Supplementary information

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This document lists the salient aspects and mass flows of the processing technologies for the life cycle assessment of managing liquid fraction of pig manure (LF).

## Salient features

### Functional unit

The study's functional unit is 1 tonne of LF, the characteristics of which are listed in Table S1. These parameters were monitored weekly from May 9th to December 10th, 2019 at a pig manure treatment facility in Gistel-Zevekote, Belgium, capable of raising 11,000 fattening pigs and 5,400 piglets. The treatment facility's influent flow is estimated to be 120 m3/day (Farmer 2021) .

Table S1 Characteristics of LF. The functional unit is 1 tonne of liquid fraction and values expressed in fresh matter basis

|  |  |  |
| --- | --- | --- |
| Parameter | Unit | Value |
| Dry matter (DM) (%) | % | 3.61 ± 0.05 |
| Total Nitrogen (N) | kg/tonne | 4.34 ± 0.13 |
| NH4-N | kg/tonne | 2.86 ± 0.09 |
| NO3-N | kg/tonne | 0.06 ± 0.003 |
| Total Phosphorus (P) | kg/tonne | 0.42 ± 0.003 |
| Biological oxygen demand (BOD) | kg/tonne | 4.58 ± 0.19 |
| Chemical oxygen demand (COD) | kg/tonne | 34.03 ± 0.82 |
| Total Potassium (K) | kg/tonne | 4.1 |

### Scenarios considered

Table S2 describes the salient features of the scenarios considered to process LF. Scenarios S3 and S4 are imaginary and do not take place at mentioned treatment facility). However, the data for S3 was obtained by the technology provider whereas the data for S4 was obtained from another full-scale treatment facility (Waterleau New Energy) and its relevant mass flows were adjusted as per the functional unit. The life cycle inventory (LCI) for all scenarios has been embedded in an excel document.

Table S2 Salient aspects for all scenarios.( S1: nitrification-denitrification (NDN); S2: Stripping-Scrubbing (SAS) + NDN+ Constructed wetlands (CW); S3: Reverse osmosis (RO) +evaporation; S4: Evaporation

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **S1** | **S2** | **S3** | **S4** |
| Mass flows | Estimated from STOAT | SAS: Measured | Strocon Inc (2021) | Brienza, van Puffelen et al. (2021) |
| NDN: Same as S1 |
| CW: Meers, Tack et al. (2008) |
| Energy requirements | Corbala-Robles, Sastafiana et al. (2018) | SAS: Measured | Strocon Inc (2021) | Brienza, van Puffelen et al. (2021) |
| NDN: Same as S1 |
| CW: Corbella, Puigagut et al. (2017) |
| Auxiliaries | Corbala-Robles, Sastafiana et al. (2018) | SAS:Measured | Strocon Inc (2021) | Brienza, van Puffelen et al. (2021) |
| NDN: Same as S1 |
| Infrastructure | Doka (2021) | Corbella, Puigagut et al. (2017) | RO: (AICE 2018) | (Anonymous 2021) |
| Strocon Inc (2021) |
| End product | Biological effluent (Transport + field application) | Ammonium nitrate  (field application) | Filtrate (microfiltration)  Transport | NK concentrate (field application) |
| NK concentrate (field application) | Condensed ammonia water |

### Emissions calculation from field application of end product

In Flanders, the effluent from NDN is applied on the fields. We consider that this practice as effluent disposal rather than as fertilization. Therefore, the burdens from field application are included, whereas the fertilizer credits are not. The emissions from field application of the biological effluent are provided in Table S3

Table S3: Emissions from field application

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Emission/  substitution | Unit | Biological effluent | Ammonium nitrate a | | | Mineral concentrate a | | |
| Grassland | | Arable land | Grassland | Arable land | |
| NH3-N a | %TAN | 2.5 | 2.5 | | | 6 | 0.64 | |
| N2O-N a | %N | 1 | 1.2 | 1 | | 0.6 | 1.95 | |
| NO-N a | %N | 0 | 0 | | | 0.55 | 0 | |
| NO3-N b | %N | 5 | 15.8 | | | 18.1 | | |
| P c | kg / kg P2O5 | 0.00184 | 0 | | | 0 | | |
| N fertilizer replacement value a | % | 0 | 100 | | | 60 | | 70% |

a Lagerwerf, Bannink et al. (2019)

b Roy, AU - Misra et al. (2003)

c Corbala-Robles, Sastafiana et al. (2018)

### STOAT model

STOAT is a tool to model activated sludge systems, that can treat LF of manure through nitrification-denitrification pathway. As shown in Figure S1, N removal is carried out using an activated sludge process, in two separate tanks. Nitrification occurs in the aerobic tank, which is the second stage of the system. After nitrification, the NO3- rich flow is recirculated to the anoxic tank, which is also connected to the inflow of an organic carbon source (raw liquid fraction of manure) and a chemical carbon source (methanol, acetic acid). A chemical carbon source has to be added in order to obtain a nearly complete denitrification. After NDN, the treated effluent is separated from the active sludge in a clarifier and a part of the sludge is usually returned to maintain bacterial activity. The remaining sludge can be used as a soil conditioner. We based our assumption of NDN system on the German wastewater treatment guidelines .

Diagram

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Figure S1 Typical layout of an NDN system

The organic fractions in ASM1 are characterized by chemical oxygen demand (COD) and the COD is subdivided based on solubility, biodegradability, biodegradation rate and biomass viability. The COD balance in ASM1 is illustrated in Figure S2. The readily biodegradable COD (Ss) is assumed to constitute simple molecules that can be broken down by heterotrophic biomass (XH), to form new biomass. In contrast, the slowly biodegradable COD (Xs) consists of complex molecules that require enzymatic breakdown prior to utilization. The nonbiodegradable COD (Xi, Si ) end up as recalcitrant fractions in the sludge and effluent. Similarly, total Nitrogen is fractionated into soluble (SNO ,SNH) and particulate (XND) components (Figure S3). The particulate organic nitrogen is hydrolysed into soluble organic nitrogen and this occurs in parallel with hydrolysis of Xs.

Diagram

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Figure S2 COD balance in ASM1; Where Xi : particulate inert COD, XH: heterotrophic biomass; Xs:slowly biodegradable COD; Ss: Readily biodegradable COD; SI: Soluble inert COD

The soluble organic N (SND) is converted to ammonia nitrogen (NH3-N) through ammonification and NH3-N serves as nitrogen source for biomass growth. The subsequent autotrophic conversion of NH3-N results in nitrate nitrogen.

Diagram

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Figure S3: N fractionation according to ASM1; SNO:Soluble nitrate and nitrite; SND: soluble organic nitrogen; XND: particulate organic nitrogen; SNH: soluble ammonia nitrogen

The ASM1 includes eight processes that are fundamental to the activated sludge process. These are: aerobic and anoxic growth of heterotrophic biomass, death of heterotrophic biomass, aerobic growth of autotrophic biomass, decay of autotrophic biomass, ammonification of soluble organic nitrogen and hydrolysis of both entrapped particulate organic matter and entrapped organic nitrogen. The process kinetics in ASM1 are based on the Peterson’s correlation matrix (Figure S4) and the nomenclature is listed out in Table S3. Unless specified otherwise, all the default values for constants are obtained from Henze, Gujer et al. (2000).

Table S3: Nomenclature used in ASM1

|  |
| --- |
| Ig Inhibition kinetics for soluble oxygen (—) |
| KL,A Oxygen transfer coefficient (day−1) |
| KNH Ammonia half-saturation coefficient for autotrophic biomass (mg N l−1) |
| KNO Nitrate half-saturation coefficient for denitrifying heterotrophic biomass (mg N l−1) |
| KO,A Oxygen half-saturation coefficient for autotrophic biomass (mg O2 l−1) |
| KO,H Oxygen half-saturation coefficient for heterotrophic biomass (mg O2 l−1) |
| KS Substrate half-saturation coefficient for heterotrophic biomass (mg COD l−1) |
| KX Half-saturation coefficient for hydrolysis of particulate biodegradable substrate (—) |
| SI Concentration of inert soluble organic material (mg COD l−1) |
| SO Concentration of soluble oxygen (mg l−1) |
| SO,max Maximum concentration of soluble oxygen (mg l−1) |
| XB,A Concentration of active autotrophic particulate mass (mg COD l−1) |
| XB,H Concentration of active heterotrophic particulate mass (mg COD l−1) |
| XND Concentration of particulate biodegradable organic nitrogen (mg COD l−1) |
| XI Concentration of particulate inert organic matter (mg l−1) |
| XP Concentration of non-biodegradable particulate product arising from biomass decay (mg COD l−1) |
| XS Concentration of slowly biodegradable particulate substrate (mg COD l−1) |
| YA Autotrophic yield coefficient (g COD (g N)−1) |
| YH Heterotrophic yield coefficient (g COD (g COD)−1) |
| bA Autotrophic decay coefficient (day−1) |
| bH Heterotrophic decay coefficient (day−1) |
| fp Fraction of biomass yielding particulate products (—) |
| iXB Nitrogen content in biomass (mg N (mg suspended solids)−1) |
| iXP Nitrogen content in inert particulate (mg N (mg suspended solids)−1) |
| kA Ammonification coefficient (l mg (COD day)−1) |
| kh Hydrolysis coefficient (day−1) |
| μ max, A Maximum specific growth rate for autotrophs (day−1) |
| μ max, H Maximum specific growth rate for heterotrophs (day−1) |

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Description automatically generated.Figure S4 Process kinetics and stoichiometry for ASM1

## Scenario 1: NDN

Scenario 1 represents the nitrification-denitrification (NDN) of LF of manure.. The inputs to STOAT are listed in Table S4,based on which the mass balance of the NDN system was calculated according to the process kinetics of ASM1.

Table S4: Input parameters into the STOAT model. Unless specified otherwise, the default values for input parameters were obtained from ATV-DVWK (2000)

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | | Value | Comment |
| Qd (m3/ day) | | 120 | Daily inflow (farmer, personal communication) |
| CODtot (mg/l) | | 34032 | Measured |
| CODeffluent (mg/l) | | 1000 | Expected COD concentration in biological effluent |
| Oxygen uptake (mg/l) | | 20813 |  |
| XCOD, sludge produced(mg/l) | | 14023 |  |
| (mg/l)  Y (yield factor)  b (decay co-efficient)  *default values for ASM1* | | 5000 | b = 0.17 d-1 |
|  | | 5610 |  |
| Daily Oxygen requirement (kg O2/day) | For C | 2373 |  |
| For N | 1826 |  |
| Volume of biological reactor (m3) | | 1120 |  |
| Sludge Volume Index (l/kg) | | 100-150 | (ATV-DVWK 2000) |
|  | | 4.6 | MLSS concentration (ATV-DVWK 2000) |
| Mass of suspended solids in the aeration tank (MLSS) (kg) | | 5155 |  |
| Sludge age upon which dimensioning is based (days) | | 17 |  |
| Methanol consumption | | 1.9-6.81 | (ATV-DVWK 2000) |

The energy demand for NDN is sub-divided into aeration energy, energy for mixing and energy for pumping. For aeration, diffused bubble aerators are considered and their energy demand is estimated to be 3 to 5 kWh per kg of O2 supplied. Most mixing configurations in WWTPs are either continuous rapid (<30 seconds) or continuous. We consider continuous mixing and mechanical aerators, that provide both O2 and maintain MLSS are considered. The energy for mixing is estimated to be 0.48 kWh/m3. For pumping, the energy demand is 9.88 e-02 kWh/m3 (Corbala-Robles, Sastafiana et al. 2018). The total energy requirement is **9.93 kWh/m3 of LF**, while Smet, Debruyne et al. (2003) estimate a maximum of 15 kWh/m3. Post treatment, the biological effluent is transported to nearby fields to be applied. The estimated transport distance is approximately 6km.

Regarding fugitive emissions, it is difficult to establish an emission factor for N2O and NH3 since their formation in the NDN system is not well known. However, based on Hou, Velthof et al. (2017), we estimate a 1% loss of influent N in the form of N2O and 0.5% of influent N in the form of NH3.

Table S5 lists the N concentration at each stage of the NDN, obtained from STOAT. Based on these N concentrations, the nutrient flow was estimated and scaled according to the functional unit, i.e. 1 tonne of LF (Table S6). The mass and nutrient flows are represented in the Sankey diagrams (Figure S6 and S7).

Table S5 Output from STOAT: N flows at each stage

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Stage | (1) | (2) | (3) | (4) | (5) |
| Influent | Biological effluent | Influent FC | Excess sludge | Recirculated sludge |
| Av. Temperature (deg. C) | 15 | 15 | 15 | 15 | 15 |
| Av. NH3 (mg/l) | 3041 | 269 | 286 | 276 | 276 |
| Max. NH3 (mg/l) | 3041 | 303 | 304 | 304 | 304 |
| Av. NO3 (mg/l) | 62 | 48 | 6 | 7 | 7 |
| Max. NO3 (mg/l) | 62 | 300 | 235 | 32 | 32 |
| Av. TN (mg/l) | 4407 | 317 | 740 | 2280 | 2280 |
| Av. NH3 (kg/h) | 15 | 0.75 | 1.93 | 0.06 | 1.03 |
| Max. NH3 (kg/h) | 15 | 0.85 | 2.05 | 0.06 | 1.14 |
| Av. NO3 (kg/h) | 0 | 0.13 | 0.04 | 0.00 | 0.02 |
| Max. NO3 (kg/h) | 0 | 0.84 | 1.59 | 0.01 | 0.12 |
| Av. TN (kg/h) | 22 | 0.89 | 5.00 | 0.06 | 1.06 |
| Max. TN (kg/h) | 22 | 1.55 | 5.38 | 0.06 | 1.14 |

Diagram

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Figure S6: Mass flows in the NDN system

### Mass balance

Table S6 Mass balance for Scenario 1

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Stage** | **Flows** | **Mass flow** | **BOD** | **TKN** | | | | | **NO3-** | **Total N** | **P** | **Total COD** | **COD** | | | | |
| **SNH** | **XI** | **SI** | **SND** | **XND** | **Si** | **Ss** | **Xi** | **Xs** | **XBH** |
| **kg/FU** | **(mg/l)** | **(mg/l)** | | | | | **(mg/l)** | **(mg/l)** | **(mg/l)** | **(mg/l)** | **(mg/l)** | | | | |
| Influent | Influent | 1000 | 4536 | 3041.98 | 108.64 | 108.64 | 434.56 | 651.85 | 57.51 | 4403.2 | 432 | 34032 | 1701.6 | 6,806.40 | 3,403.20 | 15,314.40 | 6806 |
| Final clarifier | Biological effluent | 750 | 140 | 117 | - | - | - | - | 200 | 317 | 80 | 1000 | 50 | 200.00 | 100.00 | 450.00 | 200 |
| Excess Sludge | 60 | n.a. | 840 | - | - | - | - | 1440 | 2280 | 2440 | 2830 | n.a. | | | |  |
| NDN | Recirculated sludge | 190 | n.a. |  |

Diagram

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Figure S7: Nutrient flows for Scenario 1

## Scenario 2: Stripping-scrubbing as pre-treatment

The flows and inventory for stripping and scrubbing (SAS) were measured at the pig manure processing facility at Gistel. Post SAS, the stripping effluent was treated via NDN. Similar to Scenario 1, the influent parameters after stripping and scrubbing were fed into STOAT to compute the mass balances during NDN. After NDN, the effluent was treated in a constructed wetlands set-up to meet discharge norms. For the infrastructure of the CWs, the LCI from Corbella, Puigagut et al. (2017) was taken into consideration.

The mass balances for constructed wetlands (CW) was along the basis of ,Meers, Tack et al. (2008) who monitored a full-scale CW processing biological effluent of pig manure. The estimated removal efficiencies were 99.3%, 99.6% and 97.7% for N, P and COD respectively (Meers et al., 2008). Plant uptake accounted for 9% of the N removal and 31% of the P removal. Another 7% of P was recuperated from sludge removal. N was the limiting factor, and it was determined that a loading rate of 0.89 g m-2 day-1 can be processed to meet the effluent discharge norms.

Based on a loading rate of 0.89 g N m-2 day-1, the land requirement to treat 1 m3 of LF after SAS and NDN is 170 m2.

Emissions from CWs were obtained from (Aben, Oliveira Junior et al. 2022), who quantified GHG emissions and their impacts on Azolla filiculoides, Ceratophyllum demersum, Elodea canadensis and Myriophyllum spicatum. from intense nutrient loading. For a loading rate of 1 g N m-2 day-1, the ensuing GHG emissions are 12 g CO2-eq.m-2.day-1. Considering a hydraulic retention time of 17 days for 1 m3 of NDN effluent, the GHG emissions are 204 g CO2-eq, out of which 98% is due to N2O (201.14 g CO2-eq or 0.67 g N2O).

Diagram

Description automatically generated

Figure S8 Mass balance for horizontal flow constructed wetlands (Meers et al., 2008)

The mass and nutrient balances for Scenario 2 is represented in Table S7 and Figure S9

### Mass balance

Table S7 Mass balance for Scenario 2

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Stage** | **Flows** | **Mass flow** | **BOD** | **TKN** | | | | | **NO3-** | **Total N** | **P** | **Total COD** | **COD** | | | | |
| **SNH** | **XNI** | **SNI** | **SND** | **XND** | **Si** | **Ss** | **Xi** | **Xs** | **XBH** |
| **kg/FU** | **(mg/l)** | **(mg/l)** | | | | | | **(mg/l)** | **(mg/l)** | **mg/l** | **(mg/l)** | | | | |
| Influent | Influent to SAS | 1000 | 4536 | 3041.98 | 108.64 | 108.64 | 434.56 | 651.85 | 57.51 | 4403 | 432 | 34032 | 1701.6 | 6,806.40 | 3,403.20 | 15,314.40 | 6806 |
| SAS | Ammonium nitrate | 25 | - | - | - | - | - | - | - | 41600 | - | - | - | - | - | - | - |
| Influent to NDN | 1000 | 2370 | 1955.8 | 69.85 | 69.85 | 279.4 | 419.1 | 60 | 3300 | 432 | 26874 | 1343.7 | 5374.8 | 2687.4 | 12093.3 | 5374.8 |
| Final clarifier | Biological effluent to constructed wetlands | 750 | 140 | 79.34 | n.a. | n.a. | n.a. | n.a. | 146.66 | 226 | 80 | 787 | 39.35 | 157.4 | 78.7 | 354.15 | 157.4 |
| NDN | Excess Sludge | 60 | n.a. | 640 | n.a. | n.a. | n.a. | n.a. | 1160 | 1800 | 2440 | 2234 | - | - | - | - | - |
| Recirculated sludge | 190 | n.a. |
| CW | Sludge | - | - | - | - | - | - | - | - | 0.01 | 0.04 | - | - | - | - | - | -- |
| Effluent | - | - | - | - | - | - | - | - | 1.15 | 0.24 | 23 | - | - | - | - | - |

Diagram

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Figure S9: Nutrient flow for Scenario 2

## Scenario 3:Membrane filtration and evaporation

### Mass balance

The mass and nutrient flows for Scenario 3 were obtained by a technology provider in the Netherlands who supply membrane filtration and vacuum evaporation units to treat liquid manure fractions (Table S8, Figure S10).

Table S8 Mass and nutrient flow for Scenario 3 (Anonymous 2021)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Stage** | **Flows** | **Mass flow** | **TN** | **TP** | **TK** |
|
| **kg/FU** | **kg** | **kg** | **kg** |
| Influent | Influent | 1000 | 4.34 | 0.42 | 4.1 |
| Trommel filter | Trommel rejects | 50 |  |  |  |
| Permeate | 950 | 4.34 | 0.42 | 4.1 |
| Microfiltration | MF Retentate | 95 | 2.56 | 0.33 | 2.14 |
| MF Permeate | 855 | 1.78 | 0.09 | 1.96 |
| Reverse osmosis | RO Retentate | 213.75 | 2.06 | 0.09 | 2.07 |
| RO Permeate | 748.13 |  |  |  |
| Vacuum evaporator | Concentrate | 106.87 | 1.78 | 0.09 | 1.96 |
| Condensate | 106.88 | 0.28 |  | 0.11 |
| Ion exchanger | Clean water | 748.13 |  |  |  |

Diagram

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Diagram

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Figure S10 Mass and nutrient flows for Scenario 3

The main infrastructure used in this scenario included a micro-filtration module, reverse osmosis (RO), evaporator and ion exchanger respectively. For RO module, the process used was “seawater reverse osmosis module production, 8-inch spiral wound, baseline”. For microfiltration, the membranes were manufactured from ceramic and the LCI was obtained from (AICE 2018). The lifespan for both modules is assumed to be 5 years. For ion exchange, the LCI from (Guida, Conzelmann et al. 2021) was considered. Their study estimated that for an inflow of 3650 m3/ year, the corresponding raw material usage was 0.5 tonnes 0.5 tons of stainless steel, 0.5 of reinforcing steel, 10 m3 of concrete and 5 tons of PE. The lifetimes of the equipment were estimated to 25 years for concrete, 20 years for steel and 5 years for polyethylene.

For vacuum evaporation, the configuration is assumed to be a falling-film. In a falling film design, the LF to be concentrated is supplied to the top of the heating tubes and distributed in such a way

Diagram, schematic

Description automatically generated

Figure S11 Cross section of a falling-film evaporator

as to flow down the inside of the tube walls as a thin film (Figure S11). The liquid film starts to boil due to the external heating and is partially evaporated as a result. The downward flow, caused initially by gravity, is enhanced by the parallel, downward flow of the generated vapor. The residual film liquid and vapor is separated in the lower part of the equipment

The heating tubes are assumed to be made of brass, with a diameter of 25 mm and 3m length. The surface area is 0.70 m2.

## Scenario 4: Evaporation

The mass flows for Scenario 4 was obtained from (Brienza, van Puffelen et al. 2021). For infrastructure, the LCI from Scenario 3 are used for vacuum evaporator (Table S9, Figure S12.

### Mass balance

Table S9 Mass and nutrient flow for Scenario 4

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Stage** | **Flows** | **Mass flow** | **NH4-N** | **Organic**  **N** | **TP** | **TK** | **N loss** |
|
| **kg/FU** | **kg** | **kg** | **kg** | **kg** | **kg** |
| Influent | Influent | 1000 | 2.86 | 1.48 | 0.42 | 4.1 |  |
| Aeration tank | Recirculated process water | 351 | 0.31 |  |  | 0.01 | 0.13 |
| Influent to storage | 1350 | 3.17 | 1.48 | 0.42 | 4.1 | 0.05 |
| Vacuum evaporator | Process water | 213.75 | 0 | 2.06 | 0 | 2.07 | 0.13 |
| Concentrate | 120 | 0.16 | 1.35 | 0.42 | 1.96 | 4.09 |
| Cooling, cleaning water | 864.41 | 0.71 | 0 | 0 | 0 | 0 |
| Condensed ammonia water | 107 | 1.7 | 0.07 | 0 | 0 | 0 |

Chart, waterfall chart

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Figure S12 Mass and nutrient flows for Scenario 4

## Life Cycle Inventory

The LCI for all scenarios has been embedded in the excel workbook titled ‘LCI.xlsx’.

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