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https://systemicproject.eu/

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Synthesis of the performance of the demonstration plants (end of project)

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Preface

This study was carried out and published as Deliverable D1.17 "Synthesis of the performance of the demonstration plants" under the European demonstration project SYSTEMIC funded by the H2020 programme (project number 730400). The project SYSTEMIC focuses at five large scale biogas plants where innovative nutrient recovery processing techniques were implemented and monitored.

This report is, following SYSTEMIC grant agreement, 'a report compiling the technical performance, operational performance and product evaluation (scientific, agronomic, and ecologic) of the nutrient recovery technologies in the 5 demonstration plants'.
This report summarises the major findings in relation to mass- and energy balances, product quality, agronomic efficiency and environmental impact using information from the following deliverables:

- D1.5. Final report on mass and energy balances, product composition and quality and overall technical performance of the demonstration plants (Published as Brienza et al., 2022)
- D1.13 Final document on product characteristics, lab results and field trials (Published as Sigurnjak et al., 2022)
- D1.15 Full report on environmental impact assessment of recovered products (Published as Schoumans et al., 2022)
- D2.6 Final report on LCA analysis and sustainability indicators of products (Published as Hermann et al, 2022a).
- D2.2 Report on business case evaluation of 5 demonstration plants (Published as Hermann et al., 2022b)

A thorough synthesis of these aspects is vital for our understanding of potential advantages and disadvantages of certain NRR technologies as well as trade-off effects that may occur. This report is the final version of the synthesis that will be become public at the end of the four-and-a-half-year SYSTEMIC project. The report follows op on the confidential mid-term synthesis report that was reviewed during the second project review. Following the reviewers advices, this report now includes a clear description of the indicators in relation to the technical performance, product quality and environmental benefits.

We would like to acknowledge the plant owners and staff of Acqua&Sole, Am-Power, Waterleau NewEnergy, BENAS and Groot Zevert Vergisting whom delivered information about the product quality of the produced biobased fertilisers and information on the distribution and application of their products.

The authors

Summary

The synthesis report combines data collected within the H2020 EU project SYSTEMIC (2017-2021) which had the objective to demonstrate economically viable business cases for nutrient recovery and reuse (NRR) from biowaste (Chapter 1).

This report covers information on the technical, environmental and economic performance of five full scale demonstration plants. The demonstration plants are all anaerobic digesters (AD) that invested in NRR technologies and are located in different EU member states (the Netherlands, Germany, Belgium, Italy). The demonstration plants are pioneers and have the ambitions to create more value out of their digestate through investment in NRR technologies and production of biobased fertilisers (BBFs) from digestate.

Five demonstration plants are (Chapter 2):

- Groot Zevert Vergisting (GZV, the Netherlands) where pig slurry and residues from agro- and food industry are converted into biogas, reverse osmosis (RO) concentrate, solid fraction (SF), purified water and a low-P soil improver.
- Am-Power (Belgium) where biowaste is converted into biogas, a dried SF, evaporator concentrate and purified water.
- Acqua&Sole (Italy) where sewage sludge is converted into biogas, ammonium sulphate solution and digestate
- BENAS (Germany) where energy crops and poultry litter are converted into biogas, ammonium sulphate solution, LF and SF of digestate and low-N organic fibres
- Waterleau NewEnergy (WNE, Belgium) were biowaste and manure are converted into biogas, dried SF, evaporator concentrate, purified water and condensed ammonia water. The latter is used in industry .

The five demonstration plants are all located within 'Nitrate Vulnerable Zones' (NVZs) and in regions characterised by intensive livestock farming (Chapter 3). In the Netherlands and Flanders, BBFs compete with the disposal of animal manure and Am-Power and WNE therefore aim to reduce the volume of the BBFs by means of dryers and evaporators in order to reduce costs for transport of the BBFs to France. GZV, on the other hand, followed a different approach focussing on production of BBFs that can be used locally without competing with the use of animal manure. They recover nitrogen (N) as an RO concentrate which complies with criteria for RENURE products and is used within the region of the plant replacing synthetic N (called 'GENIUS process'). GZV furthermore treats the SF of digestate to separate phosphorus (P) and organic matter (called 'RePeat process'). The low-P organic matter is used as a soil improver in the region or as ingredient for potting soil whereas the precipitated P salts are exported. Acqua&Sole is using all BBFs in the nearby region of the plant, partly on own land, and they have implemented a N stripper to control ammonia levels in the AD to enhance biogas formation. BENAS is using BBFs on their own land producing energy crops. They furthermore recover organic matter fibres that are being further processed into paper and cartons.

Technical performance and mass and energy balances are summarised in Chapter 4. For **GZV,** composition of RO concentrate and SF were in line with the expectations but the overall separation efficiency of the GENIUS installation was below expectations as the amount of dischargeable water amounted to 18% whereas 50% was foreseen at the start of the project. The RePeat installation was used from time to time and was able to extract and recover 85% of P contained in the SF but the dry matter (DM) content of the precipitated P salts was yet too low. At **Am-Power**, commissioning of the new evaporators was seriously delayed due to several reasons but once running, the installation effectively converted one tonne of LF into 0.75 tonne of condensed water and 0.25 tonne of concentrate. Also consumption of chemical additives reduced as compared to the old situation in with LF was treated by RO. **WNE** is operating a similar installation as Am-Power which the difference that Am-Power acidifies the LF prior to the evaporator thereby producing a concentrate with a high ammonium (NH_4) and sulphur (S) content whereas at WNE, NH_4 volatizes and is recovered as condensed ammonium water. At **BENAS**, 44% of total ammoniacal N

(TAN) in digestate is recovered as ammonium sulphate by means of N stripping followed by absorption of NH_3 through a reaction with gypsum producing calcium carbonate as a by-product. In addition, BENAS could produce about 8000 ton of organic fibres per year if the FibrePlus installation is running at full capacity. The new N stripper at **Acqua&Sole** had the capacity to remove and recovery 35% of TAN from the side stream of digestate fed to the stripper. The overall mass over the AD plant showed that 5% of TAN was recovered as ammonium sulphate in 2021.

Specific biogas production was low for Acqua&Sole (45 m^3 biogas per tonne of feedstock), medium for GZV, Am-Power and WNE (99-150 m^3 biogas/tonne) and high for BENAS (237 m^3/tonne) and this was due to differences in feedstock. Am-Power, WNE and BENAS have large amounts of thermal energy because of converting biogas to into electricity generating thermal energy as a by-product. This is why these plants invested into NRR technologies with a high thermal energy demand leading to an overall consumption of 211 - 321 kWh_{th}/tonne digestate. GZV and Acqua&Sole have far less thermal energy available which is why they choose NRR technologies with a lower thermal energy demand per tonne of digestate (41-61 kWh_{th}/tonne). For GZV, little thermal heat is available because they sell 80% of biogas to a nearby factor whereas thermal heat at Acqua&Sole is limited due to the fact that the specific biogas production of sewage sludge is low. All demonstration plants proved that energy production in the form of biogas exceeds on-site energy consumption and each year, 5.8 to 35 GWh of energy was sold to grid or an external user.

Product composition (Chapter 5) was compared with market demand and assessed in relation to emissions of nutrients to air or groundwater. Solid fractions are primarily to be considered as organic P fertilisers. The fraction of easily available P however differed among the demonstration plants due to difference in feedstock and use of iron salts. N-rich BBFs (ammonium sulphate, evaporator concentrate) are generally rich in S due to the use of sulphuric acid. It is therefore advised to only replace part of the synthetic N dosage by S-rich BBFs in order to prevent over-fertilization with S. Purified water meets criteria for discharge onto surface water and was free of residues from organic micro-pollutants.

Chapter 6 gives a synthesis of the performance of each demonstration plant and Chapter 7 a general synthesis and these outcomes are summarised in Table S1.

Table S0.1. Summary of the main conclusions per category, based on the evaluation of the five demonstration plants within the project.

Categories	**Main outcomes for demonstration plants**
Compliance with market demand and legislative criteria	• Demonstration plants produce biobased fertilising products that better fit with market demand compared to unseparated digestate. • Implementation of RENURE criteria is of importance for GZV. • Though the FPR is expected to simplify export of biobased fertilising products, it is still uncertain whether demonstrations will comply with the criteria; bottlenecks include exclusion of sewage sludge and industrial sludge as well as the minimum levels for nutrients which are not met for RO- and evaporator concentrates.
Technical performance & Mass- and energy balances	• Generally, AD plant owners underestimated the time needed to develop, implement and optimise a novel NRR installation. • Percentage of energy contained in biogas that is used externally (electricity or gas) is low for AD plants were biogas is converted into electricity (17-36%) and high for plants selling biogas/biomethane (69-71%). • The thermal heat demand of dryers, N-strippers and evaporators is covered by waste heat from CHPs. Hence, these AD plants rely on the conversion of biogas to electricity generating waste heat meaning that these plants could not shift towards upgrading biogas to biomethane whereas the latter is preferred in terms of replacing fossil energy outside the premises of the AD plant.

	• NRR installations effectively separate nutrients and/or reduce water content. All demonstration plants use considerable amounts of sulphuric acid. Polymer is used on those plants that perform a high-tech solid/liquid separation.
Product quality & environmental effects	• SFs of digestate are primarily P fertilisers. The fraction of easily available P deviates strongly among SFs from different demonstration plants. Farmers should be advised on whether to use the SFs as a fast- or slow-release P fertiliser. • Biobased N fertilising products can replace synthetic N fertilisers. However, they typically have a high S content (ammonium sulphate, evaporator concentrate), which may lead to S application rates above crop uptake and hence to leaching of sulphate to groundwater. • Purified water meets criteria for discharge, no micro-pollutants were detected. • Contents of heavy metals were generally low except for digestate from sewage sludge; use of NRR-products did not lead to an increase in heavy metal loading per hectare compared to use of digestate.
Life-cycle assessment	Production of biogas from waste has a positive impact in terms of CO_2 savings. Extending the digester with NRR technologies has only a minor effect on the CO_2 savings; NRR installations consume energy but this compensated for by a reduction in transport volumes and distances.
Economic feasibility	• Business cases of the demonstration plants include very high margin operations (A&S, BENAS), medium margin (GZV, WNE) and low margin operations (Am-Power). Implementation of NRR improves the business case and security for product disposal compared to scenario's without NRR though the economic benefits of NRR are generally low compared to revenues from biogas production and/or gate fees.

List of abbreviations

AD : Anaerobic digestion

AmP: Am-Power

AS : Ammonium sulphate solution

CAN: Calcium ammonium nitrate fertiliser

CHP : Combined Heat and Power installation

DAF: Dissolved air flotation

DM : Dry matter

DOM : Dissolved organic matter

EC : Electrical conductivity

EIA : Environmental impact assessment

EOM : Effective organic matter

FM : Fresh matter

GHG : Greenhouse gases

GZV : Groot Zevert Vergisting

HC : Humification coefficient

IO : Ionic exchange

JRC : Joint Research Centre

LF : Liquid fraction

NFRV : Nitrogen fertilizer replacement value

NRR : Nutrient recovery and reuse

NVZ: Nitrate-vulnerable zone

OC : Organic carbon

OM : Organic matter

PAHs : Polycyclic Aromatic Hydrocarbons

PCBs : Polychlorinated Biphenyls

RO : Reverse osmosis

SF : Solid fraction

SOM : Soil organic matter

TAN: Total Ammoniacal Nitrogen

TOC : Total organic carbon

UGhent: Ghent University

VFG : Vegetables-, fruit- and garden waste

WENR : Wageningen Environmental Research

WNE: Waterleau NewEnergy

WWTP : Waste water treatment plant

List of definitions

Term	Definition
Digestate	Solid material remaining after the anaerobic digestion of a biodegradable feedstock.
LF of digestate	Liquid fraction (LF) after separation of digestate by a decanter centrifuge or screw press.
SF of digestate	Solid fraction (SF) after separation of digestate by a decanter centrifuge or screw press.
RO concentrate	Concentrate remaining after removal of water from a liquid stream (e.g. LF of digestate or evaporator condensate) by reverse osmosis (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 (reverse osmosis) and IO (ionic exchange), purified to be used as process water or to be discharged to surface water.
Low-P organic soil improver	Solid fraction of the digestate after flushing with water and sulphuric acid to remove most of the phosphorus (P).
Precipitated phosphate salts	Precipitated phosphate salts, obtained by precipitation of phosphate (PO_4) with calcium or magnesium, and which are recovered as a sludge or in solid form.
Dried SF of digestate	Solid fraction (SF) of digestate after a thermal drying process.
Evaporator concentrate	Liquid fraction (LF) of digestate, after evaporation of water and volatile components including ammonia.
Ammonium sulphate (AS) solution	Solution of ammonium sulfate obtained after ammonia stripping followed by recovery of gaseous ammonia in sulphuric acid (Acqua&Sole) or with gypsum (FibrePlus at BENAS).
Evaporator condensate	Condensate after evaporation of LF of digestate which contains water and volatile compounds including ammonia, bicarbonate and volatile organic acids.
Condensed ammonia water	Condensate after evaporation of LF of digestate with a high content of ammonium, and treated by RO (reverse osmosis) to reduce the water content.
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: Solid fraction obtained by a screw press from digestate after nitrogen (N) stripping-scrubbing in the Fibreplus system and used for production of fibre .
Calcium carbonate sludge	Precipitate of calcium and carbonate produced as a by-product of the FibrePlus N stripping unit at BENAS by the reaction of striped air containing ammonia and carbon dioxide with gypsum ($CaSO_4$) leading to the formation of ammonium sulphate and calcium carbonate precipitate.

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 'an 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) to reduce waste to a minimum, (b) to promote re-use and recycling of materials and products and (c) to 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 fertilizing product.

The overall objective of the SYSTEMIC project was to demonstrate economically viable business cases for nutrient recovery and reuse from biowaste while simultaneously contributing to sustainability targets including:

- Increasing the use of nutrients and organic matter from biowaste as BBFs thereby contributing to the transition towards a circular economy.
- Reducing emissions of greenhouse gases (GHG) from biowaste processing, handling and application of derived BBFs. GHGs include carbon dioxide (CO_2), methane (CH_4) and laughing gas (N_2O)
- Reducing or controlling risks for losses of nitrate (NO_3) and phosphate (PO_4) to ground- and surface water and atmospheric emissions of N as ammonium (NH_3)
- Avoiding spreading of contaminants (heavy metals, organic micro-pollutants) to the environment.

Five large-scale anaerobic digesters (AD) participated within the project and demonstrated the effective combination of AD with novel nutrient recovery and reuse (NRR) technologies (TRL 7) for producing biobased fertilizers and soil improvers from Europe's most abundant biowaste streams (residues from agro-food industry, source-separated food waste, sewage sludge and animal manure) and, at one demonstration plant, energy-crops. The demonstration plants are located in different EU member states (the Netherlands, Germany, Belgium, Italy) and hence operate in different legal, commercial and agricultural context. Each demonstration plant is therefore unique and different (combinations of) NRR technologies were implemented at the demonstration plant converting a variety of feedstocks into an even larger variety of end products for the regional or European market. Three main NRR strategies can be distinguished:

1) **Recovery of mineral N or P strategy**: Biobased N fertilising products that have a high nitrogen fertiliser replacement value (NFRV) can be used to replace synthetic N fertilisers. Examples include production of ammonium sulphate (BENAS, Acqua&Sole) and RO concentrate (GZV). This strategy is typically applied in regions where there is a surplus of N in the form of manure or organic fertilisers. Nitrogen stripping is also applied to control levels of ammonia in the anaerobic digester to avoid inhibition of biogas production due to ammonia toxicity. For fertilisers from animal manure, the application rate is limited by 170 kg N/ha when applied on agricultural fields in areas designated as a 'Nitrate Vulnerable Zone' (NVZ) as stated in the Nitrates Directive. In order to apply an N fertiliser produced from animal manure as a synthetic fertiliser, the product shall comply with the RENURE (Recovered Nitrogen from animal manURE) criteria which have been set by the Joint Research Centre (JRC, Huygens et al., 2020) but that are not yet formally implemented by the European Commission.

2) **Volume reduction strategy:** Reducing the volume of digestate-derived products with the objective to produce concentrated fertilising products that can be transported to regions with a demand for fertilising products. This strategy is employed by demonstration plants operating in regions with intensive livestock farming leading to a regional surplus of nutrients (Am-Power,

Waterleau NewEnergy). This strategy involves high-tech NRR installations such as dryers, evaporators and reverse osmosis (RO) systems for removal of water from digestate and its subsequent purification to meet limits for on-site re-use or discharge onto surface water.

3) **High-grade products strategy:** Creating revenues from the sale of recovered organic fibres from digestate for use as fibres in cardboard products (BENAS) or as an ingredient for substrate or potting soil (GZV). This strategy involves careful selection of plant-based feedstocks (high fibre content), implementation of treatment steps is required to meet quality criteria, and a solid marketing strategy in order to bring these new biobased products to the market.

Strategy 1 is typical for demonstration plant Acqua&Sole (Italy) where digestate of sewage sludge is separated into ammonium sulphate and N-reduced digestate. Strategy 2 is valid for demonstration plants Am-Power and Waterleau NewEnergy (Flanders) which both focus on production of solid organic fertilising products for export to France. The latter plant also produces ammonia water which a strategy-1 approach. The business model of demonstration plant BENAS (Germany) includes aspects of strategy 1 (N-stripping) and strategy 3 (low-N organic fibres). The business model of demonstration plant GZV includes aspects of all three defined strategies; they produce a RENURE fertilising product replacing mineral N fertiliser (strategy 1), purified water that is being discharged onto surface water (strategy 2) and low-P organic soil improver for use in potting soil (strategy 3).

This report combines data and insights on the technical, environmental and economic performance of five full scale demonstration plants. Information on these indicators has been collected within the SYSTEMIC project by means of monitoring of five large-scale AD plants applying NRR technologies (Brienza et al., 2022; Sigurnjak et al., 2022, Pigoli et al., 2022) and further assessment done related to the environmental impacts (Schoumans et al., 2022), GHG emissions (Hermann et al., 2022a) and business models (Hermann et al, 2019, 2022b) and are here evaluated in coherence with the plants regional context and strategy.

Evaluation of the performance and benefits of NRR at large-scale AD plants shall include all aspects related to its technical performance, mass- and energy balances, product quality and compliance with market demands, emissions of green-house-gases (GHGs) and economic benefits. For each category, indicators have been identified (Table 1.1.).

Table 1.1 Overview of the evaluation categories and corresponding indicators

Categories	Performance indicators
1) Compliance with market demand and legislative criteria	• Compliance with demand for fertilisers in the region of use • Compliance with criteria for RENURE products (if relevant) • Compliance with the EU Fertiliser Product Regulation (for exported products)
2) Technical performance & Mass and energy balances	• Energy production compared to on-site energy consumption per ton of digestate (electrical and thermal energy) • Separation efficiencies of NRR installation compared to envisaged efficiencies • Consumption of chemicals (polymer, anti-foaming, sulphuric acid, iron salts) • Operational issues, technical robustness of the NRR system.
3) Product quality & environmental effects	• Efficiency of biobased fertilisers in supplying mineral N and P for crop uptake compared to synthetic N and P fertilisers. • Ratio’s between macro-nutrients (N,P,K,S) compared to crop demand • Effect of biobased fertilisers on o carbon sequestration, o leaching of nutrients (N,P,S),

	○ emissions of nitrogen (NH_3, N_2O) and, ○ accumulation of heavy metals in soils compared to the use of synthetic fertilisers or raw digestate
4) GHG emissions	• The CO_2 footprint of the AD plant applying NRR compared to reference scenario without NRR.
5) Economic feasibility	• Main driver of the business case and qualitative assessment on resilience of the business case.

Reader

This report starts with a general introduction of the five AD plants that participated within the project as demonstration plants (Chapter 2). Chapter 3 deals with the regional nutrient balances and market demands for biobased fertilisers including legislative criteria highlighting the differences in operational context for the five demonstration plants. Technical aspects related to the NRR technologies and the performance thereof are dealt with in Chapter 4 which also includes detailed energy balances of the demonstration plants. Chapter 5 elaborates on product quality in terms of agronomic efficiency, presence of unwanted substances and compliance with regulations and market demand. Chapter 6 includes the overall assessment per demonstration plant whereas Chapter 7 and 8 present the discussion and conclusions.

2 Demonstration plants

2.1 General Description

The five large-scale demonstration plants are located in Belgium (Am-Power, Pittem and Waterleau New Energy, Ieper), Germany (BENAS, Ottersberg), Italy (Acqua & Sole, Vellezzo Bellini), and the Netherlands (Groot Zevert Vergisting, Beltrum). Table 2.1 gives an overview of the feedstock and produced products of the demonstration plants. The locations of the plants are depicted in a map in combination with the regional livestock density, showing that all five demonstration plants are situated in regions with a high livestock density (Figure 2.1).

Table 2.1 General characteristics of the five demonstration plants.

Name	**Location**	**Capacity** (ktonne/y)	**Feedstocks**	**Biobased fertilisers**
Groot Zevert Vergisting (GZV)	Beltrum (NL)	115	Pig slurry, residues from agro-food industry, glycerine	• RO concentrate (RENURE product)[1] • MF concentrate[1] • Solid fraction of digestate • Precipitated P salts • Low-P soil improver • Purified water
Am-Power (AmP)	Pittem (BE)	135	Residues from agro-food industry	• Dried solid fraction of digestate • Evaporator concentrate • Purified water[2]
Acqua&Sole (A&S)	Vellezzo Bellini (IT)	77	Sewage sludge, residues from agro-food industry	• Ammonium sulphate • Digestate
BENAS (BNS)	Ottersberg (DE)	87	Energy crops (maize and rye) and poultry litter (until 2020)	• Solid fraction digestate • Liquid fraction of digestate • Ammonium sulphate • Calcium carbonate sludge • Low-N organic fibres
Waterleau NewEnergy (WNE)	Ieper (BE)	66	Pig manure, sludge and biowaste from agro-food industry	• Dried solid fraction of digestate • Evaporator concentrate • Condensed ammonia water • Purified water

[1] RO: reverse osmosis, MF: micro-filtration.

[2] At the time of writing, Am-Power was not yet equipped with an RO and IO installation for treatment of the condensate of the evaporator into permeate water, hence producing condensate rather than purified water.

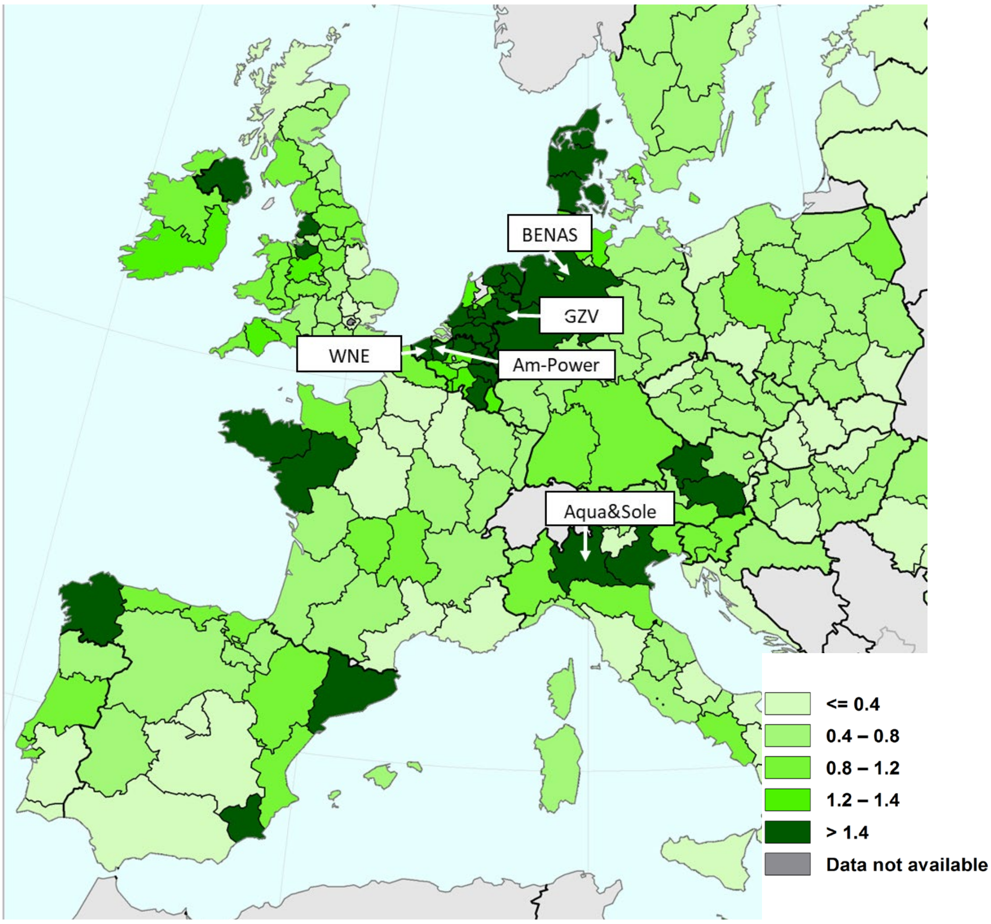


Figure 2.1 Map of livestock density in livestock units per ha in the EU (Eurostat) and locations of SYSTEMIC's demonstration plants (ref: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Livestock_density_EU-28,_2013.png)

2.2 Groot Zevert Vergisting (GZV)

Groot Zevert Vergisting is situated in the eastern part of the Netherlands in a region with intensive agriculture where disposal of manure and digestate is costly because the livestock sector produces more manure than can be applied within the crop- and soil specific P application limits (17-52 kg P/ha or 40-120 kg P_2O_5/ha) and the limit for N from animal manure (170 kg N/ha, NVZ). GZV started their biogas activities in 2004 and have since then expanded to become one of the largest AD plants in The Netherlands, treating nowadays about 115 ktonne of manure (pig slurry) and residues from agro-food industry and producing about 10 Mm^3 biogas on a yearly basis. Until 2018, digestate was exported to Germany over distances of 200 to 300 km. To lower costs for digestate disposal and to reduce their dependency on German buyers, GZV decided to develop a new business case for valorisation of their digestate. They invested in an installation (named GENIUS) for the production of a SF of digestate, RO concentrate and purified water in order to reduce the volume of their end products. Though RO concentrate is still considered 'animal manure', they were granted a temporary exemption to use RO concentrate as a replacement for synthetic N fertiliser under the pilot 'biobased fertilisers Achterhoek'. The MF concentrate is a by-product consisting of the sludge produced by the micro-filtration unit. The SF of digestate was still exported to regions in Germany with a demand for P fertilisers. In order to turn SF of digestate into a valuable product, GZV developed a new technological approach (named RePeat) together with Wageningen Environmental Research and Nijhuis Industries to separate SF of digestate into a low-P soil improver and an precipitated P salt, as calcium phosphate (Ca~P) or magnesium ammonium phosphate (Mg~P, struvite). The low-P soil improver can be used as a source of organic matter on sandy soils in the region of the plant or can be further upgraded towards a peat replacer to be used in potting soil. The performance of the installations and quality of the end products have been monitored as part of the SYSTEMIC project (Brienza et al., 2021).

Table 2.2 Groot Zevert Vergisting plant characteristics (data for the year 2020)

Date of commissioning	2004 (biogas plant) 2019 (decanters, microfiltration and RO installation) 2020 (RePeat installation)
Annual substrate processing capacity / processed	135,000 t / 93,000 t (71 kt pig slurry/ 23 kt biowaste)
Installed electric capacity	6.5 MW
Installed biomethane capacity	Desulfurized biogas is directly transported to a nearby dairy factory via a 5-km long pipeline (38.1 MWh)
Digester volume	15,000 m³
Annual biogas output / biogas per t of feedstock	10 Mm³ / 104 m³/t
Annual electricity net-output (fed to the grid)	1.8 MWh (5,000 MWh_{eltot})
Annual biogas output	9.7 Mm³
Digester type	Thermophilic Continuous Stirred-Tank Reactor (CSTR)
Nutrient recovery & recycling (NRR) facilities	GENIUS – decanter centrifuges, DAF, microfiltration, RO, IO (2019) RePeat – mixing tanks, screw presses, P precipitation reactor and settling tank (2020)
NRR Products	Reverse osmosis concentrate Micro-filtration concentrate Solid fraction of digestate (high P) Low-P soil improver Precipitated P salts
Framework conditions relevant to the business case	High livestock density and surplus of manure in the region Demand for organic soil improvers with low P and N content Limited availability of heat due to direct use of biogas at end users High demand for synthetic N fertilisers. Temporary exemption to use RO concentrate from co-digested manure on top of the application limit for N from manure pending on the acceptance of RENURE products

2.3 Am-Power (AMP)

Am-Power is located in the western part of Flanders (Belgium), a region characterized by an excess of animal manure and still a high market demand for formulated synthetic fertiliser. In 2011 the first biogas production activities started and they are now the largest biogas installation in Belgium (Table 2-3). Though Am-Power's digestate is not designated as manure – they solely process organic residues from domestic sources and food industry - their digestate has a negative economic value due to the surplus of manure in their region. Prior to the start of SYSTEMIC, Am-Power was already equipped with a novel treatment line for the production of dried SF of digestate and RO concentrate from their digestate. Poor economic results, however, forced Am-Power to further enhance their business case. They developed a novel technological approach based on vacuum evaporation in combination with RO through which they expect to reduce both operational costs (lower use of chemicals compared to baseline) and costs for product disposal. Their aim is to produce fertilising products with a high nutrient value, and hence a low water content, which can be transported over larger distances to regions with a demand for nutrients. In addition, they will convert part of their digestate into purified water to be used on-site for cleaning purposes and to be discharged to surface water.

Table 2.3 Am-Power plant characteristics (data 2020)

Date of commissioning	2016
Amount of substrate processed	153 ktonne (Residues food processing, non-manure)
Installed electric capacity (IEC)	7.5 MW
Installed biomethane capacity	None
Digester volume	20,000 m³
Digester type	Mesophilic Continuous Stirred-Tank Reactor (CSTR)
Biogas output / biogas per t of feedstock	15 Mm³ / 95 m³/t
Electricity net-output/ fed to the grid	32,166 MWh / 27,946
Annual bio-methane output	None
Nutrient recovery & recycling (NRR) facilities	Decanter centrifuge; dryer for solid fraction, air scrubber; evaporator and reverse osmosis for liquid fraction
NRR Products	Dried solid fraction of digestate (high P content) Evaporator concentrate (high N,K,S) Permeate water
Framework conditions relevant to the business case	High livestock density in the region Products need to be transported to other regions or treated Large amount of waste heat available

2.4 Acqua & Sole (A&S)

Acqua & Sole s.r.l. is an operator of anaerobic digestion activity. The main driver behind this investment was the desire for recycling organic waste flows and particularly urban waste flows to organic fertilisers (Table 2.4). Acqua & Sole is located in an area with some 100,000 ha of arable land, of which 85% is used for rice cultivation. Livestock rearing is not a major activity in the region, only 1.7% of animals reared in Lombardy live in the area, that is about 33,000 out of a total of 32 million. Animal manure is therefore neither an environmental issue, nor an available fertilising material. The vicinity of Milano (15 km) with close to 3.3 million people, and the food industry are the main sources of feedstock for Acqua & Sole. Services are consequently focusing on the offtake of sewage sludge from communal WWTPs and food waste from urban and commercial suppliers.

Waste streams are converted into hygienised digestate and ammonium sulphate with two applications in mind:

- About 1,000 ha of own farmland;
- About 4,000 ha farmland in the neighbourhood of the plant.

The first benefits of N stripping is control of ammonia levels in the digester, enabling them to run the digester at thermophilic conditions rather than at mesophilic conditions, without inducing inhibition of the biogas production due to toxicity of ammonia. This translates into a higher biogas production as well as hygienisation of their digestate. Secondly, lowering the N content of digestate offers economic benefits because more digestate, and also more organic matter, can be applied per hectare of soil within the N application rate limits. There is no P application limit in Italy.

The business model does not aim at revenues from energy conversion but on closing the nutrient and organic materials loop. Recovery of nutrients and organic matter is a major driver for the AD plant Acqua & Sole, especially since incineration is also an upcoming alternative treatment and disposal route for sewage sludge in Italy. Incineration means a loss of nitrogen and organic matter and, if ashes are not used as a fertiliser, also a loss of phosphorus. Recycling of organic matter is considered of high importance due to the progressing degradation of the per-urban, industrially managed farmland south of Milano.

Table 2.4 Acqua & Sole plant characteristics (data 2020)

Date of commissioning	2016
Annual substrate processing capacity / processed	87,000 t / 87,000 t (74 kt sludge/13 kt food waste)
Installed electric capacity (IEC)	1.6 MW
Installed biomethane capacity	none
Digester volume	13,500 m³
Annual biogas output / biogas per t of feedstock	3.3 Mm³ / 38 m³/t
Annual electricity net-output / fed to the grid	7,032 MWh / 5,483 MWh
Annual bio-methane output	None
Digester type	Thermophilic Continuous Stirred-Tank Reactor (CSTR)
Nutrient recovery & recycling (NRR) facilities	Ammonium recovery system (stripper, scrubber, ancillary equipment)
NRR Products	Hygienised digestate Ammonium sulphate
Framework conditions relevant to the business case	Owners cultivate 1,400 ha agricultural land Low livestock density in the region, dominant crop is rice. High gate fee for sewage sludge Use of sewage sludge on agricultural land is allowed though it is subject of debate No subsidy on biogas

2.5 BENAS

The biogas plant BENAS (Table 2.5), located in Ottersberg (near Bremen, Germany), was realized in 2006 and convert energy crops (mostly maize) and poultry litter into biogas and fertilisers. The input of the digester varies between the years as the intake of poultry manure depends on the market prices. High prices for poultry litter led to a decline in the portion of poultry litter in the input of the AD plant in 2020 compared to the years before. In order to reduce NH_3 levels in the digester, BENAS has implemented a N-stripping system (*FiberPlus* system) in 2007/2008. The N-stripping system has been developed by GNS which is a consultancy company and partner within SYSTEMIC.

The innovative N-stripping and scrubbing system relies on binding NH_3 and CO_2 with dihydrate calcium sulphate (gypsum), producing a mixture of AS solution and liming substrate. The liming substrate is predominantly composed by calcium carbonate ($CaCO_3$) with traces of calcium sulphate ($CaSO_4$). This mixture is indicated from now on as calcium carbonate (CC) sludge. AS solution and CC sludge are separated by means of a filter press. The digestate with a reduced NH_4 content is fed back into the digester diluting the feedstocks and preventing ammonia inhibition. Digestate after the post-digester is separated into a solid and liquid fraction and used for fertilization of cropland owned by BENAS to grown energy crops for the AD plant. An additional product of the FiberPlus installation are the low N-fibres which are obtained by means of a screw press from the digestate leaving the N stripper and which therefore has a low NH_4 content. An additional product of the FiberPlus installation are the low N-fibres which are obtained by means of a screw press from the digestate leaving the N stripper and which therefore has a low NH_4 content. Over the course of the SYSTEMIC project, BENAS and GNS developed a new market for these low-N fibres. They now use the low-N fibres for on-site production of paper- and cardboard.

Table 2.5 BENAS plant characteristics (data 2020)

Date of commissioning	2006
Annual substrate processing capacity / processed	174,000 t / 86,600 t (52 ktonne maize, 25 ktonne silage rye, 4 ktonne grass and 5 ktonne other)[1]
Installed electric capacity (IEC)	11.3 MW
Installed biomethane capacity	1,200 m³/h
Digester volume	39 100 m³
Annual biogas output / biogas per t of feedstock	20 Mm³ / 194 m³/t
Annual electricity net-output (fed to the grid)	26,972 MWh (23,610 MWh_{eltot} + 25,580 Mwh_{heat})
Annual bio-methane output	8,78 Mm³ (1,200 m³/h)
Digester type	Thermophilic Continuous Stirred-Tank Reactor (CSTR)
Nutrient recovery & recycling (NRR) facilities	FiberPlus ammonium stripping and recovery system (2007) Screw press for recovery of low-N fibres Fibre moulding and paper making machine
NRR Products	Digestate Ammonium sulphate (3,700 t/y) Calcium carbonate (1,000 t/y) Low-N organic fibres (8,000 t/y)
Framework conditions relevant to the business case	Biogas storage capacity 39,000 m³ Owners cultivate 3,500 ha agricultural land, of which 2,000 ha about 200 km distant from biogas plant Desulphurisation gypsum used for ammonium sulphate production FibrePlus system for production of paper production for pots and mulch papers with an on-site fibre moulding and paper machine

[1] In 2017-2019, between 13-27 ktonne of poultry litter was processed. But this decreased towards zero in 2020 due to an increase in the market price for poultry litter

2.6 Waterleau New Energy (WNE)

Waterleau New Energy (WNE) BV operates a mesophilic AD plant in Ypres (80 km west of Ghent), West-Flanders, Belgium. The plant is in operation since 2012 with a total annual substrate treatment capacity of 120,000 t to process manure, sewage sludge and residues from agro-food industry (Table 2.6). WNE is located in a nitrates-vulnerable-zone.. Since there is a surplus of N from animal manure in the region, WNE implemented a process to recover ammonia from the LF of digestate as condensed ammonia water to be sold as flue gas DeNOx reductant thereby reducing their dependency on the local manure market. Until 2020, the remaining evaporator concentrate, which contains a mixture of macro-nutrients but is low in N, was sold to arable farmers in The Netherlands. Nowadays, evaporator concentrate is blended with the dried SF of digestate and sold to a composting company that eventually exports the end product to France. WNE aims to improve the market value of the end products to improve their overall business case.

Table 2.6 Waterleau New Energy: Plant characteristics (data 2020)

Date of commissioning	2012
Annual substrate processing capacity / to process	120,000 t / 71,000 t (21 kt manure, 49 kt biowaste, 2 kt glycerine/molasse)
Installed electric capacity (IEC)	3.2 MW
Installed biomethane capacity	None
Digester volume	12,000 m³

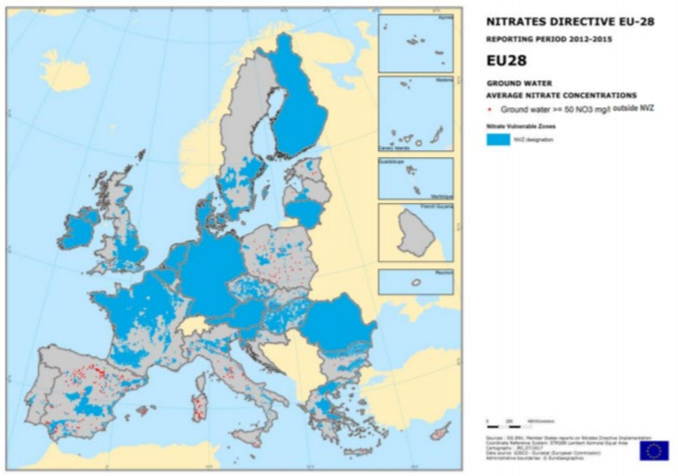
Annual biogas output / biogas per t of feedstock	10.3 Mm³ / 150 m³/t
Annual electricity net-output (fed to the grid)	3200 MWh_{elec} (total production: 5000 MWh_{elec})
Annual bio-methane output	None
Digester type	Mesophilic digestion
Nutrient recovery & recycling (NRR) facilities	Hygienisation (70 °C, 1 hr), solid/liquid separation, drying of the solid fraction and removal of water from the liquid fraction through evaporation.
NRR Products	Dried solid fraction of digestate Evaporator concentrate Purified water
Framework conditions relevant to the business case	High livestock density in the region End products transported to France and the Netherlands Nearby buyer for condensed ammonia water

3 Market demands, framework conditions and legislative criteria

3.1 Legislation

3.1.1 Application rate limits & RENURE products

To Nitrates Directive (91/676/EEC) aims to protect waters against pollution caused by nitrates from agricultural sources. Regions which are sensitive to nitrate leaching are therefore designated as 'Nitrate Vulnerable Zones' (NVZ) including The Netherlands, Belgium, Germany and part of France (Figure 3.1). Excessive application of animal manure contributes to nitrate leaching and the EC therefore implemented an application rate limit for livestock manure of 170 kg N/ha for agricultural land located in NVZs. Additional synthetic nitrogen may be given depending on the nationally-defined crop-specific application rates for effective nitrogen.



Map A. *Area designated as Nitrates Vulnerable Zone and groundwater monitoring stations with average nitrates concentrations above 50mg/L outside NVZ, period 2012-2015[44].*

Figure 3.1 Area designated as Nitrates Vulnerable Zone, period 2012-2015

The Nitrates Directive defines livestock manure as 'waste products excreted by livestock, even in processed form' (art. 2(g))[1]. So today, nitrogenous mineral fertilising products derived from manure or co-digested manure are subjected to the same application rate limits as untreated livestock manure. As manure is abundantly available in many livestock producing regions of the EU, farmers are unlikely to want to pay for recovered nutrients from manure when the recovered products are also restricted by the same application limit. The European Commission has recognised this barrier and has recently published the **RENURE**[2] report (REcovered Nitrogen from manURE), which proposes criteria to authorise use of manure-derived recycled nitrogen fertilising products above the application standard of 170 kg N/ha for manure-derived nitrogen fixed by the Nitrates Directive (Huygens et al., 2020). These criteria are, in short, a NH_4/TN ratio>90% and a TOC:TN ratio below 3.0 kg/kg. In addition, Cu and Zn may not exceed 300

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[1] Nitrates Directive, article 2g. (g) 'livestock manure': means waste products excreted by livestock: or a mixture of litter and waste products excreted by livestock, even in processed form;

[2] SYSTEMIC contributed to the SAFEMANURE study which led into the RENURE report through the submission of product factsheets on Ammonium Sulphate, Ammonium Nitrate, Ammonium Water, Mineral concentrate and liquid fraction digestate, all of which can be found at www.systemicproject.eu/downloads

mg/kg DM and 800 mg/kg DM, respectively. The European Commission has not yet made a final decision upon the acceptance of RENURE products. If accepted and implemented, this will give opportunities for manure treatment plants to process manure into fertilising products that replace synthetic N in regions with intensive livestock farming, avoiding long-distance transport.

SYSTEMICs demonstration plants are all located in NVZs except for Acqua&Sole. In addition to the restrictions on the application of animal manure, fertiliser use is restricted by application rate limits for total N (including mineral or synthetic fertilisers) and P. Application rate limits for N and P are set at a national level and hence differ among the SYSTEMIC demonstration plants. The application rate limits relevant for end products of the demonstration plants are summarized in Table 3.1 and further discussed in paragraph 3.2 in relation to the local demand for fertilising products.

Table 3.1 Overview of legal status of end products and N- and P application standards for the demonstration plants.

	Designated as:	N application standards[1]	P application standards	Remarks
Am-Power- Organic residues agro-food				
Evaporator concentrate	Organic fertiliser (non-manure)	Application standards for effective N (crop- and soil specific)	P application standards (45-115 kg P_2O_5 /ha) (crop- and soil specific)	-
Dried SF of digestate	Organic fertiliser (non-manure)	Application standards for effective N (crop- and soil specific)	P application standards (45-115 kg P_2O_5 /ha) (crop- and soil specific)	-
Groot Zevert - Pig slurry and organic residues agro-food				
RO concentrate	Manure	Temporary exemption to be used as synthetic fertiliser, i.e. on top of the limit of 170 kg N/ha	P application standards	Exemption till 2021 within the pilot 'biobased fertilisers Achterhoek'
Precipitated P salts	Manure	Max. 170 kg N/ha (Nitrates Directive)	P application standards	-
Low P organic soil improver	Manure	Max. 170 kg N/ha (Nitrates Directive)	P application standards	-
Acqua & Sole - Sewage sludge and organic residues agro-food				
Ammonium Sulphate	Mineral fertiliser	Application standards for total N (crop- and soil specific)	Not relevant (no P in product)	End of Waste and Reach registration
Digestate	Sewage sludge	Application standards for total N (crop- and soil specific).	No standards	Limit of 170 kg N/ha does not apply to sewage sludge
BENAS - Energy crops, poultry litter				
Ammonium sulphate	Mineral fertiliser	Application standards for total N (crop- and soil specific)	Not relevant (no P in product)	Exempted from limit for N from animal manure.
Solid fraction	Biowaste/manure	Max. 170 kg N/ha (Nitrates Directive)	P application standards though depending on targets for increasing organic matter in soil.	In Germany, the application limit of 170 kg N/ha is also applied to non-manure organic fertilisers.
Waterleau NewEnergy - Biowaste and manure				
Condensed ammonia water		Not relevant	Not relevant	Not used as fertiliser but sold to industry
Dried SF of digestate	Manure	Max. 170 kg N/ha (Nitrates Directive)	P application standards (45-115 kg P_2O_5 /ha) (crop- and soil specific)	-

[1] Effective N: In organic fertilisers, effective N is calculated as the amount of mineral N plus the fraction of the organic-N that is expected to mineralise within one year after application (also referred to as N replacement value). For mineral or synthetic fertilisers, effective N is equal to 100%

3.1.2 Fertilisers Product Regulation

The EU **Fertilisers Product Regulation (FPR)**[3] will come into force in 2023 and will regulate free trade of fertilising products with the objective of placing secondary raw materials on the EU fertiliser market to better facilitate a circular nutrient economy. Whereas the previous EU fertiliser regulation 2003/2003[4] only regulated fertilisers from chemical (synthetic) origin for free trade, the new regulation also regulates fertilising products from animal and vegetative origin and thus provides an excellent regulatory tool for the free trade of fertilising products from renewable resources (including animal manure and products thereof) and potential access to important new markets. Free trade is particularly important for those AD plants that export biobased fertilisers and whom are currently forced into lengthy and costly bilateral negotiations to have their products approved in neighbouring Member States.

The FPR lays out seven product function categories (PFC) (groups of fertilising products) which may only be produced from designated component material categories (CMC). Currently, eleven CMCs are designated of which CMC 4 (fresh crop digestate), CMC 5 (other digestate), CMC 10 (Animal by-products) and CMC 11 (industrial by-products) are of particular relevance for SYSTEMICs demonstration plants. However, definitions and criteria for CMC 10 and 11 are however not yet defined and this hampers evaluation of compliance of SYSTEMICs products with the criteria of the PFR. The FPR regulates trade of organic fertilising products but the application of CE fertilisers is, as any other fertiliser, regulated by other European and national legislation. A detailed assessment of product composition of SYSTEMICs demonstration plants in relation to the criteria of the FPR is included in Sigurnjak et al. (2022).

3.1.3 National legislation

All AD plants have to comply with national legislation for fertiliser products. Table 3.2 gives a short summary of national legislation applicable to the end products of the demo plants. A comprehensive overview of EU and national legislation related to digestate application was previously published as SYSTEMIC deliverable D2.1 (Hermann *et al.*, 2019).

Am-Power processes organic waste from the agro-food industry, therefore they have to comply with the Flemish Waste Legislation (Vlarema). This regulation includes a criteria for heavy metals, PAH's and mineral oil. These criteria apply to both the solid fraction and NK concentrate. A full list of criteria is available in Hermann et al. (2019).

GZV meets the criteria for a co-digestion plant, which implies that their feedstock consists of at least 50% animal manure and only approved co-products are used. The digestate and other end products therefore are still considered manure and there are no criteria for heavy metals or organic contaminants (because co-products are examined on presence of contaminants before being approved). In case of export, hygienisation is required. The same applies for their future end products including the RO concentrate, precipitated P salts and organic soil improver.

Acqua & Sole applies sewage sludge in the Lombardy region (Italy). Criteria for digestate are laid down in national legislation (DGR X/2031/2014) and its subsequent rules (DGR X/5269/2016 and X/7076/2017). This includes criteria for heavy metals, PAK's, PCB's and AOX (Hermann et al., 2019). Digestate of sewage sludge is legally considered a waste. According to the Waste law, the maximum amount of sewage sludge digestate that can be applied is dependent on the pH and cation exchange capacity of the soil where fertilisers will be applied. In addition, the European Sewage Sludge Directive prescribes regular analyses of heavy metal contents in soil.

[3] Regulation of the European Parliament and of the Council laying down rules on the making available on the market of CE marked fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009

[4] Regulation (EC) No 2003/2003 of the European Parliament and of the Council of 13 October 2003 relating to fertilisers https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32003R2003

Ammonium sulphate is considered as a product (EoW) since it complies with National regulation of fertiliser (italian Law nr. D. Lgs 75/2010) and it is registered as a chemical substance under REACH procedure.

BENAS' digester is fed with energy crops and poultry manure. Their digestate can be applied in agriculture when they comply with the Ordinance on Biowaste[5], which includes criteria for heavy metals, hygienisation and physical impurities.

Waterleau NewEnergy in Belgium, Flanders, is processing biowaste and animal manure and has to comply with criteria laid down in the Vlarema legislation as explained for Am-Power.

All demonstration plants have confirmed that their end products comply with national fertiliser regulations by sharing their certificates.

[5] https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Abfallwirtschaft/bioabfv_engl_bf.pdf

Table 3.2 Overview of national legislation to which end products of SYSTEMIC's demonstration plants have to comply

	Feedstock	Country were to be applied	Relevant regulations	Parameters included in regulation
Am-Power				
Evaporator concentrate	Biowaste	Belgium	Waste legislation (Vlarema)	Heavy metals, organic micro-pollutants (a.o. PAH, PCB, mineral oil,...)
Dried SF of digestate	Biowaste	France	Flanders waste legislation (Vlarema)and French criteria (NF U42-001)	Heavy metals, organic micro-pollutants (a.o. PAH, PCB, mineral oil,...)
GZV[2]				
RO concentrate	Manure	Netherlands	-	-
SF of digestate		Germany	Bi-lateral agreements between member states on export manure	Hygienisation
MF concentrate		Netherlands	-	
Precipitated P salts		Netherlands or export	Bi-lateral agreements between member states on export manure	Hygienisation
Soil improver		Netherlands	-	-
Acqua & Sole				
Ammonium Sulphate	Fertiliser	Italy or industry	End-of-waste status and REACH registration	-
Digestate	Sewage sludge	Italy, Lombardy	Regional regulation: DGR X/2031/2014 and its subsequent rules DGR X/5269/2016 and X/7076/2017	Heavy metals, organic micro-pollutants (a.o. PAH, PCB, mineral oil,...), *E* coli, salmonella,
BENAS				
Ammonium sulphate	Fertiliser	Germany	Considered as a synthetic fertiliser within Germany-	-
Solid fraction	Biowaste	Germany	Ordinance on biowaste	Criteria for heavy metals and sanitation
WNE				
Evaporator concentrate	Biowaste, manure	France	Flanders waste legislation (Vlarema) and French criteria (NF U42-001)	Heavy metals, organic micro-pollutants (a.o. PAH, PCB, mineral oil,...)
Dried SF of digestate		France		
Ammonia water		Industry	Flemish manure Decree. "Marketing to private individuals/industry"	-

3.2 Market for feedstocks and end products

3.2.1 Groot Zevert Vergisting

Groot Zevert Vergisting is located in the eastern part of the Netherlands in a region with intensive animal husbandry and an excess of animal manure, mostly pig manure. Years of over-fertilisation in the past have led to P saturated soils and introduction of P application standards targeting at P equilibrium fertilisation. The P application standards, which depend on the soil P-status, range between 50 to 75 kg P_2O_5/ha arable land and 80-100 kg P_2O_5 ha^{-1} for grassland and arable land, respectively. As a consequence, farmers have to export or process part of their manure. In 2017, 40% of the pig manure and 5% of the cattle manure produced in the Netherlands was exported to neighbouring countries. This ratio is higher for pig manure because most pig farmers do not own land and because pig slurry is richer in phosphorus compared to cattle manure. Phosphorus is generally the most constraining factor for manure application and hence the most important factor determining manure disposal costs. For N, the application rate is limited by the N application standards and the standards for animal manure which amount to 170 kg N ha^{-1} or 230-250 kg N ha^{-1} on derogation farms. The majority of cattle farmers in the Netherlands make use of this derogation, which allows them to use more N from cattle manure. The derogation conditions, however, do not allow the use of pig manure or synthetic P fertiliser.

The N and P_2O_5 production in the form animal manure in The Netherlands is shown in Figure 3.2. GZV is situated in a region where both N and P are produced in excess. Being situated close to Germany, their former disposal route was export to Germany, typically to the Eiffel region (200 km). However, transportation costs were high and the demand for digestate in the Eiffel region decreased due to the increasing pressure on the manure market in West Germany.

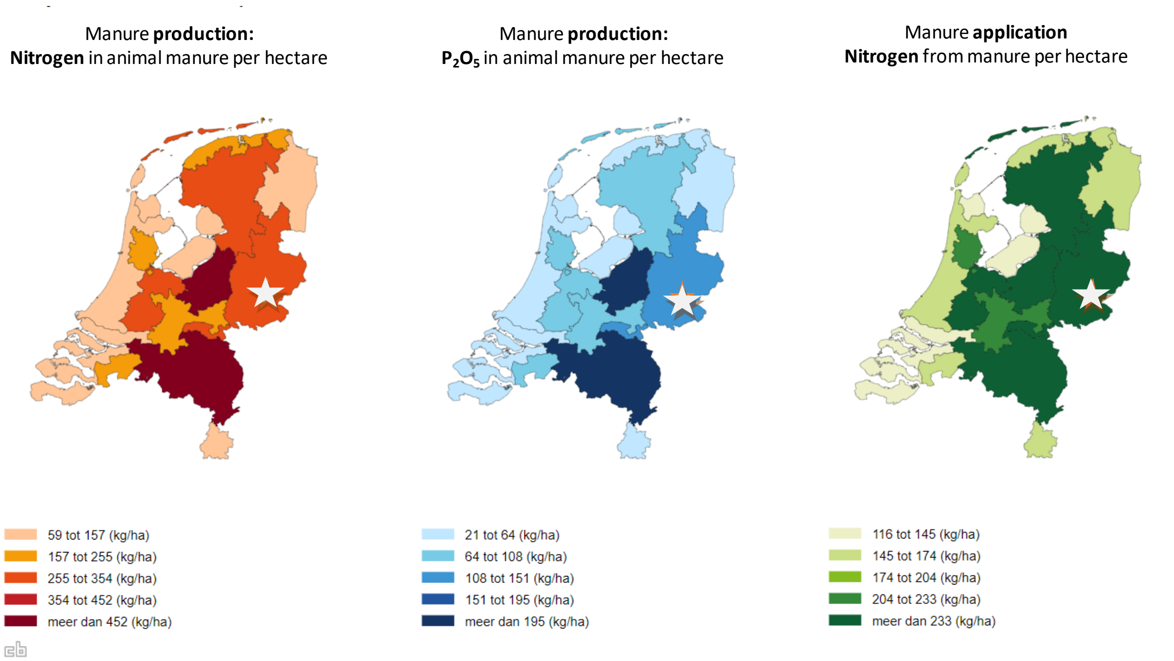

Figure 3.2 Manure production (kg N and P_2O_5 per hectare) and manure application rate (kg N from manure per hectare) in the Netherlands in 2017. The symbol denotes the location of GZV. Data taken from CBS statline.

Phosphorus is the most pressing nutrient and its transportation costs can be reduced by applying a solid-liquid separation step and exporting only the solid fraction of the digestate. This disposal route was not cost effective, however, since there is no market for a P-rich solid fraction within 500 km from GZV. As a consequence, disposal costs for the solid fraction amounted to about 25 euro's per tonne in 2018. Due to a decline in the number of livestock animals, disposal costs for solid fraction declined to 18 euro per tonne in 2021.

Within the SYSTEMIC project, GZV implemented a new technique to separate SF of digestate into two valuable products: a low-P soil improver/peat replacer and a precipitated P salt (Regelink *et al.,* 2019, Schoumans *et al.,* 2017). The goal of GZV is to sell the organic soil improver to arable farmers in the region who have need for organic soil improvers in order to maintain organic matter contents in their soils. The P fertiliser can be used as raw material for the production of organic or mineral fertilising products for export.

Meanwhile, circularity became more and more important, which stimulated GZV to investigate the opportunities to produce fertilisers and soil improvers for the local markets. Farmers use synthetic N fertiliser on top of N from animal manure to meet crop demands for N. GZV decided to invest in an installation for the production of RO concentrates. GZV now produces a mineral concentrate that is sold on the market as 'Green Meadow Fertiliser' after blending it with other N fertilisers such as urea or ammonium sulphate in order to produce a customer-specific fertilising product. GZV received a temporary exemption to use their product as synthetic N fertiliser – hence on top of the limit for N from animal manure - within the pilot 'biobased fertilisers Achterhoek' which is part of the 6^{th} action programme on the Nitrates Directive in the Netherlands. The target within this pilot project is to process a mineral N fertilising product that meets requirements of the EU fertilising regulation for liquid inorganic fertilisers (PFC1c)[6], which implies that blended product shall contain at least 15 g/kg N and that the sum of the nutrients is at least 70 g/kg. On top of that, the product must meet national requirements for mineral concentrates:

- At least 90% of N is present as mineral N
- The N to P_2O_5 ratio is at least 15 or higher
- The EC value is at least 50 mS/cm

Mineral concentrates are most effective at the start of the growing season. The rest of the year, NK concentrate is disposed of as animal manure to farmers in the north of the country. They anticipate to reduce digestate volume with at least 50% meaning a 50% reduction in transport cost for GZV and less storage capacity needed on the accepting farm.

3.2.2 Am-Power (Belgium)

Am-Power is situated in Flanders, a region with an excess of manure from livestock farming. Both N and P_2O_5 are available far in excess in the region. Flanders is a NVZ and only 14% of the arable land in Flanders has a derogation to use more N from animal manure. Additional N must come from synthetic N or non-manure fertilizing products. The total amount of applied N should remain below the crop- and soil specific N application standards (Table 3.2). Also for P_2O_5, there are crop- and soil-specific application standards targeting equilibrium fertilisation. Livestock animals in Flanders produce more manure than can be applied within these application rate limits. In 2017, 37% of N and 32% of P produced by livestock animals was disposed of through processing and/or export (Vlaamse Landmaatschappij, 2018).

The AD plant of Am-Power converts biowaste (non-manure) into digestate, which is further processed into organic fertilisers. Though these fertilisers are designated as 'other organic fertilisers' rather than as manure, the products compete with animal manure when disposes of within Flanders meaning that farmers only accept these organic fertilising products if being payed. Synthetic N fertilisers, on the other hand, are in high demand. In 2017 – 2018, Am-Power produced an RO concentrate containing 5 kg N/tonne which was used on grassland and potato fields in a radius of about 60 km from the plant. The product was, however, to dilute to be transported over longer distances to regions where the product has a positive market value.

Am-Power could follow the example of GZV and produce a NK concentrate with low P content and high NH_4/TN ratio to be sold in the region as an alternative for synthetic N fertilisers. This is possible under the existing regulations because Am-Powers digestate is free of animal manure meaning that a farmer can apply A-Powers fertilisers on top of the limit of 170 kg N/ha. Development of a market for biobased N fertilisers is, however, lengthy process because Am-Power would need to change the farmers perception of biobased fertilisers as being similar to animal manure rather than suitable alternatives for synthetic N.

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[6] Zesde Nederlandse actieprogramma betreffende de Nitraatrichtlijn (2018 - 2021)

Am-Power therefore chose another strategy: they are located in the vicinity of France and focus on disposal of the dried SF of digestate and evaporator concentrate to arable farmers in France. To do so, the volume of the fertilising products is reduced as much as possible to minimize costs for transport. They already produce dried SF of digestate with a high P content and export it to France (Champagne region), where is it applied as a fertiliser for cultivation of rapeseed and alfalfa. The dried SF has a low N content. With the implementation of an evaporator, N, K and S are recovered in the evaporator concentrate at higher concentrations compared to the previously produced RO concentrate. Direct export of evaporator concentrate to France is, however, not possible; the French fertiliser regulation facilitates import of solid organic fertilisers but not liquid organic fertilising products. Also, the concentrate does not meet the criteria for minimum amount of nutrients to be excepted as an CE fertiliser under the new European FPR. As an alternative, Am-Power is now blending the dried SF and evaporator concentrate to a tailor-made fertiliser with N/P ratio on demand for export to France.

3.2.3 Acqua & Sole (Italy)

Sewage sludge is Acqua & Sole's pre-dominant feedstock and it is associated with a significant gate-fee representing a large fraction of the plant's revenues. Its availability is not an issue, on the contrary, Northern Italy faces a shortage of sludge disposal facilities. However, public acceptance of sewage sludge derived fertilisers is a challenge, even after thermophilic digestion and corresponding hygienisation. In response to these barriers, Acqua&Sole has paid much attention and dedicated significant investments to run the digester in thermophilic mode which required an investment in N stripping to reduce ammonia levels and prevent toxic conditions in the digester. Besides, Acqua & Sole payed attention to abatement of odours by closed unloading facilities and direct injection into farmland.

In 2018, Acqua & Sole produced 59.569 tonne of digestate and 637 tonne of ammonium sulphate. In the same year 88.662 tonne of digestate and 512 tonne of ammonium sulphate were applied on arable fields and another 112 tonne of ammonium sulphate were used in industrial sector. Products are conceived to meet the requirements of sustainable rice cultivation with two applications in mind:

- About 1,000 ha of own farmland;
- About 4,000 ha farmland in the neighbourhood of the plant.

Farmers who use digestate from Acqua & Sole are mainly located near the AD plant; the furthest farmer is 35 km away from the plant. Ammonium sulphate (AmS) is a safe mineral product that could contribute to the financial results of the plant if sold to third parties. However, in the form of AS solution it cannot be transported over long distances.

Application rates of digestate are restricted by the crop-specific N application rate limits. it is important to note that digestate of Acqua & Sole does not fall under the limit of 170 kg ha^{-1} y^{-1} (Nitrates Directive, 91/676/EEC), as for livestock slurry or digestate from co-digestion of livestock slurry. Reducing the N content of the digestate by means of stripping enables applying a larger amount of digestate per ha within the N application rate limits.

3.2.4 BENAS (Germany)

The BENAS company owns 3,500 ha of agricultural land of which 1,000 ha in the vicinity of the plant and 2,500 ha at a distance of 200 km in Saxony-Anhalt. Digestate and ammonium sulphate are used on their own land to produce energy crops to feed the digester. Nitrogen is generally the limiting factor for application of digestate. In Germany, the application of organic fertilisers is limited to 170 kg N/ha irrespective of whether this fertiliser is designated as animal manure or as an other organic fertiliser. From that perspective, it is irrelevant for BENAS whether they include poultry manure in the ration of the AD or not. Stripping of nitrogen lowers the N content in the digestate, meaning that the application rate of digestate per ha can be increased and hence, a larger part of the digestate can be used on land nearby the AD plant.

Nitrogen is recovered as ammonium sulphate, which is far more concentrated than digestate and can therefore be transported over longer distances. In Germany, ammonium sulphate from digestate is already accepted as an alternative for synthetic N fertiliser and can therefore be applied on top of the limit of 170 kg N/ha. Disposal of ammonium sulphate is therefore no problem as there is sufficient demand for N fertiliser on their land and because ammonium sulphate can be stored throughout the winter season. Due to the high sulphur content however, the application rate of ammonium sulphate should not exceed the crop demand for sulphur which is generally rather low (10-20 kg S/ha) compared to the N demand. Arable crops with a high demand for sulphur include oilseed rape and cabbage. Furthermore, the plant produces a liming product with 40% CaO which is applied on agricultural land. Due to the possession of own land, BENAS business case is independent of fluctuations in the market prices for disposal of animal manure and digestate.

Due to use of maize and corn silage in the digester, digestate of BENAS contains a large amounts of organic fibres which can be easily recovered by means of a screw press. The low-N organic fibres, recovered from digestate leaving the N stripper, is potentially a suitable alternative for wood fibres used in production of cardboard. During the SYSTEMIC project, BENAS and GNS actively worked on marketing of the low-N organic fibres. They initially targeted industrial companies whom were interested in purchasing the fibres as a commodity for fibre board production, but would not pay enough to create a positive business case. BENAS then realised that their fibres – being fully biodegradable and from organic origin – have unique selling points and that this would open up the way to niche markets, but only if they would be able to convert the raw material into market-ready end-products by themselves. They are now producer of the first FiBL-certified[7] mulch paper being marketed under the name MagaVerde (www.magaverde.de) targeting application in organic vineyards. In addition, the purchased a paper machine for production of fully biodegradable pots all marketed under the name MagaVerde.

3.2.5 Waterleau New Energy

Similar as Am-Power, WNE is located in west Flanders, a region characterised by intensive pig husbandry, and therefore has to cope with a manure surplus and stringent local fertilizing legislation. WNE treats surplus of animal manure and biowaste. Application of its digestate in the region of plant is restricted by the N-application rate limit for N from animal manure. WNE decided to focus on export of solid fraction to France. At WNE, nitrogen is recovered as condensed ammonia water which is used in DeNox installations in industry.

[7] FiBL is the Research Institute of Organic Agriculture. An FiBL-certification allows use in organic farming

4 Technological advancements and mass- and energy balances

4.1 Technological advancements

4.1.1 Groot Zevert Vergisting (GZV)

GZV has invested in NRR technology to convert their digestate into NK concentrate, a soil improver, a P fertiliser and clean water. The process starts with a decanter centrifuge producing a solid and liquid fraction. The first decanter centrifuge separates digestate into a solid and liquid fraction without addition of polymer or iron salts; avoiding these chemical additives was a deliberate choice to produce a fibrous solid fraction free of additives. Some magnesium-chloride is added to precipitate ortho-phosphate forming struvite to increase the separation efficiency for phosphorus. Prior to the second decanter centrifuge, polymer is added, and this decanter produces a sludge. Any remaining particulate material is removed from the liquid by means of micro-filtration producing MF concentrate. Removal of particulate matter and phosphorus is necessary in order to prevent scaling of RO membranes. The effluent of the micro-filtration unit is concentrated in the reverse osmosis unit creating an RO concentrate (1/3 v/v) and permeate (2/3 v/v). Sulphuric acid is dosed on the RO to increase retention of ammonia (NH_3 is able to pass membrane) and to prevent calcium carbonate scaling on RO membranes. The permeate of the RO is treated by ionic exchange module to meet criteria for discharging the water onto surface water.

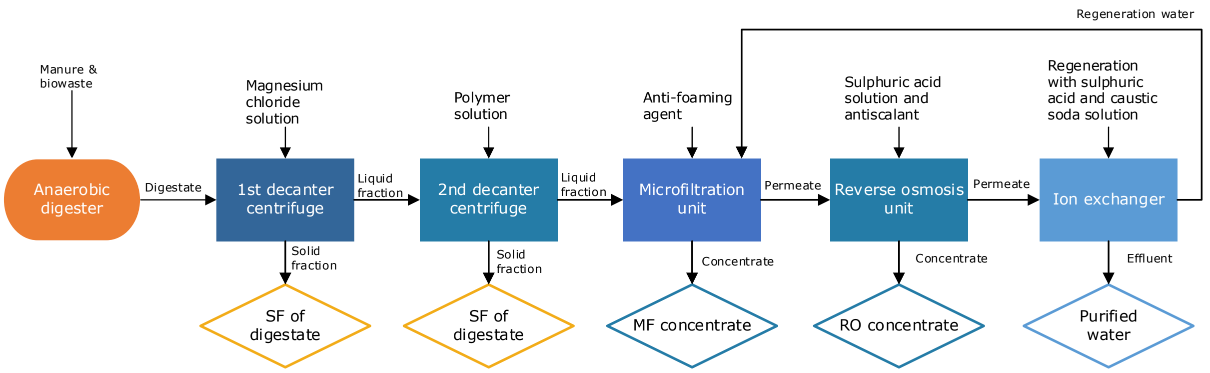

Figure 4.1 Process scheme of the NRR facility for treatment of the digestate and liquid fraction at Groot Zevert Vergisting (the Netherlands)

The solid fraction – which contains about 70% of the P – is exported to Germany or further treated in the RePeat system. The latter process (Figure 4.2) includes two acidification steps where phosphorus is extracted at a pH of 5.5, thereby separating the solid fraction into a low-P organic soil improver and a precipitated P salt. The acid and P-rich liquid fraction is first treated in a clarifier to remove organic material, creating a sludge stream. The effluent of the clarifier is then fed into a precipitation tank were the pH is controlled at pH 7.0 through addition of calcium hydroxide. Calcium hydroxide is used instead of magnesium hydroxide to prevent struvite scaling within the installation. A drawback of using calcium hydroxide, however, is that phosphate forms a poorly dewaterable sludge whereas addition of magnesium hydroxide would lead to formation of struvite which is superior in terms of dewaterability.

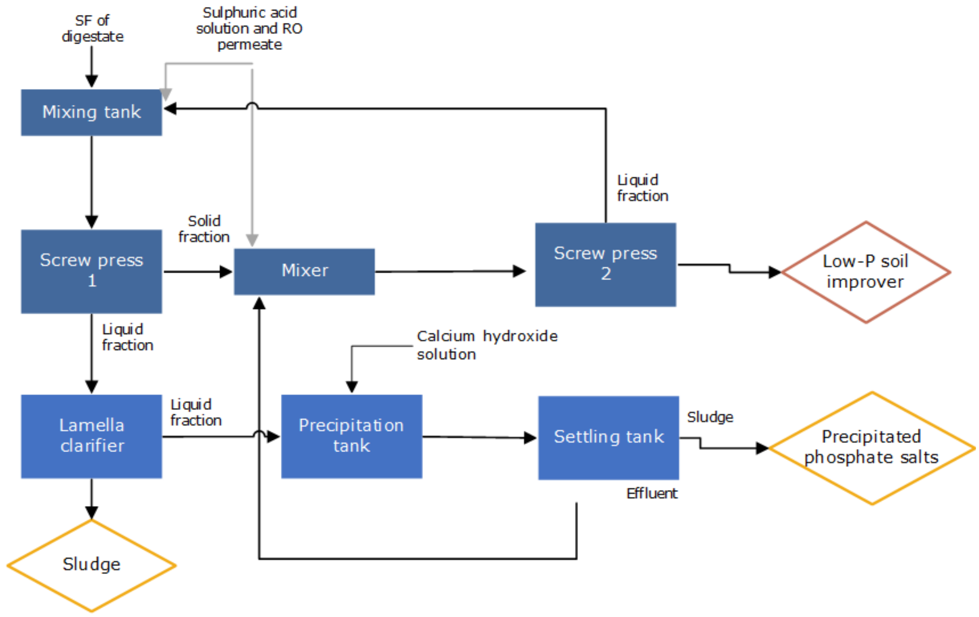

Figure 4.2 Process scheme for the treatment of the solid fraction at Groot Zevert Vergisting (the Netherlands)

Construction and commissioning of the GENIUS installation (Figure 4.8) was finalised by the end of 2018. This was followed by a period in which the process was optimised leading to changes in the original configuration of the installations. Monitoring of the GENIUS installation started in April 2019. Installation of the RePeat installation was delayed and finalised during early 2020. Also here, further adjustments were needed including alterations in the software and instalment of cover plats and extraction fans to control H_2S emissions.

Figure 4.3 The new GENIUS installation at GZV

4.1.2 Am-Power

At the start of the SYSTEMIC project, Am-Power was equipped with a centrifuge for solid/liquid separation of the digestate and fluidized bed dryer to dry the SF of digestate. This part of the process remained while the treatment of LF of digestate has been improved during the project through investment in evaporators. In the old system, liquid fraction was treated in a DAF to remove fine particulate matter and thereafter fed into an RO installation producing a concentrate and permeate water.

The old system had some severe disadvantages:

- High consumption of Fe-salts and polymer for flocculation on the DAF,
- Low water production of the RO installation (50% of RO-feed was converted into water)
- Large volume of RO concentrate to be disposed of against payment

Am-Power therefore decided to replace the DAF and RO installation for an evaporator with the aim to:

- Reduce use of polymers and Fe-salts and associated costs
- Reduce volume of concentrate (i.e. increase water production)
- Sanitize the concentrate (criteria export)

Figure 4.3 schematically depicts the new NRR process. Digestate is separated into a SF and LF by means of a decanter centrifuge after addition of polymer (active ingredient polyacrylamide). The SF is dried to about 90% DM removing water and ammonia as exhaust gas that is being treated in an air scrubber to recover ammonia as ammonium sulphate. The LF of digestate is fed into the evaporator were it is separated into an evaporator concentrate (25% of ingoing mass) and condensed water (75% of ingoing mass). To prevent volatilisation of ammonia, LF of digestate is acidified to a pH below 7.0 using sulphuric acid. This keeps ammonia within the concentrate upon evaporation resulting an condensate with a low ammonia content. This is what distinguishes the process of Am-Power from the process of Waterleau NewEnergy where no acid is added to the LF leading to production of a low-N concentrate and a high-N condensate (condensed ammonia water). Initially, Am-Power also aimed to produce condensed ammonia water to be sold to industry, but they found that market opportunities for this product were limited in their region. The evaporator offers the flexibility to switch between both configurations depending on the market opportunities. Condensate of Am-Powers systems contains some ammonia and further treatment on RO is needed to produce a permeate that meets criteria for discharge onto surface water. This RO installation has not yet been installed and so far, the condensate is used on-site for cleaning and dilution of the feedstocks of the digester.

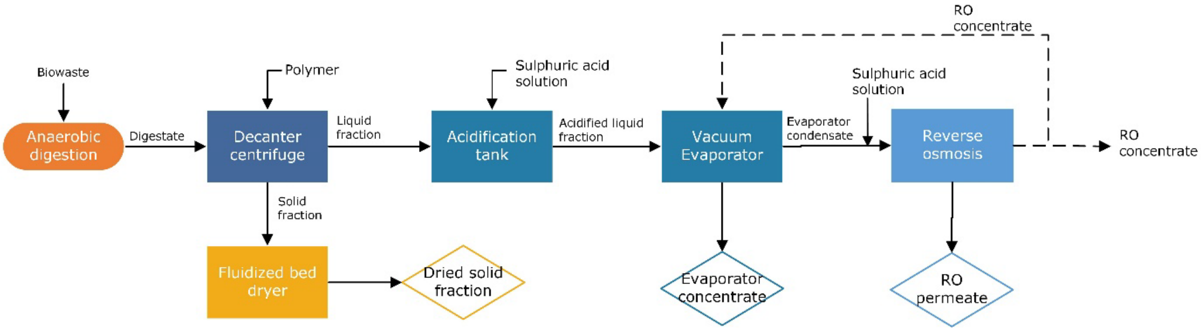

Figure 4.4 Process scheme of the NRR facility at Am-Power (Belgium). The RO installation was not yet operational during the monitoring period.

Instalment of the evaporators at Am-Power was delayed due to difficulties in the arrangement of financial guarantees to secure the investment for Am-Power as well as the technology supplier. Instalment took place in June/July 2019 after which a period of testing followed in order to find the right settings and write software for automatic control of the system. The evaporators are now working as envisaged.

Figure 4.5 Photo of the new evaporators at Am-Power (upper) and RO installation for treatment of the condensate of the evaporator (below)

4.1.3 BENAS

The BENAS AD plants treats both energy crops and poultry litter and the latter lead to high ammonia concentrations in the digestate that may subsequently inhibit biogas production. To control ammonia levels in the digester, GNS, an engineering company and partner within the SYSTEMIC project, invented a modified ammonia stripping process, by which ammonia and carbon dioxide are removed under slightly negative pressure at temperatures of 50-85 °C without addition of chemicals. By binding ammonia and carbon dioxide with gypsum instead of sulfuric acid, CO_2 emissions are reduced and calcium carbonate is formed as a by-product (Figure 4-4). BENAS preferably uses gypsum from flue gas desulphurisation (FDG) which is by-product from coal-fired electricity plants. The low-N digestate is either fed back to the digester or first separated by means of a screw press to recover the low-N fibres that are being used for the production of paper and cardboard. Digestate from the post digester is separated by means of a screw press into a LF and SF and both are used on their own fields.

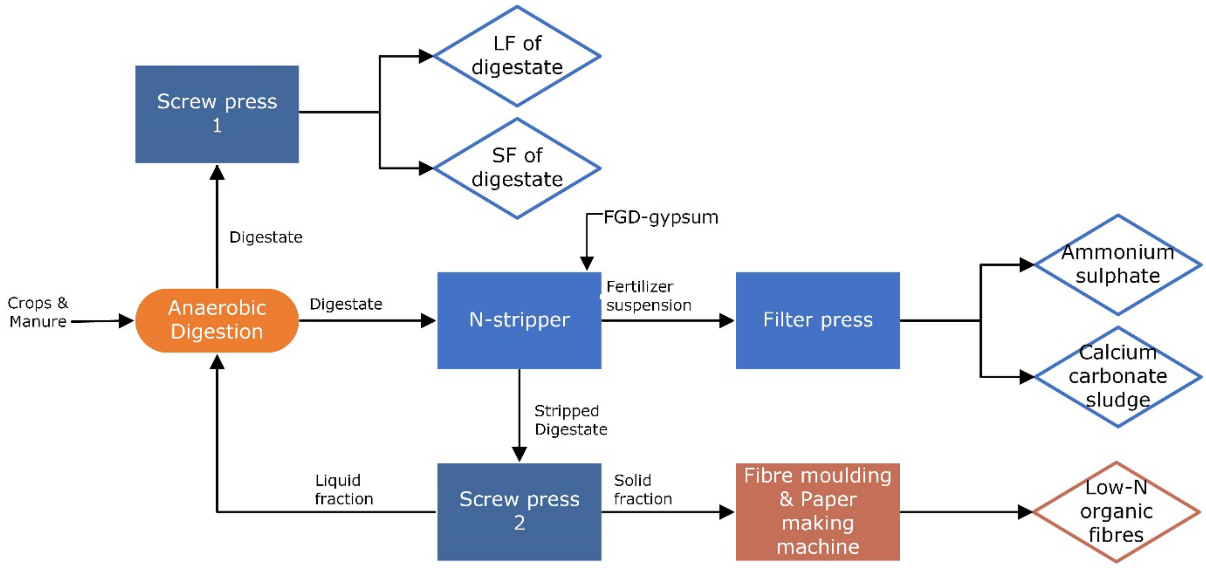

Figure 4.6 Process scheme of the anearobic digester and NRR facility at BENAS (Germany).

The NRR installation at BENAS (Figure 4. 7) except for the fibre moulding and paper making machine was already installed and in operation before the SYSTEMIC project. During the course of the project, BENAS developed a new product to be produced from the low-N organic fibres and purchased a fibre moulding and paper making machine in 2021 after extensive market research and development. During the course of the project, BENAS made several advancements in the power generation enabling them to increase or cut down power production depending on the demand for electricity on the grid which enables to operates as a grid stabilizer.

Figure 4.7 Aerial photo of the AD plant of BENAS (Germany) including the N stripping towers.

Figure 4.8 The NRR installation at BENAS; N stripping towers, paper producing machine and pots produced from recovered fibres.

4.1.4 Acqua&Sole

In 2018, Acqua & Sole produced 59.569 tonnes of digestate and 637 tonne of ammonium sulphate. In the same year 88.662 tonne of digestate and 512 tonne of ammonium sulphate were applied on arable fields and another 112 tonne of ammonium sulphate were used in industrial sector.

The previous N stripper removed about 10% of N-NH_4 from the digestate after which it was recovered as an AmS solution with 7% N. Within the SYSTEMIC project, Acqua&Sole invested in an enhanced N stripper with the goal to increase the N removal efficiency till 30% of the ingoing N-NH_4. Ammonium stripping occurs at a temperature of 65-73 ° C. There is no need to add chemicals for pH-control. The new N-absorber has a novel design and is made from high performance material (Alloy 825), which allows to reach higher process temperature and it is also more acid resistant. After leaving the column, the stripping gas is then passed through acid traps filled with sulphuric acid to recover the ammonium producing AmS.

No polymers or iron are used on the plant because the digestate is disposed of in its liquid form however, the digestate may contain residues of polymers and iron that have been applied at the waste water treatment plants (Figure 4-5).

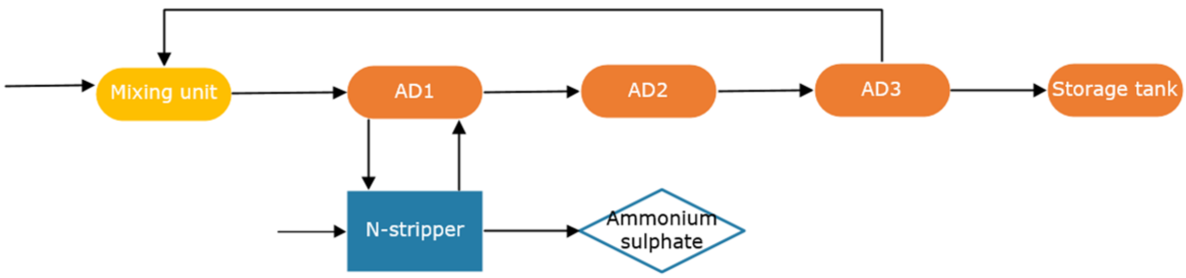

Figure 4.9 Process scheme of the anearobic digester and NRR facility at Acqua&Sole (Italy)

Acqua&Sole faced a delayed in the construction of the new N-stripper due to difficulties in selecting and acquiring the right metal that could withstand the harsh conditions in the N-absorber. Alloy825 is the only material not being damaged by corrosion under the conditions in the N stripper. The supply of Alloy 825 was however delayed and installation was therefore postponed to October 2019.

Figure 4.10 The new N stripper at Acqua&Sole (Italy)

4.1.5 Waterleau New Energy

Digestate is separated into a solid and liquid fraction by a decanter centrifuge, where separation is enhanced by the addition of a polymer solution. The solid fraction is dried in a rotating disc dryer which can evaporate 1–1.8 t of water per hour.

The liquid fraction is treated in an aerated tank for partial removal of degradable organic compounds. The effluent of the aerated tank flows to a falling film evaporator that operates at 50–60°C where the influent is thickened up to a DM content of 20%. In contrast to Am-Power, WNE does not acidify the influent of the evaporator and hence, NH_4 also volatilises as NH_3 during evaporation. Water vapor and NH_3 are recovered by condensation into a product called condensed ammonia water. This solution has a NH_4-N content of about 100 g N/kg and that is used in the DeNOx system of a local incineration plant for the cleaning of flue gasses. In addition, the evaporator produces another stream of condensed water with a low N content (<1 g/kg) that is further treated in an reverse osmosis installation producing permeate water (meeting criteria for discharge onto surface water: <15mg N/L) and an concentrate which is recirculated within the process. Concentrate of the evaporator is rich in organic matter, organic N, P and K. This concentrate is blended with the dried solid fraction and sold to a composting company after which it is exported to France.

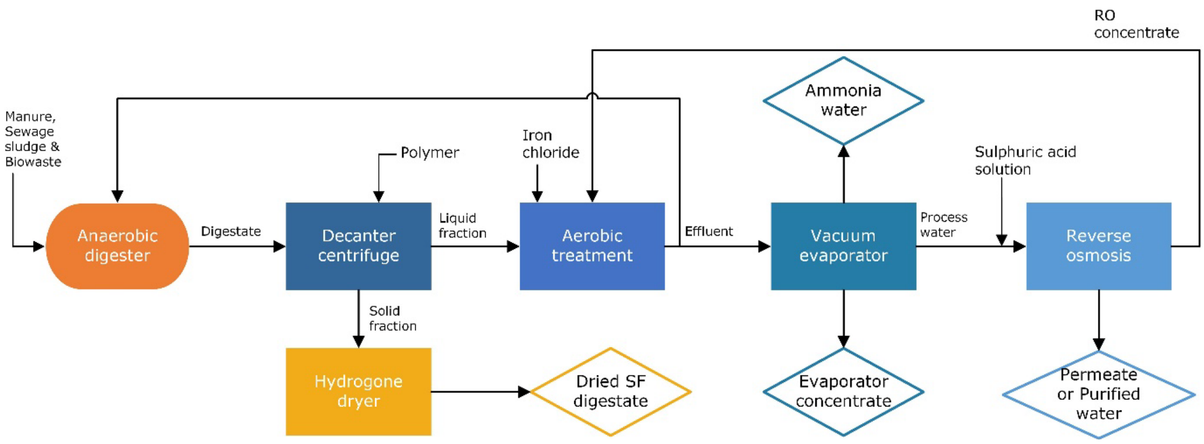

Figure 4.11 Process scheme of the anearobic digester and NRR facility at Waterleau NewEnergy (Belgium)

WNE entered the project in 2020 as a replacement for RIKA's demonstration plant in the UK which was however not constructed and therefore had to be replaced. This explains the relatively short monitoring period for this plant. The NRR installation as WNE was already running at the time that they entered the project.

Figure 4.12 Aerial photo of the demonstration plant Waterleau NewEnergy (2019).

4.2 Mass balances

4.2.1 Groot Zevert Vergisting

In 2019, the GENIUS installation for the separation of digestate into a SF, RO concentrate and purified water was in operation (Brienza et al., 2022a). Until then, GZV had disposed digestate without separation. The GENIUS installation has been monitored ever since and the mass balance derived for monitoring period after process optimisation is included in Table 4.1. One tonne of digestate was separated into 0.15 tonne of SF, 0.31 tonne of RO concentrate, 0.18 tonne of purified water and 0.44 tonne of sludge of the MF unit. The latter is a by-product of the installation. The separation efficiency of the decanter centrifuge was good, as about 66% of P was recovered in the SF which contained only 15% of the mass of the ingoing digestate. For nitrogen, 34% was recovered as RO concentrate (a RENURE product), which was less than envisaged. This is due to the fact that about 53% of N is being recovered as MF sludge which is disposed of as manure. This side stream is a sludge containing fine particulate matter that has be removed from the liquid fraction prior to treatment in the RO installation. The large volume of MF sludge however negatively affects the overall business case of the installation as a large volume of MF sludge inevitably leads to a low volumes of the target products being RO concentrates and purified water. Therefore, their initial target to convert one tonne of digestate into 0.4 tonne of purified water was not realised. Nevertheless, a 52% reduction in transport of digestate-derived products has been realised compared to the situation before NRR (Table 4.2). This is because all end-products except for the P-rich SF can be used within the Netherlands. Chemicals used at the installation include polymer and magnesium chloride (second decanter centrifuge) and sulphuric acid (RO installation). Consumption rate of sulphuric acid was substantially reduced over the course of the project thanks to a novel configuration of the double RO installation. As a result, sulphur content of RO concentrate decreased from 5.0 g/kg to 1.5 g/kg, which is low compared to RO concentrate from manure produced by other manure processors (Regelink et al., 2021). GZV deliberately avoids the use of iron salts in the AD plant and NRR processing. Iron salts are commonly used to bind hydrogen-sulphide (H_2S) and P; At GZV, biogas is de-sulphurised biologically and magnesium chloride is used for removal of ortho-P from the LF which is a pre-requisite for treatment of the LF on the RO.

The end products of the RePeat installation, for production of low-P soil improver, are not yet included in this overall mass balance of the AD plant because the installation was not used continuously and hence processed amounts of solid fraction were low. Monitoring of the installation (Brienza et al., 2022) showed that the separation efficiency for P was as envisaged as 85% of P from the ingoing solid fraction was recovered as precipitated P salts. The low-P soil improver therefore had a composition as envisaged but the precipitated P salts were recovered as sludge with 17% dry matter. A higher dry matter content is needed in order to create revenues from the sale of the precipitated P salts which is still a cost item. Over the course of the project, GZV shifted its focus from production of a low-P soil improver towards production of organic fibres for use in potting soil or substrate. The latter applications allow the product to have a higher P content, meaning reducing the use of sulphuric acid and a lower S content of the end products. Further optimisation is foreseen to comply with product criteria of potting soil or substrate industry.

Table 4.1 Average amounts of ingoing digestate and outgoing end products of the GENIUS system at Groot Zevert Vergisting per day for the monitoring period September 2020 – February 2021. The distribution over the end products as percentage of the ingoing digestate is given between brackets.[1]

Parameter	**Unit**	**Digestate**	**RO concentrate**	**Solid fraction**	**Purified water**	**Sludge of microfiltration and 2nd decanter**
Total mass	tonnes d^{-1}	168 (100%)	52.4 (31%)	24.8 (15%)	30.6 (18%)	73.8 (44%)
TN	kg d^{-1}	1234 (100%)	420 (34%)	287 (23%)	0.008 (0%)	656 (53%)
NH_4-N	kg d^{-1}	865 (100%)	415 (48%)	163 (19%)	0.006 (0%)	324 (37%)
TP	kg d^{-1}	335 (100%)	7.45 (2.2%)	220 (66%)	0.0002 (0%)	97.9 (29%)
TK	kg d^{-1}	768 (100%)	412 (54%)	114 (15%)	0.002 (0%)	309 (40%)
S	kg d^{-1}	115 (100%)	74.9 (65%)	46.0 (40%)	0.091 (0%)	74.0 (64%)

[1] Averages calculated based on five sampling rounds. Monitoring was conducted only when the installation was running without technical problems. Hence, these mass balances reflect the optimal conditions. The actual mass balances over a longer period of time, based on amounts of products trucked off-site, is given in Table 4.2.

Table 4.2 Masses of GZV based on masses of end products trucked off-site, expressed per. ton of digestate and corresponding transport distances. Mass-weighted average transport distance is compared to the situation in which untreated digestate was exported. [1]

Product	Disposal route	Mass	Distance
SF of digestate	Export to Germany	0.15	300 km
MF concentrate	Use on arable fields in northern provinces of the Netherlands (within the application rate limit for N from animal manure)	0.45	150 km
RO concentrate	Used on grass and maize as alternative for synthetic N fertiliser	0.25	25 km
Purified water	Discharged onto surface water	0.15	-
Mass-weighted average transport distance			**118 km**
Reduction as compared to transport of raw digestate over 250 km			**52%**

[1] Mass balance as realised in Jan - June 2021 based on masses of end products trucked off-site (data supplied by GZV). The mass balances therefore deviates from the detailed mass balance in Table 4.1 which has been derived by monitoring of the installation in another period.

4.2.2 Am-Power

The mass balance of the new NRR system including evaporation is given in Table 4.3. Digestate is processed into dried SF of digestate (7% of ingoing mass), LF of digestate (20% of ingoing mass), evaporator concentrate (15% of ingoing mass) and evaporator condensate (46% of ingoing mass).

The decanter centrifuge effectively separates P from the digestate, recovering 95% of P in the dried SF without addition of iron salts but with addition of polymer. Part of the LF after the decanter was disposed of without further separation because the evaporator was not yet running at full capacity. The other part of the LF was treated in the evaporator in which its volume was decreased by 75%. Ammonia was retained within the concentrate because the pH of the LF was lowered to pH <7.0. On average, 5 kg of 98% H_2SO_4 was dosed per tonne of ingoing digestate (Brienza et al. 2022) which would cost about 0.75 euro per tonne of digestate (sulphuric acid 98%, € 0.15/kg). About 50% of the NH_4 in the digestate was recovered in the evaporator concentrate and this would increase to about 70% once all LF is being processed in the evaporator. A part of the NH_4 is now recovered as evaporator condensate which is still used on-site to dilute feedstocks and for cleaning of trucks etc. However, once the RO installation is running as envisaged, evaporator concentrate will be treated into dischargeable permeate water.

Before the SYSTEMIC project, Am-Power treated the LF with a DAF and RO installation producing a concentrate with a N content of 5.0 g/kg. The new NRR system produces a concentrate with a N content of 12 g/kg and is hence twice as efficient in reducing the volume of the RO concentrate.
Another advantage of the new NRR system is that there is no need for pre-treatment of the LF with a DAF which also avoids use of polymer and iron chloride. However, the DAF also effectively removed the remaining P from the LF. In the new system without DAF, part of the P is recovered in the evaporator concentrate which has a P content of 1.0 g/kg. Though only 10% of the ingoing P is recovered in the concentrate, it hampers disposal of concentrate in Flanders where the amount of P that can be applied on land is limited by P application rate limits. The shift towards the evaporator led to an increase in the use of sulphuric acid and anti-foaming agents. A full list of consumed chemicals and dosages is available in Brienza et al., 2022.

Table 4.3 Mass balances of Am-Power in 2020 (taken from Brienza et al., 2022) .

		Digestate	Dried SF of digestate	LF of digestate[2]	Evaporator concentrate	Evaporator condensate[2]	AS air scrubber
Flow	tonne y^{-1}	97,285	6,680	19,507	15,774	45,963	16.318
N	tonne y^{-1}	480	150	78	156	48	42
N-NH4	tonne y^{-1}	2232	9.0	46	84	40	44
P	tonne y^{-1}	134	125	4.2	14	-	
K	tonne y^{-1}	326	91	60	161	-	
S	tonne y^{-1}	100	75	4.1	186	1.3	56

[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.

4.2.3 BENAS

Mass balances for BENAS 2017 and 2019 are given in Table 4-4. Mass balances for 2017 and 2019 were derived based on periodic monitoring campaigns in August 2017 and Jan-April 2019 and data were extrapolated to yearly averages. BENAS digester is operated at thermophilic conditions, which requires removal and control of ammonia levels in order to prevent negative effects of ammonia on biogas production. Overall, about 44% of the ammonium contained in the digestate is recovered as ammonium sulphate thereby reducing the ammonium content of the digestate with 44%. Nitrogen stripping occurs through heating and without chemicals. Ammonia is recovered through a reaction with gypsum forming ammonium sulphate and, as a by-product, a sludge of calcium carbonate. In terms of volume, calcium carbonate sludge is less than 3% of the total volume of the end products from the AD plant.

Digestate from the post digester is separated by means of a screw press which is a low-cost separation technique that operates without addition of polymer or other additives. The separation efficiency of a screw press is however low which evident from the mass balance showing that the SF of digestate contains only 30% of total P contained in the digestate.

The mass balances do not yet include the separation of low-N fibres used for the production of paper and cardboard. Low-N fibres were during the course of the project recovered on demand and for research purposes. From 2021 onwards, BENAS invested in the paper making machine and started producing low-N fibres on a larger scale. Full-scale implementation of the production of low-N fibres will lead to a lower mass of SF of digestate (the latter is obtained from digestate of the post-digester) but has little effect on the overall composition of the other end products. BENAS could produce about 8,000 tonnes of low-N fibres on a yearly basis.

Table 4-4 Mass balances of BENAS in 2017 and 2019 converting digestate into liquid- and solid fraction of digestate, ammonium sulphate and calcium carbonate (% of total amounts in end products)

BENAS		**Liquid fraction of digestate**	**Solid fraction of digestate**	**Ammonium sulphate**	**Calcium-carbonate sludge**	**Low-N organic fibres[3]**
Year	**2017**[1]					
Mass	tonne y^{-1}	65,000 (74%)	18,000 (20%)	4,000 (5%)	1,000 (1%)	pilot
N	tonne y^{-1}	475 (58%)	110 (13%)	212 (26%)	18 (2%)	
N-NH4	tonne y^{-1}	219 (46%)	29 (6%)	212 (44%)	18 (4%)	
P	tonne y^{-1}	117 (70%)	51 (30%)	0 (0%)	0 (0%)	
K	tonne y^{-1}	475 (82%)	106 (18%)	0 (0%)	0 (0%)	
S	tonne y^{-1}	51 (15%)	15 (4%)	241 (72%)	29 (9%)	
Year	**2019**[2]					
Mass	tonne y^{-1}	46,000 (71%)	12,000 (19%)	4,000 (7%)	2,000 (3%)	Pilot. Full capacity: 8 000 ton of fibres per year
N	tonne y^{-1}	344 (50%)	107 (16%)	203 (30%)	30 (4%)	
N-NH4	tonne y^{-1}	205 (42%)	54 (11%)	203 (41%)	28 (6%)	
P	tonne y^{-1}	70 (71%)	28 (28%)	0 (0%)	0 (0%)	
K	tonne y^{-1}	308 (82%)	69 (18%)	0 (0%)	1 (0%)	
S	tonne y^{-1}	54 (13%)	20 (5%)	256 (62%)	81 (20%)	

[1] Data originate from the monitoring period Aug-Sept 2017 and assumed be representative for the whole year. Data were taken from Brienza et al., 2022 and converted to tonne/year.

[2] Data originate from the monitoring period Jan-April 2019 and are assumed to be representative for the whole year. Data were taken from Brienza et al., (2022, Deliverable 1.5) and converted to tonne/year.

[3] Production of low-N organic fibres was still low because the installation was only running to produce fibres on demand for testing purposes. In 2021, BENAS commissioned the paper production and fibre moulding installations. The production capacity amounts to 8 000 tonne of fibres per year.

4.2.4 Acqua & Sole

The N stripper treats a side stream of the AD plant. The removal efficiency for ammoniacal N amounted to 35% as was determined through analyses of N contents before and after the N stripper (Di CAcqua et al., 2021). The overall mass balance of the AD plant showed a lower N removal efficiency, corresponding to 7% of ammoniacal N in the feedstock, which is because the N stripper operated on a side stream of the AD plant (Brienza et al., 2021). The mass balance in Table 4.3 is based on the actual production of ammonium sulphate and digestate in 2020 and shows that 5% of ammoniacal N was recovered as ammonium sulphate. This lower value is due to the fact that the N stripper was out of production during certain periods in this year.

An advantage of Acqua&Soles process is that no other chemicals are used besides sulphuric acid in the acid washer for absorption of ammonium. Sulphuric acid consumption amounts to 5.0-7.0 kg 50% H_2SO_4 per tonne of digestate (Brienza et al., 2021) (density 1.4 kg/l, molarity 7.1 mol/L). This corresponds to 2.5-3.5 kg 98% H_2SO_4 per tonne digestate (density 1.8 kg/l, molarity 18 mol/l).

Table 4.3 Average mass balances of Acqua & Sole based on the overall production of digestate and ammonium sulphate in 2020 (Brienza et al., 2022).

		Digestate[1]	**AmS[2]**
Flow	tonne y^{-1}	114608 (100%)	481 (0%)
N	tonne y^{-1}	825 (97%)	22 (3%)
$N-NH_4$	tonne y^{-1}	436 (95%)	22 (5%)
P	tonne y^{-1}	160 (100%)	0
K	tonne y^{-1}	699 (100%)	0
S	tonne y^{-1}	126 (100%)	26 (17%)

4.2.5 Waterleau New Energy

WNE effectively converts digestate into a dried solid fraction, ammonia water and condensed water. As a by-product, sludge of the aeration tank is being produced which is recirculated to the AD.

The decanter centrifuge separates 73% of P and 63% of organic matter to the solid fraction. The dry matter content of the solid fraction is increased from 23% to 94% in the dryer during which ammonia is emitted and recovered as air scrubber water where it is absorbed in sulphuric acid. The liquid fraction after the decanter, containing 5.8 g N/kg, is first treated in an aeration tank to remove easily biodegradable organic matter. As a side effect, the pH is increased as a result of stripping of CO_2. A drawback is that the aeration tank produces a rather large sludge stream, corresponding to 30% of ingoing digestate, which is recirculated to the digester and used to dilute the ingoing feedstocks but also reduces the capacity of the digester.

The evaporator turns one tonne of liquid fraction into 0.12 tonne of concentrate, 0.86 tonne of condensed water and 0.016 tonne of condensed ammonia water. Hence, the volume of the liquid fraction is reduced by 86% producing an evaporator concentrate with 17% dry matter containing a mixture of macro-nutrients (NPK = 12, 1.6 and 25 g/kg). Ammonium sulphate from the air scrubber is added to the evaporator concentrate increasing its S content. A large volume of condensed water is being produced which is partly used on-site for cleaning purposes and dilutions of chemicals. Nitrogen is recovered as condensed ammonia water with 10.5% N, that is being sold to industry.

The mass balance as depicted in Table 4.3 includes volumes of internally recirculated flows (sludge and 41% of the condensed water) and which hence add up again on the digestate. In terms of efficiency, it is more informative to express the mass of end-products as percentage of the total mass of the end-products leaving the plant. Following this approach, the plant produced 6% dried solid fraction, 3% ammonia water, 26% evaporator concentrate and 65% water. Sulphuric acid consumption amounted to 4.2 kg 98% H_2SO_4 based on the total amount purchased in 2020 (Brienza et al. 2022). Additionally, polymer and iron chloride are being used as additives.

Table 4.4 Mass balances of WNE based on monitoring in June-Dec 2020 and recalculated to tonne/year, between brackets, as % of digestate.

		Digestate*	**Dried SF of digestate**	**Sludge Aerated unit****	**Ammonia water**	**Evaporator concentrate**	**Condensed water evaporated and for cleaning (60%)*****
Monitoring period: June – December 2020							
Flow	tonne y^{-1}	89,333	2,628 (3.0%)	26,738 (30%)	1,424 (1.5%)	10,950 (12%)	47,287 (52%)
N	tonne y^{-1}	584	74 (12%)	123 (21%)	150 (26%)	132 (23%)	74 (13%)
N-NH_4	tonne y^{-1}	353	13 (3.7%)	86 (24%)	144 (41%)	16 (4.5%)	71 (20%)
P	tonne y^{-1}	82	64 (78%)	5.1 (6.3%)	0.0006 (0.001%)	18 (22%)	0.026 (0.001%)
K	tonne y^{-1}	359	41 (12%)	78 (22%)	0.0002 (0.001%)	262 (73%)	0.046 (0.01%)
S****	tonne y^{-1}	80	25 (24%)	18 (16%)	0.82 (0.76%)	71 (66%)	0.68 (0.63%)

* Digestate including recirculated sludge

** Recirculated back to AD

*** 13% of process water sent to RO for polymer preparation (RO not working over monitoring period); 28% recirculated to aerated step; 48% evaporated (cooling towers + Biofilter); 12% used for cleaning

**** 34.6 t S added via sulphuric acid in the air scrubber

4.3 Energy Balances

The core business of AD plants is the production of biogas and the subsequent revenues from the sale of renewable energy in the form of biogas, biomethane or electricity to the grid or another consumer. In addition, biogas and waste heat from the CHP are used on-site to cover the energy demand of the AD plant and NRR processes. Insight into the overall energy balance of the AD plant, including the on-site energy consumption, is therefore essential for the evaluation of environmental benefits and GHG emissions. In this chapter, energy balances of the SYSTEMIC's demonstration plants are being evaluated. Table 4.4 gives a details overview of energy balances at the demonstration plants.

Specific biogas production varied between 45 m^3 per tonne for Acqua&Sole and 237 m^3 per tonne for BENAS and can be related to differences in quality and dry matter content of the feedstocks. Feedstocks with a low dry matter content, including sewage sludge and animal manure, generate less biogas per m^3 of feedstock compared to feedstocks with a high dry matter content including energy crops or residues from agro-food industry. For example, at GZV, the ration of the digester consists for 77% v/v of pig slurry and 23% v/v of residues from agro-food industry; the latter residues explain about 75% of the biogas production. High biogas production rates at BENAS are due to the intake of energy crops. The methane content of the biogas produced at the various locations is rather similar and varies between 54 and 60%.

The demonstration plants have different energy valorisation strategies (Tbale 4.3). Am-Power, WNE and Acqua&Sole convert all biogas to electricity whereas BENAS and GZV only convert a part of the biogas into electricty. GZV sells the majority of its biogas to a nearby dairy factor where it is mixed with natural gas and used in burners. GNS converts part of its biogas into biomethane, which is fed into the national gas grid. The other part is converted into electricity and fed to national electricity grid. BENAS acts as a so-called 'grid stabilizer' meaning that they adjust the amount of electricity fed to grid to comply with the demand on the grid. In exchange, they receive a higher subsidy for the green energy produced.

Table 4.5 Biogas valorisation routes at SYSTEMIC's demonstration plants

Demoplant	Biogas valorisation route
Groot Zevert Vergisting	Biogas (≈58% CH_4) to consumer via a 5-km pipeline to a dairy factory
Am-Power	Electricity to the national grid
Acqua & Sole	Electricity to the national grid
BENAS	Biomethane for the national gas grid and electricity for the national grid (grid stabilisation; electricity production shuts down in case if there is no demand for electricity on the grid)
Waterleau New Energy	Electricity to the national grid

Figure 4.13 shows the biogas production (expressed in kWh/tonne feedstock) and the amount of energy ultilised outside the AD plant as electricity, biogas or biomethane. Differnces between energy production and energy utilisation elswehere are due to (i) losses in enery upon convertion biogas to electricity and (ii) consumption of energy on-site for running the AD plant and NRR installation.

GZV and BENAS, 70 and 71% of the caloric value of biogas is utilised outside the AD plant. This is because they valorise biogas and biomethane thereby avoiding losses of energy during conversion to electricity. Am-Power, Acqua&Sole and WNE convert biogas to electricity using combined heat and power (CHP) installations that typically have an efficiency of 40% for electrical energy and 40% for thermal energy. The remaining 20% is lost. As a result, 31-37% of the energy contained in biogas is utilised outside the AD plant for these demonstration plants. However, it is important to realise that these plants rely on the thermal energy generated by the CHPs to fullfill the heat demand of the AD plant (heating of digesters) and the NRR processes. It is therefore that AD plants with a large supply of thermal energy have invested in heat-consuming NRR processes including dryers, evaparotors and N-strippers.

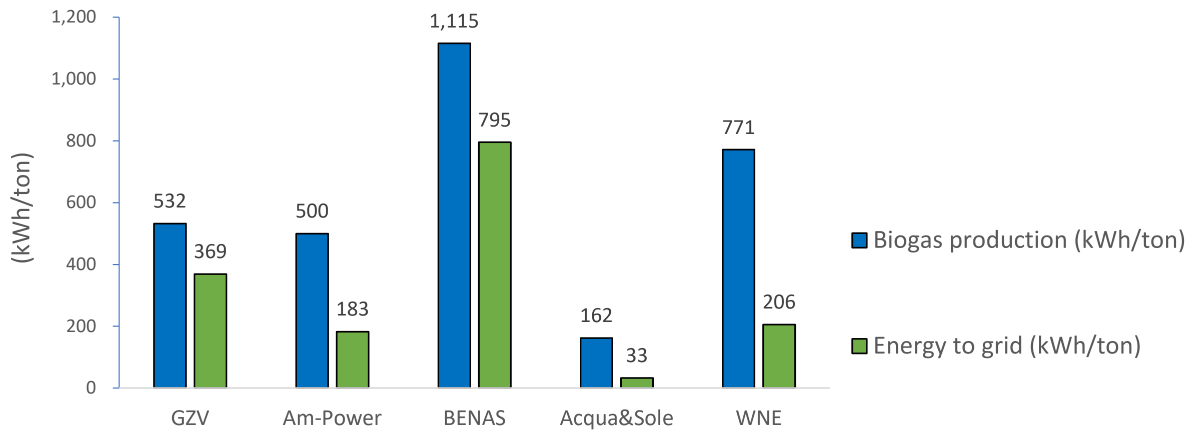

Figure 4.13 Energy production in the form of biogas (kWh/tonne feedstock) and amount of energy used outside the AD plant in the form of electricity, biogas or biomethane (kWh/tonne feedstock).

Table 4.6 Energy balances of the demonstration plants in 2020 taken from Brienza et al., (2022) (n.s. = not specified)

Parameter	Unit	GZV[1]	AmP[2]	BNS[3]	A&S	WNE
Year		2020	2020	2020	2019	2020
Feedstock	(ktonne)	93	152	86.6	74.0	71.0
Biogas production	(MNm^3/y)	9.7	15	20.5	3.3	10.3
Specific biogas production	(Nm^3/tonne)	104	99	237	45	150
Methane content	(%)	58	57	53	63	55
Methane production	(MNm^3/y)	5.6	8.6	10.9	2.1	6.2
Biogas production[6]	(GWh)	50	76	97	18	55
Biogas/Green Gas to Grid	(GWh)	33	0	42	0	0
Biogas conversion CHP	(GWh)	16	76	54	17	55
Electricity (CHP)	*(GWh)*	*5.6*	*32*	*28*	*7.0*	*21.3*
Thermal energy (CHP)	*(GWh)*	*5.6*	*32*	*25*	*7.0*	*22.8*
Losses (CHP)	*(GWh)*	*4.8*	*12*	*2*	*3.4*	*11*
Electricity to grid	(GWh)	1.8	27.8	27	5.5	14.6
Electricity consumption	(GWh)	3.8	4.2	1.3	1.6	6.7
Electricity - digester	*(GWh)*	*1.9*	*n.s.*	*1.1*	*1.3*	*n.s.*
Electricity - NRR	*(GWh)*	*1.9*	*n.s.*	*0.1*	*0.3*	*n.s.*
Thermal heat consumption	(GWh)	3.8	32	25	8.7	22.8
Thermal heat to digester	*(GWh)*	*1.9*	*9*	*1*	*n.s.*	*n.s.*
Thermal heat to NRR	*(GWh)*	*0.8*	*24*	*10*	*n.s.*	*n.s.*
Other (heating buildings, drying substrates)	*(GWh)*	*1.1*	*n.s.*	*14*	*n.s.*	*n.s.*
Biogas consumption[7]	(GWh)	0.3	-	-	1.7	-
Energy to grid (electricity + gas)	**(GWh)**	34.8	27.8	69	5.8	14.6

[1] In 2020, 80% of digestate was treated by the decanter, MF and RO. For the solid fraction, less than 5% was treated in the RePeat installation.

[2] For BENAS, reported heat consumption of the NRR is set equal to the consumption in 2019. In 2020, the N stripper was only temporarily in use due to maintenance issues.

[3] For Am-Power, heat consumption was not measured but estimated based on capacity of the machines. NRR system was not yet used at full capacity; about 25% of the liquid fraction of digestate treated in the evaporator in 2020.

[4] Acqua&Sole is burning biogas in a boiler to produce additional heat during cold periods. The amount of biogas send to the CHP and biogas boiler hence varies among the years and is not accurately reordered but estimated from the overall heat consumption by the installations.

[5] For WNE, the heat consumption was not measured but calculated from the capacity of the machines.

[6] Using the caloric value of methane (8.89 kWh/m^3)

[7] Biogas used on-site to overcome shortages of heat in f.e. cold periods when thermal heat from CHP is not sufficient.

Figure 4.13 depicts the on-site consumption of electrical en thermal energy. This includes energy consumed at the AD plant as well as the NRR installation. Processes with a high demand for electricity are mixers (mixing of digestate in the digester), decanter centrifuges, aerators, micro-filtration and reverse osmosis. Thermal energy, on the hand, is consumed by dryers, evaporators and N-strippers.

Differences in choices for NRR technologies are reflected in electrical and thermal energy consumption. Electrical energy consumption is highest for WNE and GZV both operating installations with a high electrical power (WNE: aerators, reverse osmosis, evaporation GZV: micro-filtration and reverse osmosis). Consumption of thermal energy is lowest at GZV and is solely used for heating of digesters, hygienisation of digestate and heating of buildings. This is a deliberate choice because they have little thermal energy available. Other plants have more thermal energy available which is subsequently used in N-strippers, dryers and evaporators.

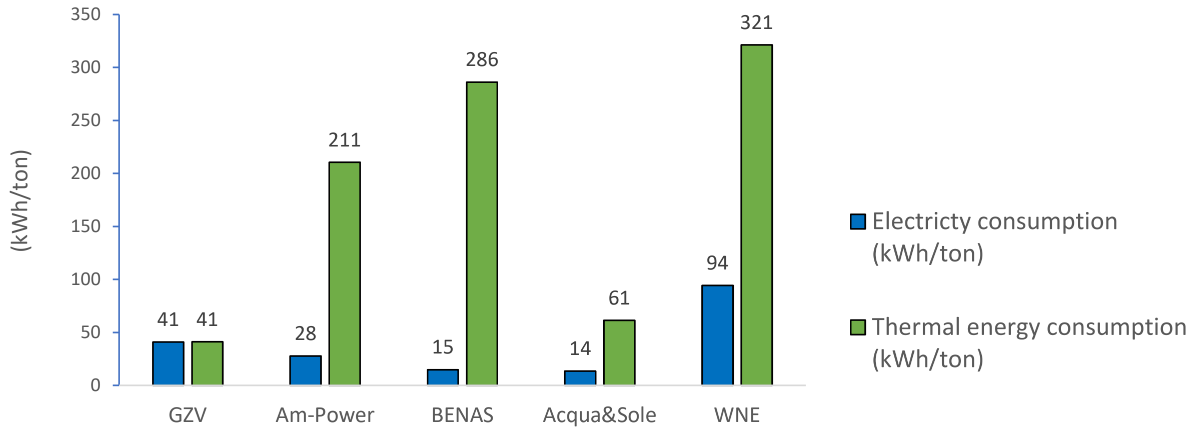

Figure 4.14 Consumption of electrical (kWh_{el}/tonne feedstock) and thermal energy (heat, kWh_{th}/tonne feedstock) used on-site on the AD plant and NRR installations.

5 Product evaluation and environmental impact

5.1 Approach

This chapter is drafted based on the average product composition taken from Sigurnjak et al. (2022), data from field trials, pot experiments and lab tests as reported by Sigurnjak et al., (2022) and results from the environmental impact assessment (EIA). The EIA involved a scenario analysis. For each demonstration plant, scenarios were defined representing different soil/crop combinations relevant for the region of application as well as different combinations of BBFs and mineral fertilising products. If applicable, national or regional application standards for N (effective N), animal manure (total N) or P were respected within the scenarios; effective N application rates of BBFs were calculated by applying the NFRVs as laid down in national regulations. A modelling approach based on MITERRA-EUROPE was used to calculate the following effects on a time scale of 100 years:

- Nitrogen surplus and nitrate leaching
- P surplus and leaching
- Atmospheric N emissions (N_2O, NH_3)
- Accumulation and leaching of heavy metals (here discussed in paragraph 5.3)
- Trends in soil organic carbon (SOC)

Full results of the EIA are reported elsewhere (Schoumans et al., 2022). Here, results are summarized and discussed in relation to other analyses done within the project.

5.2 Agronomic quality of end products

5.2.1 Liquid organo-mineral fertilisers

Liquid organo-mineral fertilisers include digestate after stripping, RO concentrate and evaporator concentrate.

GZV produces an RO concentrate from digestate that is practically free of P and has a N-NH_4/N ratio of >90% in line with criteria for RENURE products. Pending the final implementation of RENURE criteria, GZV has been granted a temporarily exemption to use RO concentrate as a synthetic N fertiliser on top of the limit of 170 kg N/ha for animal manure. Its high pH value, however, makes the product prone to ammonia emissions during storage and field application. Reducing ammonia emissions has a high priority in the Netherlands. Based on earlier lab- and field trials, ammonia emissions associated with application of RO concentrate are 50% lower compared to raw manure because RO concentrate has a lower viscosity therefore easily penetrates into the soil but its emission factor is higher as compared to synthetic CAN (calcium-ammonium-nitrate) (Velthof & Hummelink, 2011; Huijsmans & Hol, 2011).

The product is primarily a nitrogen fertiliser (8.1 g/kg) but also contains potassium (7.8 g/kg). Though RO concentrates generally have a high sulphur content due to addition of sulphuric acid (Regelink et al., 2021), GZV has managed to reduce sulphuric acid consumption due to a novel configuration of the double RO (Brienza et al., 2022, Regelink et al, 2021). The N/S ratio is in line with crop demand and S application rates are similar to crop demand when using RO concentrate as an alternative for CAN on top of the application of digestate or manure (Schoumans et al., 2022). GZV is selling RO concentrate after blending with urea and ammonium sulphate to a TMF in which N/S/K ratio’s match crop demand. Recent field trials on maize- and grassland – performed as part of the four-year project 'biobased fertilisers Achterhoek' – confirmed that the NFRV of this blended product is similar to synthetic N fertiliser (CAN) provided that the product is injected (Ehlert, 2020).

A by-product of GZVs installation is concentrate of the micro-filtration unit, containing a mixture of N,P and K in which 59% of N is present in mineral form. The product therefore does not comply with RENURE criteria and shall be used under the limit of 170 kg N/ha for animal manure. Levels of ammonia emissions and nitrate leaching are expected to be similar as raw manure or pig slurry. The legal NFRV is 80% (similar as for LF of manure) though this may not be reached in practice as the NH_4/TN ratio is low (59%) as compared to typical values for LF of manure (>80%).

Am-Power's evaporator concentrate is being acidified prior the evaporator in order to retain ammonia within the concentrate resulting in a high N-NH_4/N ratio of 78%. An additional benefit is that the pH of the concentrate is near-neutral (pH 6.2) which is expected to reduce risks for ammonia emissions during storage and field application compared to non-acidified digestate-derived products or raw manure which typically have pH values of 7.0 or higher. A drawback of dosing sulphuric acid is that it leads to enrichment of concentrate with S. Applying maximum allowable dosages of concentrate would lead to sulphur dosages up till 300 kg S/ha which is far above crop uptake (Table 5.4) (Schoumans et al., 2022).
Evaporator concentrate is produced from non-manure feedstocks and can hence be applied until either the P or N application rate limit is met. When the product is applied in Flanders, a farmer could apply xx ton of concentrate (33 kg P/ha and xx kg TN/ha) because the limit for N from animal manure does not apply. In the EIA, nitrate leaching is a function of the N surplus which is in turn a function of the TN application rate. The legal NFRV of evaporator concentrate is 60% meaning that replacing mineral N fertiliser by evaporator concentrate leads to an increase in nitrate leaching in the modelling study (Schoumans et al., 2022). However, since the TAN/TN ratio is 78%, a higher NFRV is justified which would reduce the N surplus and nitrate leaching.

Despite the fact that this is a non-manure product, Am-Powers is experiencing difficulties in disposing the product to arable farmers because (i) they are not convinced that the product is a suitable alternative for synthetic N even though the product can be applied on top of animal manure and (ii) because the concentrate contains 1.0 g P/kg and therefore competes with the use of animal manure as both are restricted by the P application rate limits. As an alternative, Am-Power therefore aims to develop a market for evaporator concentrate in France.

Waterleau NewEnergy evaporator concentrate is produced without adding acid and hence a larger part of the NH_4 is being vaporized which results in a lower TAN/TN ratio (46%) as compared to the concentrate produced by Am-Power. A low TAN/TN ratio increases risks for nitrate leaching if mineralisation of Norg occurs outside the growing season. The scenario modelling however, does not predict an increase in nitrate leaching because of the assumption that the NFRV of evaporator concentrate is similar to that of digestate/manure amounting to 60% when applied in Flanders. It is however questionable whether this NFRV is realised in practice as the TAN/TN ratio is low as compared to untreated digestate. The sulphur content is nevertheless high due to addition of ammonium-sulphate of the air washer. As a consequence, the S/N ratio of evaporator concentrate is similar to that of ammonium sulphate meaning that S will be given in excess of plant demand when the product dosage is based on the N application rate (Schoumans et al., 2022). The product is not used in Flanders but sold to a composting company where it is blended with compost and sold to France and any risks for overfertilization with S are therefore minimized.

Acqua&Sole is stripping NH_4 from digestate which results in an digestate with a TAN/N ratio of 53%. Stripping ammonium from digestate would lower risks of for ammonia emissions assuming an equal dosage in terms of total N. Nevertheless, injection of digestate is required to reduce emissions as the digestate has a high pH at which ammonia easily volatilizes. In field trials performed for this project, ammonia emissions amounted to 10% of applied TAN (total ammonical nitrogen) after injection of digestate at a depth of 15 cm and crop yield was similar to plots fertilised with urea (Zilio et al., 2021). Hence, ammonia emissions are higher as compared to CAN (2.5% of TN) but similar to urea (14% of TN). In the scenario analyses of Schoumans et al., (2022), an emission factor of 2% of TAN was used based on standard EFs just in the Netherlands for injection of digestate/manure on arable land which in hence an underestimation of the actual emissions based on field measurements.

Acqua&Sole's philosophy is to increase SOC in soil by applying digestate with a reduced N content. As digestate application rate limits are only limited by its effective N content (50% of TN) up to 45 ton of digestate per hectare can be applied corresponding to 2800 kg OM. Over a period of 100 years, this practice indeed contributes to increasing SOC contents in soil. However, the corresponding P application rate (153 kg P/ha) exceeds P crop uptake by a factor five leading to accumulation of P in soil and, on the longer term, to leaching of phosphate to ground- and surface water (Schoumans et al., 2022). This is under the assumption that P contained in digestate is similar in terms of availability as compared to mineral P fertiliser. For digestate of Acqua&Sole, this assumption seems justified as the molar P/Fe ratio amounts to 0.3 indicating that at maximum 15% of P is bound to Fe-oxides under the assumption that one mol of Fe can absorb 0.5 mol of P (Regelink et al., 2022). Phosphorus chemistry in soils is highly complex and the applied model was developed for Dutch soils without being verified on Italian soils which typically contain more calcium carbonate. Applying the maximum allowable application rates of digestate will lead to accumulation of P in soil, but it is uncertain at which time scale and to what extent this translates into leaching of P from the soil to ground water.

In the EIA (Schoumans et al, 2022), nitrate leaching was predicted under the assumption that 45 ton of digestate is applied corresponding to 360 kg TN/ha and assuming that the legal NFRV of 50% is valid for this product. Under this assumption, organic N in soil is expected to increase over time leading, on the longer term, to increased levels of nitrate in leachate exceeding the limit of 50 mg NO_3/L due to uncontrolled mineralisation of organic N. However, the model used an NFRV of 50% (legal value) whereas a higher NFRV of 70-80% is justified based on field trials (Zillio et al., 2022). Risks of nitrate leaching can be effectively reduced by assigning a higher NFRV to digestate corresponding to its actual performance under field conditions which also means lowering digestate application rates. In field trials, nitrate residue after the growing season was found to be similar in plots fertilised with digestate as compared to urea. Similar as for P, this discrepancy may be either due to simplification of the model (f.e. possible underestimation of dentification rates) and/or due to differences of time scales as the model assumes equilibrium for nitrate mineralisation which may not (yet) be reached in practice.

Increasing the NFRV and/or implementing P application rate limits would effectively avoid build up of P and organic-N in soil but means that far less digestate can be applied. As a consequence, OM application rates would decrease from 2800 (no restrictions to P application rates) to 800 kg OM/ha at P equilibrium fertilisation. Hence, a sustainable balance must be found between the goal to add more OM to soils from digestate and possible future drawbacks due to accumulation of P and organic N in the soil.

Table 5.1 Composition of the organo-mineral fertilisers produced by the demonstration plants (data: Signurjak et al., 2022)

(Organo-) Mineral nitrogen		***GZV***	***GZV***	***AmPower***	***WNE***	***BENAS***	***A&S***
		RO concentrate	*MF concentrate*	*Evaporator concentrate*	*Evaporator concentrate*	*Digestate (after N stripping)*	*Digestate (after N stripping)*
pH	(-)	8.4	8.4	6.2	7.7	8.3	8.6
Dry matter	(g/kg)	37	49	115	190	106	107
Organic matter	(g/kg FM)	14	35	63	92	63	73
N-total	(g/kg FM)	8.1	7.1	9.0	11	8.0	7.2
NH_4-N	(g/kg FM)	8.0	4.2	7.0	5.1	3.7	3.8
P-total	(g/kg FM)	0.15	0.4	1.0	2.1	3.4	1.4
K-total	(g/kg FM)	7.9	4.1	9.7	22	0.59	6.1
S-total	(g/kg FM)	1.5	0.6	12	12	1.1	1.1
N-NH_4/N	(%)	99%	59%	78%	46%	46%	53%
N/P	(kg/kg)	54	17	9.0	5.2	2.4	5.1
S/N	(kg/kg)	0.2	0.08	1.3	1.1	0.3	0.8
Legal NFRV[1]		100%	80%	60%	60%	60%	50%

[1] Nitrogen Fertiliser Replacement Value to be used to calculate effective N (for the N application rate limit) based on national or regional legislation (taken over from Schoumans et al., 2022).

5.2.2 Ammonium sulphate & precipitated P salts

Ammonium sulphate produced by BENAS and Acqua&Sole contains 75 and 46 g N/kg, respectively, which is present in the form of NH_4SO_4 and hence a suitable alternative for synthetic nitrogen fertilisers. Ammonium sulphate of BENAS has an alkaline pH due to the of gypsum rather than sulphuric acid and this increases the risks for ammonia emissions during storage or application compared to the slightly acidic ammonium sulphate produced by Acqua&Sole. Modelling predicts that ammonia emissions and nitrate leaching remain similar as compared to scenario's in which CAN is used (Schoumans et al., 2022).

Ammonium sulphate has, by definition, a high sulphur content leading to sulphur application rates of 150-300 kg S/ha when the products are being used to replace mineral N fertilizers (Schoumans et al., 2022) thereby exceeding average sulphur uptake rates of gras and arable crops that typically vary between 12 and 50 kg S/ha (Table 5.3). The surplus of sulphur will leach to groundwater as sulphate – which is highly mobile in soil – and will contribute to eutrophication via a process called 'secondary eutrophication'. Additionally, leaching of sulphate coincides with leaching of other cations (K, Ca, Mg) which results in acidification of the top soil. Ammonium sulphate is therefore advised to be used for arable crops with a higher sulphur demand such as cauli flower, rapeseed and cabbage and farmers are advised to use ammonium sulphate to replace part but not all of the mineral nitrogen fertiliser (SYSTEMIC farmers factsheet, Appendix A).

Precipitated P salt produced by GZV has a low DM content of 17% due to poor dewaterability of the sludge. The sludge is a mixture of organic matter, phosphate salts (calcium phosphate and struvite) and gypsum. Also, the N content is rather high as a result of the high OM content as well as due to presence of NH_4 in struvite ($NH_4MgPO_4 \cdot 6H_2O$). Its high OM content hampers uptake in industry as a raw material for mineral fertilisers as was initially foreseen. A high OM content is no limitation for use as feedstock in production of organic fertilisers which would however require delivery of a solid material rather than a sludge. GZV is still working on increasing the DM content of the sludge to enable uptake by the organic fertiliser industry. Blending of the P salts with other fertilisers is required as the current product would not meet crop demands mainly because the sulphur content (S/P ratio) is too high.

Table 5.2 Composition of ammonium sulphate and precipitated P salts produced by the demonstration plants (data; Signurjak et al., 2022)

Mineral fertilising products		***GZV***	***BENAS***	***A&S***
		Precipitated P salts	*Ammonium Sulphate*	*Ammonium sulphate*
pH	(-)	7.3	7.8	5.9
Dry matter	(g/kg FM)	171	360	233
Organic matter	(g/kg FM)	70	n.m.	n.m.
Total organic carbon	(g/kg FM)	n.m.	<1	0.35
N-total	(g/kg FM)	8.4	75	46
NH_4-N	(g/kg FM)	5.2	71	45
P-total	(g/kg FM)	9.3	<0.02	<0.01
K-total	(g/kg FM)	2.6	<0.02	<0.01
S-total	(g/kg FM)	15	85	54
N-NH_4/N	(%)	60%	95%	98%
N/P	(kg/kg)	0.9	-	-
S/N	(kg/kg)	1.8	1.1	1.2

Table 5.3 Sulphur demand of grass and arable crops

Crop	**Kg S/ha**
Maize	12
Cereals	20
Leek	24
Grass	20-40
Cauliflower	50
rapeseed	20-40
sprout	50-80

[a] Sulphur fertilisation advice is crop demand minus sulphur available in the soil. SO_3 = 2.5*S

5.2.3 Solid organic fertilisers and soil improvers

Solid organic fertilisers or soil improvers are being produced by GZV, Am-Power, WNE and BENAS. There is a wide variation in nutrient composition and nutrient ratio's between the SFs due to differences in composition of digestate but, most notably, due to differences in digestate processing. Products are here evaluated based on their nutrient contents and ratios (Sigurnjak et al., 2022), humification- and N-mineralisation coefficients (Egene et al., 2021) and fractions of easily available P (Regelink et al., 2021).

Am-Power & WNE both produce a **dried SF** with a DM content of >80% and a P-content of 19 and 25 g/kg, respectively. Dried SF is primarily a P fertiliser because of its high P/OM ratio. When applying 30 kg P/ha (P equilibrium fertilisation), the OM dosage amounts of 800 kg OM per hectare which is similar to scenario's in which raw digestate is applied (Schoumans et al., 2022). In practice, higher dosages may be given as the product is applied in France were its application rate is not restricted by a P application rate limit. Ammonia emissions upon field application are not of environmental concern as ammonia has been removed during drying. Nitrogen is dominantly present in organic form (Norg) and though Norg is generally related to nitrate leaching, this is not the case for these products because TN dosages are low when equilibrium fertilisation for P is respected. As a consequence, additional mineral N fertiliser is needed to meet crop demand (Schoumans et al., 2022). WNE is blending dried SF with concentrate to increase its N,K and S content relative to P to better meet crop demand.

Though the dried SFs are primarily P fertilisers, it has to be noted that the fraction of easily extractable P fraction[8] was low indicating that part of the P is retained in P-Fe precipitates or other poorly soluble crystals (Regelink et al., 2021). Though Am-Power nowadays avoids the use of Fe-salts, the dried SF still contains considerable amount of Fe (26 g/kg FW) presumably due to the intake of iron-rich flotation sludges from industrial waste water treatment plants. For WNE, the high Fe content in the dried solid fraction is due the use of iron sludge to control H_2S concentrations in the digester and the intake of Fe-rich flotation sludges. Overall, low fractions of available P mean that the farmer shall use these products as slow release fertilising products. It is also lowers the risks for P leaching which may be reason to accept higher P application rates similar as the exemption made for composted biowaste in Flanders and The Netherlands[9]. Respecting P equilibrium fertilisation would mean that the product dosages are at maximum 2 ton of product per hectare and it is practically impossible to spread such a low amount of a solid product uniformly on soil. This could be circumvented by applying a larger amount once every two or three years. In practice, dried SFs are exported to France were application rates are not limited in terms of P and likely higher dosages are applied.

GZV produces a **SF of digestate** with a high P content and a low OM/P and N/P ratio. Hence this product is primarily a P fertiliser. The agronomic efficiency of the SF as a P fertiliser is evident from the high fraction of easily soluble P (87% of P-total) that is extractable under mildly acidic conditions, and this is due to the choice of GZV to avoid use of iron salts in their process. The product has not been dried and contains N as ammonium (6.6 g NH_4/kg). The SF shall therefore be incorporated into soil after field application to lower volatilization of ammonium. Surface spreading alone would lead to high ammonia emissions.

The **low-P soil improver of** GZV has a nine-times lower P content compared to the SF of digestate that has not been treated in the RePeat installation. The product is primarily a soil improver enabling a dosage of nearly 30 tonne product per ha (6000 kg OM/ha) within the P application rate limit of 30 kg P/ha. In practice, a farmer would apply about 10 tonne product (2000 kg OM/ha) in addition to manure or digestate. Contents of N and N-NH_4 are low as well because these nutrients have been removed during flushing of the SF within the RePeat process. This is profitably because N in the low-P soil improver counts for the application rate limit for animal manure (170 kg N/ha). Moreover, the low N and consequently high C/N ratio of the soil improver induces N immobilisation upon application to soil as is evident from two incubation tests (Egene et al., 2021; Regelink et al., 2019). This may offer opportunities to temporarily lower nitrate concentrations in soil porewater if applied shortly after the growing season in order to reduce nitrate leaching to groundwater. The S content is however elevated to 5.8 g/kg due to the addition of sulphuric acid which adds sulphur in the form of sulphate (SO_4). Moreover, the S/P ratio has increased to 5.3 kg/kg pointing to an surplus of S compared to P. Though there are no application rate limits for S, excessive application of S as sulphate must be avoided to prevent leaching of sulphate to groundwater. It is hence advised to lower the S content of the low-P soil improver and/or adjust the application rate to lower the S application rate.

Solid fractions of **BENAS** are characterised by low nutrient contents which is because energy crops are its major feedstocks and because ammonia is removed from the digestate prior to solid/liquid separation. The high OM content in combination with low N,P and S contents make both SFs suitable for use as an organic soil improver which however have a low market value. BENAS therefore developed a new market for the low-N fibres which are now being further processed into carton used for the production of pots and mulch mats (see paragraph 5.4.3).

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[8] Extracted in 10 mM $CaCl_2$ at a fixed total P/L ratio of 150 mg P/L and after adjusting the pH to 5.5 (Regelink et al., 2021)

[9] In the Netherlands and Flanders, 50% of P in compost is free of the P application rate limit.

Three products with contrasting properties were tested in incubation tests to assess the humification coefficient and N-mineralisation rate (Egene et al., 2021). The humification coefficient, *i.e*. the % of TOC remaining in soil one year after addition of the organic fertiliser, was nearly similar for the three products, varying between 70 and 75% (Table 5.2), which is in between the humification coefficient for non-digestated SF of manure (51%) and composted biowaste (93%, Egene et al., 2021). The higher humification coefficient compared to SF of raw manure can be explained by the fact that part of the easily degradable organic matter has been degraded during anaerobic digestion. However, its suitability as a soil improver depends mostly on its nutrient contents. with products with OM/P and OM/N ratios can be used as soil improvers without inducing risks for enhanced accumulation of P or leaching of nitrate to ground- and surface water.

N-mineralisation rates, on the other hand, differed among the products as did the initial NH_4/TN ratios of the SFs. Differences in the NH_4/TN ratio can be explained by differences in processing leading to lower NH_4/TN ratio in SFs after leaching or drying. The fraction of N-organic (TN – N-NH_4) that is being mineralised amounted to 83% and 27%, respectively, for the SF of GZV and dried SF of Am-Power. In the low-P soil improver however, a negative N mineralisation coefficient was reported implying N immobilisation during the three-months incubation period. Nitrogen immobilisation is a known phenomenon that typically occurs in organic fertilisers in which the ratio between organic carbon and organic N is above 25.

Overall, there are large differences between solid organic fertilising products in terms of nutrient ratios and availability of P and N pointing to the need for product-specific advice to farmers on the use of these products.

Table 5.4 Composition and nutrient ratios of the organic fertilisers and soil improvers produced by SYSTEMICs demonstration plants[a]

		GZV	***GZV***	***AmP***	***WNE***	***BNS***	***BNS***
Solid organic fertilisers		*SF of digestate*	*Low-P soil improver*	*Dried SF of digestate*	*Dried SF of digestate*	*SF of digestate*	*Low-N organic fibres*
Dry matter	(g/kg FM)	313	237	823	904	234	234
Organic matter	(g/kg FM)	241	212	511	637	203	203
N-total	(g/kg FM)	11.6	5.3	23	30	7.3	4.6
N-NH_4	(g/kg FM)	6.6	2.0	0.9	2.6	3.0	<0.1
P-total	(g/kg FM)	8.9	1.1	19	25	2.2	2.3
K-total	(g/kg FM)	4.6	1.1	13	15	5.6	5.7
S-total	(g/kg FM)	1.8	5.8	11	11	1.3	1.2
Nutrient ratios							
OM/P		27	193	27	25	92	88
OM/N		21	40	22	21	28	44
N-NH_4/N		54	38	3.9	8.7	41	<1
N/P		1.3	4.8	1.2	1.2	3.3	2.0
S/P		0.2	5.3	0.6	0.4	0.6	0.5
Easily available P [b]	(% of P)	87	40	21	37	45	26
Humification coefficient [c]	(% of TOC)	70	73	75	n.d.	n.d.	n.d.
N-mineralisation rate [d]	(% of N_{org})	81	-7	27	n.d.	n.d.	n.d.
Nutrient dosages as an application rate of 30 kg P/ha (P equilibrium fertilisation)							
Organic matter		785	5782	807	764	2768	2648
P		29	30	30	30	30	30
N		38	145	36	36	100	60
S		6	158	17	13	18	16

[a] FM: Fresh matter, OM; organic matter, n.d.: not determined

[b] Easily available P was determined by extraction of P-PO_4 in 0.01 M $CaCl_2$ after adjustment of pH to 5.5, and is expressed as % of total P content of the organic fertiliser (Regelink et al., 2022, Sigurnjak et al., 2022).

[c] Humification coefficient is defined as the % of TOC remaining one year after application of the organic fertiliser to soil. Data taken from Egene et al, 2021

[d] N-mineralisation rate is defined as N released as N-(NH_3+NO_3) during an 112-days incubation trial and is expressed as % of organic N content of the fertiliser. Organic N is defined as N-total minus N-NH_4. Negative value means N-immobilisation

5.2.4 Organic fibres

GZV and BENAS produce fibrous products that can either be used as soil improver (nutrient contents, Table 5.4) or as alternative for peat or wood fibres, thereby generating more value per tonne of product compared to disposal as soil improver in agriculture. The organic fibres are low in P and N thanks to stripping of P by means of sulphuric acid (GZV) and stripping of N (BENAS) and are free of odour.

Both products have been tested successfully in a pot experiment as replacement for fossil peat in potting soil. The pot experiment showed that both products could replace a substantial part of peat in potting soil while maintaining a high water holding capacity and without inducing negative effects on plant growth or nutrient uptake. A point of improvement is however the salt content (EC value) which exceeds the criteria for potting soil for the product of GZV. BENAS decided to invest in machinery to upgrade fibres to cardboard and carton for other criteria, in particular length of fibres and low ammonia contents, are of importance as explained elsewhere (Hermann et al., 2022b)

Table 5.5 Characteristics of organic fibres from demonstration plants GZV and BENAS compared to characteristics of conventional potting soil based on peat.

		GZV	***BNS***	***Peat-based potting soil***
		Low-P soil improver	*Low-N organic fibres*	
pH	(-)	5.4	8.1	5.7
EC	(mS/cm)	5.4	1.1	0.6
Bulk density	(g/l)	99	91	95
Total pore volume	(% v/v)	94	94	95
Water holding capacity at pF 3 (saturation)	(% v/v)	71	65	68
Oxygen uptake rate	(mmol O_2/kg/h)	9.6	8.1	2.3

Figure 5.1 Organic fibres produced by BENAS (Germany) which are used for the production of biodegradable paper, mulch mats (for weed control in vineyards) and pots which are marketed under the name of Magaverde. Magaverde products are certified for use in organic agriculture.

5.2.5 Condensed ammonia water

Waterleau NewEnergy produces condensed ammonia water with nearly 10% N and a pH of 11 through a process of ammonia stripping followed by condensation. The product is, technically speaking, condensed water and its composition is not similar to synthetic ammonia water. Synthetic ammonia consist of ammonium-hydroxide (NH_4OH) whereas condensed water is a mixture of ammonium-hydroxide and ammonium-carbonate ($(NH_4)_2CO_3$) due to the concomitant stripping and condensation of carbon-dioxide from the digestate. Condensed ammonia water is unsuitable as an nitrogen fertiliser because it is prone to emitting gaseous ammonia due to the high pH and high carbonate content (not measured). Waterleau New Energy sells condensed ammonia water to a nearby company were it is used as a reductant in a DeNOx installations thereby replacing synthetic ammonia water. Their business case therefore depends on local buyers purchasing condensed ammonia water because long-distance transport of the product would be too expensive because the N content of condensed ammonia water is low compared to similar synthetic products. In general, condensed ammonia water is not perceived as a good N fertiliser since it has high pH and hence N can volatilise easily. This was also confirmed in a one-year field trial with maize where products of WNE were tested compared to the use of CAN (Sigurnjak et al. 2022).

Table 5.6 Composition of condensed ammonia water produced by SYSTEMICs demonstration plants

Non-fertilising products		**WNE**
		Condensed ammonia water
Dry matter	(g/kg FM)	n.m.
Organic matter	(g/kg FM)	n.m
N-total	(g/kg FM)	93
NH_4-N	(g/kg FM)	87
P-total	(g/kg FM)	<0.01
K-total	(g/kg FM)	<0.01
S-total	(g/kg FM)	0.5
pH		11

5.2.6 Purified water

GZV produces purified water by treating the RO permeate by an ion exchanger. This purified water is discharged to the surface water. Purified water leaves the plant with an ammonia concentration of 0.2 ± 0.06 mg L^{-1} and meets discharge limits as are set by the local waterboard. WNE treats process water from the condensator (i.e. condensed water after evaporation of the liquid fraction of digestate) with an double pass RO system producing purified water that meets Flemish discharge limits for COD (125 mg/l), TSS (35 mg/l), TN (15 mg/l) and TP (2 mg/l). The full composition of the purified waters is given in Deliverable D1.13 (Sigurnjak et al., 2022).

In the Netherlands, the rise of manure treatment plants has raised concerns about the presence of organic micro-pollutants, in particular residues of veterinary pharmaceuticals, in purified water from digestate- and manure treatment plants. In this project, no residues of veterinary pharmaceuticals, herbicides or pesticides were detected above the detection limit of 0.5 µg/l in purified water of GZV and WNE, even though residues were detected in the digestate or concentrates. Hence, these analyses confirm other monitoring studies (Hoeksma et al., 2021) showing that RO membranes effectively retain organic micro-pollutants within the concentrate and that purified water can be safely discharged onto surface water.

Am-Power treats the acidified LF of digestate by means of evaporation producing condensed water which does not meet criteria for discharge onto surface water due to its high ammonia concentration (28 mg $N\text{-}NH_4$/l). In the near future, the installation will be extended with an RO installation to purify the condensed water. Considering the high removal efficiencies of RO installations at GZV and WNE, it is foreseen that Am-Power will be able to upgrade its permeate water to purified water meeting limits for discharge onto surface waters by investing in an RO installation.

5.3 Contaminants & risk assessment

Heavy metal contents in digestate and end-products are published in D1.13 (Sigurnjak et al., 2022) and further used to calculate heavy metal loadings on agricultural soils for various fertiliser scenario's in D1.15 (Schoumans et al., 2022). Additionally, Sigurnjak et al. (2022) includes results on a monitoring on residues of herbicides, pesticides and pharmaceutically-active compounds.

Separation of nutrients in NRR installations also leads to separation of heavy metals. Heavy metals are generally associated with humic-like compounds present in the OM fraction and upon separation, heavy metals tend to follow the OM. As a result, heavy metals are absent or low in mineral fertilisers recovered from digestate including ammonium sulphate and RO concentrate. Whereas contents of heavy metals in solid fractions and organo-mineral fertilisers (evaporator concentrate) are similar to levels measured in the raw digestate when expressed on dry weight.

Contents of copper and zinc are relatively high in digestate of GZV, where copper and zinc originate from animal manure, and in digestate of Acqua&Sole were it founds is origin from sewage sludge. On sandy soils, leaching of copper is expected to increase upon long-term application of digestate-derived products from GZV, Acqua&Sole and BENAS. For the other considered nutrients, including chromium, nickel, lead and arsenic, application rates are generally low and model calculations show that application of digestate-derived products has no or minor consequences on leaching of these heavy metals from soil.

Digestate from Acqua&Sole contains higher levels of heavy metals as compared to the other demonstration plants but complies with criteria for heavy metals in sewage sludge as well as with criteria for organic fertilising products under the FPR. When applying the maximum allowable dosage of digestate (45 ton/ha) accumulation of zinc and copper will occur. Though zinc and copper are micro-nutrients, dosages far beyond crop uptake rate shall be prevented. Applying 45 ton of digestate per ha will, on the longer term, lead to concentrations of Zn and Cu in percolate exceeding the PNECs (point of no effect concentrations) for surface water which amount to 34 and 14.3 ug/l, respectively (EC 2008a,b). For the other heavy metals considered in the EIA (Ni, Cd, Cr, Pb), dosages are not of environmental concern (Schoumans et al., 2022).

Generally, lowering nutrient contents of organic fertilisers (f.e. after stripping N from digestate) with the goal to increase the application rate of the digestate-derived fertiliser slightly increases heavy metal loadings per ha of soil. However, since heavy metal contents are low in the feedstocks of systemic demonstration plants, risks of heavy metal accumulation are not of environmental concern with the exception of digestate of Acqua&Sole.

A screening on organic micro-pollutants in digestate and end-products revealed that residues were present though the variety of compounds detected varied among the demonstration plants (Sigurnjak et al., 2022). Detected compounds were residues from herbicides, pesticides and pharmaceutically active compounds. Detected residues from herbicides and pesticides originate from products that are allowed within the EU. Remarkably, no residues of pharmaceutically active compounds were detected in digestate from Acqua&Sole which could point to degradation of these compounds during thermophilic digestion, which confirmed previous analyses on o.a. residues of antibiotics on this digestate (Pigoli et al., 2021). Purified water (GZV, Waterleau) and ammonium sulphate (Acqua&Sole, BENAS) were free of organic residues. Hence, discharge of purified water from digestate does not pose any risks on spreading of organic micro-pollutants.

5.4 Compliance with Fertiliser Product Regulation

The five demonstration plants operate under different regulatory requirements. Compliance of end products with criteria of the European Fertiliser Product Regulation (FPR) for free trade of fertilising products as well as compliance with national regulations is discussed in detail in D1.13 (Sigurnjak et al., 2022). The European FPR has been developed in order to facilitate trade of organic fertilising products among EU countries replacing the otherwise bilateral agreements between member states. The FPR lays out seven PFCs which may only be produced from designated CMCs. However, the new FPR does not have any benefits for the five demonstration plants so far because only Am-Powers digestate would fit within the description of CMC 5 (other digestate). The other demonstration plants either have animal manure (WNE, GZV, BENAS) or sewage sludge (Acqua&Sole, WNE) in the ration of their digester which still automatically excludes them from trading their end products as EC fertilising products. For BENAS, it would be possible to avoid using animal manure but for the GZV and WNE, intake of manure is part of their business case. However, a separate CMC for animal by-products (CMC 10) is foreseen which may, depending on its criteria, offer new possibilities. For those plants treating sewage sludge however, it is still decided that digestate will not be accepted as feedstock for EC fertilising products.

Am-Power has a separate digester and treatment line for animal manure meaning that there main digester is solely fed with biowaste and could potentially comply with criteria of CMC 5. Secondly, the end products must comply with one of the PFCs. Am-Powers dried SFs complies with criteria for solid organic fertilisers (PFC 1) as does the dried SF of WNE. Solid fractions of GZV and BENAS, which have a DM contents of ≈30% DM, do not comply because of too low nutrient contents. Similar, organic liquid fertilising products of GZV and Am-Power do not meet criteria for the minimum nutrient content for liquid organic fertilisers (PFC 1A) implying that these products could not be traded as EC fertiliser product unless blended with other more concentrated organic or synthetic fertilisers. Ammonium sulphate, on the other hand, does comply with criteria for inorganic fertilisers under the FPR and could be traded as EC fertilising product once criteria for scrubbing salts are set under CMC 11 (industrial by-products) which is still pending.

Overall, SYSTEMICs demonstration plants continue to rely on bilateral agreements with accepting nations for disposal of their organic fertilising products from digestate.

6 Evaluation of demonstration plants

6.1 GZV

General
GZV successfully implemented NRR installations which allows them to separate digestate into different biobased fertilising products including RO concentrate that is used as a RENURE fertiliser on fields in the nearby region. Construction and commissioning of the novel installations took more time than expected and further optimisation is still needed to improve the overall mass balances of the NRR installations and reach the set goals.

Energy balance
- Biogas production per tonne of feedstock amounts to 104 m^3 (55% methane) of which 77% originated from co-products and 23% from animal manure.
- About 70% of biogas is sold to a nearby dairy factor; direct use of biogas is the most efficient way of utilising energy contained in biogas, avoiding losses that would occur during conversions of biogas to electricity.
- About 30% of biogas is converted into electricity and thermal energy by a CHP. This is sufficient to cover the overall electricity- and heat demand on-site, leaving 1,800 MWh of electricity that is fed to the national grid. Thermal heat consumption is low compared to other demonstration plants (no drying or heating involved).

Mass balance and consumption of additives
- One tonne of digestate is separated into 0.15 tonne SF, 0.25 tonne RO concentrate, 0.15 tonne purified water and 0.45 tonne sludge of the microfiltration unit (February - June 2021).
- Water production was lower as envisaged and the volume of sludge (a side stream from the micro-filtration unit) was higher than envisaged. A higher water production is needed in order to gain economic benefits.
- Low consumption of chemicals: sulphuric acid consumption on the RO installation was low due to the novel configuration of the RO installation, and use of iron salts on the AD plant is avoided by biological desulphurisation of biogas and addition of magnesium chloride for removal of ortho-P from the liquid manure fraction.
- Processing SF into low-P soil improver needs further optimisation; P separation efficiency was as envisaged but chemical consumption rate was too high (costs) and P was recovered as a sludge requiring an additional drying step.

Quality of end-products and compliance with market demand
- Solid fraction of digestate is free of iron and polymer. Avoiding iron is beneficial for the fraction of easily extractable P (86% of P-total) which was highest of all demonstration plant whereas avoiding polymer is expected to increase acceptance of the low-P organic matter as an ingredient for potting soil.
- RO concentrate meets criteria for RENURE products. Injection in soil is needed to reduce ammonia emissions. GZV is blending RO concentrate with other liquid N fertilisers to overcome imbalances in nutrient ratio's and to increase the N content of the RO concentrate that is still rather low (8 g/kg). Replacing synthetic N fertiliser (KAS) by RO concentrate will not affect nitrate leaching but does lead to an increase in ammonia emissions (Schoumans et al., 2022).
- The residual sludge stream is rich in N but has a low NFRV; its use may lead to increased nitrate leaching.
- The low-P soil improver (2 g P/kg and 80% organic matter) can be used as a source of organic matter for sandy soils in the region of the plant provided that its sulphur content can be reduced. Due to its high water-holding capacity, it is also a suitable replacer for peat in potting soil or substrate.

Unwanted substances

- Though some residues of herbicides and veterinary pharmaceuticals were detected in digestate, no residues were detected in purified water that is being discharged onto surface water.
- Digestate of GZV contains Zn and Cu (from animal manure) and its use may lead to exceedance of PNEC values in leachate for Zn (34 µg/l) though not for Cu. Other heavy metals were nearly absent and not of environmental concern (Schoumans et al., 2021).

Life-Cycle-Assessment

- The AD plant has a net negative carbon footprint mostly due to the production of biogas/electricity replacing energy based on fossil fuel. Including NRR only has a minor effect on the overall carbon footprint. NRR reduces the impact of transport but this is compensated by a the consumption of electricity in the NRR process (Hermann et al., 2022).
- Energy consumption of the NRR process is compensated for by the lower transport distances of end product resulting in a higher amount of CO_2 emissions being avoided compared to a scenario in which unseparated digestate is exported.

Resilience of the business case

- Sale of biogas incl. subsidies is the main source of income. Implementation of NRR has a small positive effect on the overall business case. The sale of de-sulphurised biogas to a nearby dairy factor via a direct 5-km long pipeline offers long-term security for biogas sales without the need for upgrading biogas to biomethane. More importantly, implementation of NRR opens new markets for end-products thereby increasing flexibility and certainty for product disposal.
- High uncertainty in the future gate-fee and disposal costs for animal manure due to pending decision making by national authorities that may either result in a decrease in supply of manure (lower number of livestock animals) or an increase in the supply of manure (mandatory treatment of manure from livestock farms without land).
- It is technically feasible to produce RENURE products and high-grade soil improvers/peat replacers from digestate however, business case of the RePeat installation depends on acceptance of organic fibres from co-digested manure by industry and is still uncertain. Negative image of digestate and exclusion of digestate from manure under the FPR hamper market uptake of the end products by industry.

Compliance with legislation and legislative barriers

- GZV received a temporary exemption to use RO concentrate as an alternative for synthetic N pending the EC decision on the acceptance of RENURE products as synthetic N fertilisers. Its business case relies on a definite implementation of RENURE criteria.
- It is still uncertain if implementation of the FPR will be of benefit for GZV; this is because criteria for CMC 10 on animal by-products are still unknown. Secondly, it is still unclear whether fibres from co-digestated manure will be accepted as input material for growing media (PFC 4). The solid fraction does not meet criteria for the minimum sum of nutrients. Precipitated P salts do not comply with criteria for 'STRUBIAS' materials (Huygens et al., 2019) due to exceedance of the maximum level or organic carbon, and it is still unknown whether this type of processing will be allowed under CMC 10 for animal by-products.

Outlook

- Key-priorities of GZV are further product- and market development in order to generate revenues from the low-P soil improver. This includes optimisation of the RePeat process to meet criteria as a peat-replacer.
- The future business case of the AD plant is uncertain due to external factors: the number of livestock animals is decreasing and hence is the supply of animal manure to treatment installations. The current gas crisis and expected increase in the market value of N fertilisers may positively influence the business case.

Realisation of targets

*Table 7.1 Targets set by **Groot Zevert Vergisting (the Netherlands)** at the start of the SYSTEMIC project (Brienza et al., 2022) and realisation at the end of the project in 2021*

Sustainability targets	Realisation
1. 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.	Realised. The NRR installations have been implemented but the RePeat installation needs further optimisation. Long-distance transport of digestate has been reduced by 57% due to separation of digestate. Benefits of lower transport (in terms of CO_2 emissions) outweighed additional energy consumption of the NRR installation.
2. Reduce transport of digestate and products thereof, in terms of mass and distance, compared to trucking raw digestate to Germany.	Realised. Production of dischargeable water is lower than anticipated but nevertheless an 57% reduction in mass-based average transport distances has been realised due processing digestate into a solid fraction for export and liquid fertilising products that can used within the region of the plant.
3. Further reduce the carbon footprint of manure- and biowaste treatment compared to the situation without NRR	The production of renewable energy replacing fossil energy avoids emissions of CO_2. Energy consumption of the NRR processing is compensated by a lower consumption of fuel for product transport but overall, theCO_2 footprint has not changed after implementation of the NRR installations.
4. Replace peat in growing media by fibres recovered from digestate	The low-P soil improver meets criteria for use in growing media. Depending on the application though, an additional post-treatment is required to reduce the level of salt. Industrial partners have shown interest, however, product- and market development is a lengthy process that will be continued after the SYSTEMIC project. Exclusion of manure-based products in current certifications, the image of products from co-digestate and the rather low production capacity of GZV compared to market demand for fibres are bottlenecks to be overcome.
Economic targets	
5. Reduce costs for digestate handling and disposal as well as increasing security for product disposal (reduce dependency on Germany for acceptance of digestate)	Overall, economic benefits of the NRR installation as compared to the old situation (disposal of untreated digestate) are small. However, they have accessed new markets (i.e. sale of RO concentrate as a RENURE product, and possible sale of low-P fibres to potting soil industry). Overall, instalment of the NRR installation has increased GZVs flexibility in terms of

	end-products and buyers, thereby improving their resilience under changing market conditions.

6.2 Am-Power

General

- Am-Power successfully turns biowaste into renewable energy and organic fertilisers. During the SYSTEMIC project, they successfully implemented a novel evaporator for volume reduction of the liquid fraction of digestate.

Energy balance

- Am-Power has a high specific biogas production rate of 99 m^3 CH_4 per tonne of feedstock which is all converted into electricity and heat. Heat is used on-site by the digesters, dryers and evaporators. As a consequence, Am-Power has no option to switch to production of biomethane since the digestate treatment line strongly relies on the availability of waste heat.

Mass balance and consumption of additives

- During the monitoring period, digestate was processed into dried SF of digestate (7% of ingoing mass), LF of digestate (20%), evaporator concentrate (15%) and evaporator condensate (46%).
- The evaporator effectively reduced the volume of LF by 75%, producing a concentrate and condensed water. The later can be discharged onto surface water after purification by means of an RO system.
- The addition of sulphuric acid to the LF prior to evaporation effectively kept ammonia within the evaporator concentrate.
- The advantage of the evaporator compared to an enhanced pre-treatment of the LF with a DAF and/or microfiltration becomes redundant therefore avoiding the use of polymer and iron-salts on the DAF. The decrease is consumption of chemicals is however partly offset by an increased consumption of sulphuric acid and anti-foaming agents. The biggest advantage is the reduction of fouling risk on the RO units, because evaporation creates a much cleaner end product (i.e. condensed water) compared to the liquid fraction after DAF (+ microfiltration). This represents a huge cost reduction on RO membrane maintenance and stability of the RO system in general.

Quality of end-products and compliance with market demand

- The dried SF of digestate is primarily an organic P fertiliser. The fraction of easily available P was however low (21%), implying that the dried SF functions acts as a slow-release P fertiliser. A slow-release P fertiliser is a suitable fertiliser if the farmer's aim is to replenish P removed with crops, but it is less effective compared to artificial P fertiliser in overcoming P shortages at the start of the growing period.
- Am-Power's evaporator concentrate contains 9.0 g N/kg of which 85% as N-NH_4. Its neutral pH – due to addition of sulphuric acid – avoids ammonia emissions. From an agronomic perspective, it is a suitable alternative for synthetic N fertilisers and applying the product on top of the limit of 170 kg N/ha for animal manure is allowed, because the initial digestate was not originated from manure. Nevertheless, there is no demand for the concentrate in the region because (i) it does compete with the surplus of animal manure in the region because of its P content of 1.0 g/kg and (ii) farmers associate the product with manure and are only willing to apply concentrate against payment. Another drawback is the high S content of the concentrate (12 g S/kg) which would lead to S dosages far beyond crops demand if the product is dosed in line with the crops demand for N (Schoumans et al., 2022)

Unwanted substances

- Dried SF of digestate and evaporator concentrate contain heavy metals but in amounts below criteria set in the FPR for solid and liquid organic fertilisers, respectively. The EIA showed that there is no increase in heavy metal loading on agricultural land compared to the reference scenario in which unseparated digestate is applied.
- Residues of herbicides and pesticides were detected in the dried solid fraction and, in lower contents in the evaporator concentrate. An assessment of the potential risks of the detected levels of residues was beyond the scope of this study.

Life-Cycle-Assessment

- Processing biowaste into biobased fertilising products contributes to reuse of (non-renewable) nutrients and its hence a sustainable alternative compared to incineration. Nevertheless, the plant owner should be aware that the selection of input materials influences the agronomic and environmental quality of the end products. For example, intake of residues or sludges with a high Fe content negatively affect P availability in the solid fraction.
- Biogas production is responsible for about 300 kg CO_2 savings per ton of digestate. Implementation of NRR however slightly reduces this positive impact due to high energy use for NRR production and small advantages in terms of reduced transport (Hermann et al., 2022).

Resilience of the business case

- Revenues from green electricity including subsidies form the core of AM-Powers business case whereas digestate handling and disposal is a cost item (Hermann et al., 2022). Implementation of the NRR installation effectively reduces the volume of digestate-derived products but the CAPEX and consumption of chemicals (sulphuric acid, anti-foam) on the evaporator is high. The high heat demand of the evaporator and dryer make this process only economically viable for AD plants that have access to large amounts of residual heat against low prices.

Compliance with legislation and legislative barriers

- Dried SF of digestate is still traded to France under a bilateral agreement between local authorities in Flanders and France. Implementation of the FPR may facilitate the export of Am-Powers end-products. Whether all feedstocks of the digester comply with the CMC5 criteria has been not been assessed.

Outlook

- Am-Power will implement an RO installation for treatment of the evaporator condensate and this will enable them to produce a permeate that meets criteria for discharge onto surface water.
- It is recommended to develop a market for evaporator concentrate in order to sell this fertiliser within the region of the AD plant and without payment. Demo-trials and collaboration with local farmer organisations could help to shift the perception of farmers from concentration as being similar to animal manure towards concentrate as an alternative for synthetic N fertiliser.

Realisation of targets

*Table 7.2 Targets set by **Am-Power (Belgium)** at the start of the SYSTEMIC project (Brienza et al., 2022) and realisation at the end of the project in 2021*

Sustainability targets	Realisation
1. Reduce CO_2 emissions related to digestate transport by reducing water content and hence volume of the liquid NK fertiliser (evaporator concentrate).	Fully realised, the evaporator reduces the volume of the LF with 75% and this is twice as much as compared to the old NRR system. Impact on CO_2 emissions was however low due to consumption of energy by the NRR system.

2. Reduce the use of additives and chemicals: reduction of polymer dosage and elimination of iron sulphate ($FeSO_4$) and iron chloride ($FeCl_3$)	Partly realised. Omitting the DAF has indeed resulted in avoidance of use of polymer and iron salts. However, this has been replaced by use of anti-foaming agents and an increased consumption of sulphuric acid
3. Increase production of clean water suitable for reuse and discharge to surface water	Partly realised. Condensate of the evaporator needs post-treatment on an RO installation prior to discharge onto surface water. The RO installation has been installed but was not yet operational during the monitoring campaign due to problems with membrane fouling. Once operational, permeate water is expected to meet criteria for discharge onto surface water
4. Reduce the distance for fertilisers transport by producing bio-based mineral fertiliser for local application.	Not realised. The initial plan was to develop a market for evaporator concentrate within the region of the plant but Am-Power is now foreseeing to blend concentrate with SF of digestate for sale to France.
Economic targets	
5. By improving RO efficiency, Am-Power estimated that approximately 160 m³ of water per day will become available as dischargeable water (after polishing) or used on site. This amount of water does not have to be transported and treated.	Partly realised. During the monitoring campaign, 265 tonne of digestate was converted into 126 t of evaporator condensate and this could easily increase to 160 t of water per day when the evaporators are working at full capacity.
6. By replacing DAF for an evaporator, the costs for additives (flocculants) used on the DAF will be drastically reduced.	See point 2. the shift from polymers to anti-foaming agents and sulphuric acids has presumably led to a cost reduction but consumption of chemicals is still high compared to other demo plants

6.3 BENAS

General performance

- BENAS turns energy crops and poultry litter into renewable energy, mineral- and organic fertilisers and organic fibres. During the SYSTEMIC project, they successfully developed a new market for the recovered organic fibres.

Energy balance

- Specific biogas production (193 m^3/tonne) is highest of all demonstration plants, due to the use of energy crops.
- BENAS operates as a grid-stabiliser implying that electricity to the grid is delivered on demand. The remaining biogas is upgraded to biomethane and send into the national gas grid.
- Overall, 70% of the energy contained in the biogas is used to replace fossil energy outside the AD plant in the form of biomethane or electricity.

Mass balance and consumption of additives

- The N stripper removes up to 44% of ammoniacal N from the digestate thereby preventing ammonia toxicity in the digester and lowering the total N content of the digestate.

- BENAS does not use any chemical additives in the digestate processing line except for gypsum, which is a waste product from coal-fired plants. Nitrogen stripping is done by increasing the temperature without addition of chemicals.
- On full capacity, BENAS could produce 8,000 tonne of organic fibres suitable as raw material for paper or card board.

Quality of end-products and compliance with market demand

- Ammonium-sulphate has a slightly alkaline pH of 7.8 thereby increasing risks for ammonia emissions during storage and application. Hence, injection is required in order to avoid ammonia emissions. The alkaline pH is due to the use of gypsum as a sulphur source rather than sulphuric acid.
- Digestate has a reduced content of ammoniacal N (NH_4/TN= 46%) due to stripping, enabling higher application rates within the application rate of 170 kg N/ha (total N). Corresponding dosages of other macro-nutrients match crop demand. However, the product has a low NFRV and this may lead to exceedance of the limit for nitrate in groundwater (50 mg NO_3/L) (Schoumans et al., 2022).
- Low-N organic fibres are suitable raw material for the production of paper and card-board. The fibres also meet criteria for use as potting soil ingredient replacing peat.

Unwanted substances

- The majority of the feedstock at BENAS consists of energy crops; heavy metal contents in digestate are therefore low and not of environmental concern.
- The environmental impact assessment points to a risks on over-fertilisation with sulphur when using ammonium-sulphate as a N fertiliser. Hence, farmers should seek for combinations of ammonium sulphate and other N fertilisers within the fertiliser plan to avoid sulphur dosages far beyond crop uptake.

Life-Cycle-Assessment

- The use of energy crops (maize and corn) for energy production is under debate. BENAS could improve its footprint by switching towards treating of plant residues and biowaste rather than energy crops. Feedstock may however impact the quantity and quality of the recovered fibres.

Resilience of the business case

- Flexibility in terms of energy production (biomethane and electricity) has strengthen their business case.
- A strength of BENAS is that they created a market for cardboard products from organic fibres. Potential production of organic fibres (8000 tonne, dry weight) already exceed market demand. Collaboration with other AD plants producing similar fibrous products could lead to win-win situations.
- The quality and market acceptance of the recovered fibres depends on the type of feedstocks that are being processed meaning that they rely on feeding expensive high-fibrous feedstocks to their AD plant.

Compliance with legislation and legislative barriers

- Ammonium sulphate is still accepted as a synthetic fertiliser in Germany. Once the FPR is implemented, BENAS could market its products with a CE label though this may not be in their interest considering the fact that all products are used within the national borders.
- Low-N fibres and products thereof (mulch mats, etc) are FiBL certified and therefore allowed in organic agriculture.

Recommendations from the SYSTEMIC team:

- BENAS is a true frontrunner demonstrating new directions to create revenues from digestate-derived products. The use of energy crops that have been solely grown to serve as feedstock for biogas products is however under debate. The CO_2 footprint of the overall plant would be improved by replacing energy crops for organic residues. The SYSTEMIC team however also realises that a shift towards other feedstocks may have consequences for the quality of the extracted fibres and the image of the paper- and cardboard products. As such, intake of plant material with a high content of fibres will remain crucial in order to sustain production of high-grade fibres.

Outlook

- BENAS has invested in a paper making and fibre moulding machine. Market development and upscaling of production will be key tasks for the near future.

Realisation of targets

Table 7.3 Targets set by ***BENAS (Germany)*** *at the start of the SYSTEMIC project (Brienza et al., 2022) and realisation at the end of the project in 2021*

Sustainability targets	**Realisation**
1. To demonstrate a novel approach to strip and absorb ammonium from digestate.	Realised. The N stripper reduced the NH_4 content of the digestate with 44% without addition of chemicals. Ammonium is recovered through a reaction with gypsum. Control of ammonium levels in the digester allows them to take in more poultry litter or other N-rich feedstocks that would otherwise lead to ammonia-inhibition
2. Development of a new market for low-N fibres recovered from digestate	Realised. BENAS and GNS successfully developed a series of new products based on paper and cardboard produced from low-N fibres. Production takes place on-site and products are sold under the brand name 'MagaVerde'.
Economic targets	
1. Create a positive business case for the AD plant and digestate handling.	Realised. Key factors contribution to the positive business case are: (i) higher revenues for energy from biogas due to production of biomethane and electricity on demand, (ii) avoiding costs for synthetic N fertiliser due to use of ammonium sulphate on own land and (iii) foreseen revenues for products from recovered fibres due to approaching niche markets (e.g. organic agriculture).

6.4 Acqua&Sole

General performance

Acqua & Sole treats more than 120,000 tonne of sewage sludge and aggro-industrial waste per year. Besides biogas, Acqua&Sole produces ammonium sulphate and digestate that is being used as an liquid organic fertiliser. Recovered organic fertilisers not only supply nutrients, but also organic matter, which is of particular importance in the southern regions of Italy where soils are typically low in organic matter. Nevertheless, application of digestate from sewage sludge has a negative image. Acqua&Sole aims to showcase that sewage sludge can be converted into safe and effective fertilisers by means of thermophillic digestation.

Energy balance
Specific biogas production amounted to 38 m^3 biogas per tonne of feedstock in 2020, which was low compared to the other demonstration plants because the ration of digester consists of 85% sewage sludge (low energy content) and only 15% organic residues from agro-food industry. Nevertheless, electricity and heat demand of the AD plant and NRR installation were fully covered by the energy delivered from the biogas and the remainder of 5800 MWh of electricity was fed to the national grid.

Mass balance and consumption of additives

- The N stripper removed 35% of $N\text{-}NH_4$ in digestate when working continuously.
- The process does not include solid/liquid separation; this has the advantage that use of chemical additives such as polymer are being avoided. Sulphuric acid consumption amounts to 2.5-3.5 kg 98% sulphuric acid per ton of digestate.

Quality of end-products and compliance with market demand

- Ammonium-sulphate has a neutral pH of 5.9 and therefore a lower risks on ammonia emissions compared to raw digestate that typically has a pH> 7.5. It consists for 100% of mineral N and can hence replace synthetic N fertilisers.
- The high N/S ratio of ammonium-sulphate, however, leads to risks for over-fertilization with sulphur when solely using ammonium-sulphate to cover the nitrogen demand. Hence, farmers should seek combinations of ammonium sulphate and other nitrogen fertilisers within the fertiliser plan to avoid sulphur dosages far beyond crop uptake.
- Digestate has a reduced N content due to stripping, enabling a higher product application rate within the N application rate standards (based on effective N, *i.e.* 50% of total N for digestate). There is no application rate limit for P or total N in Italy.

Environmental impact and Life-Cycle-Assessment

- Lowering the N content of digestate through stripping enables applying dosages of 45 tonne digestate per hectare (4.5 tonne DM/ha). An advantage is that large amounts of organic matter (>2.0 tonne/ha) can be added, but on the longer term this may lead to enhanced leaching of nitrate and/or accumulation of phosphorus and heavy metals. This was predicted based on modelling approach that predicted effects after 100 y of application (Schoumans et al., 2022) though not confirmed in recent field trials (Signurjak et al., 2022). Leaching of N and P is hence not considered as an current risks but as a point of attention.
- Though levels of heavy metals in digestate of Acqua&Sole are well below national criteria for heavy metals in sewage sludge, its use may, on the longer term, lead to accumulation of heavy metals, particularly zinc and copper, in soil. However, due to the alkaline pH-values of soils in this region, risks for leaching are limited. Accumulation of heavy metals can be avoided by applying equilibrium fertilisation for P.
- Residues of pharmaceutically active compounds were all below the detection limits. The screening included a selection of commonly used pharmaceuticals (Pigoli, 2021, Sigurnjak et al., 2021). Though Acqua&Sole does not use a polymer in its process, digestate may still contain residues from polymer that have been used for sludge dewatering on the WWTPs.
- In the LCA, Acqua&Solesaves CO_2 emissions mostly due to avoidance of synthetic N and secondly due to production of biogas. Avoided emissions exceed emissions associated to transport and hence, the overall effect in terms of CO_2 emissions is positive (Hermann et al., 2022).

Resilience of the business case
Acqua&Sole's receives a gate fee of about 90 euro per tonne for the intake of sewage sludge, which is their major source of income. Revenues for green energy are, however, low due to the lack of a support system in Italy. Digestate is applied for free. They have a solid business case since, at least in the short term, and no competition from other companies offering disposal solutions for sewage sludge is expected.

Compliance with legislation and legislative barriers

- Ammonium-sulphate is REACH-registered and can hence be used as a synthetic N fertiliser. This also allows trade and export of the fertiliser, but this is not in their interest since there is sufficient demand for ammonium sulphate in their region.
- Digestate, on the other hand, complies with national and regional legislation for sewage-sludge-derived fertilisers – which enables local use - but is explicitly excluded from the FPR.

Outlook

- The NRR process works as envisaged. Acqua&Sole will continue to work on their research on n the effective and safe use of fertilizers from digested sewage sludge.

Table 7.4 Targets set by ***Acqua&Sole (Italy)*** *at the start of the SYSTEMIC project (Brienza et al., 2022) and realisation at the end of the project in 2021*

Sustainability targets	**Realisation**
1. Increase N removal and recovery from 10% to 40% of N-NH_4 in digestate.	Realised. The new N stripper could reached a N removal efficiency of 35% of ammonium in digestate which is a significant improvement compared to the previous stripper.
2. Close nutrient cycles through the use of fertilisers produced from sewage sludge and biowaste;	Realised. Nitrogen, phosphorus and organic matter are effectively reused within agriculture thereby avoiding losses of nutrients as would occur during combustion.
3. Showcase that fertilisers from sewage sludge and biowaste are agronomically effective and environmentally friendly;	Both digestate and ammonium sulphate are effective fertilising products though farmers are advised to make a fertilisation plan for all macro-nutrients in order to prevent over-fertilization of organic-N, P or S. Residues of pharmaceutically-active compounds were not detected above the detection limit.
4. Reduce NH_3, NO_3^- and N_2O emissions during digestate application and eliminate unpleasant odour during digestate injection to improve public acceptance.	Acqua&Sole demonstrated that ammonia emissions after injection of digestate were of a similar level compared to injection of urea (Zilio et al., 2021).
Economic targets	
5. Reduce the costs for handling and disposal of digestate through (i) a controlled anaerobic digestion process without NH_3 inhibition and (ii) production of high-quality mineral fertilizer (AS).	Acqua&Sole can compete with gate fees for incineration plants. Their business case is still robust though it is for the longer term uncertain whether new incineration plants will be constructed that may compete for intake of sludge.

6.5 Waterleau NewEnergy

General

Waterleau NewEnergy had already invested in an advanced digestate treatment line. Digestate is separated into a dried solid fraction. The liquid fraction is further treated by means of an evaporator were ammonium is removed and recovered as condensed ammonia water. The remaining concentrate of the evaporator is low in ammonium but contains other macro-nutrients. Other innovations include blending of the dried solid fraction and evaporator concentrate producing tailor-made organic fertiliser products with N,P,K ratio's in accordance to farmers demands.

Mass and Energy balance

- Specific biogas production (150 m^3 biogas/tonne of feedstock) is high due to the intake of organic residues from food industry. Biogas is converted into 21,300 MWh of electricity of which 70% is fed to the grid and the remainder used on-site. Thermal heat produced by the combined heat and power (CHP) generator is used on-site to meet the energy demand of the dryer and evaporator-NH3 stripper.
- The evaporator effectively reduces the volume of the liquid fraction by 86%, producing an evaporator concentrate with 17% dry matter. Ammonia is volatilised and recovered as a 10% N solution. Condensate of the evaporator is containing a mixture of macro-nutrients (NPK: 12, 1.6 and 25 g/kg).
- Chemical consumption includes polymer, anti-foam, iron salts and sulphuric acid (air scrubber and RO).

Quality of end-products and compliance with market demand

- Dried solid fraction (92% dry matter) can be effectively transported over long distances. It is nowadays partly blended with evaporator concentrate and sold in France as an organic P fertiliser. The remainder, which cannot be blended with WNE's dried solid fraction, is sold to a trader who exports it to the Netherlands and probably also blends it with other organic fertilisers.
- Blending has several benefits; (i) blending avoids formation of dust which is a problem with the current dried solid fraction and (ii) evaporator concentrate has a low ammonia content which avoids odour and ammonia emissions during composting, storage and field application (iii) blending balances the concentrated nutrients to lower concentrations, creating a multi-nutrient organic fertiliser.
- Condensed ammonia water (93 g N/kg) is suitable to replace urea or synthetic ammonia water in DeNoX installations. Because of its high pH, it is unsuitable as an N fertiliser because and has a high cost for transportation (i.e. high risk transport)..
- Evaporator concentrate, remaining after evaporation of water and volatilization of ammonia, is high in K (25 g K/kg) and N (12 g N/kg). However, N is dominantly present in organic form (N-min/N = 13%) meaning that the product cannot replace synthetic N fertiliser. This, and its rather high P content, hinder use of evaporator concentrate in Flanders/Netherlands were it has to compete with animal manure, which translates into very high disposal cost (40 euro/tonne incl. transport).

Environmental impact and Life-Cycle-Assessment

- WNE converts organic residues into green energy and biobased fertilisers thereby recycling (non-renewable) elements including P. Energy demand of their process is fully covered by energy production from biogas (electricity and thermal heat). Use of condensed ammonia water in industry avoids ammonia emissions from use as fertiliser and prevents surplus manure N from ending up on Flemish agricultural soils (i.e. "manure processing").
- Though residues of herbicides and pesticides were detected in digestate, purified water (for discharge) was free of organic residues (< detection limit) showing that purification was effective and eliminating risks for spreading residues onto surface water.

Resilience of the business case

- WNE has long-term contracts for disposal of end-products to France where there is demand for these types of organo-mineral fertilisers. For disposal of ammonia water, however, they rely on acceptance of one buyer. To reduce this dependency, they also consider shifting to production of ammonium sulphate for use as a fertiliser.

- The NRR process relies on the availability of thermal heat from the conversion of biogas into electricity. As a consequence, shifting from electricity production to green gas production would not be possible.

Compliance with legislation and legislative barriers

- Products are now exported under a mutual recognition between exporting and accepting member states. Implementation of the FPR may simplify this procedure if feedstocks and treatment procedures comply with the FPR. WNE may also benefit implementation of RENURE criteria if they decide to produce ammonium sulphate instead of condensed ammonia water.

Outlook

- Additionally, they aim to increase their flexibility in terms of end users for the sale of N-rich products; WNE is therefore exploring options to convert ammonia water into ammonium sulphate for use as a RENURE fertilising product.

Realisation of targets

Table 7.5 Targets set by ***Waterleau NewEnergy (Belgium)*** *at the start of the SYSTEMIC project (Brienza et al., 2022) and realisation at the end of the project in 2021*

Sustainability targets	**Realisation**
1. Reduce the volume of liquid fraction by means of evaporation thereby reducing costs for long-distance transport	Realised. The evaporator reduced the volume by 86% which is the highest reduction in volume among the demonstration plants
2. Cooperation with local manure processor for synergetic use of companies' technologies (f.e. biological nitrification-denitrification and evaporator/N-stripper, RO-units) to reduce transport of liquid streams (liquid fraction, concentrate)	Not yet realised because this is something that they consider for the longer term. The fact that they already investigate possible collaborations shows that they are well-prepared to adjust their NRR process; improving their flexibility to respond to changing external conditions.
3. Optimising heat and energy production and (re-)use throughout the plant	This has not been assessed within the SYSTEMIC project, but WNE has been outsourcing a heat optimisation study.
4. Creating dischargeable water or in the future even storing this as irrigation water for surrounding agriculture	Partly realised. During the monitoring period, the RO installation was not functioning, but normally the water is treated.
Economic targets	
5. Reduce the costs for handling and disposal of the end products in particularly for the evaporator concentrate (disposal costs €40,-/tonne including transport)	Realised. Once the blending step for the dried solid fraction and concentrate is implemented and additional drying capacity is installed, disposal costs will be reduced. Moreover, selling a blend to France – where there is a demand for organic fertilisers - reduced there dependency on Dutch buyers who only accept the product against high payments.

7 Synthesis

The five SYSTEMIC demonstration plants are pioneers in the production of biobased fertilisers (BBFs) from digestate and they invested in full scale nutrient recovery and reuse (NRR) technologies. The demonstration plants operate in different legal, commercial and agricultural context, within the European Union though they have in common that they are being situated in regions with intensive livestock farming leading to regional surpluses of nutrients. Nevertheless, each of the five demonstration plants show-cases a unique combination of feedstocks, NRR technologies and BBFs. The feedstocks include residues from agro-food industry, source-separated organic household waste, animal manure, sewage sludge and energy crops.

The overall objective of the SYSTEMIC project was to demonstrate economically viable business cases for nutrient recovery and reuse from biowaste while simultaneously contributing to sustainability targets including:

- Increasing the use of nutrients and organic matter from biowaste as BBFs thereby contributing to the transition towards a circular economy.
- Reducing emissions of greenhouse gases (GHG) from biowaste processing, handling and application of derived BBFs. GHGs include carbon dioxide (CO_2), methane (CH_4) and laughing gas (N_2O)
- Reducing or controlling risks for losses of nitrate (NO_3) and phosphate (PO_4) to ground- and surface water and atmospheric emissions of N as ammonium (NH_3)
- Avoiding spreading of contaminants (heavy metals, organic micro-pollutants) to the environment.

To evaluate the overall performance and pro's and con's of the newly implemented NRR technologies, an assessment of the demonstration plants was performed on five categories (Chapter 7). This chapter gives a general synthesis of the five AD plants and recommendations for other AD plants.

Table 8.1 Summary of the main outcomes of the evaluation of SYSTEMICs demonstration plants.

Categories	Main outcomes for demonstration plants
Compliance with market demand and legislative criteria	• Demonstration plants produce biobased fertilising products that better fit with market demand compared to unseparated digestate. • Generally, AD plant owners underestimate the influence of market evaluation, and market strategy for novel NRR products and they tend to not focus on this hereby missing out on the untapped revenue potential. BENAS and Groot Zevert Vergisting are here the exceptions (e.g. Magverde biogas fiber-products and "Green Meadow Fertiliser"). • Implementation of RENURE criteria is of importance for GZV and could also improve the market revenues for other Demo Plants that currently don't have the pilot status that GZV has (i.e. area-oriented "pilot Mineral Fertiliser-free Achterhoek"). • Though the FPR is expected to simplify export of biobased fertilising products, it is still uncertain whether demonstration plants will comply with the criteria; bottlenecks include exclusion of sewage sludge and industrial sludge as well as the minimum levels for nutrients which are not met for RO- and evaporator concentrates.
Technical performance & Mass- and energy balances	• Generally, AD plant owners underestimate the time needed to develop, implement and optimise a novel NRR installation. • Percentage of energy contained in biogas that is used externally (electricity or gas) is low for AD plants were biogas is converted into electricity (17-36%) and high for plants selling biogas/biomethane (69-71%). • The thermal heat demand of dryers, N-strippers and evaporators is covered by waste heat from CHPs. A drawback is that these AD plants cannot shift from electricity production to biomethane. • NRR installations effectively separate nutrients and/or reduce water content. All demonstration plants use considerable amounts of sulphuric acid. Polymer is used on those plants that perform a high-tech solid/liquid separation.
Product quality & environmental effects	• SFs of digestate are primarily P fertilisers. The fraction of easily available P deviates strongly among SFs from different demonstration plants. Farmers should be advised on whether to use the SFs as a fast- or slow-release P fertiliser. • Biobased N fertilising products can replace synthetic N fertilisers. However, they typically have a high S content (ammonium sulphate, evaporator concentrate), which may lead to S application rates above crop uptake and hence to leaching of sulphate to groundwater. They should be applied cautiously on crops with higher S requirements (e.g. potatoes, grassland). • Purified water meets criteria for discharge, no micro-pollutants were detected. • Contents of heavy metals were generally low except for digestate from sewage sludge; use of NRR-products did not lead to an increase in heavy metal loading per hectare compared to use of digestate.
Life-cycle assessment	• To be completed when final LCA is available. • For animal manure, avoiding methane emissions from slurry pits is the main benefit in terms of GHG emissions.
Economic feasibility	• Business cases of the demonstration plants include veryt. high margin operations (A&S, BENAS), medium margin (GZV, WNE) and low margin

	operations (Am-Power). Implementation of NRR improves the business case and security for product disposal compared to scenario's without NRR though the economic benefits of NRR are generally low compared to revenues from biogas production and/or gate fees. • Getting funding for implementation of NRR technologies is often difficult or underestimated by biogas plants. Banks are more reluctant in providing loans in the biogas sector and funding from EU or even Member State level is difficult to access or poses a high administrative burden for SME's.

7.1 Compliance with market demand and legislation

- Demonstration plants produce BBFs that better fit with market demand compared to unseparated digestate. The choice for NRR technologies and BBFs depends on the region-specific context. For example, AD plants that operate under conditions of surpluses of animal manure focus on reducing the volumes of BBFs enabling transport over longer distances to regions with demands for organic fertilisers. Legislative context is also of influence on the choice of NRR technologies. For example, AD plants operating in nations that have not implemented P application rate limits invested in N strippers reducing the N content of digestate and enabling higher dosages of digestate within the N application rate limits.

- A definite implementation of RENURE criteria is of importance for GZV that is yet selling RO concentrate as an alternative for synthetic N fertiliser under a temporary exemption of the Dutch government. None of the other demonstration plants is yet producing a RENURE product but a final implementation of RENURE may alter the treatment strategy of WNE that is yet producing condensed ammonia water (for industry) but could also produce ammonium sulphate (a RENURE product). The JRC considered implementation of RENURE products as an alternative for biological treatment of LF of manure (during which nitrogen is converted into harmless nitrogen gas) avoiding production of synthetic N through the Haber-Bosch process. They concluded that production of RENURE products reduces the carbon-footprint as compared to biological treatment (Huygens et al., 2020) which is common practice in a.o. Flanders and Italy. In the Netherlands though, biological treatment of manure is rarely applied. Instead, LF of manure is transported over 100-150 km to regions with arable farming and used as an organic fertiliser. Implementation of RENURE will shift this current practice towards using RO concentrate as synthetic N fertiliser on fields within the vicinity (25 km) of the AD plant or manure processor (Regelink et al., 2021). In the latter case, production of RENURE products is primarily meant to save costs for transport of LF of manure or digestate. Though RENURE products are similar to synthetic N fertilisers in terms of nitrogen-use-efficiency (Ehlert, 2020, Sigurnjak et al., 2022) they also contain other macro-nutrients such as sulphur (ammonium sulphate, RO concentrate) and potassium (RO concentrate). Farmers must be advised on the application rates to avoid excessive dosages of sulphur or potassium as is mentioned in the SYSTEMIC product factsheets.

- Though the EU FPR (2019/1009) is expected to simplify export of biobased fertilising products, it is still uncertain whether demonstrations will comply with the criteria; bottlenecks include

    - Post-processing of digestates (CMC4&5) is not yet allowed under the current EU FPR which, per definition, excludes all BBFs produced within the SYSTEMIC project. The European Sustainable Phosphorus Platform (ESPP) proposed post-processing techniques for digestate that covers the techniques applied within this project.

- It is yet unclear whether polymers, which are used to improve separation efficiencies, are allowed and whether they have to comply with CMC 9 meaning that it has to be fully degradable to CO_2 and water.
- AD plants within the project may need to avoid part of the current feedstocks such as sludge from industrial WWTPs, to comply with the criteria defined under CMC4&5.
- For liquid products (RO and evaporator concentrate) blending with other fertilisers is needed in order to comply with PFC criteria for the minimum amounts of nutrients.

7.2 Technical performance & mass- and energy balances

- Overall, implementation of NRR had a small but positive effect on the business case of the AD plants (Hermann et al, 2022b). Nevertheless, implementation of NRR technologies was not without setbacks and economic risks. Generally, plant owners seriously underestimated the time needed to develop, implement and optimise a novel NRR installation. Lack of materials and skilled personnel as well as unforeseen issues during commissioning of installations were mentioned as reasons for delay. Subsidies for implementation and demonstration of novel NRR technologies, such as within the SYSTEMIC project, turned out to be helpful to overcome these barriers. Plant owners also highly appreciated the opportunities given by the project to share knowledge on practical issues as was evident from the large number of attendees at the living lab meetings, plant visits and webinars. Networking and knowledge sharing is hence effective and shall be stimulated and promoted.

- Biogas production per ton of feedstock strongly varied among the demonstration plants due to differences in type of feedstock being processed. Sewage sludge and animal manure generate less biogas per ton of feedstock as compared to biowaste. Nevertheless, all demonstration plants were able to supply energy to the grid in addition to covering the on-site demand for electricity and thermal energy.

- Separation efficiencies varied among the plants depending on the targets of the plant owner. High separation efficiencies were found for decanter centrifuges used in combination with polymer (>90% of P to solid fraction). Nitrogen strippers were found to remove 35% to 44 of ammoniacal N from digestate. Evaporators reduced the volume of liquid fraction by 75-85% meaning a higher separation efficiency as compared to the RO systems treating liquid fraction of digestate (55% volume reduction). The latter however produces permeate that meets (after IX) criteria for discharge onto surface water whereas the condensate of evaporators need further post-treatment by RO and IX. In order to assess the overall performance of the NRR installation, it is crucial to consider return flows such as side streams being recirculated to the digester or purified water being used for flushing of installations, dilution of polymer or cleaning; these return flows generally have a strong negative effect on the overall mass balance of the AD plant.

- Increasing separation efficiencies requires higher inputs of either electrical energy, thermal energy or chemicals and it is a challenge for the plant owner to find a balance between the costs for these inputs and benefits of an improved separation. The choice for the NRR installation is intertwined with the use of biogas which is in turn steered by national criteria for subsidies on biomethane. Those AD plants that convert biogas into electricity have plenty of thermal energy available (a side product of the CHP) which made them choose to implement heat-demanding NRR technologies such as evaporators, N strippers and dryers. A drawback is that they rely on the availability of thermal energy which prevents them from shifting towards production of biomethane.

- Polymers are used to improve separation efficiencies of decanters and DAFs. Polymers are based on poly-acrylamide and is yet uncertain whether this is accepted as an additive for production of CE fertilising products. GZVs process is designed as such that a solid fraction is free of polymers while accepting a lower separation efficiency for P and OM; this was a deliberate choice as it is thought to increase acceptance of the solid fraction and the thereof produced low-P soil improver by the potting soil industry. Nevertheless, GZV uses polymers on the second decanter treating the liquid fraction of the first decanter. GZV tried to avoid the use of polymers within their process but this seemed incompatible with the minimum separation efficiencies needed to process liquid fraction into an RO concentrate/RENURE product. Sulphuric acid is used in considerable amounts at all demonstration plants (2.5 – 5.0 kg 98% H_2SO_4 per ton digestate) except for BENAS were gypsum ($CaSO_4$) is used instead of sulphuric acid. Sulphuric acid is used in N absorbers, in RO installations (to lower the pH in order to retain ammoniacal N within the RO concentrate), in one of the two evaporator systems (to lower the pH in order to prevent volatilization of ammoniacal N) and in the RePeat system (to extract P from the solid fraction). This leads to enrichment of BBFs with sulphur in the form of sulphate.

7.3 Product quality & environmental effects

The five demonstration plants processed digestate into a variety of BBFs including solid and liquid organic fertilisers (solid fraction, liquid fractions, evaporator concentrate), mineral N fertilisers (ammonium sulphate, RO concentrate), precipitated P salts, organic fibres and purified water.

- SFs of digestate are primarily organic P fertilisers, contributing little to N and OM fertilisation when applied at dosages respecting equilibrium fertilisation for P (Schoumans et al., 2022). For some products though, the fraction of easily available P is low which is partly due to the choice of feedstocks (Fe-rich sludges or garden waste), partly due to the use of Fe salts on the AD plant and is partly unexplained (Regelink et al., 2021). Plant owners are advised to avoid the use of iron salts and iron-rich feedstocks but nevertheless, differences in availability of P between SFs from different feedstocks are partly unavoidable. For fertiliser products with low fractions of easily available P, higher dosages are acceptable without inducing risks on phosphate leaching. Also, farmers should be advised on whether to use the SFs as a fast- or slow-release P fertiliser.

- Mineral biobased N fertilising products in which the TAN/TN ratio is 0.90 or higher can replace synthetic N fertilisers. The demonstration plants recovered 5 to 50% of TAN contained in digestate as ammonium sulphate or RO concentrate. Mineral biobased fertilising products have a low viscosity and therefore penetrate easily in the soil upon injection reducing ammonia emissions. Ammonia emission factors can be lower (ammonium sulphate) or higher (RO concentrate) as compared to CAN (Schoumans et al., 2022).

- Production of mineral N fertilisers coincides with production of organic fertilisers (stripped digestate, SF, MF sludge) with a lower NFRV as compared to raw digestate. As dosages of low NFRV-products are generally limited by the P-application rate limit, this does not lead to an increase in nitrate leaching In general, anaerobic digestion and NRR leads to changes in TAN/TN ratio of end products as compared to conventional digestate/manure and consequently, legal NFRV may not be representative for actual NFRVs. This is for example the case for digestate of Acqua&Sole having a legal NFRV of 50% whereas field trials confirmed a NFRV of 80% (Zilio et al., 2021) and as well for evaporator concentrate of Am-Power. To prevent nitrate leaching, NFRVs of biobased fertilisers shall be determined and included in the law.

- Biobased N fertilisers however, typically have a high S content (ammonium sulphate, evaporator concentrate), which may lead to excessive S dosages and hence to leaching of sulphate to groundwater. Blending with other biobased or synthetic fertilisers to tailor-made-fertilisers is an option to adjust NPKS ratio's to crop demand. An example the 'Green Meadow Fertiliser' marketed by GZV, which consists of RO concentrate and urea. WNE and Am-Power are blending evaporator concentrate with dried SF is also effective to reduce S application rates. Blending of S-rich fertilisers with digestate of manure shall however be avoided due to risks for formation of toxic di-hydrogen-sulphide (H_2S) gas which is formed from sulphate when stored under anaerobic conditions. To prevent overfertilization with sulphur, farmers should be advised on how to incorporate biobased N fertilisers in their fertilisation plan.

An alternative for sulphuric acid is nitric acid. Though it is technically possible to use nitric acid in nitrogen strippers, one must be careful and take safety measurements because nitric acid is far more hazardous compared to sulphuric acid and the final product, ammonium-nitrate, can be explosive under certain conditions. Therefore, ammonium nitrate solutions with more than 28% nitrogen by weight compared to ammonium nitrate must successfully pass the detonation test defined in (EC) Regulation n° 2003/2003 in order to be free in circulation in the internal market (Seveso-inspectiediensten 2009). They must also meet a certain number of technical requirements regarding their porosity, the size of the particles, the pH and the percentage of impurities (e.g. a very low limit for organic substances). Ammonium nitrate could be a precursor for explosives when the water is removed by evaporation (Regulation (EU) No 98/2013 on the marketing and use of explosives precursors). This is, in addition to the much higher costs for nitric acid, the reason that sulphuric acid is still the preferred option. Another alternative that avoids the use of acid is the production of ammonium-nitrate fertilisers through biological nitrification of ammonium to nitrate. A first installation based on this process (GreenSwitch) has recently been constructed in the Netherlands and received a lot of attention because it not only avoids sulphur, but also minimises ammonia emissions upon field application, which is an urgent topic in the Netherlands and Flanders.

- High sulphuric acid consumption is also a bottleneck in the RePeat installation of GZV because of enrichment of the low-P organic soil improver with sulphur. Also here, the S crop demand should be taken into account when defining desired product dosages.

- Purified water meets criteria for discharge, no residues of herbicides, pesticides or veterinary pharmaceuticals were detected.

- Contents of heavy metals were generally low except for digestate from sewage sludge; use of NRR-products did not lead to an increase in heavy metal loading per hectare compared to use of digestate. Generally, heavy metals loadings were not of environmental concern unless P equilibrium fertilisation was respected.

- In terms of soil organic carbon (SOC) contents of soils, the EIA showed that the contribution of organic fertilisers was relatively small as compared to the amount of organic matter entering the soil as crop residues and below-ground biomass. Reducing the N content of digestate in order to increase the allowable dosage (in countries without a P application rate limit) enables a farmer to give high dosages of OM to soil (>2000 kg OM/ha) but this practice leads to accumulation of P. Generally speaking, organic BBFs such as digestate, evaporator concentrate and SFs are primarily to be considered as organic fertilisers and secondarily as soil improvers. Nevertheless, other researchers found in scenario analyses that using organic fertilisers including manure/digestate offers the largest potential to increase SOC contents in soil (Lessmann et al., 2021).

7.4 Economic feasibility

Currently, SYSTEMIC business cases depend on the availability of a national support scheme, typically frequently changing and even absent in some member states. Support schemes may consist of fixed feed-in tariffs for electricity or biomethane, of market premiums on top of the market price or of green certificates, all related to energy supplies. Nutrient recovery and recycling has never been subject to a support scheme. Producing BBFs can contribute to the viability of the business case, but cannot sustain the capital expenses and operations of a biogas plant - it can hardly sustain the nutrient recovery and recycling operations including capital expenses for their installation.

The added (nutrient use efficiency) value of BBFs and tailor-made fertilising products is not yet reflected in product prices. This is in part due to the fact that BBFs are less concentrated meaning higher costs for product storage, transport and field application. This is in particular true for RO concentrate (GZV) containing 0.8% N and for costs for product handling exceed the potential market value in terms of its N content and the price for synthetic N. In addition, farmers are not used to pay for BBFs as they rather consider the origin than the nutrient value of the products.

Considering the real value of converting biowaste into renewable energy and tailor-made fertilisers one must include:

- Bio-methane (LNG/CNC) is carbon-neutral or even carbon-positive - a fact that needs to be monetarised (e.g., by carbon credits)
- Digestate-based fertilisers avoid CO_2 emissions from the use of untreated food and agricultural residues and from (open air) composting or incineration
- Nutrient (N) transfer rates and N use efficiencies are up to 3-times higher in digestate-derived, tailor-made products than in their feedstock
- Use efficiencies of mineral BBFs are frequently comparable to synthetic NK fertilisers.

Low hanging fruits are N-P-K blends which better correspond to the nutrient demand of crops as compared to non-blended RO concentrate. New business models such as have been developed by Groot Zevert Vergisting (potting soils) and BENAS (mulching mats and packaging material from the fibrous fraction) have the potential to significantly improve the revenues from customised products. Overall, the demonstration plants have proved that creating higher revenues from BBFS is possible but time-consuming. Examples of activities included regional field tests to demonstrate new BBFs to local farmers, collaborations with potting soil or carton industry to develop new products. For those AD plants exporting BBFs to other countries, these marketing activities are not f use as the end users are yet willing to pay for the products. For these AD plants, costs reduction e.g. reduction of volume to be transported is most relevant.

In the course of implementing the Fit for 55 Package, all anaerobic digestion-derived added values in terms of carbon-neutral or carbon-positive energy and fertilisers should be monetarised. The SYSTEMIC suggestion is to extend the European Trading System to agricultural and biogas activities and to allow stakeholders to benefit from saved CO_2 emissions from renewable energy and from carbon-neutral fertilising products.

8 Conclusions

The five demonstration plants successfully implemented novel NRR technologies converting biowaste, manure and sewage sludge after anaerobic digestion into fertilising products thereby offering a sustainable alternative as compared to conventional disposal routes.

Phosphorus is 100% recovered as organic fertilising products however its use efficiency may be lower as compared to synthetic P fertilisers. This is more of agronomic rather than of environmental concern as risks for P leaching are reduced upon using BBFs in which a substantial part of P is non-available.

BBFs with a similar product name, f.e. SF of digestate, may still show considerable variation in nutrient ratio's, nutrient use efficacies for N and P and OM content; It is recommended that plant owners collect and disseminate this data to farmers in order to advise them on proper use of the products.

Biobased mineral N fertilisers can effectively replace synthetic N fertilisers though care should be taken to prevent ammonia emissions and over-fertilisation with sulphur. Organic N fertilisers can effectively replace manure of raw digestate but to prevent nitrate leaching, it is advised to limit the dosage to 170 kg TN/ha in NVZs even though this may be no prohibited by law.

Even though some BBFs have similar NUEs as compared to synthetic fertilisers, farmers are not yet used to pay for these products. But as BBFs are less concentrated as compared to synthetic fertilisers, also costs for product disposal, transport and field application for which farmers should also be compensated. Some of the demonstration plants have proved that creating higher revenues from BBFS is possible but time-consuming. Others have shown that costs can be reduced by lowering the volume of the BBFs meaning cheaper transport to regions where there is yet a demand for this type of fertiliser.

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SYSTEMIC

Circular solutions for biowaste

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

Consortium

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