A biorefinery approach to exploit digestate as key feedstock in the energy–nutrient nexus

D4.2 Scenario analysis of six unique technology cascades

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This assessment includes values and results that may diverge from actual conditions. Such discrepancies can arise due to several factors including, but not limited to, unanticipated experimental outcomes, incomplete data, assumptions necessitated, measurement inaccuracies, and material losses. Each of these may significantly impact the accuracy and reliability of the conclusions drawn.

Furthermore, it should be noted that the technologies examined in this analysis are subject to ongoing refinement and optimization. The results and conclusions drawn here reflect the current state of understanding and capabilities, but future advancements and improvements in technology may influence these findings. Therefore, readers are advised to interpret the conclusions cautiously, considering the dynamic nature of technological advancements and the inherent uncertainties in the data and methodologies employed.

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1 General aim

The application of digestate as fertilizer presents a significant challenge in the biogas industry in Flanders and Turkey. Flanders is considered a Nitrate Vulnerable Zone (NVZ) with stringent nitrogen and phosphor limits to prevent severe problems associated with an oversupply of nutrients in the soil and nitrate leaching. In Turkey, the continuous application of digestate to agricultural land is prohibited in areas with intensive livestock activity. As a result, the disposal routes for digestate in Turkey, Flanders, and other areas with high livestock density and nutrient surpluses are limited and therefore costly, at this moment posing a burden on the business models of biogas plants in these regions.

The CORNET-TETRA project BioDEN aims to create extra revenues for the biogas sector by valorizing the digestate and increasing biogas and biomethane production. The project focuses on different elements: (i) enhanced biogas production via anaerobic digestion (AD), (ii) ammonia recovery via stripping and scrubbing, and (iii) phosphorus recovery via precipitation and adsorption (Figure 1). Although some of the processes already receive attention in research and industry, effective linking of the processes to obtain a successful cascade is still missing.

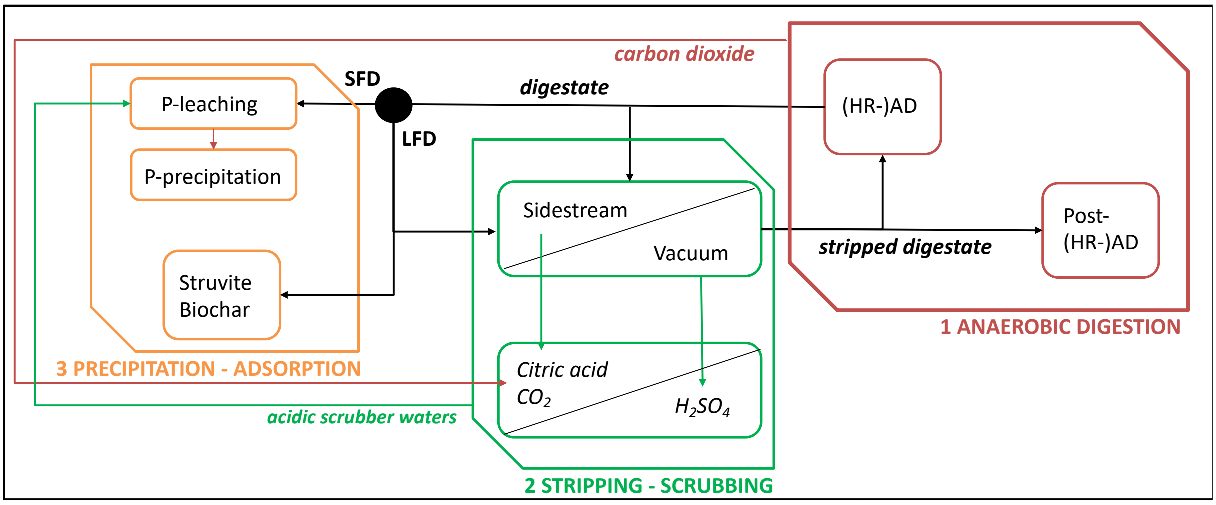


Figure 1. Overview of the conducted experiments during the BioDEN project to create extra revenues for the biogas sector.

To this end, the developed technologies are combined into six unique technology cascade scenarios. The report aims to assess the cascades as these would be implemented in practice and to benchmark the impact of implementing the scenario against the current situation. The different scenarios are evaluated based on technical, ecological, and economic performance. The goal is to show the potential of the different researched technologies.

2 Technology cascades

This report focuses on six unique technology cascades aiming to successfully link the innovative technologies investigated during the BioDEN project with an existing biogas installation. The technology cascades are implemented in a "default" business case scenario, based on an existing biogas plant in Flanders or Turkey.

Waterleau NewEnergy (Ieper, Belgium)

Waterleau NewEnergy is located in Ieper (Belgium). The region is characterized by an agricultural typology of 'intensive livestock farming', more specifically pig husbandry. Waterleau NewEnergy has operated a mesophilic anaerobic digester (treatment capacity of 120.000 tonnes) since 2012, processing both manure and biowaste.

Figure 8. Waterleau NewEnergy in Ieper, Belgium.

Seleda Biyogaz (Babaeski/Kirklareli, Turkey)

Seleda Biyogaz is located in Babaeski / Kırklareli (Turkey) where it has been operational since 2017. The plant digests livestock manure and agricultural organic waste (1.000 tonnes per day). The installation has an annual fertilizer production capacity of 120.000 tonnes.

Figure 9. Seleda Biyogaz in Babaeski/Kirklareli, Turkey.

Only experiments conducted on the same input stream are combined into the same cascade. Six different cascades are defined in total (Table 1.).

Table 1. The six different technology cascades are linked to an existing biogas installation. *Post-AD: Post anaerobic digestion.*

Cascade	Input	Biogas ↑	N-recovery	P-recovery
1	Dairy manure	Post-AD	Stripping-scrubbing	/
2	Pig manure	/	/	P-leaching
3	Dairy manure	Post-AD	Stripping-scrubbing	P-leaching
4	Organic waste	Post-AD	Stripping-scrubbing	/
5	Chicken manure	Vacuum stripping		Struvite
6	Chicken manure	Vacuum stripping		Biochar

During the project, these scrubbing acids were researched: sulphuric acid, waste sulphuric acid, citric acid, and CO_2 and the following leaching agents: sulphuric acid, citric acid, waste sulphuric acid, ammonium sulphate, and ammonium citrate. In what follows, all cascades are described one by one, and choices/assumptions made regarding consumables are explained.

2.1 Cascade 1 – post AD and nitrogen recovery from dairy manure

In cascade 1 dairy manure is digested (Figure 2). The resulting digestate is air-stripped and the obtained nitrogen-rich gas is scrubbed with **citric acid** leading to a clean airstream and ammonium citrate. The nitrogen-stripped digestate is post-digested to increase biogas production. Elevated temperatures (70°C) during stripping resulted in the loss of water through evaporation. This loss was compensated by adding the same amount of water to the stripped digestate, ensuring similar conditions and thus allowing a comparison between the two digestion steps. Citric acid is less hazardous and more sustainable than the commonly used inorganic acids. Next to that, scrubbing with citric acid produces ammonium citrate which is capable of improving the bioavailability of micronutrients and phosphorus (P) for plant uptake.

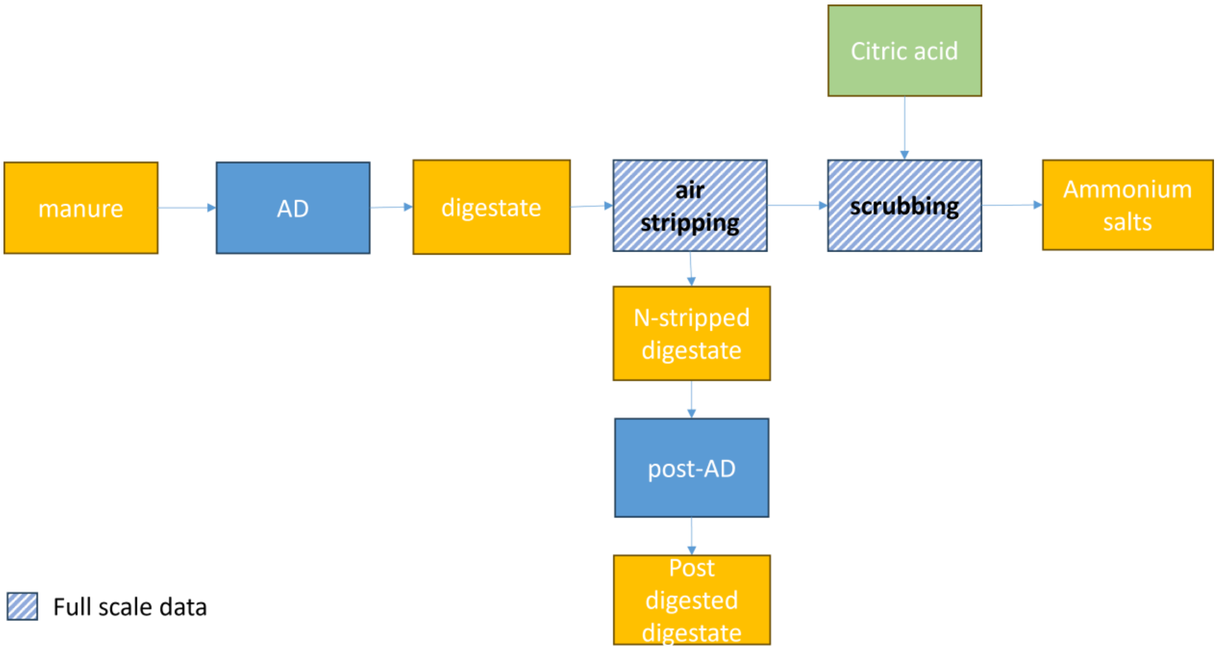


Figure 2. Cascade 1 – post anaerobic digestion and nitrogen recovery from dairy manure.

2.2 Cascade 2 – phosphorus recovery from pig manure

In cascade 2, pig manure is digested (Figure 3). The resulting digestate is separated into a liquid and solid fraction employing a centrifuge. The phosphorus is leached from the solid fraction and subsequently precipitated as struvite. In this cascade waste sulphuric acid is included as a leaching agent (25 times diluted), representing a significantly lower cost compared to pure sulphuric acid.

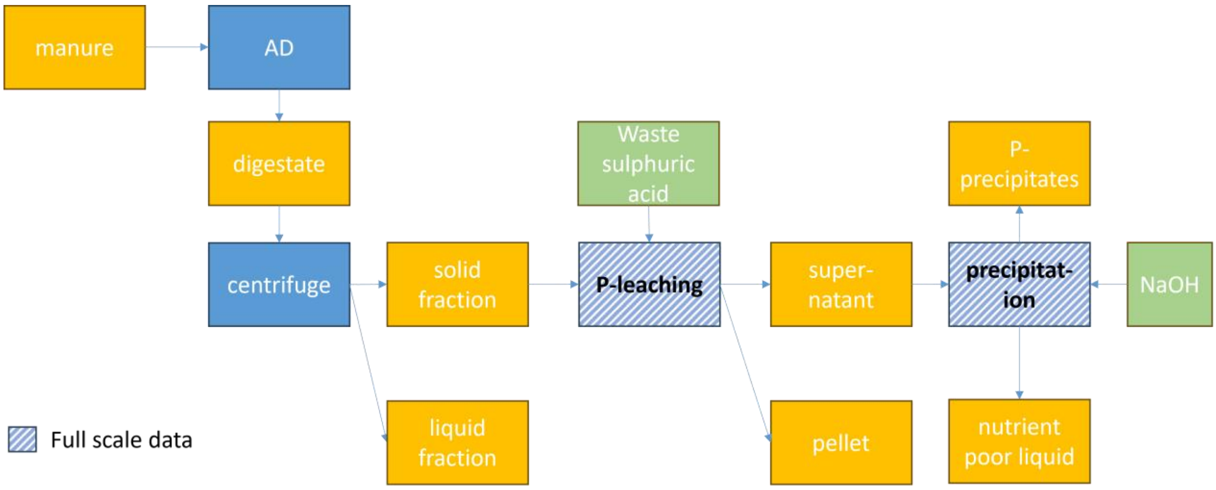


Figure 3. Cascade 2 – phosphorus recovery from pig manure.

2.3 Cascade 3 – post AD, nitrogen and phosphorus recovery from dairy manure

In cascade 3, dairy manure is digested (Figure 4). The resulting digestate is air-stripped and the obtained nitrogen-rich gas is scrubbed with sulphuric acid resulting in a clean airstream and ammonium sulphate. Part of the stripped digestate is post-digested to increase the biogas production. The other part is separated into a solid and liquid fraction employing a centrifuge. The ammonium sulphate, resulting from the scrubbing, is used as a leaching agent to leach phosphorus from the solid fraction of the digestate. The phosphorus is subsequently precipitated as struvite.

In practice, however, it is expected that all stripped digestate is post-digested and thereafter separated for P-recovery. As no experiments were conducted on post-digested stripped digestate, it was not possible to set up the cascade in that way. Nevertheless, no considerable differences are expected when the P-leaching is performed on the post-digested stripped digestate. The consumables in this cascade were chosen as such to maximize the interaction between the different technologies.

Stripping took place at elevated temperatures (70°C) resulting in the evaporation of water. For the post-digestion to be comparable to the first digestion step, the amount of water that evaporated during stripping is added to the stripped digestate.

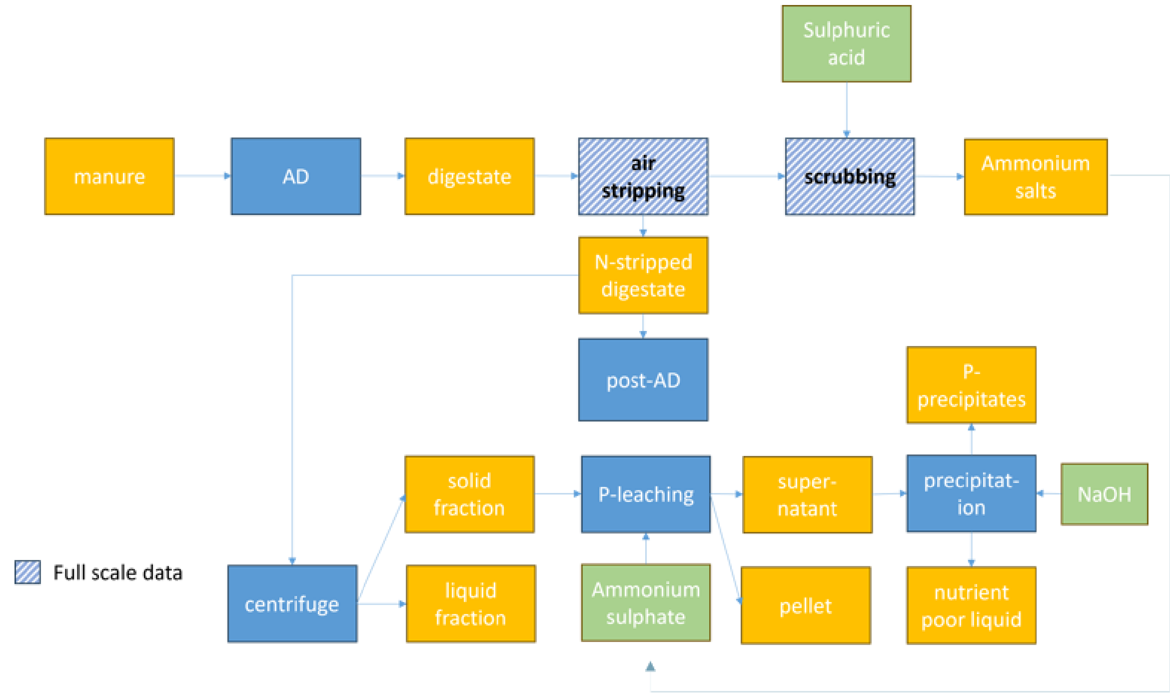


Figure 4. Cascade 3 – post anaerobic digestion, nitrogen, and phosphorus recovery from dairy manure.

2.4 Cascade 4 – post AD and nitrogen recovery from mixed organic waste

Cascade 4 follows the same principle as cascade 1 with the difference that the input stream is a combination of mixed organic waste and dairy manure instead of mono-digestion of dairy manure and **waste sulphuric acid** is used as scrubbing liquid instead of citric acid (Figure 5).

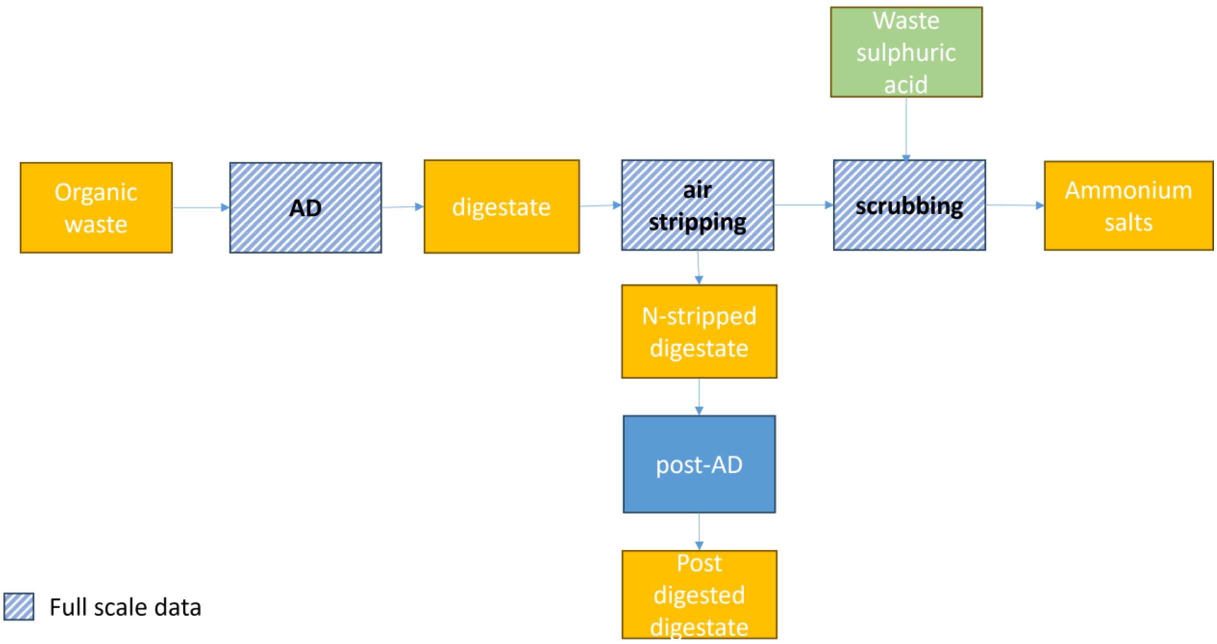


Figure 5. Cascade 4 – post anaerobic digestion and nitrogen recovery from mixed organic waste.

2.5 Cascade 5 – nitrogen recovery and phosphorus recovery as struvite

In cascade 5, chicken manure is digested and at the same time a side-stream recirculation line is operated (Figure 6). Once a day one tenth of the volume of the anaerobic digester is pumped into a vessel where nitrogen is removed using vacuum stripping. Following this, the stripped digestate is sent back to the anaerobic digester. For completeness the acquired nitrogen-rich gas is scrubbed with sulphuric acid. This was not part of the experiments and is stoichiometrically calculated. Phosphorus is recovered as struvite from the resulting digestate by adding MgCl.

During the project pilot scale struvite precipitation tests were performed on the liquid fraction of the digestate derived from the Seleda plant. However, the digestate from the Seleda plant contains only a fraction of chicken manure and differed significantly from the digestate obtained from the vacuum stripping tests. Therefore, this data wasn't included in the cascades and the lab-scale data, from the tests on the whole digestate, was incorporated.

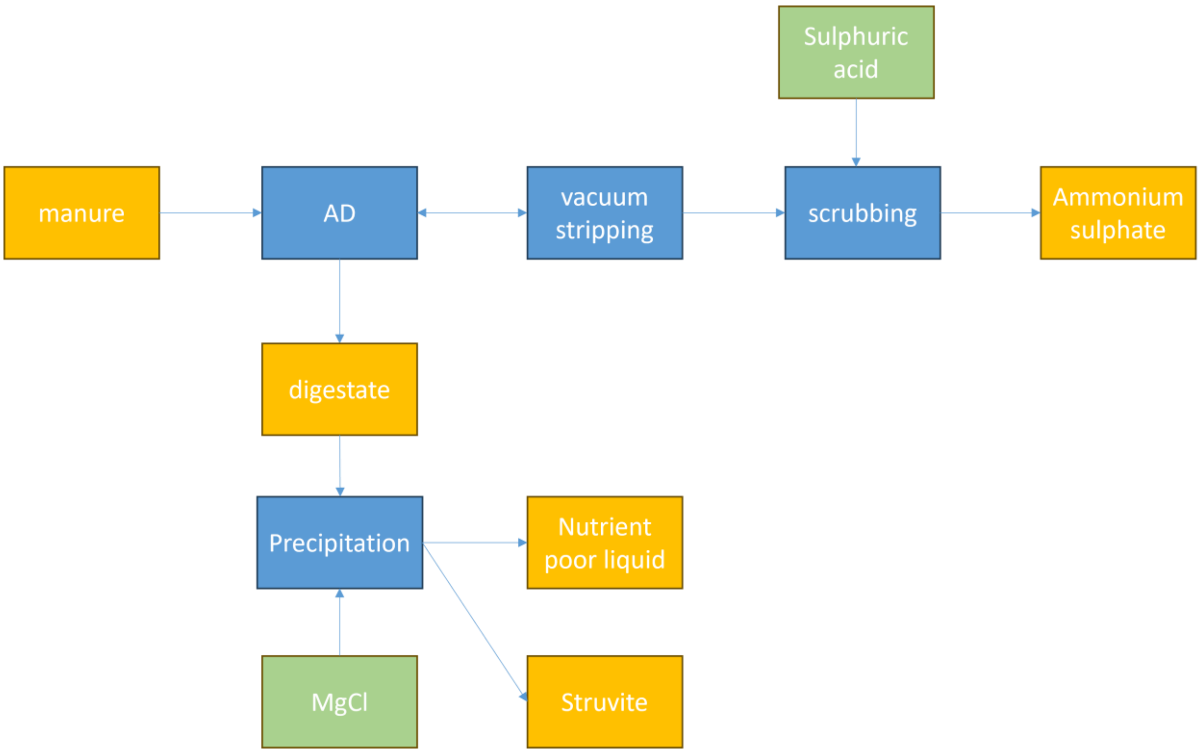


Figure 6. Cascade 5 – nitrogen recovery and phosphorus recovery as struvite.

2.6 Cascade 6 – nitrogen recovery and phosphorus recovery on Fe-modified biochar

The first part of cascade 6 (Table 7), where N is removed using vacuum stripping, is conducted in the same way as cascade 5. Fe-modified corn cob biochar is added to the resulting digestate to adsorb phosphorus.

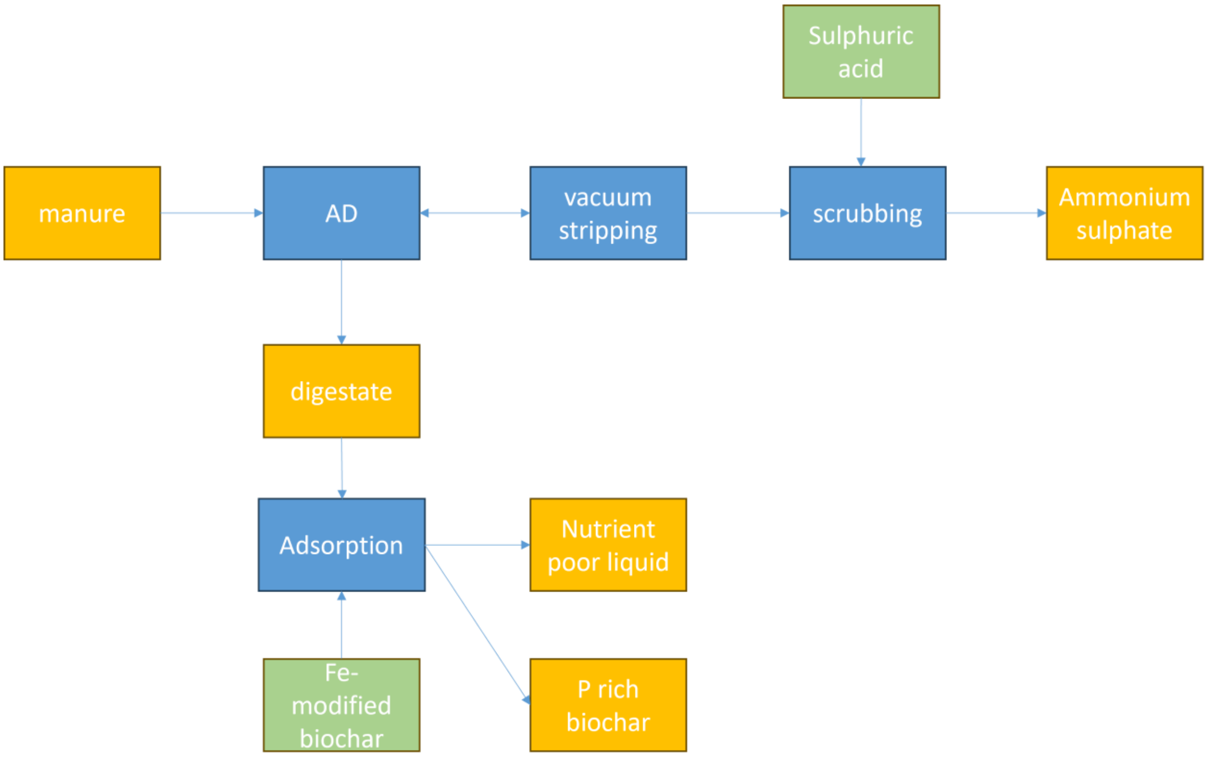


Figure 7. Cascade 6 – nitrogen recovery and phosphorus recovery on Fe-modified biochar.

3 Technical performance

The data from the lab-scale and pilot-scale tests are incorporated into a mass and nutrient balance. All data is recalculated to 1000 kg of substrate entering the system, presenting a simulated full-scale nutrient recovery treatment cascade. This chapter evaluates the different mass balances and provides an overview of the assumptions. Information based on calculations is presented in a dashed box.

Anaerobic digestion and post-treatment of digestate is mainly a continuous process. Although the content of the digester is assumed homogeneous, there can still be local variations due to for example changes in feedstock. **For this reason, deviations below 10% throughout the process are attributed to sample deviations and will not be elaborated.**

3.1 Cascade 1 – post-AD and nitrogen recovery from dairy manure

Mass

The closed mass balance can mainly be attributed to the made assumptions (Table 2). For instance, the mass of the digestate after digestion was calculated as the mass of the input subtracted from the mass of the biogas produced. This approach was used for both the first digestion and post-digestion step. The amount of used citric acid is calculated based on the measured concentration of the ammonium salt in the pilot-scale tests. The citric acid is constantly recirculated until the absorption capacity is almost reached and the pH is nearly neutral. A density of 1 kg/l was assumed for the digestate.

Nitrogen

The overall nitrogen balance is well-fitted. However, losses and surpluses above 10% appear between the different steps of the technology cascade. During anaerobic digestion, 12% of the nitrogen disappears. There is no clear reason for this. It is still assumed to be related to local variations due to changes in feedstock.

The decrease in effective nitrogen (N_{eff}) after air stripping is not equally represented in the total nitrogen content. These variables were measured using two different methods. The TAN-concentration is measured as Kjeldahl nitrogen whilst total nitrogen is determined via a TOC/TN measurement. Moreover, some impurities (e.g. proteins) might have been present in the liquid and interfered with the analysis.

For the stripping and scrubbing, which is independent of the type of input stream, pilot-scale data is included in the cascade (dashed lines). The stripping efficiencies obtained in the lab (84%) can never be reached on full scale due to less contact and lower mass transfer efficiencies. The ammonia stripping efficiency in the pilot-scale tests equalled 52%. Following, a scrubbing efficiency of 100% was reached. All nitrogen in the scrubbing waters is assumed to be present as ammonia.

Phosphorus

The overall phosphorus output decreases by 18% compared to the input (Table 2). This is the relative difference between the phosphorus concentration in the dairy manure digestate and the nitrogen-stripped dairy manure digestate, as it was assumed that the phosphorus content did not change during anaerobic digestion. The decrease can be attributed to the variation in weight loss during air stripping by the evaporation of water (±64 kg). An average weight loss of 312 kg of water is taken into account. The phosphorus analysis was performed on water-depleted stripped digestate.

Table 2. Cascade 1 - the mass balance, the nitrogen balance, and the phosphorus balance.

	IN	OUT	Difference
Mass (kg)	1019	1019	0,0%
Kg N	5,1	/*	/*
Kg P	0,49	0,40	-18%

**Cannot be depicted as it is a mixture of measured and calculated values.*

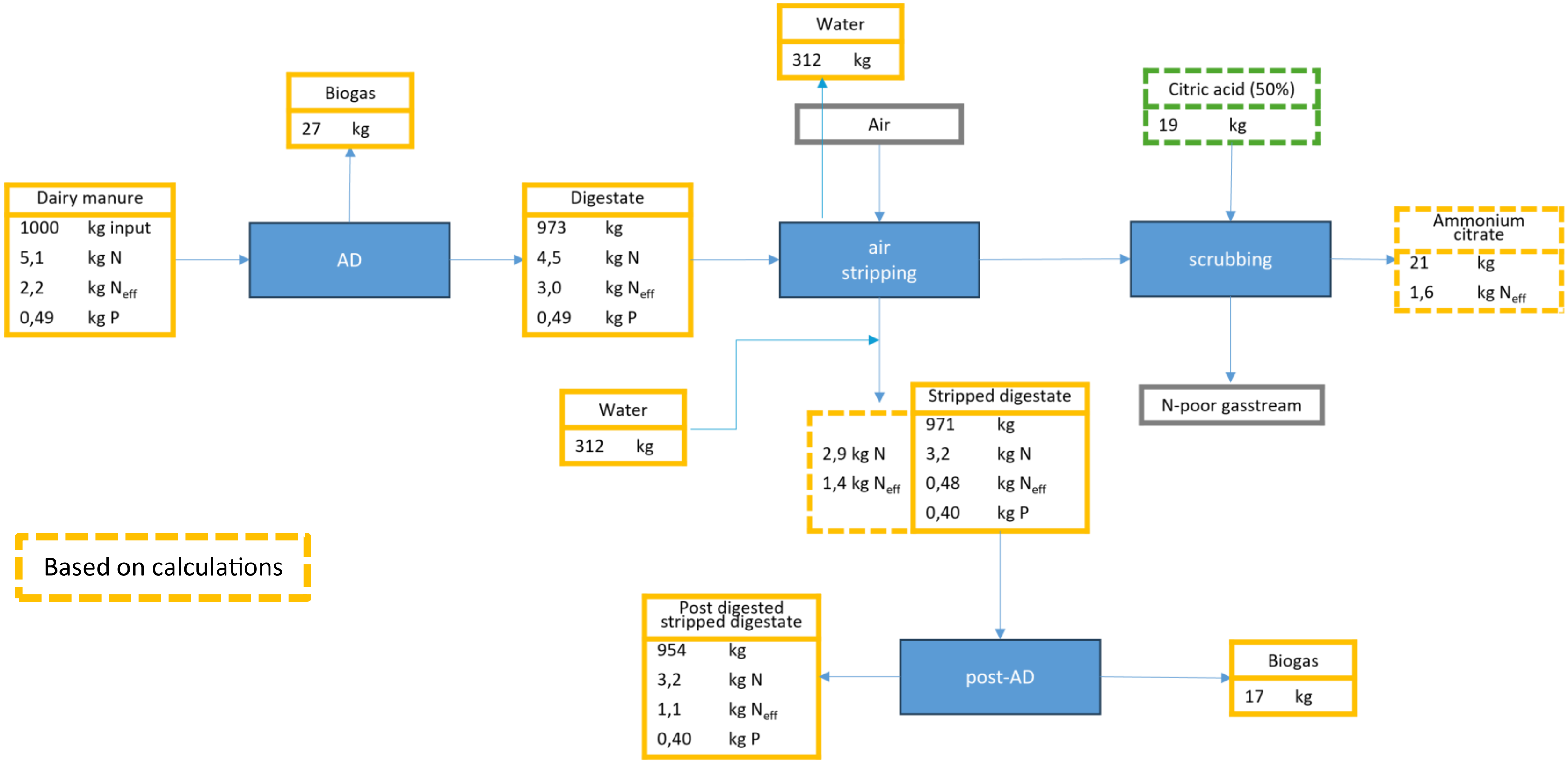


Figure 10. Cascade 1 – mass- and nutrient balance implementing post anaerobic digestion and nitrogen recovery from dairy manure.

3.2 Cascade 2- phosphorus recovery from pig manure

Mass

The mass of the digestate after digestion was calculated as the mass of the input subtracted from the mass of the biogas produced. Overall, the mass decreased by 23% (Table 3). During the pilot runs, there were losses of material after the P-leaching step, when parts of the mixture of the solid fraction and the acid got stuck in the tube connecting the tank to the centrifuge. Therefore, parts (mostly solid) of the material did not reach the centrifuge, and instead got stuck inside the tube itself, which was considerably long. It is also expected that some material may have remained in the centrifuge itself.

Nitrogen

There was no information on the nutrient content of the pig manure. Therefore, it was assumed that the nutrient content did not change during anaerobic digestion and the same values as for digestate were considered. 32% of the nitrogen is lost in the technology cascade (Table 3). Most of the nitrogen is lost during the leaching step due to the significant amount of nutrient-rich solids that remain in the tube connecting the tank to the centrifuge, and the centrifuge itself. Next to that, the amount of nitrogen decreased by 36% during the precipitation step. The characterization was performed on precipitate dried at 50°C. Hence, it is expected that nitrogen was lost to the environment during the drying step.

Phosphorus

The assumption was made that the phosphorus content does not change during anaerobic digestion. Overall, the phosphorus decreased by 69%. Similar to the loss of nitrogen, phosphorus decreased by 55% during the leaching step. This is again related to the significant loss of nutrient-rich solids that remained in the tube connecting the tank to the centrifuge, and the centrifuge itself. In the precipitation step, the remaining phosphorous decreased by 40%. This decrease can be attributed to the high standard deviation. There was a large difference in the P-content of the precipitate between the three different test runs at the pilot scale.

Table 3. Cascade 2 - the mass balance, the nitrogen balance, and the phosphorus balance.

	IN	OUT	Difference
Mass (kg)	1927	1490	-23%
Kg N	7,2	4,9	-32%
Kg P	1,7	0,53	-69%

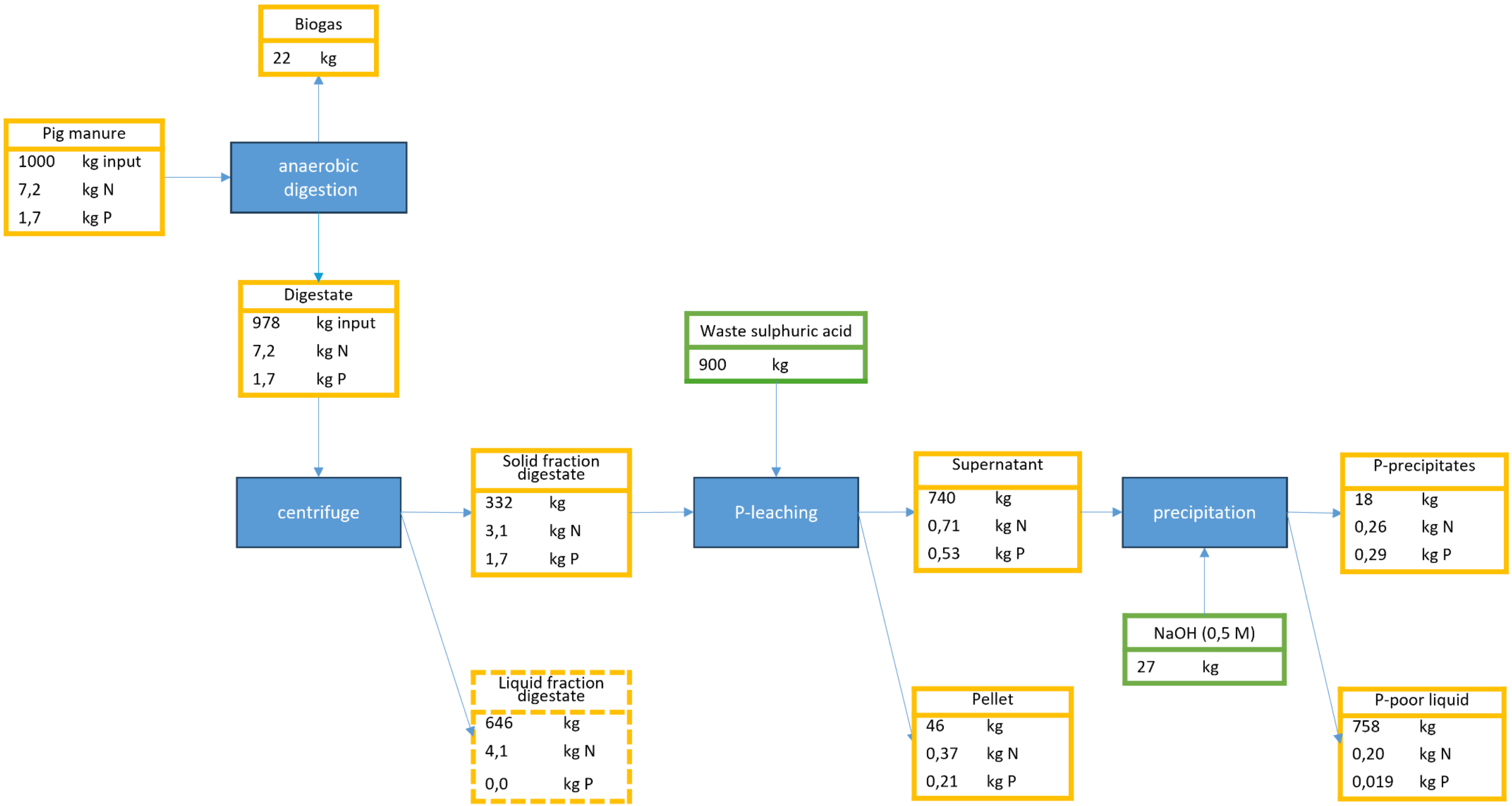


Figure 11. Cascade 2 - mass and nutrient balance implementing phosphorus recovery from pig manure.

3.3 Cascade 3 – post-AD, nitrogen and phosphorus recovery from dairy manure

Mass

The overall mass balance is closed (Table 4). The following assumptions were made: the mass of the digestate after digestion is calculated as the mass of the input subtracted from the mass of the biogas produced. This is for both the first digestion and post-digestion step. The amount of used sulphuric acid is calculated based on the measured concentration of the ammonium salt in the pilot-scale tests. The sulphuric acid is constantly recirculated until the absorption capacity is almost reached and the pH is nearly neutral. Additionally, it is assumed that no losses occur during the separation of the digestate. Next to that, a density of 1 kg/l was assumed for the digestate.

Nitrogen

The overall nitrogen balance is well-fitted. However, between the different steps of the technology cascade significant losses and surpluses of nitrogen appear. During anaerobic digestion, 12% of the nitrogen disappears. There is no clear reason for this. It is still assumed to be related to local variations due to changes in feedstock.

The decrease in effective nitrogen (N_{eff}) after air stripping is not equally represented in the total nitrogen content. These variables were measured using two different methods. The TAN-concentration is measured as Kjeldahl nitrogen whilst total nitrogen is determined via a TOC/TN measurement. Next to that, some impurities (e.g. proteins) might have been present in the liquid and interfered with the analysis. The stripped digestate was measured twice, once for the tests in part A of the cascades and once for the tests in part B. These measurements were performed by two different persons using different methods and did not match. Therefore, the results from both analyses (part A and part B) were included in the mass balance.

For the stripping and scrubbing, which is independent of the type of input stream, pilot-scale data is included in the cascade. The stripping efficiencies obtained in the lab (84%) can never be reached on full scale due to less contact and lower mass transfer efficiencies. The average ammonia stripping efficiency in the pilot-scale tests equalled 52%. Following, a scrubbing efficiency of 100% was reached. All nitrogen in the scrubbing waters is assumed to be present as ammonia.

In the second part of the cascade, 58% of the nitrogen disappeared during the precipitation step. The characterization was performed on precipitate dried at 50°C. Hence, it is expected that nitrogen was lost to the environment during the drying step.

Phosphorus

The overall phosphorus output increased by 16% compared to the input (Table 4). This is the relative difference between the phosphorus concentration in the dairy manure digestate and the nitrogen-stripped dairy manure digestate, as it was assumed that the phosphorus content did not change during anaerobic digestion. The decrease can be attributed to the variation in weight loss during air stripping by the evaporation of water (±64 kg). An average weight loss of 312 kg of water is taken into account. The phosphorus analysis was performed on water-depleted stripped digestate.

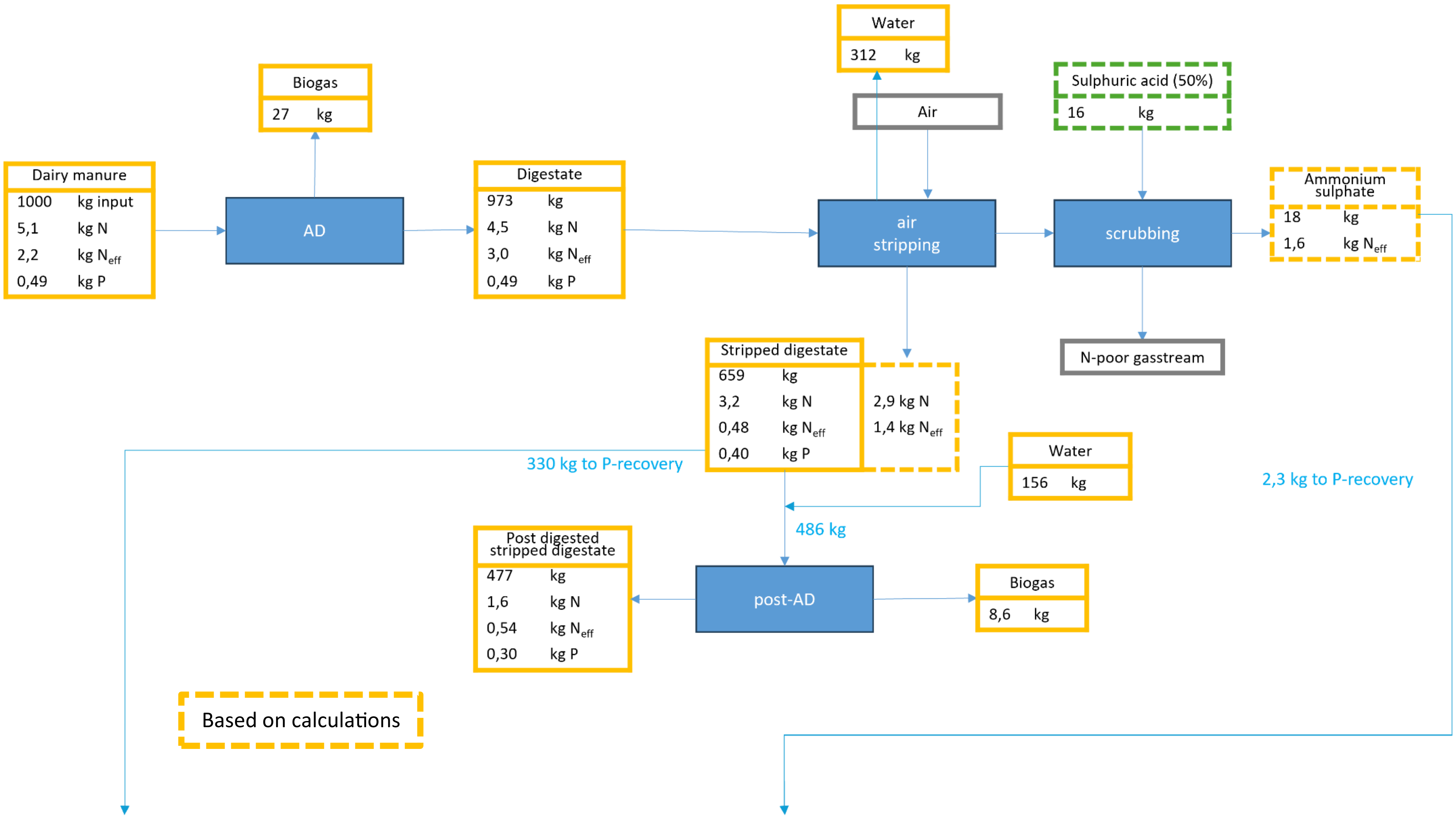
The amount of phosphorus increased by 20% after the P-leaching step. The characterization of the pellet was performed on a mix of the pellets derived from all leaching experiments (with the different acids) with the digestate and nitrogen-stripped digestate, possibly causing the deviation in phosphorus content. 53% of the phosphorus is extracted from the solid fraction of the digestate from which 94% is precipitated as struvite in the subsequent precipitation step.

Table 4. Cascade 3 - the mass balance, the nitrogen balance, and the phosphorus balance.

	IN	OUT	Difference
Mass (kg)	1466	1426	-2,7%
Kg N	5,3	/*	/*
Kg P	0,49	0,57	16%

* Cannot be depicted as it is a mixture of measured and calculated values.

(a)


Water
312 kg
Biogas
27 kg
Air
Sulphuric acid (50%)
16 kg
Dairy manure
1000 kg input
5,1 kg N
2,2 kg N$_{eff}$
0,49 kg P
AD
Digestate
973 kg
4,5 kg N
3,0 kg N$_{eff}$
0,49 kg P
air stripping
scrubbing
Ammonium sulphate
18 kg
1,6 kg N$_{eff}$
Stripped digestate
659 kg
3,2 kg N
0,48 kg N$_{eff}$
0,40 kg P
2,9 kg N
1,4 kg N$_{eff}$
N-poor gasstream
330 kg to P-recovery
Water
156 kg
2,3 kg to P-recovery
486 kg
Post digested stripped digestate
477 kg
1,6 kg N
0,54 kg N$_{eff}$
0,30 kg P
post-AD
Biogas
8,6 kg
Based on calculations

(b)

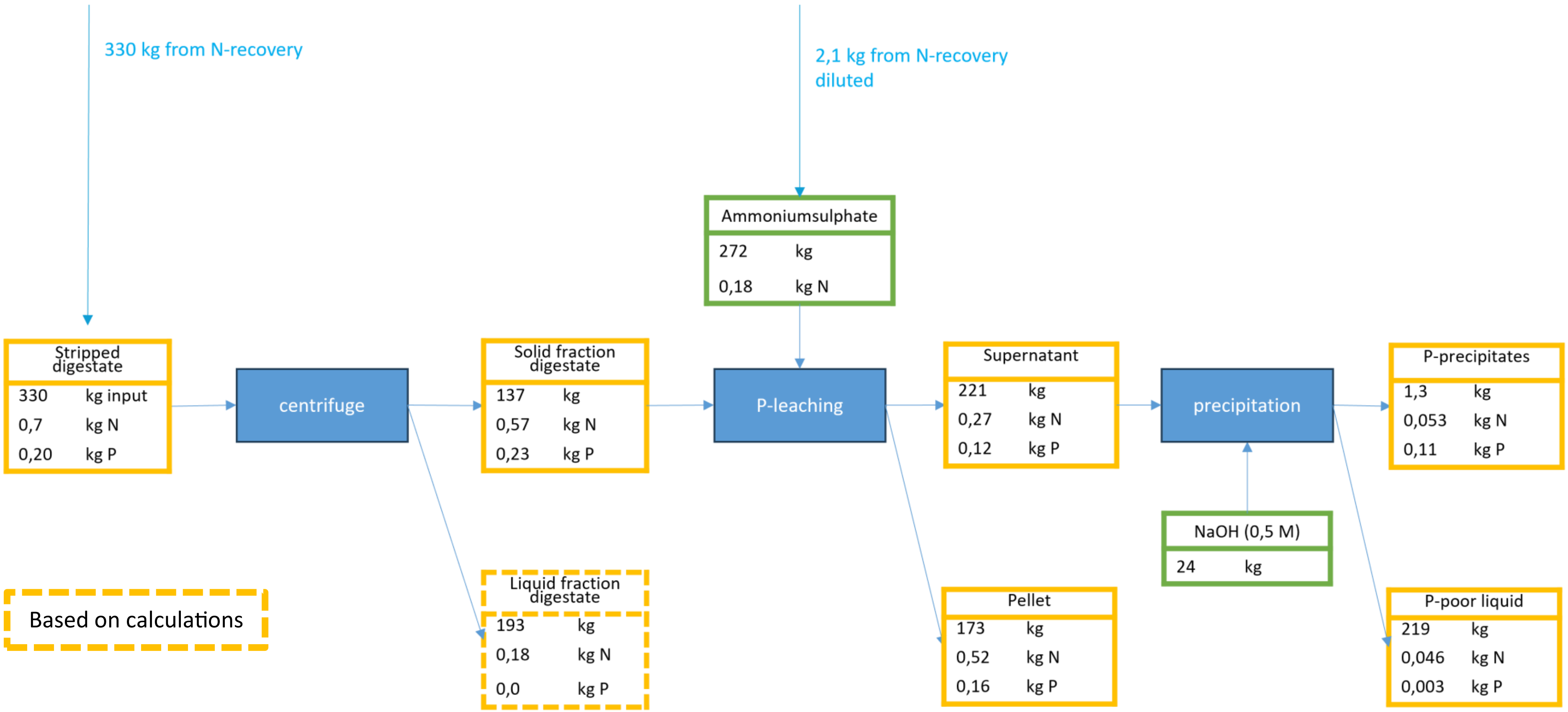


Figure 12. Cascade 3 – mass and nutrient balance implementing (a) post-anaerobic digestion and nitrogen recovery coupled with (b) phosphorus recovery from dairy manure.

3.4 Cascade 4 – post-AD and nitrogen recovery from mixed organic waste

Mass

The closed mass balance can mainly be attributed to the made assumptions (Table 5). For instance, the mass of the digestate after digestion was calculated as the mass of the input subtracted from the mass of the biogas produced. This is for both the first digestion and post-digestion step. The amount of used waste sulphuric acid is calculated based on the measured concentration of the ammonium salt in the pilot scale tests. The waste sulphuric acid is constantly recirculated until the absorption capacity is almost reached and the pH is nearly neutral. A density of 1 kg/l was assumed for the digestate.

Nitrogen

During anaerobic digestion, 29% of the nitrogen was lost (Table 5). This can be attributed to the fact that the characterization of the mixed organic waste and the digestate is performed on a different 'batch'. The feed undergoing digestion had a high variability and the characterization of the MOW and digestate was performed in different time frames. All stripped nitrogen is captured in the waste sulphuric acid. During post-AD, the N-content increased 15%. The total nitrogen content is determined via a TOC/TN measurement, some impurities (e.g. proteins) might have been present in the liquid and interfered with the analysis.

Phosphorus

The overall phosphorus balance is well-fitted (Table 5). This can mainly be attributed to the assumptions made. It was assumed that the phosphorus content did not change during post-digestion and stripping.

Table 5. Cascade 4 - the mass balance, the nitrogen balance, and the phosphorus balance.

	IN	OUT	Difference
Mass (kg)	1020	1020	0,0%
Kg N	5,1	3,9	-23%
Kg P	1,3	1,3	-4,7%

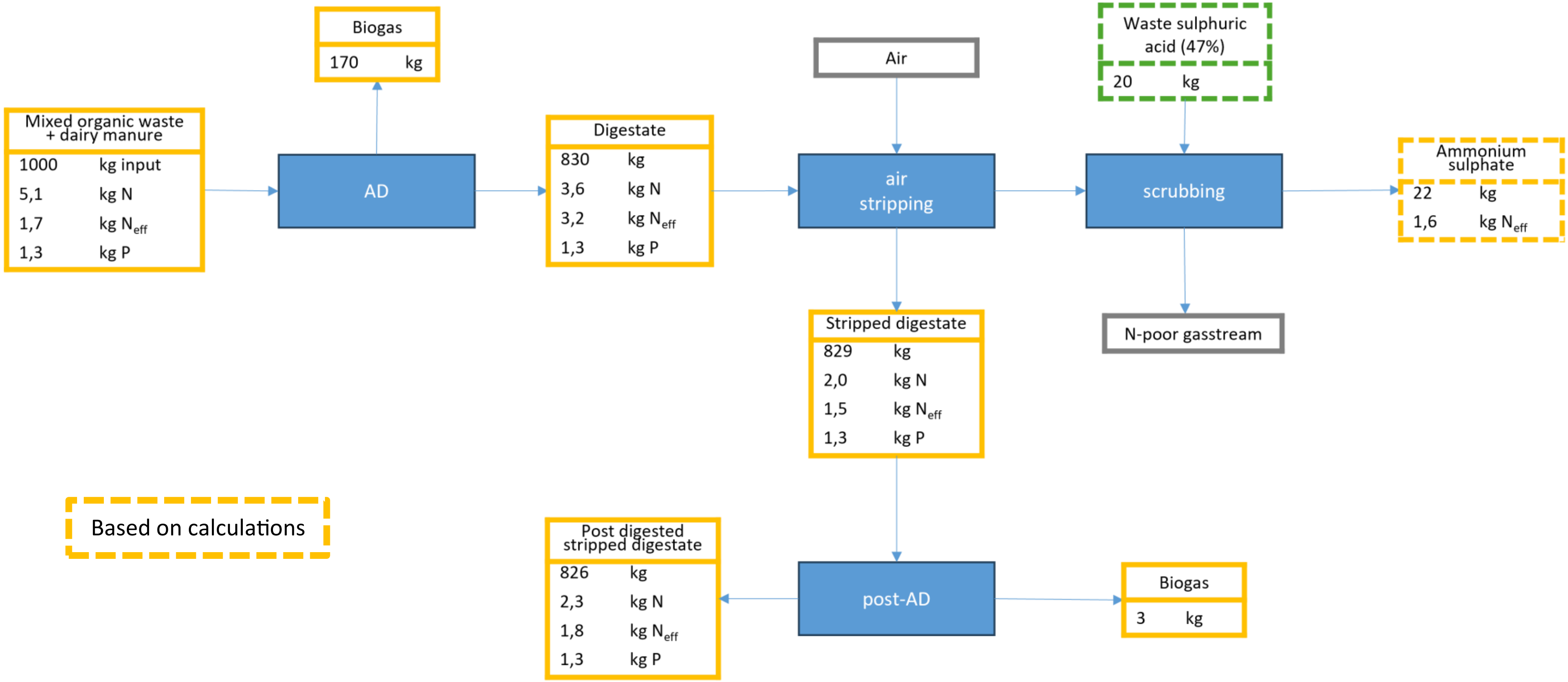


Figure 13. Cascade 4 – mass and nutrient balance implementing post-anaerobic digestion and nitrogen recovery from mixed organic waste and dairy manure.

3.5 Cascade 5- nitrogen recovery and phosphorus recovery as struvite

Important: the first part of the presented mass balance is based on the average data from the lab-scale side-stream vacuum stripping on an internal recirculation line (days 249 to 403). During this period, the organic loading rate to the test and control reactors was gradually changed. Because of the increased loading rate compared to the default scenario, an increased supply of chicken manure is required compared to the default scenario.

Mass

The overall mass balance is closed (Table 6). The mass balance shows a loss in mass after anaerobic digestion, partially due to the production of biogas. Upon verification of the dry matter content, a significant drop is measured. The dry matter content of the input stream is 11,1% and drops to 5,8% in the digestate, resulting in a loss of 22% in dry matter content after anaerobic digestion. This loss can be attributed to foaming and sampling. The total solids content was determined once a week by taking samples from the reactor, not daily in the effluent. This loss is not as distinctly reflected in the mass balance as the input is diluted with water.

Nitrogen

The closed nitrogen balance can mainly be attributed to the made assumptions (Table 6). The difference in nitrogen between the input and digestate is assumed to be in the stripping gas. Scrubbing was not included in the tests. Hence the amount of H_2SO_4, a common scrubbing acid, needed to reach a scrubbing efficiency of 98% was calculated stoichiometrically, taking a safety factor of 1,5 into account. The amount of struvite, and the mass of nitrogen in the struvite, are calculated theoretically based on the phosphate removed in the depleted digestate. Nitrogen was not measured in the nutrient-depleted fraction. Therefore, the same value as in the digestate minus the nitrogen in the struvite was assumed.

Phosphorus

The closed phosphorus balance can mainly be attributed to the made assumptions (Table 6). During the experiments, only the PO_4-P was measured. To attain conformity with the other cascades, a ratio of phosphate to total phosphorus of 75% was assumed for manure and digestate based on literature and calculated for the depleted digestate[1]. The assumption was made that the phosphorus content does not change during digestion. Next to that, the phosphorus recovered as struvite is calculated based on the phosphorus concentration in the depleted digestate. The pilot-scale tests showed a phosphate recovery of 82% from the LFD which is similar to the efficiency obtained in the lab tests with raw digestate (91%).

Table 6. Cascade 5 - the mass balance, the volume balance, the nitrogen balance, and the phosphorus balance.

	IN	OUT	Difference
Mass (kg)	1002	978	-2,4%
Volume (L)	5,5	5,5	0,0%
Kg N	5,5	5,5	0,0%
Kg P	0,28	0,28	0,0%

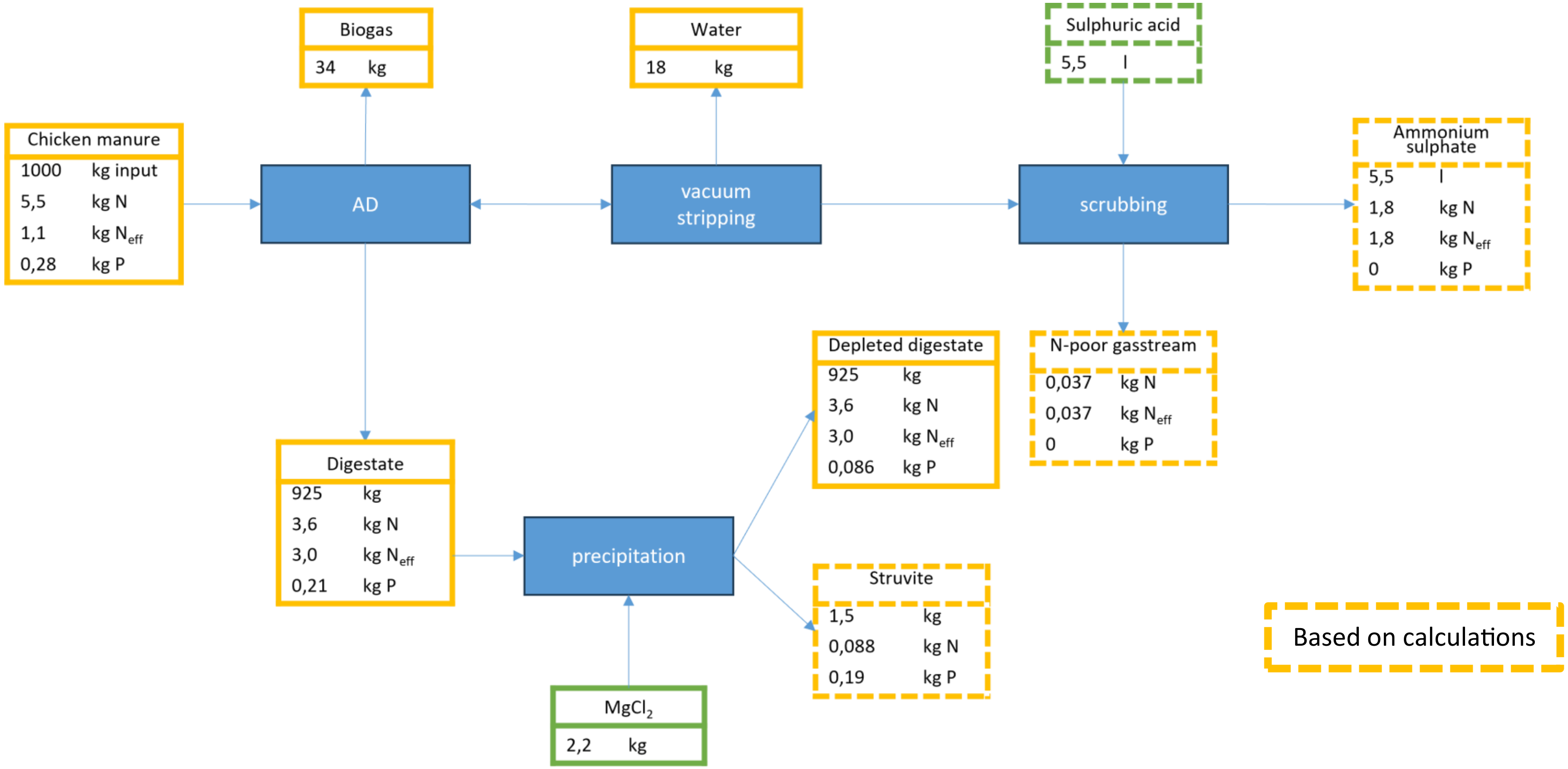


Figure 14. Cascade 5 – mass and nutrient balance implementing vacuum stripping, nitrogen recovery, and phosphorus recovery as struvite.

3.6 Cascade 6- nitrogen recovery and phosphorus recovery on Fe-modified biochar

Mass

The overall mass balance is closed. The mass balance shows a loss in mass after anaerobic digestion, partially due to the production of biogas (Table 7). Upon verification of the dry matter content, a significant drop is measured. The dry matter content of the input stream is 11,1% and falls to 5,8% in the digestate, resulting in a loss of 22% in dry matter content after anaerobic digestion. This loss can be attributed to foaming and sampling. The total solids content was determined once a week by taking samples from the reactor, not daily in the effluent.

Nitrogen

The closed nitrogen balance can mainly be attributed to the made assumptions (Table 7). The difference in nitrogen between the input and digestate is assumed to be in the stripping gas. Scrubbing was not included in the tests, hence the amount of H_2SO_4, a common scrubbing acid, needed to reach a scrubbing efficiency of 98% was calculated stoichiometrically, taking a safety factor of 1,5 into account. Nitrogen was not measured in the nutrient-depleted fraction, therefore the same value as in the digestate was assumed together with the supposition that no nitrogen is adsorbed onto the biochar.

Phosphorus

The closed phosphorus balance can mainly be attributed to the made assumptions (Table 7). During the experiments, only the PO_4-P was measured. To attain conformity with the other cascades a ratio of phosphate to total phosphorus of 75% was assumed for manure and digestate based on literature and calculated for the depleted digestate[1]. The assumption was made that the phosphorus content does not change during digestion. 41% of the phosphate present in the digestate is adsorbed onto the biochar. A higher dosage of the biochar results in a higher P-recovery. This is however not economically feasible.

Table 7. Cascade 6 - the mass balance, the volume balance, the nitrogen balance, and the phosphorus balance.

	IN	OUT	Difference
Mass (kg)	1008	985	-2,3%
Volume (L)	5,5	5,5	0,0%
Kg N	5,5	5,5	0,0%
Kg P	0,28	0,28	0,0%

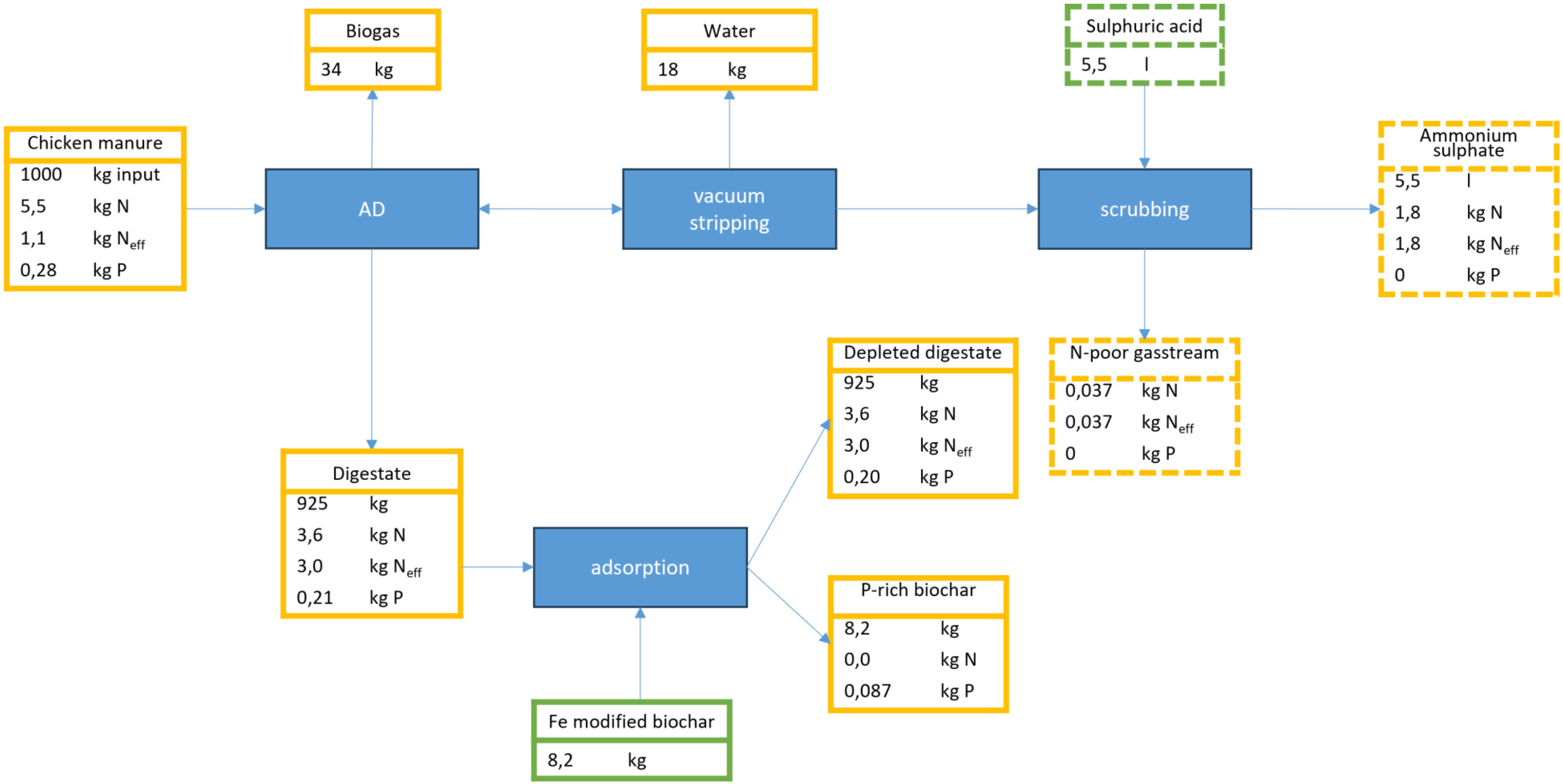


Figure 15. Cascade 6 – mass and nutrient balance implementing vacuum stripping, nitrogen recovery, and phosphorus recovery on Fe-modified biochar.

4 Ecological performance

The mass balances composed during the technical performance serve as a basis to calculate the realized CO_2-emission reduction of the technologies benchmarked to the reference without nutrient recovery. All emissions of carbon dioxide, methane, and nitrous oxide are considered. The functional unit is set at 1 tonne of substrate entering the digester.

4.1 System boundaries

The difference between the reference situation and the technology cascades only occurs during or after anaerobic digestion. Hence, upstream emissions from keeping livestock, cultivation, and harvesting… are outside the boundary. The final step of application on land is also excluded from the system boundary, because occurring emissions strongly depend on external weather conditions and handling; these are expected to differ between the two countries.

4.1.1 Reference scenario

During anaerobic digestion, biogas is produced and valorized in a combined heat and power unit to electricity and heat (Figure 16). Part of this energy is used for the AD process, while the remaining electricity is injected into the grid and replaces fossil electricity. During the digestion process, emissions to air occur (leakages, methane slip, CO_2 from burning the biogas…). After AD, the remaining digestate is temporarily stored in a gas-tight tank. Hence no emissions are expected. The digestate can be spread on land thereby fully or partially replacing artificial fertilizers.

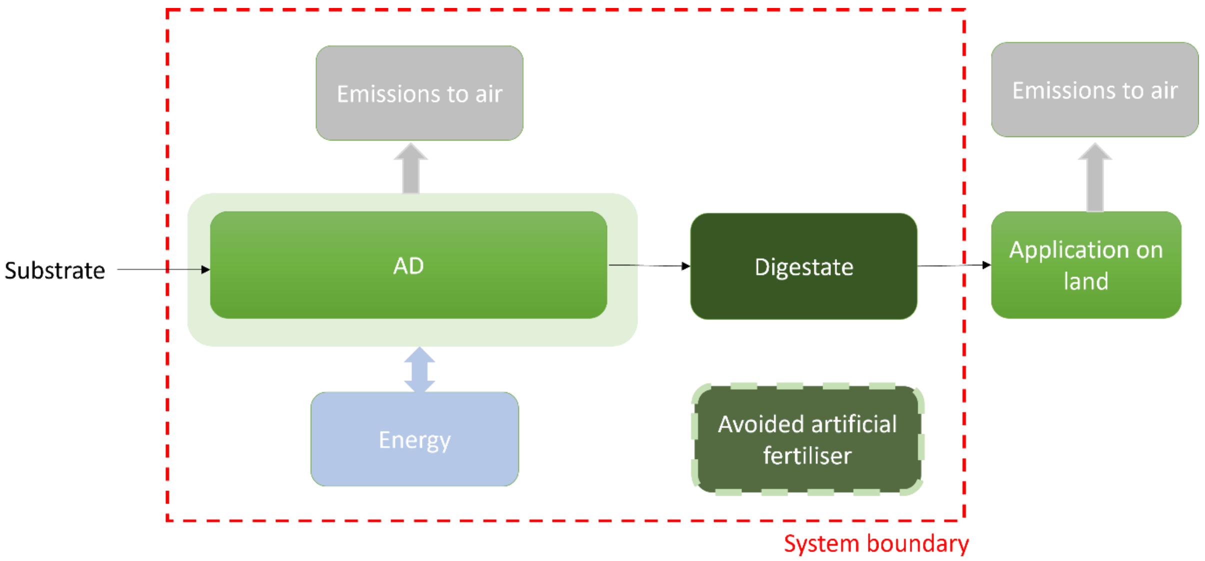


Figure 16. Emissions related to the reference situation without digestate treatment. *The red dashed line represents the system boundary.*

4.1.2 Technology cascades

Implementing the technology cascade in the reference situation results, in additional emissions to the air in the case of increased biogas production (Figure 17). Next to that, more energy can be produced but this energy will partially be used for the post-treatment. Eventually, bio-fertilizers will be produced which can replace mineral fertilizers. An additional source of emissions is the production of the consumables needed for the post-treatment. Next to that, a nutrient-depleted fraction remains.

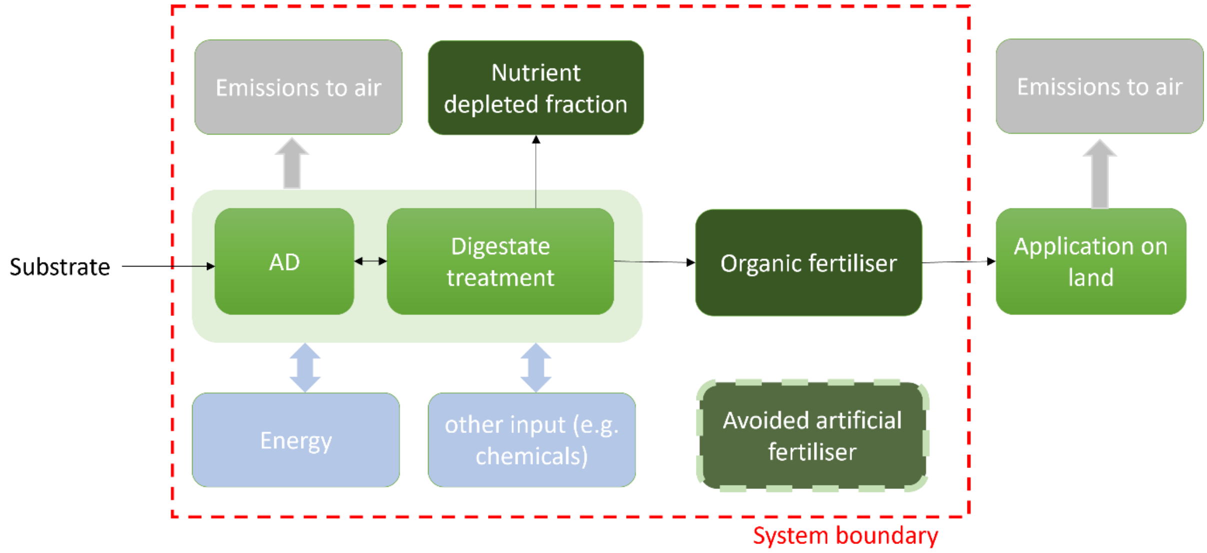


Figure 17. Generalized scheme of emissions related to the different technology cascades. *The red dashed line represents the system boundary.*

4.2 Methodology

Emission data is retrieved from various sources and linked to the technical analysis of the technology cascades. The emissions are categorized into five categories: energy, consumables, avoided fertilizer, nutrient-depleted fraction, and fugitive emissions. The methodology for the different categories is described in the following. All calculations were performed in Microsoft Excel.

4.2.1 Energy

Depending on the technology, different CO_2 emissions are related to electricity production. The mix of technologies and the share of renewable energy differs between the two countries and therefore also the CO_2-emissions related to electricity production (Table 8).

Table 8. Carbon dioxide equivalent emissions for electricity production.

Country	$CO_{2,eq}$ emissions	Source
Belgium, Flanders	195 g $CO_{2,eq}$/kWh_{el}	[2]Vlaams Energie- en Klimaatagentschap
Turkey	440 g $CO_{2,eq}$/kWh_{el}	[3]EVÇED, Çevre ve İklim Daire Başkanlığı

The energy needed for post-treatment is derived from literature or deducted from the pilot-scale tests. As the biogas is burned in a CHP heat is produced, next to electricity. It is assumed that this heat is used for reaching the higher temperatures required in the post-treatment steps (e.g. air stripping is conducted at 70°C) and no $CO_{2,eq}$-emission savings are assigned to the produced heat.

4.2.2 Consumables

Information on the upstream GHG emissions related to the production of the different consumables is extracted from the Ecoinvent database, if available. GHG emissions related to biochar production were not available in the Ecoinvent database. Even though biochar production typically results in emission savings when using best practices, as also bio-oil and syngas are produced, a conservative value of zero was assumed due to variations in emissions depending on the pyrolysis method, feedstock…[4].

4.2.3 Avoided artificial fertilizer

The resulting digestate and up-cycled bio-fertilizers are applied to the land. The fertilizer replacement value (FRV) is determined by the plant available NPK and is partially derived from literature and partially derived from the agronomic assessment performed during the project (Table 9).

Table 9. The fertilizer replacement value for digestate and the obtained organic fertilizers are based on literature.
*Nitrogen Fertilizer Replacement Value (NFRV) and Phosphorus Fertilizer Replacement Value (PFRV).*1

Fertilizers	NFRV	PFRV	Literature
Digestate	62%	100%	[5]Cavalli, et al. and *based on assumptions*
Liquid fraction of digestate	75%	100%	[5]*Cavalli, et al. and based on assumptions*
Post-digested stripped digestate	62%	100%	*based on assumptions*
Mineral fertilizers Ammonium citrate Ammonium sulphate	113%	/	[6]*Hendriks, et al.*
Struvite	33%	115%	*based on assumptions and experimental data*
Fe-modified biochar	/	40%	*based on experimental data*
P-precipitates from digestate leached with waste sulphuric acid	33%	93%	*based on assumptions and experimental data*
P-precipitates from N-stripped digestate leached with ammonium sulphate	33%	104%	*based on assumptions and experimental data*
Pellet	20%	100%	*based on assumptions*

Similar to the assumption made in the Systemic project, the PFRV is set at 100% for digestate, the liquid fraction of digestate, and post-digested stripped digestate[7]. The same assumption is made for the pellet. The NFRV value for the pellet is assumed to be the same as for the dried solid fraction of digestate.

No significant difference in nitrogen availability is expected when the digestate is post-digested. Struvite is mostly applied as a P-fertilizer due to its high P/N ratio, therefore no NFRV has been reported in the literature to our knowledge. A NFRV of 33% is assumed. The application of digestate or one of the other organic fertilizers to the field minimizes the use of artificial fertilizers. Hence, the emissions related to the production of the same amount of plant-available nutrients from artificial fertilizers can be deducted (Table 10**2**).

Table 10. Carbon emissions related to the production of chemical fertilizers. 2

Fertilizers	$CO_{2,eq}$ emissions	Source
P_2O_5 fertilizers	4965 kg $CO_{2,eq}$/kg P	[8]*Giuntoli, et al.*
N fertilizers	4572 kg $CO_{2,eq}$/kg N	[8]*Giuntoli, et al.*

4.2.4 Nutrient-depleted fraction

In most cases, the nutrient-depleted fraction still contains a considerable amount of N, P, and/or K. Therefore, application on land is assumed and the same methodology as described in Section 4.2.3 is applied.

4.2.5 Fugitive emissions

During anaerobic digestion, biogas can escape the reactor through small leakages and weak spots (e.g. pressure relief valve). Next to that, when burning biogas in a CHP a small part of the gas is emitted unburned with the flue gasses, also known as methane slip. These fugitive emissions are typically expressed as a percentage of the methane production. Possible fugitive emissions related to the post-treatment are assumed negligible, as this treatment takes place in enclosed spaces.

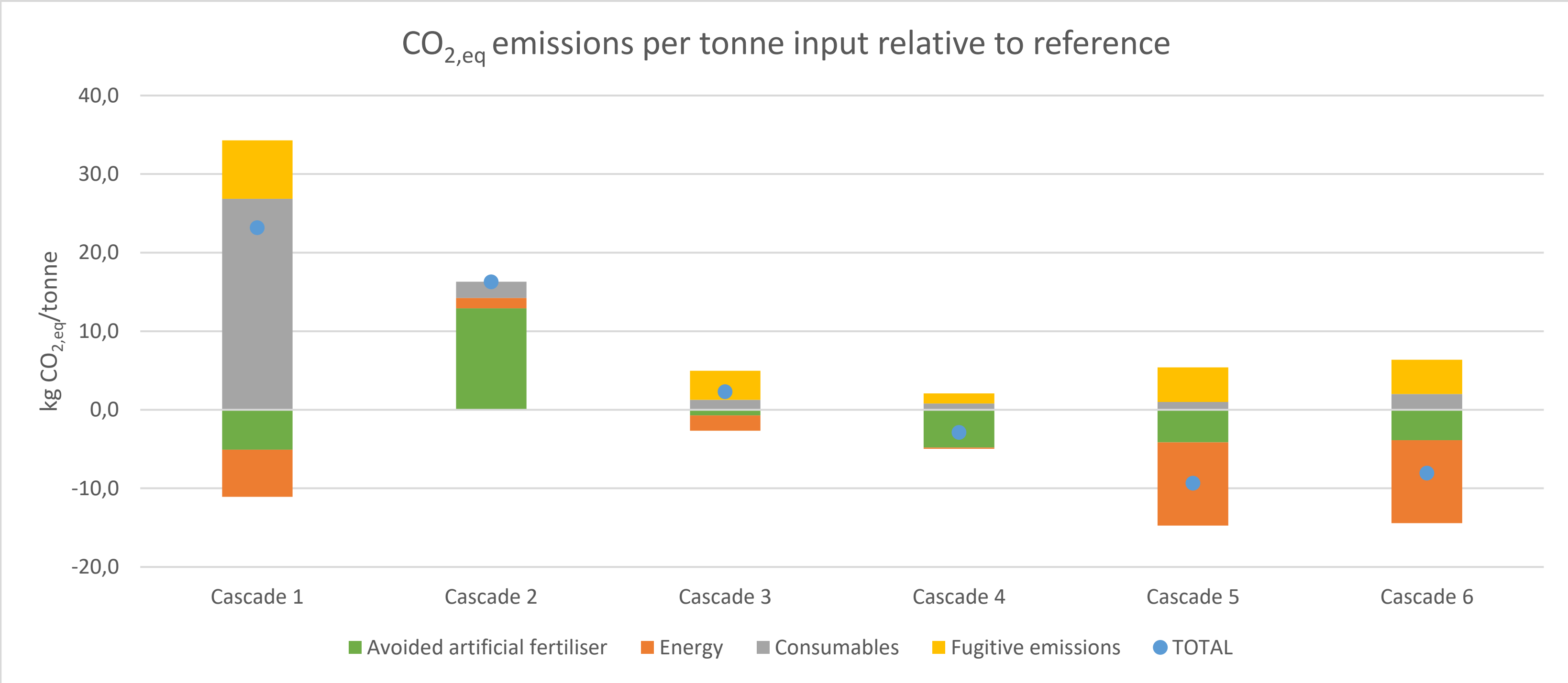
Table 11. Fugitive emissions related to biogas production.*3*

	Methane emissions	Source
Leakages reactor	1,7%	[8]*Giuntoli, et al.*
Methane slip CHP	1,5%	[9]*Verzat, et al.*

4.3 Results

The ecological analysis presented herein is fundamentally based on the technical analysis conducted in the preceding section of this study. It is crucial to acknowledge that the values and outcomes derived from the technical analysis may deviate from real-world conditions. Given these potential discrepancies, the results of the ecological analysis should be interpreted with caution. To fully grasp the context and underpinning of the ecological analysis, readers are strongly encouraged to review the technical analysis chapter. This chapter provides comprehensive details on the assumptions made, the methodologies employed, and the specific limitations encountered. By doing so, readers will gain a clearer understanding of the foundational elements and constraints that shape the ecological assessment, thereby enabling a more informed evaluation of the findings presented.

The difference in emissions ($CO_{2,eq}$) are compared to the reference scenario, for the different technology cascades (Figure 18). A distinction is made between the different emission categories.



	Avoided artificial fertilisers	Energy	Consumables	Fugitive emissions	Total
1	-5,1	-6,0	27	7,4	23
2	13	1,3	2,1	0.0	16
3	-0,7	-1,9	1,3	3,7	2,3
4	-4,8	-0,1	0,8	1,3	-2,9
5	-4,2	-11	1,0	4,4	-9,3
6	-3,9	-11	2,0	4,4	-8,1

Figure 18. $CO_{2,eq}$ -emissions per ton input relative to reference for the different cascades. *C1 = post-AD from dairy manure digestate and N-recovery with citric acid, C2 = P-leaching from SF digestate from pig manure with waste sulphuric acid, C3 = post-AD from dairy manure digestate, N-recovery with sulphuric acid and P-recovery with ammonium sulphate, C4 = post-AD from mixed organic waste digestate and N-recovery with waste sulphuric acid, C5 = vacuum stripping of chicken manure digestate and P-recovery as struvite, C6 = vacuum stripping from chicken manure digestate and P-recovery on Fe-modified biochar.*

Depending on several factors, additional $CO_{2,eq}$-emission, or emission savings are expected within the system boundaries when implementing the technology cascades. Cascades that mainly **focus on nitrogen recovery** with high availability (high NFRV) realize larger emission savings compared to cascades focusing on phosphorus recovery. For example cascade 1 and 4 compared to cascade 2 and 3. This is because the production of mineral N-fertiliser is more energy intensive and has a higher carbon footprint compared to the production of P-fertilisers. For instance, when part of the ammonium sulphate is used for P-leaching more P-fertiliser can be avoided. This is however at the expense of N-fertiliser, thus significantly lowering the possible emission reduction of avoided use of fertilizers.

The additional biogas production, when present, suffices to foresee the following digestate treatment from electricity. Even more, a surplus remains replacing fossil electricity eventually resulting in emission savings. These savings are larger in the Turkish cascades (5-6) compared to the Flemish cascades (1-4) due to the **higher carbon footprint of the electricity produced in Turkey.** However, these savings are diminished by the additional **fugitive emissions** related to the increased methane production. Methane has a high global warming potential resulting in a significant impact when methane escapes to the atmosphere. These emissions can be mitigated by amongst other things frequently performing leak detection tests.

The $CO_{2,eq}$-emission related to the production of **consumables** is comparable between the different cascades, unless when using citric acid as a scrubbing liquid, which has a high carbon footprint when being food-grade. For use as scrubbing liquid, such high-purity and crystalline forms are however not required. Citric acid is typically produced by fermentation. In case of use as scrubbing liquid, the GHG emitting process of the following ion exchange and carbon treatment, evaporation, and drying can be excluded. Next to that, the use of citric acid provides additional benefits as it is safer to use.

By further improving the leaching technology and minimizing the losses, considerable improvements are expected for cascade 2. A lot of the nutrients were lost during the leaching step, therefore resulting in a higher need for artificial fertilizer compared to the reference scenario.

5 Economic performance

5.1 Methodology

To create extra revenues for the biogas sector, six different technology cascade approaches for integrated enhanced biogas production and nutrient recovery as bio-fertilizers from digestate were compiled. The economic performance of these cascades was assessed using five different key performance indicators (KPIs) as was done in the European Union's Horizon 2020 Systemic project[10] The earnings before interest, taxes, and amortization (EBITA) and earnings before interest and taxes (EBIT) margins give a ratio of a company's operating income to net revenue, presented in percentage (Table 12). The EBITA margin measures only the operating cash flows, while the EBIT margin takes the effect of amortization into account. Both margins exclude the interest and tax rates to facilitate the overall comparison of financial results between the six investigated cascades.

However, these margins do not identify the areas of improvement for business performance. For this purpose, the substrate financial productivity, the digestate financial productivity, and the biogas financial productivity are determined (Table 12). The substrate financial productivity relates to the revenues related to the organic substrate processed by the plant per mass unit (ton). The digestate financial productivity relates to the revenues or costs to handle one mass unit of digestate (ton) and allows for a comparison of financial flows before and after implementing a technology cascade. The biogas financial productivity relates to the energy conversion per volume unit (cubic meter) and facilitates the comparison of different potential types of energy outputs of a biogas plant: biogas, electricity, and biomethane including bio-LNG and bio-CNG. Heat is also an energy output but is usually internally consumed during the digestion process.

Table 12. Five different key performance indicators (KPIs) were used to assess the economic performance of each technology cascade. *EBITA: Earnings before interest, taxes, and amortization. EBIT: Earnings before interest and taxes.*

KPI	Unit	Explanation
EBITA margin	€ EBITA / € revenues in %	Overall operational financial performance of business exclusive of interests and amortization in percent of revenues
EBIT margin	€ EBIT / € revenues in %	Overall operational and capital expenses related to the financial performance of business exclusive interests in percent of revenues
Substrate financial productivity	€ / t	Measures overall substrate-related financial productivity; the total revenues of the plant per ton feedstock processed. Indicator of the overall financial productivity of processed substrates regardless of which activity of the digestion plant.
Digestate financial productivity	€ / t	Measures the digestate-related financial productivity of substrates; net revenues of effluents or products (digestate, recycled products) per ton of feedstock. Indicator of the cost or revenues of handling/disposing of or selling the solid and liquid materials coming out of the digester which is affected by the valorization of the digestate and use/sale of bio-fertilizers.
Biogas financial productivity	€ / m^3	Measures the energy-related financial productivity of biogas; the net revenues from energy supplies per m^3 of biogas supplied. Indicator for the revenues generated from a given biogas output and affected by the type of energy carrier supply and support schemes.

To determine these KPIs, the yearly expenses and revenues of the biogas plant are assigned to seven different categories, as was done in the systemic project.

(1) "Substrate" is defined as the digester input, which can be biowaste, manure, or energy crops. Input delivered with a gate-fee is considered to be a revenue, in all other cases, it is an expense.

(2) "Energy and operational support" takes into account the conversion of biogas to electricity and heat. In Flanders, you receive operational support under certain conditions for burning biogas in a CHP to produce electricity and heat[11]. For the production of green electricity, the biogas plant owner can apply for so-called *groenestroomcertificaten* or *green electricity certificates* (GSC). For reducing primary energy use, achieved by using a CHP engine, the owner can apply for so-called *warmtekrachtcertificaten* (WKC) or *CHP certificates*. The plant receives this operational support on top of the market price for electricity. Grey electricity used on site and the use of natural gas is seen as an expense. In Turkey, as informed by Seleda, electricity produced with the support of state incentives is marketed through the Renewable Energy Resources Support Mechanism (YEKDEM) for ten years[12]. This mechanism combines revenues for heat and electricity production. Additionally, hot water and steam production generate revenues. The energy consumption of the business is seen as an expense.

(3) "Product sales/savings" takes into account the revenues from selling the bio-fertilizers or saving on mineral fertilizers by using the bio-fertiliser.

(4) "Consumables" include expenses for general operation like polymers, antifoam, and other substances.

(5) "Digestate & bio-fertilizer handling" includes expenses or revenues for the disposal of digestate or processed products hereof.

(6) "Operations" takes into account the expenses for maintenance, personnel, and overhead.

(7) "Amortization" accounts for the yearly investment cost for the biogas plant, building, and machines. For Waterleau, this amortization is paid over 20 years, while for Seleda this period is 40 years.

5.1.1 Reference scenarios

The default business scenarios as defined in Chapter 2 are fine-tuned to account for the different types of input flows (dairy manure, pig manure, mixed organic waste, and chicken manure). As such, four different reference scenarios are created (Table 13), to ensure the most accurate comparison possible. In contrast to the technical analysis, an input volume of 72.054 tons or 214.950 tons is considered respectively for the reference scenarios based on Waterleau and reference scenarios based on Seleda. By using the input volumes of the business reference the values for consumables, maintenance, cost for disposal, and general costs can be maintained.

In real life, Waterleau co-digests mixed organic waste and dairy manure and valorizes the raw digestate through reverse osmosis as mineral concentrate. To analyze the impact of implementing the technology cascades, it is assumed that raw digestate is not valorized in the reference scenarios. The raw digestate is disposed of at 18.85 euros per ton as informed by Waterleau. This indicates no revenues from sales/savings in the reference scenarios because the disposal of raw digestate as an end product is an expense as "Digestate and bio-fertilizer handling" (Chapter 5.1.). For this assumption, the expenses of the reverse osmosis installation should be excluded from Waterleau's "Amortization" in all reference scenarios based on Waterleau (Chapter 5.1.) This is not possible due to insufficient information, but it will not influence the economic analysis since the expenses are taken into account for both the reference scenario and the implementation of the technology cascades.

Reference scenario 1 retrieves economic data from Waterleau (2023) without digestate valorization. Reference scenario 2 combines the actual data retrieved from the Waterleau plant with the available lab-scale data on dairy manure digestion. To allow a fair comparison, the biogas production is altered based on the results from the lab-scale tests with dairy manure. Reference scenario 3 combines the actual data retrieved from the Waterleau plant with data on pig manure digestion in a farm-scale digester. To allow a fair comparison, it is assumed that the plant digests only pig manure, without further processing of the digestate. In real life, Seleda co-digests mixed organic waste and different manure types without valorizing the digestate. Reference scenario 4 retrieves economic data from Seleda (2023) and combines this data with lab-scale data on chicken manure digestion.

Table 13. Four different reference scenarios were generated for each type of manure input.

Business reference	Input stream	Input volume (ton)	Technology cascade	Reference scenario
Waterleau	Mixed organic waste & dairy manure	72.054	1, 3	1
Waterleau	Dairy manure	72.054	2	2
Waterleau	Pig manure	72.054	4	3
Seleda	Chicken manure	214.950	5, 6	4

Differences between the reference scenarios for the category “Substrates” can be explained by input streams with/without a gate-fee (Table 14). In Flanders, the disposal of raw digestate is an expense, while this is a small revenue in Turkey as seen in “Digestate & bio-fertilizer handling”. The “Amortization” and “Operations” expenses for Waterleau are higher compared to Seleda, which can partially be explained by the additional expenses for the reverse osmosis installation. The reference scenarios may be unprofitable due to some assumptions made. These reference scenarios are important to assess the impact of implementing the different technology cascades on the economic performance of the business case (Table 15).

Table 14. Profit and loss summary in euros for the four different reference scenarios. *Reference scenario 1 – Waterleau plant processing 72.054 tons of mixed organic waste (MOW) and dairy manure. Reference scenario 2 – Waterleau plant processing 72.054 tons of dairy manure. Reference scenario 3 - Waterleau plant processing 72.054 ton pig manure. Reference scenario 4 – Seleda plant processing 214.950 tons of chicken manure.*

	Reference 1			Reference 2			Reference 3			Reference 4		
	Revenues	*Expenses*	*Balance*	*Revenues*	*Expenses*	*Balance*	*Revenues*	*Expenses*	*Balance*	*Revenues*	*Expenses*	*Balance*
Substrate	606.413	1.461.516	-855.103	1.088.015	-	1.088.015	1.088.015	-	1.088.015	-	1.592.395	-1.592.395
Energy and operational support	3.681.507	51.362	3.630.145	376.513	568.140	-191.627	325.532	638.524	-312.992	6.052.796	325.614	5.727.182
Product sales/savings	-	-	0	-	-	0	-	-	0	-	-	0
Consumables	-	516.321	-516.321	-	516.321	-516.321	-	516.321	-516.321	-	26.648	-26.648
Digestate & Bio-fertilizer handling	-	198.300	-198.300	-	198.300	-198.300	-	198.300	-198.300	6.260	-	6.260
Operations	-	2.156.049	-2.156.04	-	2.156.049	-2.156.04	-	2.156.049	-2.156.04	-	887.132	-887.132
Amortization (20 yrs.)	-	950.000	-950.000	-	950.000	-950.000	-	950.000	-950.000	-	525.490	-525.490
	4.287.920	**5.333.548**	**-1.045.628**	**1.464.528**	**4.388.810**	**-2.924.282**	**1.413.547**	**4.459.194**	**-3.045.647**	**6.059.056**	**3.357.279**	**2.728.425**

Table 15. Key performance indicators for the four different reference scenarios. *Reference scenario 1 - Waterleau processing 72.054 tons of mixed organic waste and dairy manure. Reference scenario 2 – Waterleau processing 72.054 tons of dairy manure. Reference scenario 3 – Waterleau processing 72.054 tons of pig manure. Reference scenario 4 – Seleda processing 214.0950 tons of chicken manure.*

	Reference 1		**Reference 2**		**Reference 3**		**Reference 4**	
Type/Description	Reference	KPI	Reference	KPI	Reference	KPI	Reference	KPI
EBITA margin (€ EBITA/ € revenues in %)	-95.628	-2%	-1.974.282	-135%	-2.095.647	-148%	3.227.267	53%
EBIT margin (€ EBIT/ € revenues in %)	-1.045.928	-24%	-2.924.282	-200%	-3.045.647	-215%	2.701.777	45%
Substrate financial productivity (€/ t) EUR total revenue/tonnes feedstock	72.054	59.5	72.054	20.33	72.054	19.62	214.950	28.2
Digestate financial productivity (€/ t) EUR digestate handling/ tonnes feedstock	72.054	-2.75	72.054	-2.75	72.054	-2.75	214.950	0.03
Biogas financial productivity (€/ m³) EUR energy supplies/m³ biogas	10.808.100	0.34	1.716.326	0.22	1.398.568	0.23	26.868.750	0.23

5.1.2 Technology cascades

The KPIs of implementing a technology cascade are calculated using the data from the technical assessment (Chapter 5.1). The economic impact of implementing a technology cascade is assessed by comparing the business scenario with the reference situation (Chapter 5.1.1 Methodology). Implementing the technology cascade influences the revenues/expenses for "Energy and operational support". Moreover, additional biogas production delivers revenues from certificates for conversion to electricity, while additional energy consumption related to digestate valorization is considered an expense. If insufficient green energy was produced for the operational energy demand of the plant combined with the technology cascade, it was assumed that half of the energy consumption was grey electricity and half the use of natural gas.

For each cascade, two different scenarios are considered: the bio-fertilizers are sold (sales) or the bio-fertilizers are used as fertilizers replacement for mineral fertilizers on own fields, thus saving in purchase expenses (savings). In Europe, the Nitrates Directive limits the application of livestock manure, including all products derived from livestock manure to 170 kg N/ha/y in Nitrogen Sensitive Zone (NSZs). Products like ammonium citrate, ammonium sulphate, and P-precipitate derived from livestock manure compete with raw manure for disposal under this application limit in Flanders (NSZ). Turkey also has NSZs and is in the process of setting up a similar system to regulate the application of fertilizers. Only products that are defined in the RENURE proposal from the European Commission were considered eligible to generate revenues as "sales"[13]. A similar price for the nitrogen and phosphorus content of these products was given as for mineral fertilizers[14], as informed by Ludwig Hermann (Systemic). The plant availability of the nutrients was not taken into account because most farmers, currently, don't pay attention to this NFRV or PFRV when purchasing mineral fertilizers.

Implementing the cascades also increases expenses for the chemical products as "Consumables" used to generate the bio-fertilizers. The implementation can also influence the costs for disposal of digestate or by-products as "Digestate & bio-fertilizer handling". The cost for disposal of the liquid fraction of digestate and P-poor liquid was assumed to be the same as for raw digestate (€18.85 per ton), due to the absence of data regarding the disposal of these products.

5.2 Results

The big expenses come from “Operations”, “Amortization”, and “Consumables” and the big revenues mainly come from “Substrate” and “Energy and operational support” (Table 16). Implementing technology cascades that produce additional biogas through post-digestion or recirculation of stripped digestate increases the revenues for “Energy and operational support” compared to their reference scenario. The technology cascades that use chemicals to valorize the raw digestate increase the expenses for “Consumables” in comparison to the reference scenario.

Mainly in Turkey, selling the bio-fertilizers generates “Product sales” revenues. Saving on mineral fertilizers by replacing them with the produced bio-fertilizers generates extra “Product savings” revenues. Both “Product sales” and “Product savings” revenues are a new form of income for the biogas plant compared to the reference scenario. However, for most technology cascades this revenue does not compensate for the additional “Consumables” expense, especially not in Turkey. In Flanders, the expenses for “Digestate & bio-fertilizer handling” fluctuate between technology cascades depending on the volume of stripped digestate or products thereof that need to be disposed of. For instance, in technology cascade 2 this expense increases compared to reference because of the additional chemicals (900 kg sulphuric acid) used to produce the bio-fertilizers. In cascades 2 and 3, disposal of the pellets generates revenues for “Digestate & bio-fertilizer handling”. In Turkey, this raw digestate even generates a small revenue (17 Turkish Lira per ton) for “Digestate & bio-fertilizer handling”.

Implementing technology cascades that include additional biogas production through post-digestion or recirculation, increases the EBITA and EBIT margins making the business more profitable (Table 17). For instance: technology cascade 2 only focuses on valorizing digestate without additional biogas production, which results in a less profitable business scenario. The substrate financial productivity increases mainly due to revenues from additional biogas production. Generally, this increase is higher in the savings scenario than in the sales scenario. The reason is that the bio-fertilizers could not be sold in the current market. The digestate financial productivity increases mainly because valorizing digestate generates less digestate to dispose of while adding chemicals for valorization can increase the digestate volume that needs to be disposed of. The value is higher for the savings scenario compared to the selling scenario because in the current market, more revenues are generated by using bio-based fertilizers as replacement for mineral fertilizers than selling them. The biogas financial productivity remains similar for the cascades based on Waterleau reciprocally and Seleda reciprocally. For instance, this value increases for the implementation of technology cascade 4 because co-digestion generates enough green electricity to suffice the operational energy demand of the plant.

In contrast, implementing technology cascades 1, 2, and 3 (mono-digestion) generates insufficient biogas-derived energy to supply the energy demand. This implicates no revenues for putting green electricity on the grid, while also increasing expenses for grey electricity and natural gas.

The economic analysis is fundamentally based on the technical analysis conducted in Chapter 3. It is crucial to acknowledge that the values and outcomes derived from this technical analysis may deviate from real scenario and should be interpreted with caution. To fully grasp the context and underpinning of the economic analysis, readers are strongly encouraged to review the technical analysis chapter. This chapter provides comprehensive details on the assumptions made, the methodologies employed, and the specific limitations encountered. By doing so, readers will gain a clearer understanding of the foundational elements and constraints that shape the economic assessment, thereby enabling a more informed evaluation of the findings presented.

Table 16. Profit and loss summary in EUR for the different technology cascades. *Technology cascade 1 – dairy manure digestion with post-digestion and nitrogen recovery. Technology cascade 2 – pig manure digestion with phosphorus recovery. Technology cascade 3 – dairy manure digestion with post-digestion and nitrogen and phosphorus recovery. Technology cascade 4 – mixed organic waste and dairy manure digestion with post-digestion and nitrogen recovery. Technology cascade 5 – chicken manure digestion with recirculation and nitrogen & phosphorus recovery (struvite). Technology cascade 6 – chicken manure digestion with recirculation and nitrogen and phosphorus recovery (biochar). The bio-fertilizers are sold (sales) or used as mineral fertilizer replacements (savings). Operations include personnel, overhead, maintenance, and repair.*

	Cascade 1			***Cascade 2***			***Cascade 3***		
	Revenue	*Expenses*	*Balance*	*Revenue*	*Expenses*	*Balance*	*Revenue*	*Expenses*	*Balance*
Substrate	1.088.015	-	1.088.015	1.088.015	-	1.088.015	1.088.015	-	1.088.015
Energy and operational support	613.613	341.809	271.804	306.806	700.251	-393.445	496.486	574.306	-77.820
Product sales	-	-	0	20.103	-	20.103	2.122	-	2.122
Product savings	115.286	-	115.286	46.835	-	46.835	12.249	-	12.249
Consumables	-	604.760	-604.760	-	714.803	-3.204.989	-	688.745	-688.745
Digestate & bio-fertilizer handling	-	194.427	-194.427	6629	265.155	-258.526	36.747	81.699	-44.952
Operations	-	2.156.049	-2.156.049	-	2.156.049	-2.156.049	-	2.156.049	-2.156.049
Amortization (20 yrs.)	-	950.000	-950.000	-	950.000	-950.000	-	950.000	-950.000
Balance sales	**1.701.628**	**4.247.045**	**-2.545.417**	**1.421.553**	**4.786.579**	**-3.365.026**	**1.623.370**	**4.450.799**	**-2.827.429**
Balance savings	**1.816.914**	**4.247.045**	**-2.430.131**	**1.448.285**	**4.786.579**	**-3.338.294**	**1.633.497**	**4.450.799**	**-2.817.302**
	Cascade 4			**Cascade 5**			**Cascade 6**		
Substrate	606.412	1.461.516	-855.104	-	1.592.395	-1.592.395	-	1.592.395	-1.592.395
Energy and operational support	3.683.493	51.362	3.632.131	9.454.352	511.562	8.942.790	9.454.352	511.562	8.942.790
Product sales	-	-	0	878.301	-	1.626	878.302	-	878.302
Product savings	115.286	-	115.286	273.805	-	273.805	386.910	-	-386.910
Consumables	-	573.964	-573.964	-	4.260.768	-4.260.768	-	11.625.537	-11.625.537
Digestate & bio-fertilizer handling	-	163.795	-163.795	14.854	-	14.854	-	17.216	-16.470
Operations	-	2.156.049	-2.156.049	-	877.132	-877.132	-	887.132	-887.132
Amortization (20 yrs.)	-	950.000	-950.000	-	525.490	-525.490	-	525.490	-525.490
Balance sales	**4.289.905**	**5.356.686**	**-1.066.781**	**10.347.507**	**7.777.347**	**2.570.160**	**10.332.654**	**15.159.332**	**-4.826.678**
Balance savings	**4.405.191**	**5.356.686**	**-951.495**	**10.286.016**	**7.777.347**	**2.508.669**	**9.851.262**	**15.159.332**	**-5.308.070**

Table 17. Key performance indicators for the different technology cascades. *Technology cascade 1 – dairy manure digestion with post-digestion and nitrogen recovery. Technology cascade 2 – pig manure digestion with phosphorus recovery. Technology cascade 3 – dairy manure digestion with post-digestion and nitrogen and phosphorus recovery. Technology cascade 4 – mixed organic waste and dairy manure digestion with post digestion and nitrogen recovery. Technology cascade 5 – chicken manure digestion with recirculation and nitrogen & phosphorus recovery (struvite). Technology cascade 6 – chicken manure digestion with recirculation and nitrogen and phosphorus recovery (biochar). The Bio-fertilizers are sold (sales) or used as mineral fertilizer replacements (savings). Operations include personnel, overhead, maintenance, and repair.*

	Cascade 1				Cascade 2				Cascade 3			
	Sales		**Savings**		**Sales**		**Savings**		**Sales**		**Savings**	
KPI type (unit)	**Reference**	**KPI**	**Reference**	**KPI**	**Reference**	**KPI**	**Reference**	**KPI**	**Reference**	**KPI**	**Reference**	**KPI**
EBITA margin (€ EBITA / € revenues in %)	-1.595.417	-94%	-1.480.131	-81%	-2.415.026	-170%	-2.388.294	-165%	-1.877.429	-116%	-1.867.302	-114%
EBIT margin (€ EBITA / € revenues in %)	-2.545.417	-150%	-2.430.131	-134%	-3.365.026	-237%	-3.338.294	-230%	-2.827.429	-174%	-2.817.302	-172%
Substrate financial productivity (€ / t)	72.054	23.62	72.054	25.22	72.054	19.73	72.054	20.01	72.054	22.53	72.054	22.67
Digestate financial productivity (€ / t)	72.054	-2.7	72.054	-1.10	72.054	-3.31	72.054	-2.94	72.054	-0,59	72.054	-0.45
Biogas financial productivity (€ / m³)	2.797.136	0.22	2.797.136	0,22	1.398.568	0,22	1.398.568	0,22	2.263.216	0,22	2.263.216	0,22
	Cascade 4				**Cascade 5**				**Cascade 6**			
EBITA margin (€ EBITA / € revenues in %)	-116.781	-3%	-1.495	0%	3.095.650	30%	3.034.159	29%	-4.301.188	-42%	-4.782.580	-49%
EBIT margin (€ EBITA / € revenues in %)	-1.066.781	-25%	-951.495	-22%	2.570.160	25%	2.508.669	24%	-4.826.678	-47%	-5.308.070	-54%
Substrate financial productivity (€ / t)	72.054	59.54	72.054	61.14	214.950	48.14	214.950	47.85	214.950	48.07	214.950	45.83
Digestate financial productivity (€ / t)	72.054	-2.27	72.054	-0.67	214.950	4.16	214.950	3.87	214.950	4.01	214.950	1.72
Biogas financial productivity (€ / m³)	10.999.043	0.33	10.999.043	0,33	35.466.750	0,27	35.466.750	0,27	35.466.750	0.27	35.466.750	0.27

6 Value-chain assessment

This chapter provides an overview of the technical, ecological, and economic evaluation of the six technology cascades (Table 18). **For a complete understanding, the readers are strongly encouraged to review the previous chapters.**

6.1 Cascade 1 – post AD and nitrogen recovery from dairy manure

The cascade recovers nitrogen from dairy manure digestate as ammonium citrate and post-digests the stripped-digestate to generate additional biogas. The cascade demonstrates a strong technical and economic performance but faces ecological challenges (Table 18). Moreover, it excels in additional biogas production and shows a positive outcome for nitrogen (N) recovery as ammonium citrate, a form easily available for crops. It does not provide phosphorus (P) recovery as a bio-fertilizer other than the phosphate present in the stripped digestate. The poor ecological performance can mostly be attributed to the consumable citric acid. However, the actual ecological performance is expected to be significantly better because the $CO_{2,eq}$-emissions related to its production were overestimated. The calculations were based on food-grade citric acid as solid crystals and the actual product used is a 50% solution. Additionally, even a waste acid could be used to improve the ecological performance. The economic performance demonstrates that implementing the cascade increases both the EBITA margin and digestate financial productivity. The business case becomes more profitable because of extra revenues from additional biogas production/conversion to electricity and savings on mineral fertilizers by using ammonium citrate. Both compensate for the additional expenses linked to the energy demand for the stripping-scrubbing installation and the expenses for citric acid.

6.2 Cascade 2- phosphorus recovery from pig manure

The cascade recovers phosphorus from pig manure as P-precipitate. It performs poorly across the technical, ecological, and economic evaluations (Table 18). For the technical evaluation, there is no additional biogas production or nitrogen recovery as bio-fertilizer and the phosphorus recovery occurs suboptimal. The poor ecological aspects of the cascade are explained by lower $CO_{2,eq}$-emission savings compared to the reference. The economic performance indicates that implementing the cascade makes the business less profitable, demonstrated by a decrease in EBITA margin and digestate financial productivity. There are no extra revenues from additional biogas production/electricity conversion and the sales or savings from the P-precipitate are unable to compensate for the extra expenses for the centrifuge's energy demand and the additional expenses for the sulphuric acid and sodium hydroxide.

The business case can become more profitable by using waste sulphuric acid and sodium hydroxide of lesser quality. This poor assessment can mostly be attributed to the high losses that occurred during the treatment cascade. Optimizations should be performed to reduce the material losses, increase the recoveries, and obtain better results.

6.3 Cascade 3 – post AD, nitrogen and phosphorus recovery from dairy manure

The cascade recovers nitrogen and phosphorus from dairy manure as P-precipitate combined with post-digestion of stripped-digestate. It offers a balanced approach with strengths in technical and economic areas but moderate ecological performance (Table 18). The technical evaluation demonstrates efficient additional biogas production, efficient nitrogen recovery, and excellent phosphorus recovery. Ecologically, it results in moderately lower $CO_{2,eq}$-emission savings compared to the reference mostly related to part of the ammonium sulphate being used for the phosphorus recovery. The end product has a lower nitrogen availability for the crop and thus it replaces less mineral fertilizer. Implementing the cascade improves the economic performance of the plant demonstrated by the increase in both the EBITA-margin and the digestate financial productivity. The are extra revenues from additional biogas production/energy conversion and pellet disposal, even more than the sales/savings of the bio-fertilizer. These compensate for the extra expenses linked to the additional energy demand of the centrifuge and the purchase of sulphuric acid and sodium hydroxide. In addition, separating the stripped-digestate by centrifuge and selling the produced pellets decreases the expenses for "Digestate & bio-fertilizer handling". Because of insufficient data, the amount of digestate for post-digestion and phosphorus recovery is halved whilst this is not expected in practice. Therefore, the assessment is an underestimation of the potential.

6.4 Cascade 4 – post-AD and nitrogen recovery from mixed organic waste

The cascade recovers nitrogen from mixed organic waste and dairy manure as ammonium sulphate and post-digests stripped-digestate. It indicates mixed technical, ecological, and economic strengths and weaknesses (Table 18). For the technical evaluation, the additional biogas production is low, the nitrogen recovery increases but there is no phosphorus recovery. This low biogas production is related to the characteristics of the digestate (Chapter 7). The ecological evaluation indicates additional $CO_{2,eq}$-emission savings compared to the reference. The EBITA margin worsens for the sales scenario, while it improves for the savings scenario. The digestate financial productivity is also higher for the savings scenario, compared to the sales scenario. The sales scenario is less profitable because the extra revenues from the additional biogas production/energy conversion are small and selling ammonium sulphate does not generate revenues.

In addition, there are extra expenses for the stripping-scrubbing installation's energy demand. In contrast, the savings scenario is more profitable compared to the reference because the biogas revenues and savings compensate for the additional energy expense and expenses for sulphuric acid. The improved digestate financial productivity for the sales scenario, without sales of bio-fertilizer, can be explained by the decreased cost linked to the disposal of less stripped digestate compared to the reference.

6.5 Cascade 5- nitrogen recovery and phosphorus recovery as struvite

The cascade recovers nitrogen and phosphorus from chicken manure as ammonium sulphate and struvite combined with recirculation of stripped-digestate. It highlights strong ecological benefits with mixed technical and economic outcomes (Table 18). Technically, it shows good additional biogas production, poor nitrogen recovery as only part of the digestate is stripped, and excellent phosphorus recovery. Ecologically, it exhibits excellent additional $CO_{2,eq}$-emissions reductions compared to the reference. This can mostly be attributed to the additional avoidance of fossil electricity production. The economic evaluation indicates that implementing the cascade decreases the profitability for both sales and savings, but increases the digestate financial productivity. There are plenty of extra revenues from additional biogas production/energy conversion and sales/savings from ammonium sulphate and struvite. However, these do not compensate for the high expenses of sulphuric acid and magnesium chloride. The consumable expenses considered process for high-purity substances. Using waste sulphuric acid and magnesite dust, a waste product that is plenty available in Turkey could make the business more profitable[15].

6.6 Cascade 6- nitrogen recovery and phosphorus recovery on Fe-modified biochar

The cascade recovers nitrogen and phosphorus from chicken manure as ammonium sulphate and P-biochar combined with recirculation of stripped-digestate. It demonstrates ecological strengths with significant economic weaknesses and moderate technical performance (Table 18). The technical and ecological evaluation resemble those of technology cascade 5. The economic performance resembles this of technology cascade 5 with the difference that implementing the cascade is even less profitable compared to the reference. The Fe-modified corn cob biochar used to produce P-biochar is even more expensive compared to the magnesium chloride used to produce struvite.

In conclusion, the evaluation of various cascades for nitrogen and phosphorus recovery from different organic waste sources reveals diverse performances across technical, ecological, and economic dimensions. Each cascade demonstrates unique strengths and weaknesses influenced by varying experimental setups, assumptions, and regional frameworks differing between Turkey and Flanders. Consequently, direct comparisons among the cascades should be approached with caution due to these contextual differences.

Table 18. Value chain assessment for all six technology cascades. *The technical evaluation considers the additional amount of biogas produced, the nitrogen recovery efficiency, and the phosphorus recovery efficiency. The ecological evaluation only considers the savings on CO2,eq-emissions. The economic evaluation considers the EBITA margin and digestate financial productivity for both the sales and savings scenarios. The sales scenario reflects selling the produced bio-fertilizer and the savings scenario reflects using the bio-fertilizer as mineral fertilizer replacement value. The symbol -- indicates a big decrease in the value compared to the reference. The symbol – indicates a small decrease in the value compared to the reference. The symbol / indicates that this was not applicable. The symbol + indicates a small increase compared to the reference. The symbol ++ indicates a big increase compared to the reference.*

	Technical evaluation			Ecological evaluation	Economic evaluation			
Technology cascade	Additional biogas	N-recovery	P-recovery	$CO_{2,eq}$-emissions	EBITA margin sales	EBITA margin savings	Digestate financial productivity sales	Digestate financial productivity savings
1	++	+	/	--	++	++	+	+
2	/	/	-	--	-	-	-	-
3	+	+	++	-	+	+	++	++
4	-	+	/	+	-	+	+	++
5	+	-	++	++	-	-	++	++
6	+	-	+	++	--	--	++	++

7 Limitations and conclusion

The additional biogas production related to the post-digestion of mixed organic waste digestate and dairy manure digestate is insignificant compared to the biogas production in the digestion step, whilst when only dairy manure was used as input stream an additional 60% of biogas was produced. During stripping, part of the remaining recalcitrant material in the digestate will be disintegrated due to the increased temperature. Hence, **post-AD is an interesting additional step when digesting fibre-rich material but not when the input streams are easily degradable.** Another important sidenote is that due to circumstances the stripped digestate available for post-AD was very limited. Hence, a low organic loading rate of 0,3-0,5 g VS/L/day was maintained, logically resulting in lower biogas production.

Post-treatment of the digestate results in bio-fertilizers with additional benefits compared to digestate: these can be more concentrated, easier to handle, and more tailormade application is possible. In addition, these bio-fertilizers could be sold more locally, reducing transport distances. For this to be possible, local farmers should be made aware of these products and their benefits, for instance, by introducing them through demonstrations. However, **these (possible) benefits are not taken into account in this study due to the choice of the functional unit and system boundaries.** It is also too complex to generalize the transport distances related to the application of digestate and how much these would decrease. The agrological assessment indicates that the carbon mineralization of both P-poor and N- and P-poor fractions stabilized around 15% of the added carbon, indicating a **promising result for highly Effective Organic Matter**. Further research is necessary to investigate the long-term carbon storage in the soil and related emission savings and was therefore not accounted for in the ecological analysis. Additionally, the possible future implementation of carbon removal certificates can result in additional revenues.

In the full assessment, the **additional production of heat was not taken into account**. The ecological assessment assumed that all additional heat is necessary for the post-treatment of the digestate. The economic valorization of heat strongly depends on company-specific factors, for instance, if they can valorize the heat themselves for other industrial applications, office heating, or the presence of other heat-demanding businesses nearby.

Considering the high prices for the disposal of manure-derived products and the large price differences for consumables related to their quality, the obtained bio-fertilizers cannot be sold with significant profit both in Flanders and Turkey. This current market is influenced by the surplus of manure in NSZs and the legal framework, i.e. the bio-fertilizers are seen as livestock manure under the European Nitrates directive. Implementing the European RENURE proposal could bring additional value to the ammonium citrate, ammonium sulphate, and struvite.

This effect resembles the savings scenario since we only took into account savings for bio-fertilizers that comply with these criteria. **Other complying bio-fertilizers, like mineral concentrate, fall out of the project scope** but could be important in future studies.

Some experiments were only conducted on lab-scale. **To provide more reliable data for full-scale applications, pilot-scale experiments are of paramount importance in further research.** For instance, considerable differences in stripping and scrubbing efficiencies were observed between the lab-scale and pilot-scale stripping-scrubbing tests, pointing out the importance of conducting these tests on a larger scale. The cascades should be considered as a rough estimation of the possibilities of the technologies and provide a first impression. More in-depth research and tests are necessary to provide a more detailed view of the technical, ecological, and economic performance before implementing these techniques into your business case.

Across all evaluated cascades, significant insights have been gleaned regarding areas for improvement. Technical assessments highlight varying degrees of success in biogas production, N- and P-recovery efficiencies, and the overall suitability of recovered products as fertilizers. Ecologically, while some cascades show promising additional reductions in $CO_{2,eq}$-emission savings compared to the reference, challenges such as fugitive emissions, consumable inputs and material losses impact environmental sustainability. The economic evaluation indicates that implementing some technology cascades makes the business more profitable compared to the reference, while others worsen the profitability. As concluded in Systemic, the **additional biogas production forms the main source of extra revenues** for the business case. The high consumables expenses and the current market/legal framework remain strong limitations, however, cheaper consumable alternatives and legal changes could positively impact the business scenario.

Further research, development, and legal guidance are essential to address current limitations and optimize performance across all facets of these cascades. This includes refining technologies to improve nutrient recovery efficiencies, reducing environmental footprints, and enhancing economic feasibility. Ultimately, continued innovation and adaptation tailored to the user will be crucial to maximize the potential benefits of N- and P-recovery cascades.

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