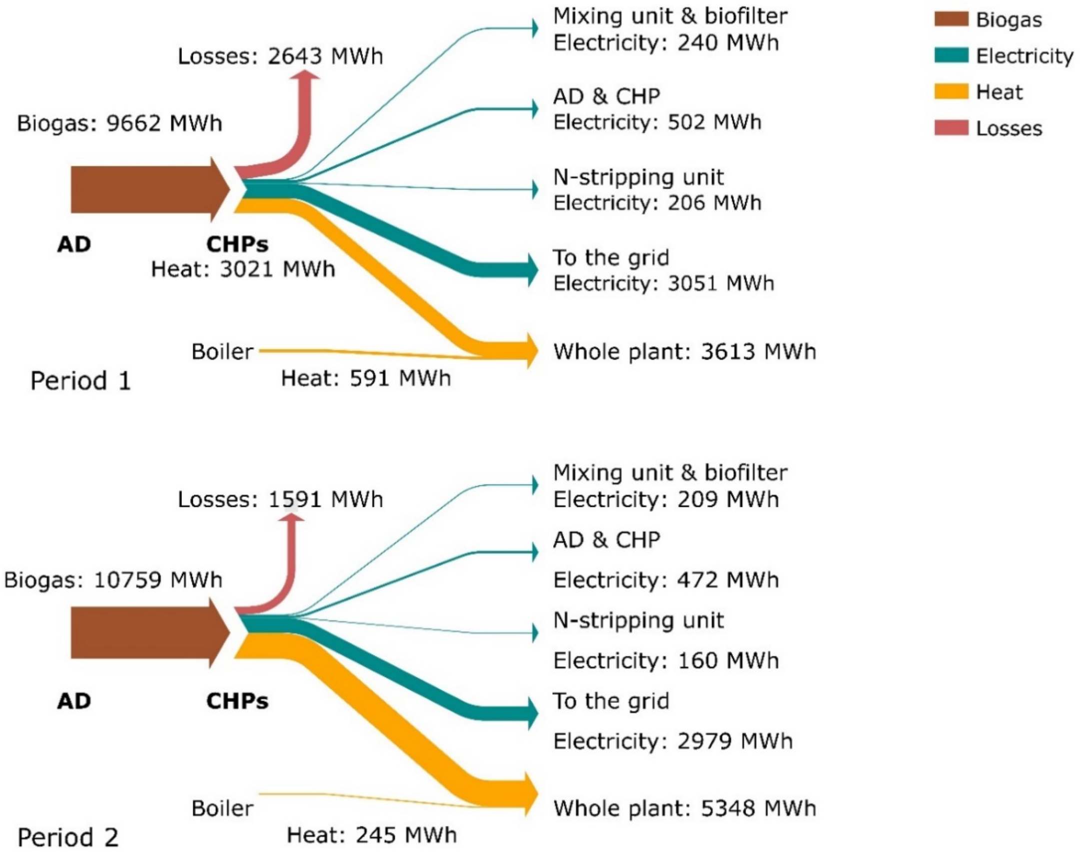

Figure 5-11 Energy production and consumption at Acqua & Sole for the period January–July 2018 (Period 1) and the period October 2020–April 2021 (Period 2). Period 2 was during the winter and hence a larger portion of the biogas was fed to the biogas boiler for conversion to thermal energy than would be the case for a year-average situation. CHPs: Electrical and thermal energy generated by the CHPs including thermal energy generated in the biogas boiler. Boiler: back-up boiler on natural gas.

5.7 Temporal variation in product composition

Since the start of the SYSTEMIC project, the composition of the digester feedstock, intermediate process streams and end products has been monitored. This paragraph gives the composition of the end products N-stripped digestate and AS solution over time.

The composition of the N-stripped digestate has been fairly constant over the course of the SYSTEMIC project for most of the measured parameters (Figure 5-12). The pH ranged between 8.0 and 9.1. OM content varied slightly, ranging between 56 and 66 g kg^{-1}. Consequently the DM content varied as well, ranging between 94 and 111 g kg^{-1}. The Ca, TS and especially TP contents varied somewhat (Figure 5-12b). For example, the highest measured TP concentration was nearly twice as high as the lowest measured TP concentration. TN and NH_4-N contents were stable over time.
Since January 2019 the contents of Cr, Cu and Ni have decreased drastically due to a stricter selection of digester feedstock. This was done to comply with new regional and national regulations and to increase the overall quality of the produced N-stripped digestate (Pigoli *et al* , 2021).

Figure 5-12 Composition (in fresh weight) over time of the N-stripped digestate produced at Acqua & Sole for the period January 2018 – May 2021: a) pH; b) calcium (Ca), total phosphorus (TP) and total sulphur (TS); c) dry matter (DM), organic matter (OM) and total organic carbon (TOC); d) total potassium (TK), magnesium (Mg) and sodium (Na); e) total nitrogen (TN) and ammoniacal nitrogen (NH_4-N).

The composition of the AS solution has been fairly constant over the course of the SYSTEMIC project for most of the measured parameters (Figure 5-13). The pH ranged between 6.7 and 7.7 (Figure 5-13a) and the ratio of NH_4-N over TN ranged between 0.96 and 1 (Figure 5-12c). The small differences between TN and NH_4-N can be attributed to the methods for chemical analysis, since only NH_4-N is removed during the N-stripping. NH_4-N and TN contents of the AS solution should therefore always be equal. Strangely the ratio of TN over TS for the AS solution varied strongly over the course of the SYSTEMIC project (Figure 5-12c and d). The TOC content of the AS solution was negligible, <1 g kg^{-1} FW (Figure 5-13b) (Pigoli *et al.*, 2021).

Figure 5-13 Composition (in fresh weight) over time of the ammonium sulphate solution produced at Acqua & Sole for the period January 2018 – May 2021: a) pH; b) dry matter (DM) and total organic carbon (TOC); c) total nitrogen (TN) and ammoniacal nitrogen (NH_4-N); d) total sulphur (TS).

5.8 Overall performance of the NRR system

The demonstration plant A&S comprises three thermophilic digesters, operating at a temperature of 55°C, placed in series. A&S anaerobically digests up to 120 kt of feedstock per year of which about 18.5% is organic waste. Each digester has a total volume of approximately 4,500 m^3. A side-stream N-stripping unit is coupled to the digesters to control the NH_4-N concentration in the digesters. This allows the 'high-solid anaerobic digestion' without NH_3 inhibition and the production of a high quality mineral fertiliser, AS solution.

A&S joined the SYSTEMIC project with the goal of demonstrating a novel N-absorber, which enables in combination with the stripper, a higher N recovery efficiency from the digestate. This is possible due to the construction material used for the N-absorber, alloy 825, which allows higher process temperature and is more acid resistant than regularly used iron alloys. Moreover, the design of the new N-absorber enables a higher gas flow rate than the previous N-absorber. This combined can increase the amount of NH_4-N from the digester feedstock that is recovered in the AS solution up to 35%. With the previous N-absorber an NH_4-N recovery of only about 20% was achieved.

The digesters are fed with a mixture of carefully selected organic wastes coming from, on a yearly basis, approximately 140–160 different waste producing plants. The majority of the digested organic wastes fall under the following categories: raw municipal sewage sludge and residues from agri-food factories. The most important co-substrates are digestate from anaerobically digested SSFW and LF of SSFW.

The biogas use strategy implemented in Period 2 optimised the on-site valorisation of the biogas, covering both the electrical and thermal energy needs of the plant. Excess biogas was converted into electrical energy and sold via the national grid.

The AD plant with incorporated NRR system produces renewable energy (biogas) and the following biobased fertilisers:

- an N-stripped digestate that can act as an organic amendment because of its high OM content and high biological stability to further breakdown, and as fertiliser because of its high nutrient content, and
- a mineral N fertiliser (ammonium sulphate solution) that can be used during plant cultivation at all stage of growth; in particular it could be used more efficiently during the tillering phase.

The chemical composition of the produced ammonium sulphate solution was fairly stable over time for all measured components except for TS. The chemical composition of the produced N-stripped digestate over time was stable for some components and varied for others. Most importantly, the measured contents of heavy metals were far lower than the limits for agricultural use due to the strict selection of digester feedstock by A&S.

6 BENAS (Germany)

6.1 General description of the plant

6.1.1 Introduction

The demonstration plant BENAS (Figure 6-1), located in Ottersberg (near Bremen, Germany), was realised in 2006. The AD plant converts energy crops (maize) and poultry manure into biogas and fertilisers. To reduce NH_3 levels in the digester in order to prevent inhibition of the AD process, BENAS has implemented an N-stripper and scrubber, as part of their NRR system called FiberPlus, in 2007/2008. The innovative N-stripper and scrubber were developed by GNS, a consultancy company specialised in energy production and nutrient recovery from biomass and organic waste. The N-stripper and scrubber remove NH_3 and CO_2 present in the digestate via addition of flue gas desulphurisation-gypsum (FGD-gypsum), thereby producing a mixture of AS solution and liming substrate. The liming substrate is composed of calcium carbonate ($CaCO_3$) with traces of gypsum, calcium sulphate dihydrate ($CaSO_4 \cdot 2H_2O$). The liming substrate is from here on referred to as calcium carbonate (CC) sludge. The AS solution and CC sludge are subsequently separated by means of a filter press. The N-stripped digestate is separated via the second screw press in an SF and LF of digestate, the latter is fed back to the digester, diluting the feedstock and thereby preventing NH_3 inhibition. The SF of N-stripped digestate, containing low-N fibres, is used for the on-site production of paper and fibre moulding products. The process for the production of paper and fibre moulding products was developed over the course of the SYSTEMIC project by BENAS and GNS. Digestate from the main digester is pumped to the post-digester. The digestate produced by the post-digester is separated into an SF and LF of digestate. Both fractions are applied on arable land owned by BENAS for the cultivation of energy crops for the AD plant.

Figure 6-1 Aerial photo of the demonstration plant BENAS in Ottersberg, Germany.

6.1.2 Technical description of the biogas plant

The plant has an AD capacity of 174 kt of feedstock per year and is equipped with four digesters, two storage tanks with a volume of 4 500 m^3 each, and one storage tank with a volume of 12 100 m^3 (Table 6-1). The biogas storage capacity of the plant is 32 500 m^3. The arable land, an aera of 3 500 ha, owned by BENAS consists of 1 000 ha near Ottersberg and 2 500 ha located at a distance of 200 km from the plant in Saxony-Anhalt. BENAS has 35 employees and its own truck fleet.

In 2018, the AD plant was renewed and expanded such that the amount of electricity that is generated at any moment is more flexible in time. Construction works consisted of:

- installation of an additional storage tank with a combined storage capacity of 12 100 m^3 digestate and 8 870 m^3 biogas;
- installation of two additional CHP installations, each with an electric power output of 3 MWe (44% conversion efficiency of biogas to electrical energy);
- replacement of foil roofs at all digesters and storage tanks.

Since January 2019, the AD plant operates in a grid stabilising mode, thereby providing an important service: power grid stabilisation. The grid stabilising mode encompasses short temporary shutdowns of the CHP installations, stopping the electricity generation, especially during nights or weekends. When this occurs, consequently also the heat supply to the digesters and the N-stripping system are seized. During these shut downs, the produced biogas is stored on-site which is possible due to the increased storage capacity and the new roofs. Part of the produced biogas is upgraded to biomethane and thereafter fed into the gas grid. The amount of biomethane fed into the grid also fluctuates in time depending on the grid's demand for biomethane.

Table 6-1 Technical information of the demonstration plant BENAS.

Characteristics	
Year of construction	2006
Maximal electric power	11.3 MWe
Volume of the digesters	39 100 m^3
Digestion process	Thermophilic
Commissioning N-stripper	2008 (start with separated digestate) 2011 (redesign with full automatisation) 2016 (redesign to FiberPlus system)
Commissioning filter press	2009
Commissioning fibre moulding and paper making machine	March 2021 (start operation of fibre moulding machine) July 2021 (start operation of paper making machine)

6.1.3 Feedstock and hygienisation

In 2017, 26% of the 103 kt of digester feedstock consisted of chicken manure. In 2018, a considerable smaller amount of feedstock (76.8 kt) was digested, of which 82% was crop material and 18% was manure (Table 6-2). Feedstock ratios for the 92.2 kt of digested feedstock were similar in 2019 (85% crop material and 15% manure). In 2020, the share of chicken manure digested decreased to less than 1% of the feedstock mass, the AD plant entirely relied on crop material, mainly maize and silage rye.

Table 6-2 Origin of anaerobic digestion feedstock of BENAS, expressed in kilotonnes per year for the period 2017–2020.

Feedstock	**2017**	**2018**	**2019**	**2020**
Maize	56	49.8	41	51.6
Chicken manure	27	13.6	13.3	0.2
Grass	11	5.5	4.4	5.6
Millet		4.3	0.215	
Corn grain		1.9	3.9	0.7
Silage rye (whole crop)	7.5	1.1	28.7	24.5
Other solids	1.5	0.5	0.65	4.0
Total	103	76.8	92.2	86.6

The chicken manure digested at BENAS came for the majority from within Germany and partially from the Netherlands. The chicken manure imported from the Netherlands was always hygienised before transport to BENAS. Hygienisation of the chicken manure coming from within Germany was not needed since it did not cross any country borders before arrival at BENAS. Since BENAS applies the end products of the plant within Germany, hygienisation of those end products is not needed. If needed in the future, a hygienisation step could be included in the NRR system, for example connected to the N-stripper to benefit from the already elevated digestate temperatures in the N-stripper.

The demonstration plant BENAS can use, from a technical point of view, chicken manure as well as other feedstock depending on the market conditions. If the prices for chicken manure increase, BENAS can reduce the use of this substrate and replace it with other cheaper feedstock (for example wet grain). At the beginning of SYSTEMIC project, chicken manure had a low value and therefore was used in high quantities. During the course of the project, chicken manure became more attractive for farmers to be used as fertiliser directly on the fields due to rising of fertiliser prices. Consequently, prices for chicken manure started rising more and more and even the availability of chicken manure for BENAS became difficult. At the end of SYSTEMIC project, the use of chicken manure was not economical for BENAS.
Regarding the use of corn grain as biogas feedstock, it must be specified the following. When it rains during the harvest period, after a short time a mildew develops on the wet grain on the fields, making it undesirable for human consumption. Therefore, BENAS can buy this grain for a low price. After drying in the drum dryer, the grain is stored or fed directly to the digesters. This is a win-win situation since wet grain is a waste for farmers and they have to get rid of.

6.1.4 Biogas production and energy generation

The production and average composition of biogas before purification at BENAS are shown in Table 6-3. The highest biogas production was achieved in 2020, 20.5 MNm^3 of which 12.4 MNm^3 were fed to CHP installation. In 2020 also the highest specific biogas production (236 Nm^3 per tonne of feedstock) was achieved. In contrast, the highest specific CH_4 production was achieved in 2018 (176 Nm^3 CH_4 per tonne of feedstock).
Biogas upgraded to biomethane and biogas fed to the CHP installations for electricity generation amounted respectively to 5.8 MNm^3 and 11.5 MNm^3 in 2017, 5 MNm^3 and 12 MNm^3 in 2018, 8 MNm^3 and 12 MNm^3 in 2019 and 8.1 MNm^3 and 12.4 MNm^3 in 2020.

Table 6-3 Production and average composition of biogas before purification at BENAS for the period 2017–2020. Abbreviations: methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and oxygen (O_2).

Parameter	Unit	2017	2018	2019	2020
CH_4	%	53	53	53	53
CO_2	%	46	46	46	46
H_2S	ppm	83	83	83	83
O_2	%	0.1	0.1	0.1	0.1
Total biogas production	MNm^3	20	16.9	20.4	20.5
Specific biogas production	$Nm^3\ t^{-1}$ feedstock	194	221	222	236
Total CH_4 production	MNm^3	10.6	9	11	10.8
Specific CH_4 production	Nm^3 CH_4 t^{-1} feedstock	142	147	168	176

6.1.5 Other information

Labour
BENAS employs 30 FTE in total, of which 0.5 FTE is dedicated to the FiberPlus system.

Waste production
On a yearly basis, the plant produces the following amounts of waste:
- 6 000 liters of oil;
- 3 t of oil-containing equipment;
- 30 t of commercial waste.

Buildings and storage capacity

BENAS has the following storage capacity:

- Digestate: 48 501 m^3 in total over three locations: 3 853 m^3 in Vorwerk, 27 828 m^3 in Ottersberg and 16 820 m^3 in Miesterhorst;
- SF of digestate mixed with CC sludge: approximately 18 600 m^3;
- AS solution: 1 500 m^3 in Miesterhorst, 125 m^3 in Ottersberg and 600 m^3 (lagoon) in Vorwerk;
- CC sludge: new silo of 300 m^2 is under construction at the time of writing;
- Gypsum: 100 m^2 (hall), which will be replaces by a new hall of 450 m^2 which is under construction at the time of writing.

6.2 Drivers for nutrient recycling

6.2.1 Motivation for nutrient recycling

Chicken manure is readily available in the region as an AD feedstock for a low gate fee. However, due to NH_3 inhibition of the anaerobic bacteria, it is difficult to digest and the N application rate limit makes it hard to get rid of the resulting digestate in the region. This leads to transport over large distances and consequently high disposal costs. BENAS, producing up to 400 t d^{-1} of digestate, has therefore been forced to search for a digestate processing technology that lowers the TN content of the digestate. The plant director owns arable land at a distance of 200 km from Ottersberg and has decided to fertilise this land with the fertilisers produced by the plant. Trucks bring the fertilisers to the arable land and drive back to Ottersberg with the energy crops that are fed as feedstock to the digester.

6.2.2 Sustainability goals

BENAS aims to produce renewable energy from energy crops and poultry manure in an environmental friendly manner. Also, with operation of the plant in a grid stabilising mode, BENAS aims to contribute to a more stable electricity grid. This is possible due to the increased biogas storage capacity and the fact that the CHP installations can be switched off for short periods of time. In terms of nutrient management, BENAS aims to close the nutrient cycle by using most of the produced digestate fractions, AS solution and CC sludge on their own fields for the production of energy crops. Furthermore, BENAS aims to find a market for the produced low-N fibres for example as a sustainable alternative for wood fibres or peat.

6.2.3 Economic benefits

An overview of the investment and operating costs of the NRR system, as well as the benefits from the production of AS solution and CC sludge are summarised in Table 6-4. The shown costs do not include costs for the AD process, digestate separation via mechanical fractionation, maintenance of the buildings and the truck fleet and transport and field application of the end products. Moreover, since the plant produces heat in excess there are no costs attributed to heating. On the other hand, incentives from the valorisation of heat generated by the CHP engines were included. The Cost-Benefit Analysis (CBA) is extensively described by Brienza *et al*. (2021) and it was computed for the year 2019, where about 68,561 t of digestate were processed to generate 3,545 t of ammonium sulphate solution.

CAPEX included capital costs for the N-stripping plant (including costs for the storage tank of AS solution) and for the filter press. Overall, the total investment amounted to 1.85 M €. OPEX involved electrical energy requirements, FGD-gypsum consumption, insurance, maintenance and labour costs. The total cost amounted to 5.8 € t^{-1} digestate, in accordance with Vaneeckhaute *et al*. (2017), Bolzonella *et al*. (2017) and Ledda *et al*. (2013) The former reported an overall cost for industrial stripping installations ranging between 2.0 and 8.1 € m^{-3}. Bolzonella *et al*. (2017) and Ledda *et al*. (2013) estimated a total cost of 5.4 and 4.2 € t^{-1} digestate treated, respectively.

Economic benefits were calculated around 7 € t^{-1} digestate and included the avoided costs for the purchase of synthetic mineral N fertilisers (3.5 € t^{-1} digestate) as well as liming substrates (0.78 € t^{-1} digestate). The economic values of AS solution was calculated at 67 € t^{-1}. However, this holds only if AS solution is used on BENAS own fields as replacement for fossil based N fertilisers. According to GNS, trade of AS solution outside BENAS farm, would decrease the N fertiliser commercial value by 50% (GNS, personal communication). This value is higher than that reported by Laureni *et al*. (2013), who estimated the price of AS solution (6% TN) at around 21 € t^{-1}. According to Ledda *et al*. (2013), a commercial value of around 50 € t^{-1} of AS solution can be reached by farms through the subscription to the Fertilisers Producers Register (Dl. 217/2006), and the product registration to the conventional fertilisers register. The difference might be explained by the different local markets.

Table 6-4 Economic assessment of the production of biobased ammonium sulphate generated at BENAS (adapted form Brienza et al., 2021)

	Cost € t^{-1} digestate	Benefit € t^{-1} digestate
Amortised capital cost	3.2	
Electrical energy	1.3	
FGD-gypsum	0.23	
Insurance, maintenance, labour	1.1	
Ammonium sulphate revenue [1]		3.5
Liming substrate revenue		0.78
Heat valorisation		2.8
Total of CAPEX and OPEX	5.8	7.0

[1] used on own cropland, revenues calculated based on the market value of synthetic N of € 1.40/ kg N which was similar to the market value in 2020. When sold onto the market, a 50% lower price is expected.

6.3 The nutrient recovery installation

6.3.1 Technical description of the installation

In 2007/2008, BENAS installed an N-stripper and scrubber developed and patented by GNS (Figure 6-2). NH_3 is stripped from digestate and recovered as AS solution without addition of acids or bases. The NH_3 and CO_2 containing vapours from the N-stripper are, in the scrubber, brought into contact with FGD-gypsum, thereby forming AS solution and CC sludge. This process takes place at a pressure slightly lower than the ambient pressure and at a temperature of 50–85°C. Furthermore, the increment in pH value which is beneficial for N-stripping is achieved by the stripping of CO_2 from the digestate (Cohen & Kirchmann, 2004). The N-stripper includes three stripping reactors with heating and cooling system. The FGD-gypsum is added in the scrubber which results in the formation of the fertiliser suspension. Due to its low price, sulphuric acid is the most commonly used acid for scrubbing of NH_3 from the vapours coming from N-strippers. More expensive acids, such as nitric acid, boric acid and organic acids have also been tested to scrub NH_3 from these vapours (Abouelenien *et al*., 2009; Jamaludin *et al*., 2018; Mohammed-Nour *et al*., 2019; Sigurnjak *et al*., 2019). However, to our knowledge, BENAS is the first AD plant with a scrubber in which gypsum is added to scrub NH_3 from the N stripper vapours. The fertiliser suspension produced by the scrubber is separated by a filter press into two marketable fertiliser end products: AS solution and CC sludge. The produced N-stripped digestate is separated into an LF and SF by the second screw press. The LF of N-stripped digestate is fed back to the digester to decrease the DM content of the ingoing digester feedstock. Since 2020, the SF of N-stripped digestate is further processed by a fibre moulding and paper making machine, although not continuously yet. The resulting product is dried, with excess heat from the CHP installations to remove residual moisture, to the end product low-N fibres. The low-N fibres are suitable for different applications in the fibre and timber industries (for example the production of fibreboard) or as alternative for peat in potting soil. The P present in the low-N fibres does not negatively impact the quality of the fibre products. Monitoring results of the fibre production at BENAS are presented in chapter 6.5. The main technical specifications of the FiberPlus system are summarised in Table 6-6.

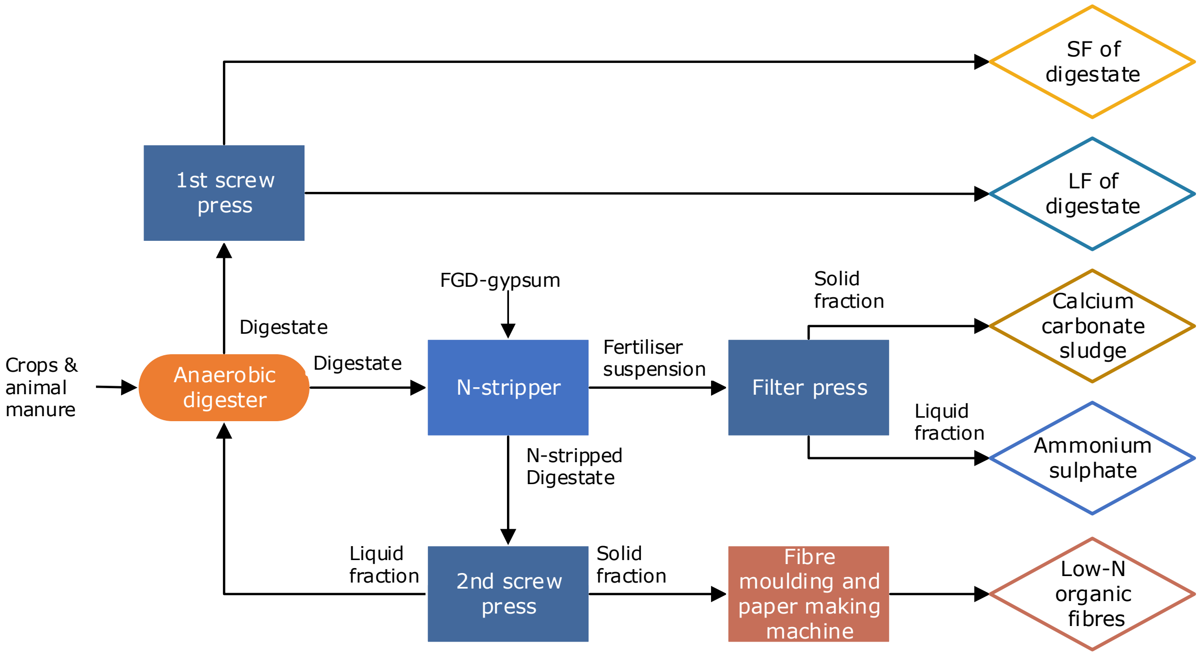

Figure 6-2 Simplified process flow diagram of the NRR system at the demonstration plant BENAS including locations of chemical addition and the major return flows (as configured in 2021).

The advantages of the FiberPlus system are:

- The plant achieves an NH_4-N recovery efficiency of 56–85% of the NH_4-N in the ingoing digestate.
- NH_3 inhibition of the digesters is prevented, increasing the biogas yield by 8%.

- Ammonia emissions upon field application of digestate are reduced.
- The process does not require an external heat source as it functions solely on the heat produced by the CHP installations (the average heat consumption is 100 kWh m^{-3} of digestate).
- The added FGD-gypsum is a by-product of coal power plants, it is compliant with the EU REACH regulation.
- The possibility to recover low-N fibres which have a high market value when used in the fibre industry or potting soil industry.

Table 6-6 Technical specifications of the FiberPlus system at BENAS.

Technical information	
Processing capacity of digestate	5–25 m^3 h^{-1}
NH_3 content of ingoing digestate	3–5 g l^{-1}
DM content of ingoing digestate	5–12.5%
NH_4-N stripping efficiency	56–85%
Consumption of FGD-gypsum	2–16 t d^{-1}
Production capacity of ammonium sulphate solution	5–40 t d^{-1}
Production capacity of calcium carbonate sludge	1.5–14 t d^{-1}
Production capacity of dried low-N fibres	1–22 t d^{-1}

6.3.2 Total production of digestate and other products

The production of LF and SF of digestate at BENAS decreased from in total 75 kt in 2017 to in total 61 kt in 2020. LF of digestate is applied on arable land as NK fertiliser whilst the SF of digestate is applied on arable land as NPK-rich organic fertiliser (Table 6-7). The highest AS solution production was achieved in 2019, with 3 545 t. In 2020, the upgrade of the FiberPlus system with a full-scale fibre moulding and paper making machine required an operational stop of the N-stripper and scrubber. As a result, only 321 t of AS solution were produced.
The approximate amounts of FGD-gypsum consumed in 2017, 2018, 2019 and 2020 were respectively 1 500, 950, 1 287 and 133 t. The amount of produced low-N fibres is still less than 1000 tonnes per year because BENAS has not yet started the production at full-scale. BENAS envisages to reach a production of 8 000 t low-N fibres per year as soon as a costumer has been found.

Table 6-7 Total production of end products at BENAS in tonnes per year for the period 2017–2020.

End product	**Unit**	**2017**	**2018**	**2019**	**2020**
LF of digestate	t y^{-1}	57 286	51 316	49 167	44 870
SF of digestate	t y^{-1}	17 600	9 921	16 375	16 444
Ammonium sulphate solution	t y^{-1}	3 696	2 011	3 545	321
Calcium carbonate sludge	t y^{-1}	1 088	592	1 128	117
Low-N fibres	t y^{-1}	<1 000	<1 000	<1 000	<1 000

6.4 Mass flows and balances of the NRR system without low-N fibre production

6.4.1 Monitoring and sampling

A mass balance for the NRR system of BENAS was drafted for the monitoring period January 2019 – April 2019. In this period no low-N fibres were produced yet. The aim of this was evaluation of the overall performance of the plant, including the achieved separation efficiencies of each process unit and the achieved nutrient recovery efficiencies. From January until April 2019 around 6.3 MNm^3 of biogas were produced (Table 6-8). In addition to the feedstock, iron sludge was added to the digesters as well. The dosage was 7.4 kg of iron sludge per added t of feedstock. The sludge had a DM content of 20%, on a mass basis 30% of the DM was iron.

Table 6-8 Production and average composition of biogas before purification at BENAS for the period January–April 2019. Abbreviations: methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and oxygen (O_2).

Component	**Unit**	**Amount**
CH_4	%	53
CO_2	%	47
H_2S	ppm	170
O_2	%	Not detected
Total biogas production	MNm^3	6.3
Specific biogas production	$Nm^3\ t^{-1}$ feedstock	224
Total CH_4 production	MNm^3	3.3
Specific CH_4 production	$Nm^3\ CH_4\ t^{-1}$ feedstock	117

Over the monitoring period, about 28 287 t of feedstock were anaerobically digested, of which 62% was corn silage, 28% was fresh or dried chicken manure, 9% consisted of agricultural substrates and 1% was goose manure (Table 6-9).

Table 6-9 Origin of anaerobic digestion feedstock of BENAS, expressed in kilotonnes for the period January–April 2019.

Feedstock	**kt**
Corn silage	17.4
Corn grain	0.9
Chicken manure	7.9
Grass silage	1.5
Goose manure	0.25
Millet	0.22
Corncob mixture	0.011
Total	28.2

6.4.2 Chemical characterisation of digestate and end products

The average composition of the intermediate process streams and end products of the NRR system at BENAS for the period January–April 2019 is shown in Table 6-10. Samples were chemically analysed by Ghent University. The full characterisation of the end products, with metal concentrations expressed in mg kg^{-1} DM, is available in deliverable 1.13.

Table 6-10 Chemical characterisation (in fresh weight) of the intermediate process streams and end products of the NRR system at the demonstration plant BENAS for the period January–April 2019. Average of four samples ± one standard deviation.

Parameter	Unit	Unseparated digestate	LF of digestate	SF of digestate	Stripper influent (digestate)
pH	-	8.4 ± 0.09	8.4 ± 0.1	8.6 ± 0.3	8.5 ± 0.12
EC	mS cm^{-1}	31 ± 2.8	31 ± 2	5 ± 0.2	29 ± 0.96
DM	g kg^{-1}	118 ± 2.1	100 ± 10	252 ± 5.5	119 ± 3.5
OM	g kg^{-1}	82 ± 9	65 ± 8.3	189 ± 10	82 ± 2.3
TN	g kg^{-1}	7.9 ± 2.1	7.4 ± 2	8.7 ± 1.2	8.2 ± 1.7
NH_4-N	g kg^{-1}	4.4 ± 0.43	4.3 ± 0.81	4.4 ± 0.94	4.5 ± 0.48
TP	g kg^{-1}	1.6 ± 0.26	1.5 ± 0.21	2.2 ± 0.22	1.8 ± 0.13
TK	g kg^{-1}	6.9 ± 0.73	6.7 ± 0.8	5.5 ± 2.3	7.1 ± 0.79
TS	g kg^{-1}	1.2 ± 0.085	1.2 ± 0.12	1.6 ± 0.27	1.2 ± 0.083
Ca	g kg^{-1}	4.2 ± 0.86	3.7 ± 1.2	4.4 ± 0.91	4.2 ± 0.83
Mg	g kg^{-1}	0.75 ± 0.15	0.69 ± 0.25	1.3 ± 0.19	1 ± 0.22
Na	g kg^{-1}	0.66 ± 0.12	0.64 ± 0.16	0.58 ± 0.16	0.66 ± 0.14
Cu	mg kg^{-1}	7.2 ± 2	7.3 ± 1.8	6.3 ± 1.5	6.9 ± 1.9
Zn	mg kg^{-1}	39 ± 13	38 ± 12	51 ± 17	40 ± 13
Al	mg kg^{-1}	69 ± 15	69 ± 15	46 ± 10	70 ± 15
Fe	mg kg^{-1}	1348 ± 776	1292 ± 754	1506 ± 689	1351 ± 839
Co	mg kg^{-1}	0.22 ± 0.075	0.21 ± 0.071	0.21 ± 0.088	0.21 ± 0.065
Ni	mg kg^{-1}	0.89 ± 0.3	0.86 ± 0.27	0.9 ± 0.33	0.88 ± 0.27
Pb	mg kg^{-1}	0.94 ± 0.77	0.95 ± 0.79	0.95 ± 0.72	1 ± 0.74
Cr	mg kg^{-1}	0.58 ± 0.19	0.55 ± 0.21	0.64 ± 0.11	0.63 ± 0.29
Mn	mg kg^{-1}	96 ± 27	98 ± 28	95 ± 22	99 ± 24
		N-stripped digestate	**Fertiliser suspension**	**Ammonium sulphate solution**	**Calcium carbonate sludge**
pH	-	9.9 ± 0.18	7.6 ± 0.083	7.8 ± 0.037	7.9 ± 0.045
EC	mS cm^{-1}	16 ± 0.46	166 ± 20	223 ± 15	15 ± 1.5
DM	g kg^{-1}	126 ± 5.5	391 ± 38	224 ± 11	695 ± 12
OM	g kg^{-1}	86 ± 3.9	-	-	-
TN	g kg^{-1}	5.8 ± 0.89	38 ± 2.3	46 ± 3.6	15 ± 2
NH_4-N	g kg^{-1}	1.8 ± 0.29	38 ± 5.8	46 ± 2.5	15 ± 2.6
TP	g kg^{-1}	1.9 ± 0.12	0.057 ± 0.0074	0.0033 ± 0.0018	0.19 ± 0.049
TK	g kg^{-1}	7.7 ± 0.97	0.13 ± 0.046	0.0039 ± 0.0017	0.4 ± 0.24
TS	g kg^{-1}	1.3 ± 0.1	50 ± 8.4	58 ± 0.81	32 ± 12
Ca	g kg^{-1}	4.8 ± 1.1	65 ± 29	1.2 ± 0.42	225 ± 39
Mg	g kg^{-1}	1.1 ± 0.19	0.1 ± 0.061	0.0067 ± 0.0015	0.33 ± 0.16
Na	g kg^{-1}	0.72 ± 0.15	0.057 ± 0.02	0.0039 ± 0.0022	0.19 ± 0.09
Cu	mg kg^{-1}	7.7 ± 1.9	0.65 ± 0.036	0.038 ± 0.022	2.1 ± 0.2
Zn	mg kg^{-1}	42 ± 13	4.1 ± 0.56	0.099 ± 0.024	12 ± 0.31
Al	mg kg^{-1}	74 ± 17	246 ± 21	0.82 ± 0.31	763 ± 155
Fe	mg kg^{-1}	1368 ± 758	219 ± 39	7.8 ± 5.2	669 ± 104
Co	mg kg^{-1}	0.23 ± 0.084	0.1 ± 0.0091	0.012 ± 0.012	0.31 ± 0.048
Ni	mg kg^{-1}	0.97 ± 0.31	0.96 ± 0.18	0.18 ± 0.051	3 ± 1.2
Pb	mg kg^{-1}	1 ± 0.82	0.38 ± 0.051	0.039 ± 0.026	1.1 ± 0.12
Cr	mg kg^{-1}	0.61 ± 0.21	0.97 ± 0.16	0.015 ± 0.005	3.2 ± 0.39
Mn	mg kg^{-1}	105 ± 25	11 ± 4.8	0.17 ± 0.051	36 ± 14

Addition of the FGD-gypsum to the NRR system is in accordance with regulation (EG) No. 2003/2003 for biotechnological treatment of animal and vegetable substances. The average composition of this FGD-gypsum is shown in Table 6-11.

Table 6-11 Chemical characterisation (in fresh weight) of the Flue Gas Desulphurisation-gypsum added at BENAS. Average of four samples ± one standard deviation.

Parameter	Unit	Amount
pH	-	7.6 ± 0.091
EC	mS cm^{-1}	2 ± 0.18
DM	g kg^{-1}	750 ± 30
OM	g kg^{-1}	-
TN	g kg^{-1}	0.26 ± 0.1
NH_4-N	g kg^{-1}	0.12 ± 0.056
TP	g kg^{-1}	0.21 ± 0.085
TK	g kg^{-1}	0.39 ± 0.13
TS	g kg^{-1}	159 ± 7
Ca	g kg^{-1}	218 ± 9
Mg	g kg^{-1}	0.28 ± 0.12
Na	g kg^{-1}	0.17 ± 0.02
Cu	mg kg^{-1}	1.9 ± 0.23
Zn	mg kg^{-1}	13 ± 2.9
Al	mg kg^{-1}	724 ± 135
Fe	mg kg^{-1}	620 ± 65
Co	mg kg^{-1}	0.31 ± 0.021
Ni	mg kg^{-1}	2.6 ± 0.24
Pb	mg kg^{-1}	1.1 ± 0.028
Cr	mg kg^{-1}	2.6 ± 0.28
Mn	mg kg^{-1}	35 ± 12

6.4.3 Mass flow analyses of macronutrients, micronutrients and heavy metals

Figure 6-3 shows the calculated mass flows for DM and water of the NRR system at BENAS for the period January–April 2019 (120 days). Mass flows were either measured by flowmeters or calculated.
On average, 236 t d^{-1} of feedstock were fed the AD plant. The resulting digestate was processed via two pathways. In the first pathway, digestate from the main digester was pumped to the post-digester. The outgoing digestate of the post-digester (167 t d^{-1}) was separated into an SF (34 t d^{-1}) and LF (133 t d^{-1}) of digestate by the first screw press. The majority of DM in the influent of the first screw press ended up in the LF of digestate. This result is in line with studies from Bachmann *et al*. (2016) and Popovic *et al*. (2012).

In the second pathway, 222 t d^{-1} of digestate from the main digester was processed by the N-stripper and scrubber for removal of NH_4-N, resulting in 210 t d^{-1} of N-stripped digestate (stripper effluent). The average temperature of the ingoing digestate and outgoing N-stripped digestate of the N-stripper were respectively 47 °C and 76 °C. The NH_3 and CO_2 containing vapour from the N-stripper were brought into contact with 5.3 t d^{-1} of FGD-gypsum in the scrubber, thereby producing 17 t d^{-1} of fertiliser suspension. The fertiliser suspension was separated by a filter press into AS solution (12 t d^{-1}) and calcium carbonate sludge (5 t d^{-1}). The N-stripped digestate produced by the N-stripper was, without further separation, fed back to a different digester than the one from which the influent from the N-stripper came. Of the water present in the influent of the stripper, 6.1% vaporized in the N-stripper, allowing the process to produce AS solution without the addition of external water.

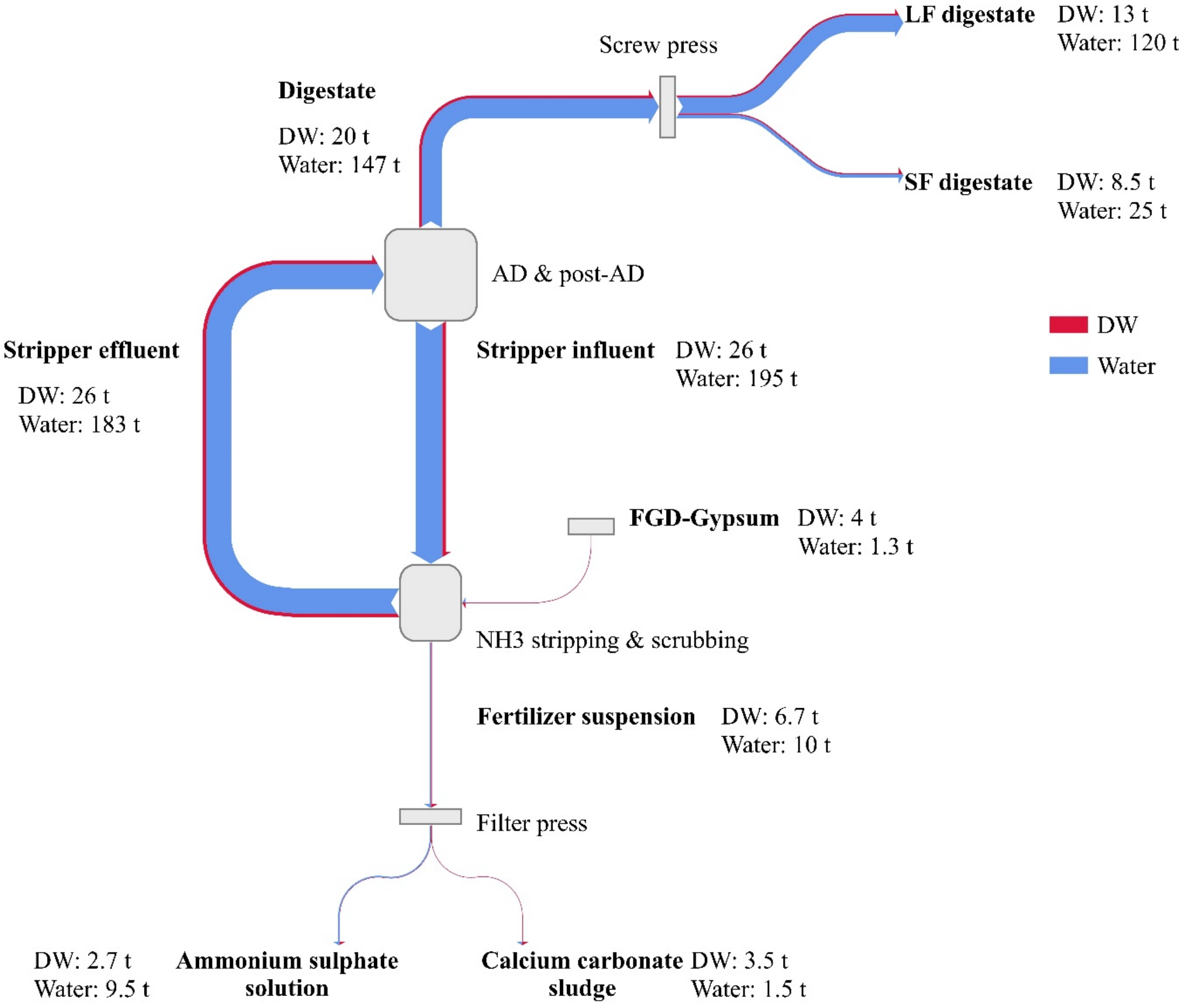

Figure 6-3 Dry matter (DM) and water mass flows of the NRR system at the demonstration plant BENAS in tonnes per day for the period January–April 2019. Abbreviations: anaerobic digestion (AD), liquid fraction of digestate (LF digestate), solid fraction of digestate (SF digestate), Flue Gas desulphurisation (FGD)-gypsum. Adapted from Brienza et al. (2021).

Figure 6-4 shows the organic N, NH_4-N, TP and TK mass flows of the NRR system at BENAS for the period January–April 2019 (120 days). Of the TN (1.8 t d^{-1}) in the stripper influent, on average about 36% ended up in the fertiliser suspension and 64% (1.2 t d^{-1}) ended up in the N-stripped digestate (stripper effluent), mainly as organic N, which was fed back to the digester. In the N-stripper, only NH_4-N evaporates whilst organic N remains in the digestate. The fertiliser suspension is therefore almost free of organic N. Of the TN and NH_4-N in the fertiliser suspension, respectively 85% and 87% ended up in the AS solution. The N-stripper on average removed 21 kg TN h^{-1}, producing an AS solution with a TN content of 4.6%.

Over the course of the monitoring campaign, BENAS produced 12 t d^{-1} of 12% AS solution, which is equivalent to 2.5 kg of NH_4-N recovered per t of digestate that is processed in the N-stripper. In contrast, the small amounts of TP and TK that were present in the fertiliser suspension ended up in the CC sludge, respectively for 95% and 97%. Of the organic N in the influent of the first screw press 73% ended up in the liquid fraction. This is in line with research by Møller *et al*. (2002) who showed that a considerable amount of the small particles present in animal manure end up in the LF of a screw press. This because a portion of the, organic N containing, particles is small enough to pass through the filter pores of a screw press. N, P and K are either likely to be present in solubilised form or in the form of small particles (Hjorth *et al*., 2011), therefore the majority of these components is expected to end up in the LF of a screw press.

This is the case for the first screw press of BENAS as well. Ingoing and outgoing mass flows over the first screw press for organic N, NH_4-N, TP and TK were similar, differing <10%.

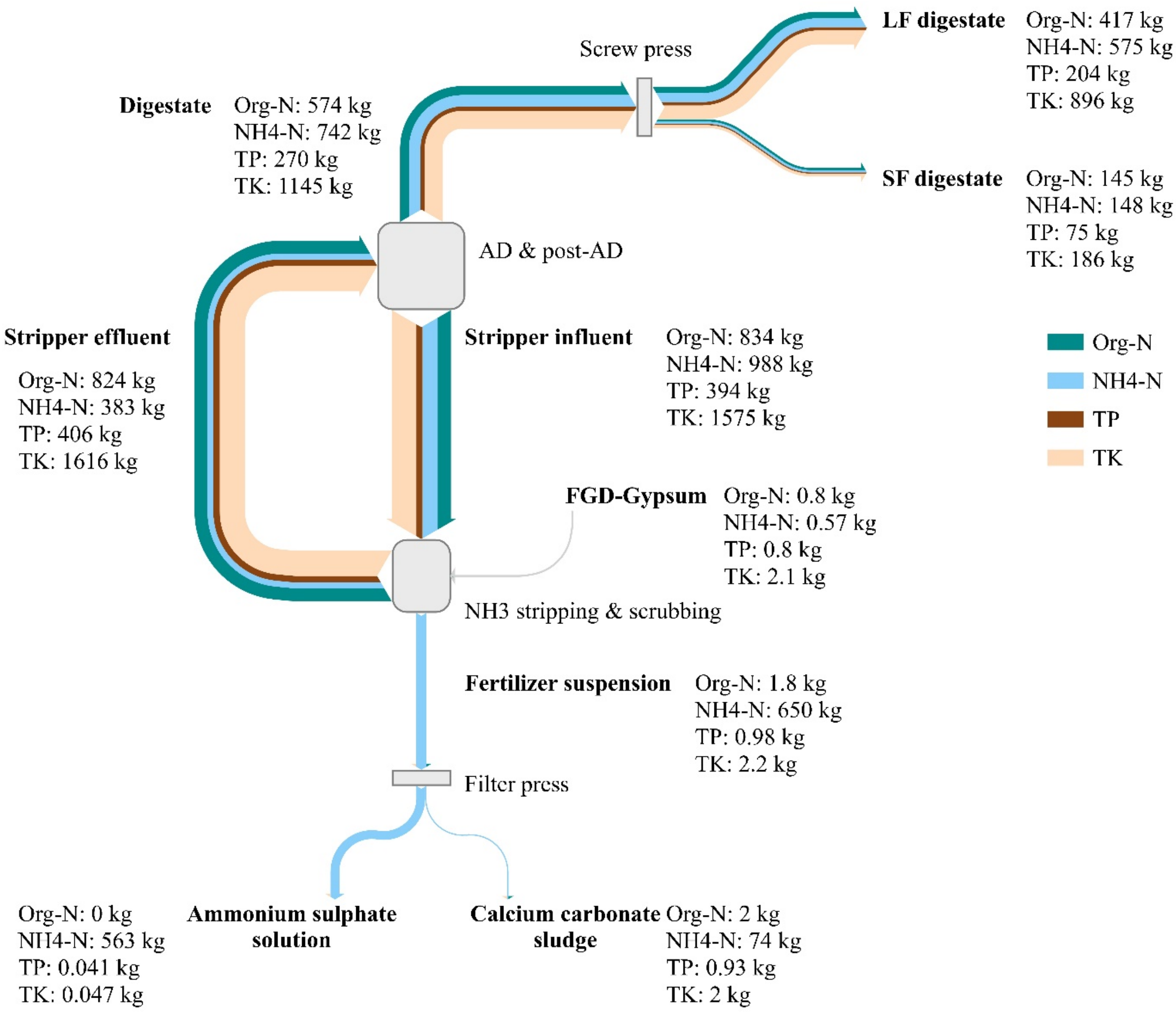

Figure 6-4. Organic nitrogen (Org-N), ammoniacal nitrogen (NH_4-N), total phosphorus (TP) and total potassium (TK) mass flows of the NRR system at the demonstration plant BENAS in kg per day for the period January – April 2019. Abbreviations: anaerobic digestion (AD), liquid fraction of digestate (LF digestate), solid fraction of digestate (SF digestate), Flue Gas desulphurisation (FGD)-gypsum. Adapted from Brienza et al. (2021).

Figure 6-4 shows the TS, Mg, Ca and Na mass flows of the NRR system at BENAS for the period January–April 2019 (120 days). Of the TS in the influent of the filter press, 82% ended up in the AS solution whereas the majority (>90%) of Mg, Ca and Na in the influent of the filter press ended up in the CC sludge. Ingoing and outgoing mass flows over the first screw press for TS, Mg, Ca and Na were similar, differing <10%. The majority of TS, Mg, Ca and Na in the influent of the first screw press ended up in the LF of digestate. Although this was the least the case for Mg.

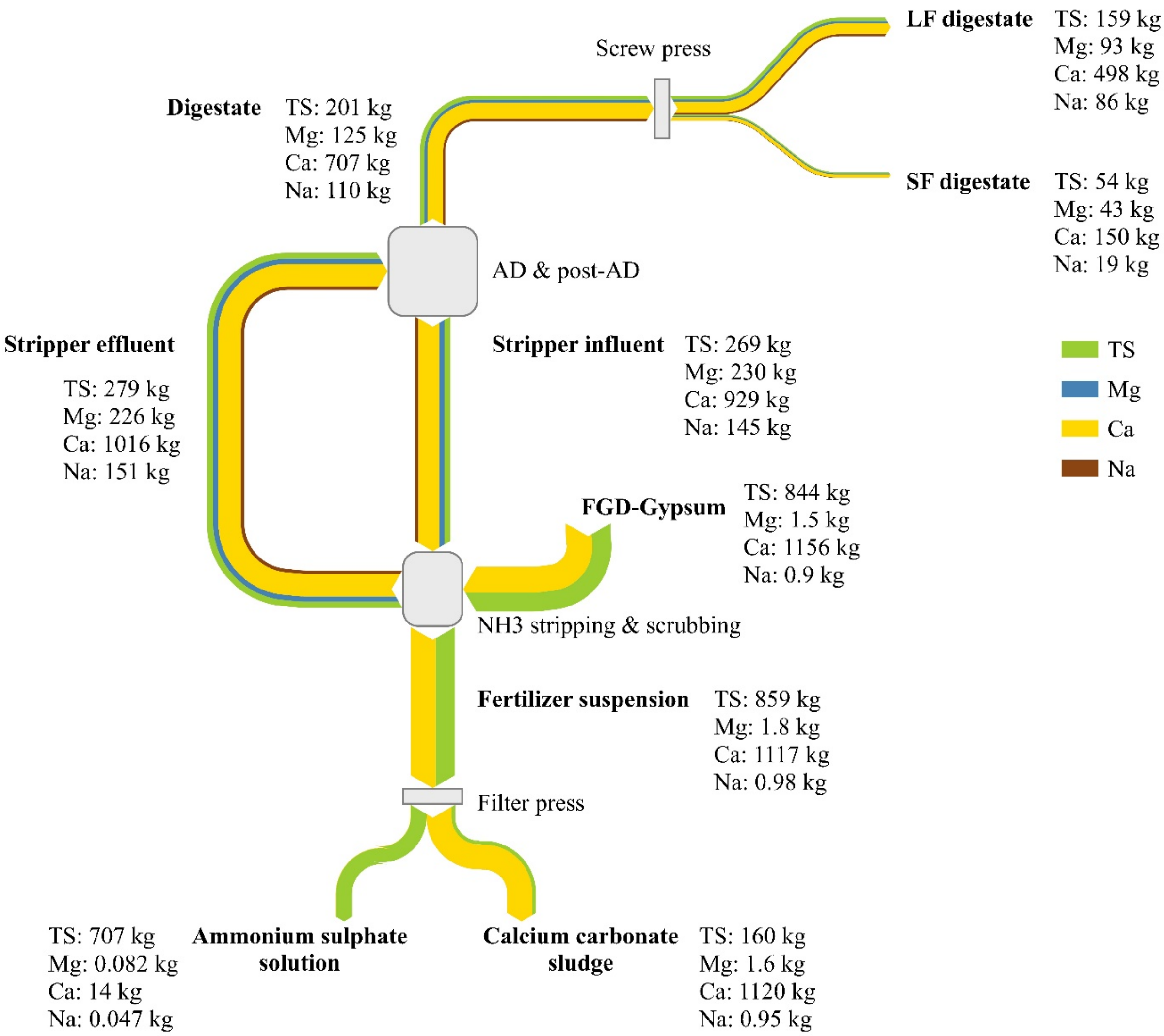

Figure 6-5 Total sulphur (TS), magnesium (Mg), calcium (Ca) and sodium (Na) mass flows of the NRR system at the demonstration plant BENAS in kg per day for the period January – April 2019. Abbreviations: anaerobic digestion (AD), liquid fraction of digestate (LF digestate), solid fraction of digestate (SF digestate), Flue Gas desulphurisation (FGD)-gypsum. Adapted from Brienza et al. (2021).

6.4.4 Separation and nutrient recovery efficiencies of process units

Table 6-12 shows the calculated separation efficiencies of the individual process units of the NRR system at BENAS as a percentage of the ingoing amount of each parameter. On average, 80% of the total mass of first screw press influent ended up in the LF of digestate and 11% in the SF of digestate. The SF of digestate contained respectively 22% and 28% of the amounts of TN and TP in the influent of the first screw press. For the other parameters comparable separations to the SF of digestate were found except for OM and DM, having higher separation efficiencies to the SF of digestate. On average, 71% of the total mass of filter press influent ended up in the AS solution and 29% in the CC sludge. Of the TN, NH_4-N and TS present in the fertiliser suspension respectively 85%, 87% and 82% ended up in the AS solution. In contrast, for the other parameters the majority of the amount in the fertiliser suspension ended up in the CC sludge. Ingoing and outgoing mass flows for all shown parameters over the first screw press and over the filter press were similar.

Table 6-12 Separation efficiencies of the process units of the NRR system at BENAS for the period January – April 2019 for the following parameters: total mass, moisture (H_2O), dry matter (DM), organic matter (OM), total nitrogen (TN), ammoniacal nitrogen (NH_4-N), total phosphorus (TP), total potassium (TK), total sulphur (TS), calcium (Ca), magnesium (Mg), sodium (Na), copper (Cu), zinc (Zn), aluminium (Al), iron (Fe), cadmium (Cd), cobalt (Co), lead (Pb), chromium (Cr), nickel (Ni) and manganese (Mn).

	Total mass	**H_2O**	**DM**	**OM**	**TN**	**NH_4-N**	**TP**	**TK**	**TS**	**Ca**	**Mg**
	%	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
First screw press											
LF of digestate	80	82	67	63	75	77	76	78	79	70	74
SF of digestate	20	18	43	47	22	20	28	16	27	21	34
Filter press											
Ammonium sulphate solution	71	93	41		85	87	4.1	2.1	82	1.3	4.6
Calcium carbonate sludge	29	4.9	52		12	11	95	90	19	100	92
	Na	**Cu**	**Zn**	**Al**	**Fe**	**Cd**	**Co**	**Pb**	**Cr**	**Ni**	**Mn**
	%	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
First screw press											
LF of digestate	78	81	77	79	77	n.a.	78	n.a.	76	77	81
SF of digestate	18	18	26	13	23	n.a.	19	n.a.	22	20	20
Filter press											
Ammonium sulphate solution	4.8	4.1	1.7	0.23	2.5	n.a.	8.3	n.a.	1.1	13	1.1
Calcium carbonate sludge	97	93	89	90	89	n.a.	92	n.a.	98	91	95

Table 6-13 shows the calculated recovery efficiencies to the AS solution and CC sludge of the N-stripper and scrubber and filter press at WNE for the period January–April 2019. Of the TN in the digestate fed to the N-stripper, 31% ended up in the AS solution and 4.2% in the CC sludge. Of the NH_4-N in the digestate fed to the N-stripper, 57% ended up in the AS solution and 7.4% in the CC sludge. The remaining amounts of TN and NH_4-N were fed back to the digester in the form of N-stripped digestate (stripper effluent).

It must be stressed that these are the recovery efficiencies based on the digestate that enters the N-stripper. These recovery efficiencies are lower than they would be if expressed as percentage of the TN and NH_4-N in the digester feedstock. This is caused by the N-stripped digestate being fed back to the digester which lowers the concentration of TN and NH_4-N in the digester.

The recovery rate of the N-stripper, scrubber and filter press increased from 18 to 24 kg h^{-1} of N recovered as AS solution over the course of the four months of monitoring (Table 6-13).

Table 6-13 Recovery efficiencies to the ammonium sulphate solution and calcium carbonate sludge of the NRR system at BENAS for the period January – April 2019 for total nitrogen (TN) and ammoniacal nitrogen (NH_4-N) as percentage of the amounts in the digestate fed to the N-stripper.

	TN	**NH_4-N**
	%	**%**
Ammonium sulphate solution	31	57
Calcium carbonate sludge	4.2	7.4

6.5 Mass flows and balances of the NRR system with fibres production

6.5.1 Monitoring and sampling

A mass balance for the NRR system of BENAS was drafted for the monitoring period July–September 2021. In this period low-N fibres were produced. The N-stripped digestate produced by the N-stripper was separated into an SF and LF by the second screw press. Only the LF of N-stripped digestate was in this period fed back to the AD. The SF of N-stripped digestate was further processed in a fibre moulding

and a paper making machine to produce marketable low-N fibres. The aim of this was evaluation of the overall performance of the plant, including the achieved separation efficiencies of each process unit and the achieved nutrient recovery efficiencies.
In this monitoring period BENAS was able to produce mulch mats, plant pots and paper rolls.

6.5.2 Chemical characterisation of digestate and end products

The average composition of the intermediate process streams and the low-N fibres of the NRR system at BENAS for the period July–September 2021 are shown in Table 6-14. Samples were collected by BENAS and chemically analysed by the laboratory of LUFA. The N-stripped digestate (stripper effluent), LF of N-stripped digestate and SF of N-stripped digestate were sampled and analysed each month. The low-N fibres were sampled and analysed once.
The full characterisation of the end products, with metal concentrations expressed in mg kg^{-1} DM, is available in deliverable 1.13.

Table 6-14 Chemical characterisation (in fresh weight) of the intermediate process streams and end products of the NRR system at the demonstration plant BENAS for the period July–September 2021. Average of three samples ± one standard deviation, except for Low-N fibres (one sample).

Parameter	**Unit**	**N-stripped digestate (stripper effluent)**	**LF of N-stripped digestate**	**SF of N-stripped digestate**	**Low-N fibres**
pH		8.0 ± 0.26	8.1 ± 0.31	7.8 ± 0.21	5.9
EC	uS cm^{-1}	1040 ± 640	1062 ± 653		
DM	g kg^{-1}	39 ± 14	33 ± 20	243 ± 2.9	895
OM	g kg^{-1}	30 ± 8.5	23 ± 14	227 ± 5.3	871
TN	g kg^{-1}	1.5 ± 0.82	1.5 ± 0.89	2.7 ± 1.0	5.8
NH_4-N	g kg^{-1}	0.63 ± 0.29	0.67 ± 0.32	0.73 ± 0.38	0.2
TP	g kg^{-1}	0.56 ± 0.31	0.64 ± 0.40	1.0 ± 0.68	1.3
TK	g kg^{-1}	2.6 ± 1.5	2.5 ± 1.5	2.2 ± 1.6	0.83
TS	g kg^{-1}	0.19 ± 0.021	0.19 ± 0.021	0.49 ± 0.057	2.5
Ca	g kg^{-1}	0.60 ± 0.33	0.61 ± 0.39	1.2 ± 0.51	3.6
Mg	g kg^{-1}	0.27 ± 0.1	0.32 ± 0.18	0.78 ± 0.26	0.66
Zn	mg kg^{-1}	0.010 ± 0.0029	0.0087 ± 0.0017	0.014 ± 0.0027	0.063
Fe	mg kg^{-1}	0.15 ± 0.083	0.15 ± 0.10	0.26 ± 0.33	4.5

6.5.3 Mass flow analyses of macronutrients, micronutrients and heavy metals

Table 6-15 shows the calculated mass balance over the second screw press at BENAS for the period July–September 2021. Outgoing mass flows were calculated based on the DM content of each process stream under the assumption that no DM losses occurred during the separation process. Ingoing and outgoing mass flows for all shown parameters over the second screw press were similar with deviations of roughly 10% with the exception of TP and Mg. For TP and Mg the sum of outgoing mass flows was respectively 16% and 23% larger than the ingoing mass flow. This is most likely caused by small temporal fluctuations in the concentrations of the process streams that cannot be captured by the performed discontinuous sampling.

Table 6-15 Mass balance over the second screw press per tonne of ingoing N-stripped digestate (stripper effluent) at BENAS for the period July–September 2021.

Parameter	Unit	N-stripped digestate (stripper effluent)	LF of N-stripped digestate	SF of N-stripped digestate
Total mass	kg	1000	969	31
DM	kg	39	32	7.4
OM	kg	30	22	6.9
TN	kg	1.5	1.5	0.082
NH_4-N	kg	0.63	0.65	0.022
TP	kg	0.56	0.62	0.032
TK	kg	2.6	2.5	0.067
TS	kg	0.19	0.18	0.015
Ca	kg	0.6	0.59	0.037
Mg	kg	0.27	0.31	0.024
Zn	kg	0.010	0.0085	0.00043
Fe	kg	0.15	0.15	0.0079

6.5.4 Separation and nutrient recovery efficiencies of process units

Table 6-16 shows the calculated separation efficiencies of the second screw press at BENAS as a percentage of the ingoing amount of each parameter. All shown parameters, except for TK were to a smaller or larger extent concentrated in the SF of N-stripped digestate as only 3.1% of the ingoing total mass became SF of N-stripped digestate. This was strongest for DM and OM.

Table 6-16 Separation efficiencies of the second screw press at BENAS for the period July–September 2021 for the following parameters: total mass, dry matter (DM), organic matter (OM), total nitrogen (TN), ammoniacal nitrogen (NH_4-N), total phosphorus (TP), total potassium (TK), total sulphur (TS), calcium (Ca), magnesium (Mg), zinc (Zn) and iron (Fe).

	Total mass %	DM %	OM %	TN %	NH_4-N %	TP %
Second screw press						
LF of N-stripped digestate	97	81	75	97	102	110
SF of N-stripped digestate	3.1	19	23	5.5	3.5	5.7
	TK %	**TS %**	**Ca %**	**Mg %**	**Zn %**	**Fe %**
Second screw press						
LF of N-stripped digestate	96	97	98	114	88	97
SF of N-stripped digestate	2.6	8.1	6.2	8.8	4.5	5.2

6.6 Energy balance

6.6.1 Energy production

In 2017, BENAS generated 23 611 MWh electricity and 28 582 MWh of useable thermal energy; similar amounts were generated in 2018 (Table 6-17). Thereafter electricity generation increased to respectively 27 993 MWh in 2019 and 27 977 in 2020 MWh. Also the amount of biomethane generated increased from 25 914 MWh in 2017 to 42 171 MWh in 2020. This was caused by an increase in the amount of biomethane produced per tonne of digestate as the amount of digestate produced did not increase.

Table 6-17 Electricity, heat and biomethane production at BENAS for the period 2017–2020.

	Digestate production ($t\ y^{-1}$)	Working days	Electricity generation		Thermal energy generation		Biomethane generation	
			MWh	kWh t^{-1} digestate	MWh	kWh t^{-1} digestate	MWh	kWh t^{-1} digestate
2017	74 886	365	23 611	315	28 582	342	25 914	346
2018	61 237	365	23 828	389	29 022	474	23 558	385
2019	65 542	365	27 993	427	25 518	389	38 451	575
2020	61 314	365	27 977	456	24 784	404	42 171	687

6.6.2 Energy consumption

In 2019, production of ammonium sulphate solution at BENAS required 8.3 $kWh_e\ t^{-1}$ of processed digestate, 3.8 $kWh_e\ kg^{-1}$ of N recovered (Table 6-18). Vaneeckhaute *et al*. (2017) reported an energy consumption for production of ammonium sulphate solution of 1.54–12 kWh_e and 62–69 $kWh_{th}\ m^{-3}$ of processed digestate. The electricity consumption for production of ammonium sulphate solution at BENAS by the N-stripper, scrubber and filter press is in line with these literature values, whereas heat consumption at BENAS is higher. In 2019, approximately 161 t of TN were removed with the N-stripping and scrubber, thereby producing 3 545 t of 22% ammonium sulphate solution. This corresponds respectively to 3.8 kWh_e and 59 $kWht_h\ kg^{-1}$ N recovered as 22% ammonium sulphate. Tampio *et al*. (2016) extensively reviewed the electricity consumption of strippers and scrubbers processing different influents, including animal manure, digestate and urine. The reported electricity consumptions ranged between 0.8 and 28.2 $kWh_e\ kg^{-1}$ of N recovered. Furthermore, Bolzonella *et al*. (2018) calculated an electricity consumption for stripping and scrubbing of 12 $kWh_e\ kg^{-1}$ of N recovered. In addition to the electricity and heat consumed by the N-stripper and scrubber, also electricity and heat are consumed for cooling of the stripping gas and biogas, for heating of the digesters and external buildings and for drying purposes. Of the total heat consumption of BENAS, 68% was used for drying of wood chips and grain in 2020. The wood chips are dried for external clients, the grain is dried to prevent moulds they contain from spreading which is needed for biogas production. The grain which BENAS feeds to the AD is usually of low quality and not suitable for consumption.

Table 6-18 Electricity and heat consumption at BENAS for the period 2018–2020.

	Digestate production (t y^{-1})	Working days	Electricity consumption		Thermal energy consumption	
			MWh_e	kWh_e t^{-1} digestate	MWh_{th}	kWh_{th} t^{-1} digestate
2018						
N-stripper and scrubber	61 237	365	608	9.9	6 215	101
Cooling of stripping gas and biogas	61 237	365	73	1.2	1 371	22
Digester & post-digester	61 237	365	666	11	2 800	46
External buildings	61 237	365	31	0.51	1 046	17
Drying purposes (wood chips, grain)	61 237	365	244	4	15 375	251
Total (2018)	61 237	365	1 622	26	26 807	438
2019		365				
N-stripper and scrubber	65 542	365	570	8.3	9 526	139
Cooling of stripping gas and biogas	65 542	365	73	1.1	2 016	31
Digester & post-digester	65 542	365	841	13	2 800	43
External buildings	65 542	365	30	0.46	1 252	19
Drying purposes (wood chips, grain)	65 542	365	190	2.9	14 959	228
Total (2019)	65 542	365	1 704	26	30 553	460
2020						
N-stripper and scrubber	61 314	92	147	8.5	2 452	142
Cooling of stripping gas and biogas	61 314	365	60	0.97	1 639	27
Digester & post-digester	61 314	365	841	14	2 800	46
External buildings	61 314	365	28	0.46	1 150	19
Drying purposes (wood chips, grain)	61 314	365	213	3.5	16 743	273
Total (2020)	61 314	365	1 289	27	24 784	507

6.6.3 Energy balance

Based on the energy input and output of BENAS, an energy balance was drafted for the years 2018, 2019 and 2020 (Figure 6-6). For this it was assumed that 1 m^3 of CH_4 from biogas corresponds to 8.89 kWh of energy and that no energy losses occurred due to upgrading of biogas to biomethane. In reality some energy losses would occur due to upgrading of biogas to biomethane.

In 2018, 21% of the useable thermal energy produced by the CHP installations was consumed by the N-stripper and scrubber. This share increased to 37% in 2019. In 2019, the calculated amount of thermal energy consumed by the plant slightly exceeded the amount of heat produced. This is caused by the fact that part of the consumed heat was first used at a higher temperature and subsequently used again at a lower temperature, resulting in double-counting. The plant did not use any external heat sources. Due to the lower amount of working days, in 2020 only 9.9% of heat consumption was recorded. The increase in heat consumption by the N-stripper and scrubber from 2018 to 2019 coincides with an increase in the amount of TN recovered as AS solution, which increased from 116 t in 2018 to 161 t in 2019. The fraction of the total electricity production used for the N-stripper and scrubber decreased from 2.6% and 2.0% in respectively 2018 and 2019 to only 0.53% in 2020.

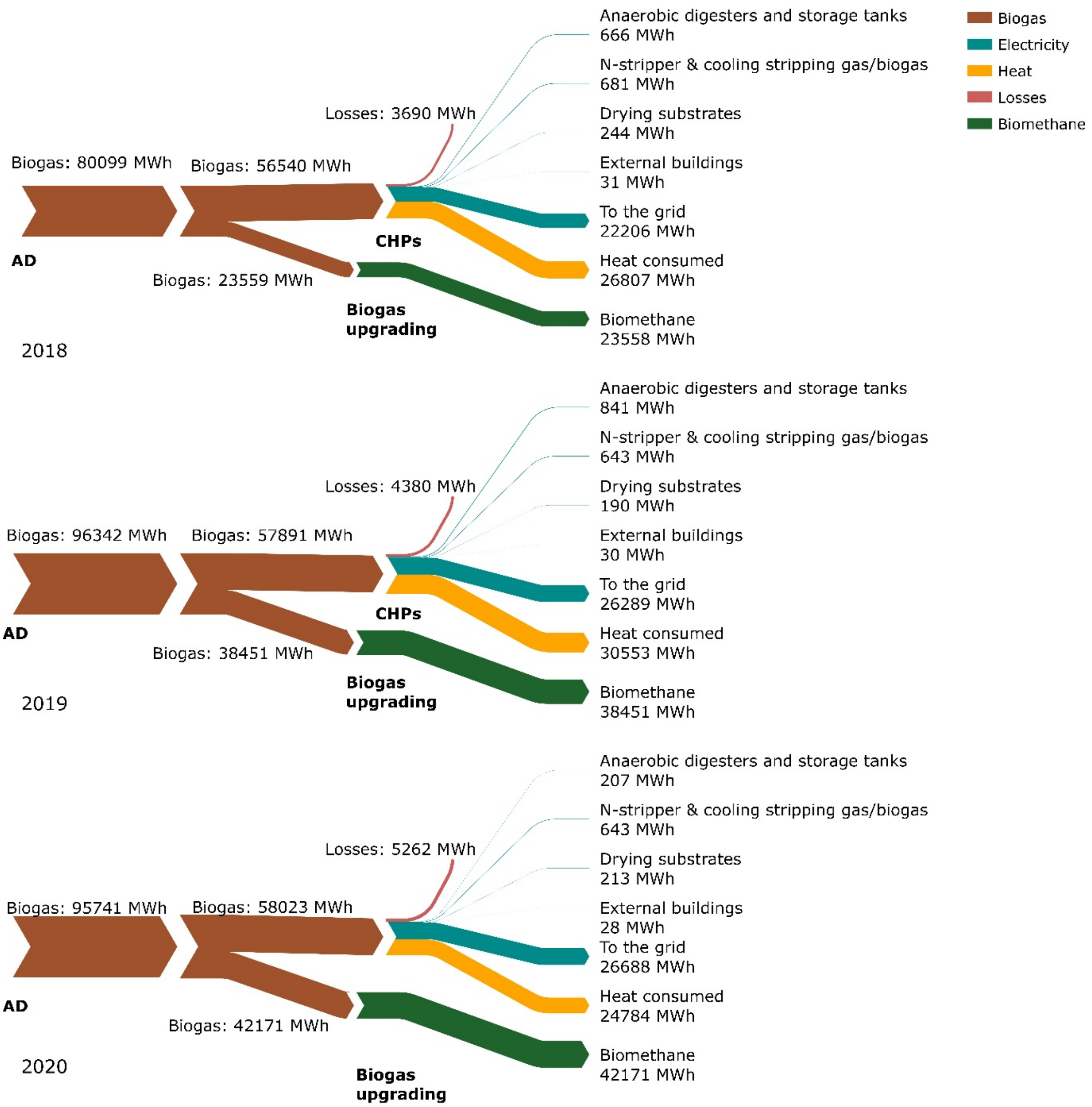

Figure 6-6 Energy production and consumption at BENAS for the period 2018–2020.

6.7 Temporal variation in product composition

Since the start of the SYSTEMIC project, the composition of the intermediate process streams and end products has been monitored. This paragraph gives the composition of the digestate and AS solution over time.

The composition of the digestate has been fairly constant over the course of the SYSTEMIC project for most of the measured parameters (Figure 6-7). The pH and EC ranged respectively from 7.9 to 8.6 and from 23 and 32 mS cm^{-1} (Figure 6-7a). OM content varied slightly, ranging between 83 and 98 g kg^{-1} (Figure 6-7b). Consequently the DM content varied as well, ranging between 87 and 122 g kg^{-1}. The TN content and to a lesser extent the NH_4-N content as well, varied strongly (Figure 6-7c). The percentage of TN that was present as NH_4-N varied between 48% and 66%. Minimum contents of TN and NH_4-N were respectively at 5.8 and 2.9 g kg^{-1}, maximum contents were respectively 9.4 and 4.9 g kg^{-1}. The TP, TK and TS contents also showed some variation over time (Figure 6-7d). A smaller number of sampling moments is available for Ca, Mg and Na. The concentrations of these components also show variation over time (Figure 6-7e).

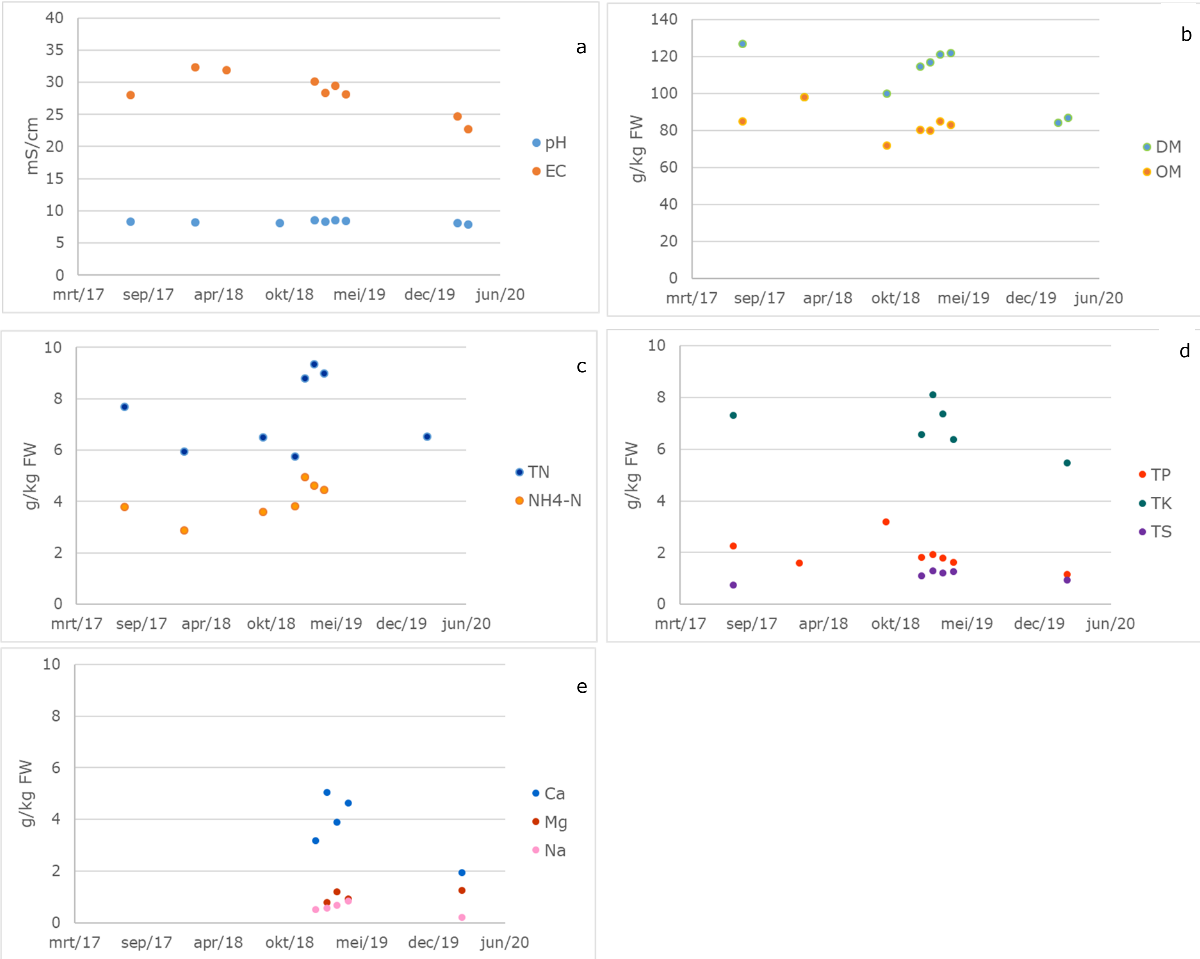

Figure 6-7 Composition (in fresh weight) over time of digestate produced at BENAS for the period August 2017 – February 2020: a) pH and EC; b) dry matter (DM) and organic matter (OM); c) total nitrogen (TN) and ammoniacal nitrogen (NH_4-N); d) total phosphorus (TP), total potassium (TK) and total sulphur (TS); e) calcium (Ca), magnesium (Mg) and sodium (Na).

The composition of the AS solution has been fairly constant over the course of the SYSTEMIC project for most of the measured parameters (Figure 6-8). The pH and EC ranged respectively from 7.6 to 8.0 and from 213 to 240 mS cm^{-1} (Figure 6-8a). The DM content varied slightly, ranging from 209 to 250 g kg^{-1} (Figure 6-8b). Contamination of the AS solution with TOC was never higher than 0.51 g kg^{-1}. The percentage of TN that was present as NH_4-N varied between 95% and 100% (Figure 6-8c). These differences between the contents of TN and NH_4-N can be attributed to small errors in the chemical analyses. This because NH_4-N is the only N containing compound that is removed by the N-stripper. Strangely the ratio of NH_4-N over TS for the AS solution varied over the course of the SYSTEMIC project. Concentrations of TP, TK, Ca, Mg and Na were low for all sampling rounds, <0.015 g kg^{-1} (Figure 6-8d).

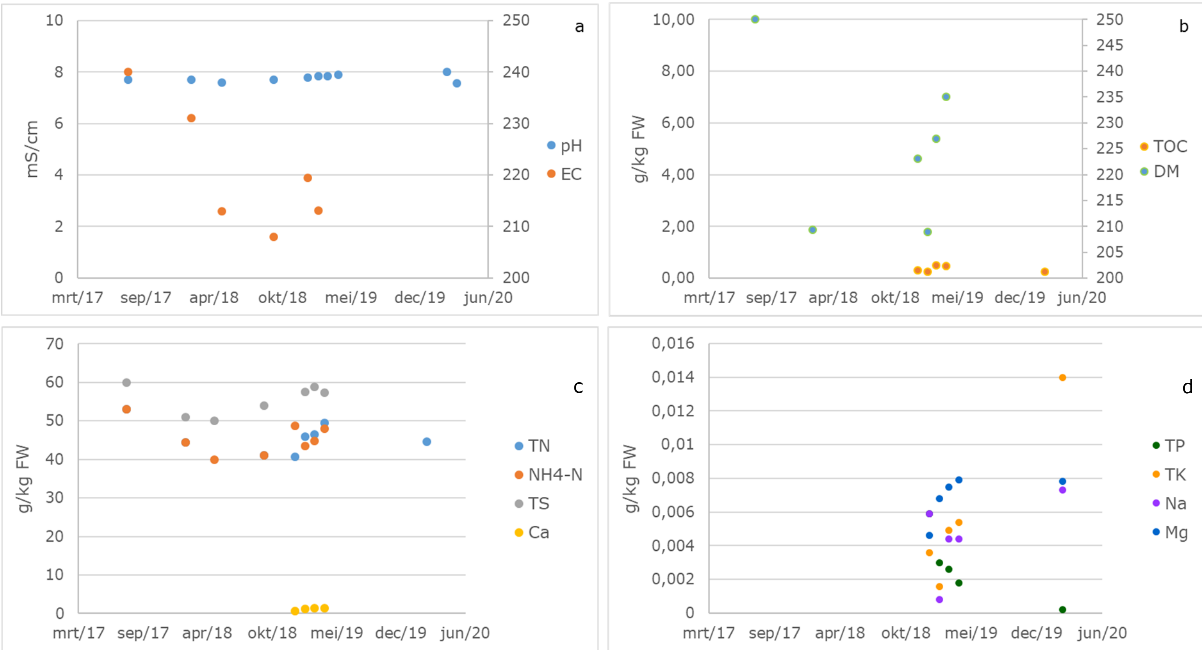

Figure 6-8 Composition (in fresh weight) over time of the ammonium sulphate solution produced at BENAS for the period August 2017 – February 2020: a) pH and EC; b) dry matter (DM) and organic matter (OM); c) total nitrogen (TN) and ammoniacal nitrogen (NH_4-N); d) total phosphorus (TP), total potassium (TK) and total sulphur (TS); e) calcium (Ca), magnesium (Mg) and sodium (Na).

6.8 Overall performance of NRR plant

AD of N-rich feedstocks, such as chicken manure, leads to formation of NH_3 which can inhibit methanogenic microorganisms when toxic concentrations in the digester are reached, thereby causing failure of the AD process (Yenigün & Demirel, 2013). N-stripping and scrubbing of digestate in combination with recirculation of the N-stripped digestate (stripper effluent) allows the removal of NH_3 from the digester and the production of NH_4 salt solutions, thereby preventing NH_3 inhibition of the microorganisms. NH_4 salt solutions are suitable raw materials for the production of mineral N fertilisers or other chemicals (Brienza *et al.*, 2020).

BENAS showcased an innovative NRR system developed by GNS which includes an N-stripper and scrubber in which NH_4-N is recovered from digestate by addition of FGD-gypsum instead of conventional synthetic acids (e.g. sulphuric acid or nitric acid). The FGD-gypsum added is a by-product from coal power plants. From the drafted mass flows and mass balances of the NRR system the separation efficiencies of the screw presses and filter press and the N recovery efficiency of the N-stripper and scrubber were calculated. On average 560 kg d^{-1} of NH_4-N were recovered over the monitoring periods of the NRR system. Moreover, the composition over time of the AS solution was fairly stable for most of the measured parameters. All produced AS solution is applied on the agricultural lands of BENAS as NS fertiliser. Its NH_4-N:TN ratio of 1 is higher than that of unseparated digestate, 0.54. The above is in line with the SYSTEMIC key performance target of 100% reuse of the recovered mineral nutrients as (raw material for) fertilisers.

In addition to the production of mineral N fertiliser, BENAS has also developed the production of marketable fibres from the N-stripped digestate (stripper effluent). The SF of the N-stripped digestate is processed by the fibre moulding machine and paper making machine into low-N fibres. At the time of writing BENAS is able to produce mulch mats, plant pots and paper rolls.

7 Conclusions

The five SYSTEMIC demonstration plants operate in different legal, commercial and agricultural context, within the European Union. As such, different combinations of AD and NRR technologies were implemented to process different biowastes (feedstock) such as animal manure, sewage sludge and food waste. One of the major expected impacts of the SYSTEMIC project is a substantial improvement of the resource use efficiency in Europe, which is in turn expected to have a positive effect on environmental impacts from agriculture such as emissions of greenhouse gases. The mass and energy balances of the demonstration plants presented in this report prove the successful operation of the implemented NRR technologies.

Two main strategies for the implementation of NRR technologies were explored in the SYSTEMIC project. The first one comprehends the upcycling of nutrients from biowastes into mineral fertilisers. Examples of this are the production of liquid mineral fertilisers such AS solution at A&S (IT) and BENAS (DE), or RO concentrate at GZV (NL). Alternatively, GZV recovers P contained the in SF of digestate in the form of precipitated P-salts. The second explored strategy is the transportation of N, P, and K from areas with a surplus of nutrients in the form of animal manure to nutrient deficient regions. NRR technologies may in this case help to up-concentrate nutrients and reduce volumes, which translates in lower transport costs. This is showcased at GZV where permeate from the membrane filtration system is, after polishing, discharged locally to surface water. AmP (BE) and WNE (BE) achieve this up-concentration of nutrients and reduction of volumes to be transported by the incorporation of a.o. an evaporator in their NRR system for the processing of digestate. The condensed water that they produce is also dischargeable to surface water after membrane filtration. The third explored strategy is the production of low-nutrient organic fibres by which can be used for a.o. the following purposes sorted in ascending order of value: low-P soil improver in agriculture (GZV), as replacement for peat in potting soil or in substrate for the growing of mushrooms (GZV) and even mulch mats and plant bots made from organic fibres (BENAS).

Overall, the following key performance targets have been achieved during SYSTEMIC project:

- Overcoming imbalances in nutrient supply between regions with intensive and extensive agriculture. GZV, AmP and WNE produce different organic and mineral fertilisers by their NRR systems. GZV, situated in an N and P surplus region called the Achterhoek in the province of Gelderland, disposes the SF of digestate and MF concentrate to Germany and the Northern part of the Netherlands respectively. WNE mixes the dried SF of digestate with the evaporator concentrate and transports the mixture, an organic fertiliser rich in macronutrients (N, P, K and S), to France. . In the near future, AmP will follow a similar strategy by exporting their NPKS-rich organic fertiliser to France as well.
- 100% reuse of the recovered mineral nutrients as (raw material for) fertilisers. A&S and BENAS produce AS solution which only contains N in mineral form. These solutions represent interesting alternatives for synthetic NS fertilisers. Finally, GZV separates P from the SF of digestate and recovers it as mineral CaP (precipitated P-salts) via the RePeat system. The other nutrients in the digestate are recovered in the form of organic fertilising products or soil improvers.
- Implementation of enhanced nutrient recovery and reuse technologies (TRL 7-8) at five large-scale demonstration plants. The biogas plants of A&S and BENAS have been equipped with side-stream N-stripping units; GZV processes digestate into precipitated P-salts, via leaching of P from the SF of digestate followed by precipitation of CaP, and RO concentrate, which can be used as replacement of mineral N-fertilisers, via membrane filtration of the LF of digestate. AmP and WNE have installed (vacuum) evaporators to reduce the water content of the LF of digestate, produced by anaerobic digestion of biowaste. An overview of end products produced at each demonstration plant at the beginning and at the end of SYSTEMIC project is summarised in the tables below. Regarding WNE, figures at the beginning of SYSTEMIC are missing because when the demonstration plant joined the project, their enhanced NRR system was already fully completed.

Table 7-1 Mass, total nitrogen (TN), ammonium nitrogen (NH_4-N), total phosphorus (TP) and total potassium (TK) of end products generated at Groot Zevert Vergisiting at the beginning and at the end of SYSTEMIC project.

	Total mass $t\ y^{-1}$	**TN** $t\ y^{-1}$	**TP** $t\ y^{-1}$	**TK** $t\ y^{-1}$
Start of SYSTEMIC				
Digestate	100 000	700	170	460
End of SYSTEMIC				
RO concentrate	25 000	168	0	230
SF 1st decanter	15 000	161	112.2	69
Purified water	15 000	0	0	0
SF 2nd decanter + sludge MF	45 000	371	57.8	184

[1] Mass balances based on amounts of end products trucked off-site in de period Jan-June 2021, recalculated to quantities on a yearly basis.

Table 7-2 Mass, total nitrogen (TN), ammonium nitrogen (NH_4-N), total phosphorus (TP) and total potassium (TK) of end products generated at Am-Power at the beginning and at the end of SYSTEMIC project.

	Total mass $t\ y^{-1}$	**TN** $t\ y^{-1}$	**NH_4-N** $t\ y^{-1}$	**TP** $t\ y^{-1}$	**TK** $t\ y^{-1}$
Start of SYSTEMIC					
RO concentrate	≈ 65 000	344	273	0.71	279
Permeate water	≈ 55 000	<8.8	1.0	<0.42	<0.525
Dried SF of digestate	7 868	244	6.3	165	86
End of SYSTEMIC					
Dried SF	6 680	150	9.0	125	91
LF not processed	19 507	78	46	4.2	60
AS in scrubber	16 318	42	44	-	-
Evaporator concentrate	15 774	156	84	14	161
Evaporator condensate	45 963	48	40	-	-

[1] Mass balances assessed for October 2020 – April 2021 – quantities on a yearly basis.

[2] At the time of monitoring about 25% of the LF after the decanter was disposed of without treatment in the evaporator because the evaporator was not yet running at full capacity.

[3] Evaporator condensate does not yet meet criteria for discharge onto surface water. A post treatment step with an RO installation is foreseen to be installed in 2021.

Table 7-3 Mass, total nitrogen (TN), ammonium nitrogen (NH_4-N), total phosphorus (TP) and total potassium (TK) of end products generated at Waterleau NewEnergy at the end of SYSTEMIC project.

	Total mass $t\ y^{-1}$	**TN** $t\ y^{-1}$	**NH_4-N** $t\ y^{-1}$	**TP** $t\ y^{-1}$	**TK** $t\ y^{-1}$
End of SYSTEMIC					
Dried SF of digestate	2 628	74	12	64	41
Sludge aerated unit	26 738	123	86	5.1	78
Condensed ammonia water	1 424	150	144	0.0006	0.0002
Evaporator concentrate	10 950	132	16	18	262
Condensed water evaporated and for cleaning	47 287	74	71	0.026	0.046

Table 7-4 Mass, total nitrogen (TN), ammonium nitrogen (NH_4-N), total phosphorus (TP) and total potassium (TK) of end products generated at Acqua & Sole at the beginning and at the end of SYSTEMIC project.

	Total mass t y^{-1}	**TN** t y^{-1}	**NH_4-N** t y^{-1}	**TP** t y^{-1}	**TK** t y^{-1}
Start of SYSTEMIC					
Digestate	91 245	730	365	246	59
AS solution	722	53	53	0.0093	0.0093
End of SYSTEMIC*					
Digestate	141 840	1135	525	482	84
AS solution	661	50	47	0.0079	0.011

* Total mass of digestate and ammonium sulphate solution produced at Acqua & Sole was communicated on 17/02/2002.

Calculation of TN, NH4-N, TP and TK flows was performed with data from table 5-12.

Table 7-5 Mass, total nitrogen (TN), ammonium nitrogen (NH_4-N), total phosphorus (TP) and total potassium (TK) of end products generated at BENAS at the beginning and at the end of SYSTEMIC project.

	Total mass t y^{-1}	**TN** t y^{-1}	**NH_4-N** t y^{-1}	**TP** t y^{-1}	**TK** t y^{-1}
Start of SYSTEMIC					
LF of digestate	65 000	475	219	117	475
SF of digestate	18 000	110	29	51	106
AS solution	4 000	212	212	0	0
CC sludge	1 000	18	18	0	0
End of SYSTEMIC					
LF of digestate	46 000	344	205	70	308
SF of digestate	12 000	107	54	28	69
AS solution	4 000	203	203	0	0
CC sludge	2 000	30	28	0	1
Low-N organic fibres	Pilot. Full capacity: 8 000 ton of fibres per year				

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Circular solutions for biowaste

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