



Environmental and economic assessment of wastewater nutrient recovery technologies

WalNUT WP5 workshop

26-01-2026

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101000752.



Introduction to WP5 - Impact Assessment

Morten Birkved - University of Southern Denmark

WP5 Obligation

Impact Assessment Pillar

Lead Beneficiary: Syddansk Universitet (SDU)



Figure 1. WalNUT approach for more efficient nutrient loops at local, regional, and European scale

Overall aim of WP5: To quantify the environmental and socioeconomic impacts of the NR and BBF technologies by performing a life cycle sustainability assessment (LCSA).

5.1 Development and implementation of data compilation strategy. [UCPH]

5.2. Inventory analysis, modeling environmental emission and soil fertility improvement, and upscaling of technology. - [SDU]

5.3. Environmental life cycle assessment of the nutrient-recovery system. [SDU]

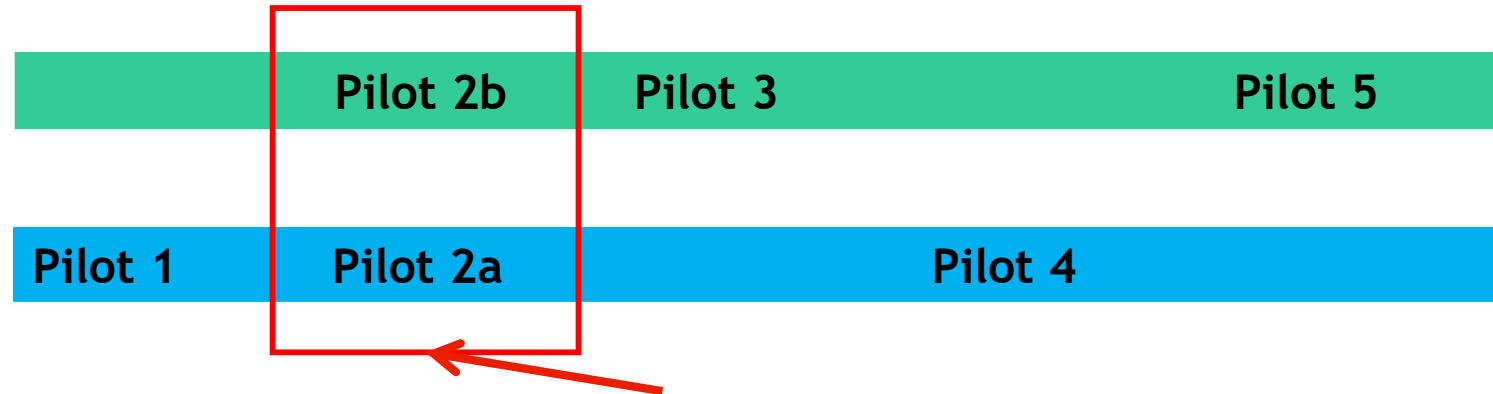
5.4. Life cycle costing and socioeconomic issues of NR and BBF systems. [UC]

5.5. Techno-environmental-socioeconomic assessment. [UC, SDU]

System boundary/task division - UC/KU/SDU

LCA

UC
(attributional)



KU/SDU
(consequential)

Pilot 2 assessed by both UC and KU/SDU using both attributional and consequential system boundaries

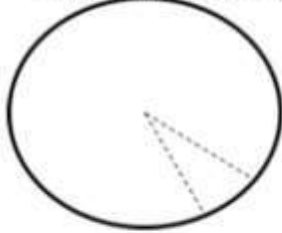
- Since the 5 pilots *are not to be compared (the systems deliver incomparable reference flows/products)*, they can be assessed in groups using different system boundaries (attributional/consequential).
- Assessments will rely on the same assessment framework (i.e. inventory database, product system modelling software and impact assessment method)

System boundary types

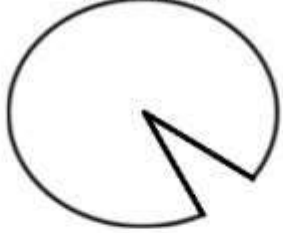
Two alternative ways to assess the impact of a product system

1. Compare impact scenarios

System with product system (realistic)

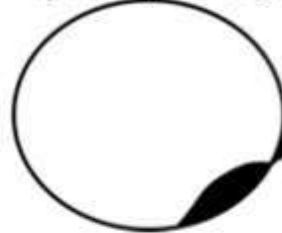


Reference system (artificial)

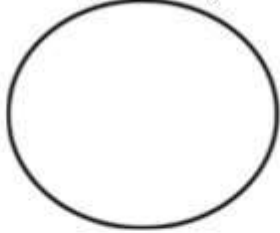


Attributional LCA

System with product system (realistic)



Reference system (realistic)



Consequential LCA

2. Specify product system impact separately within reference environment



Focus is on the impacts that be allocated to a functional unit/product.

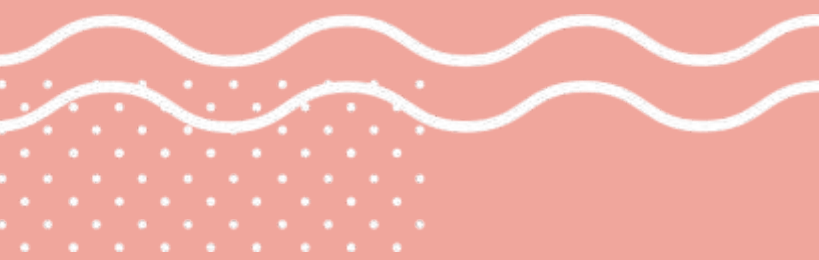
Focus is on the impact differences (i.e. before/after) induced by a functional unit/product.

Attributional and consequential assessments are per definition incomparable!

Model, software and data terminology

- **Ecoinvent (our main database)** – an inventory data - contains more than 26,000 peer-reviewed datasets for comprehensive environmental reporting and sustainable decision-making – used to model background systems across the 5 pilots – more on <https://ecoinvent.org/>
- **DAISY (a supplementary model reducing nutrients emission uncertainty)** - a sophisticated agricultural simulation software (University of Copenhagen) tracking nutrients/water in fields, or a communication theory tool (CMM) visualizing context layers around a central conversation – more on <https://daisy.ku.dk/pdfs/DaisyDescription.pdf>
- **OpenLCA (our main system modelling software)** – OpenLCA is a free, open-source desktop software for professional Life Cycle Assessment (LCA) and sustainability analysis – more on <https://www.openlca.org/>
- **Environmental Footprint (EF 3.1) (our impact assessment method)** - Environmental Footprint (EF) 3.1 is the European Commission's updated, standardized methodology for assessing a product's or organization's environmental impact across its entire lifecycle – more on <https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html>





LCA of microalgae treatment (Pilot 1)

Maja Rydgård - University of Copenhagen



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101000752.



Introduction and background:

Objective: Quantify environmental impacts of microalgae waste water treatment with production of algae bio-based fertilizer (BBF) performing a life cycle assessment (LCA)

Data from pilot plant in Valladolid, Spain (WalNUT Pilot 1):

- 🔹 Photoautotrophic and heterotrophic microalgae cultivation in waste water.
- 🔹 Separation of algae extract by centrifugation
- 🔹 Microalgae spray drying and pelletizing to BBF pellets

Current WWTP modelled as the baseline:

- 🔹 Dissolved air flotation & biological secondary treatment.
- 🔹 Sludge spreading on agricultural land.



LCA scenarios:

- ALG: Data from pilot plant in Valladolid
- Alternative ALG scenarios: alterations to scenario ALG, in attempt to optimize the environmental performance

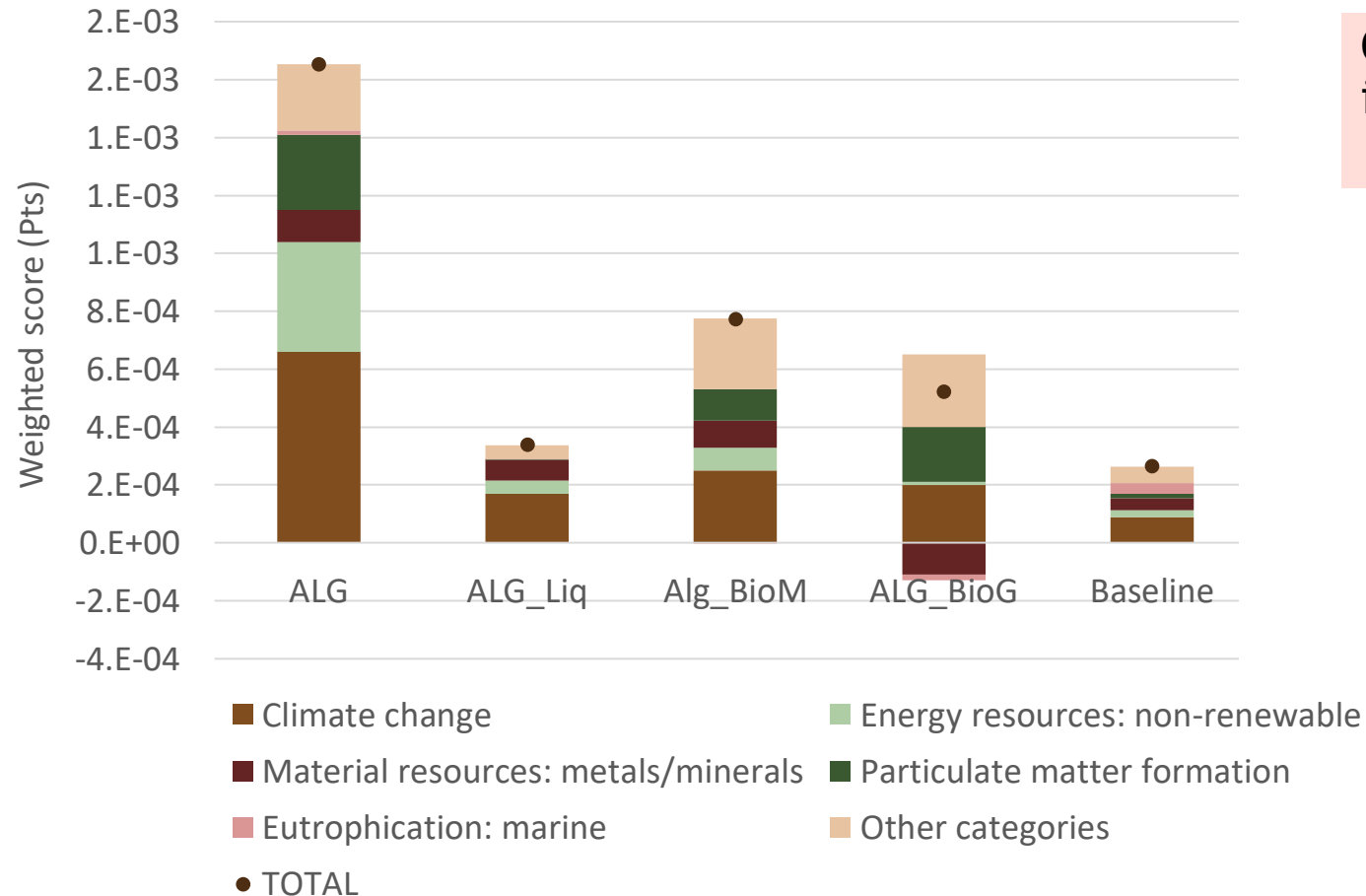
Key differences between microalgae scenarios:

Scenario	Heat source	Field application	Electricity production	Dewatering	Thermal energy source for drying	CO2 source
ALG	Biomass pellets	Pellets	PV panels	Centrifugation	Natural gas	Market for liquid CO2
ALG_Liq	Residual heat from dairy	Liquid	PV panels	Bioflocculation coupled with tangential flow filtration (TFF)	-	Market for liquid CO2
ALG_BioM	Residual heat from dairy	Pellets	PV panels	Bioflocculation coupled with tangential flow filtration (TFF)	Biomethane	Capture from biomethane upgrading
ALG_BioG	Residual heat from dairy	Pellets	Biogas CHP	Bioflocculation coupled with tangential flow filtration (TFF)	Biogas	Capture from biogas combustion

LCA results

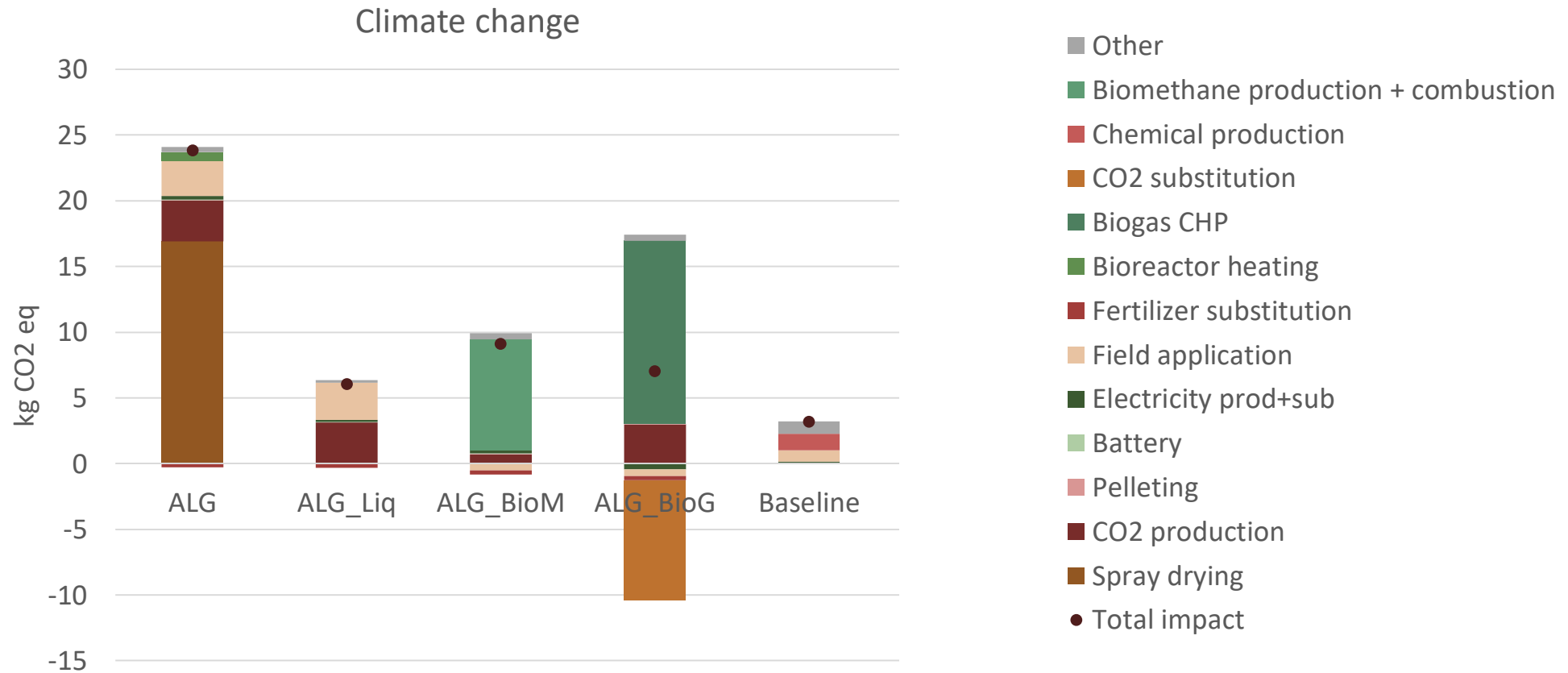
Weighted scores

Total weighted single scores (EF v3.1 method) and contributions of the five impact categories with the highest impacts on the scores.



Climate has the highest impact on the scores.

Climate impact



Hot-spots:

- Spray drying and CO2 production
- Biomethane/ biogas methane emissions through leaching

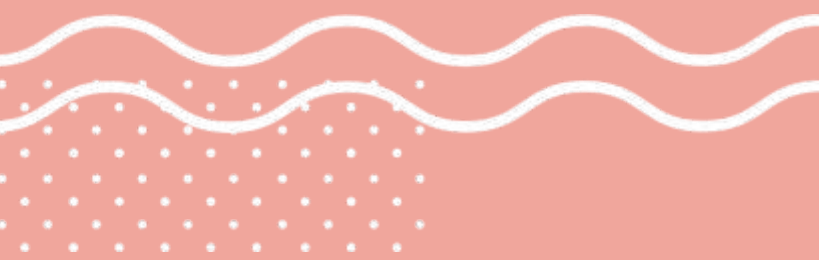
Recommendations and conclusions

Recommendations

- Spray drying has a high impact - More efficient dewatering and drying technologies should be tested and their impact on microlagae should be assessed
- Using liquid microlagae extract in fertigation seems like a promising option. However, research is needed on the potential impacts (e.g. degradation or contamination) of long-term storage of microalgae extract.
- Important to coordinate microalgae WWT with an industry, such as dairy, that can provide heat for bioreactors to avoid impacts of particulate matter from biomass combustion for reactor heating.
- Use of fossil CO₂ should be avoided. Options for using biogenic CO₂ (e.g. from biogas) should be investigated, but it is important to be careful to avoid trade-offs such as increased CH₄ emissions from biogas production.

Conclusions

- Microalgae WWT could provide benefits for the environment, associated with increased nutrient recycling and reduced chemical use and emissions of chemicals
- However, further technological developments are required to achieve an overall environmentally beneficial alternative to current WWT.
- Focus for improvement should be on the hot-spots identified in this LCA.

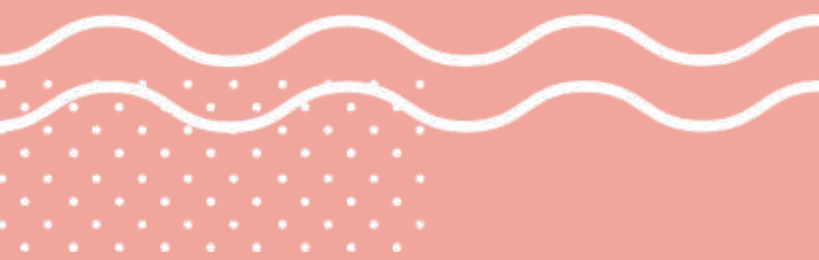


Thank you • Gracias • Grazie • Merci
Obrigado • Ευχαριστώ • Tak • Kösz • Bedankt



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LCA of ion exchange/ adsorption (Pilot 2a)

Lilla Simon - University of Southern Denmark



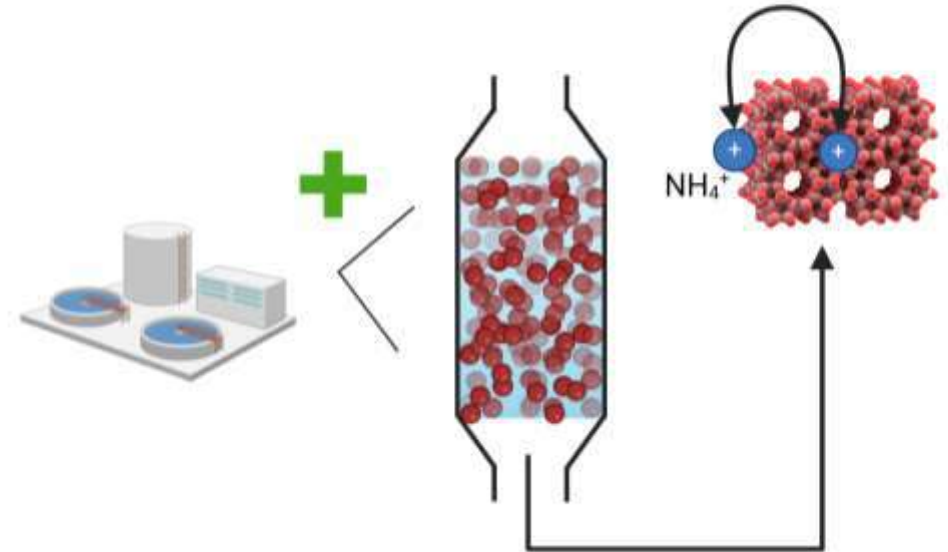
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Introduction

Pilot description

- Wastewater type: municipal (urban)
- Technology: HRAS + IEX (zeolite)
- Nutrient targeted: N (NH_4^+)
- Location: Aartselar, Flanders
- Scale: Pilot (324 L), upscaled to 190 000 PE
- Technology developer: Aquafin & Ugent



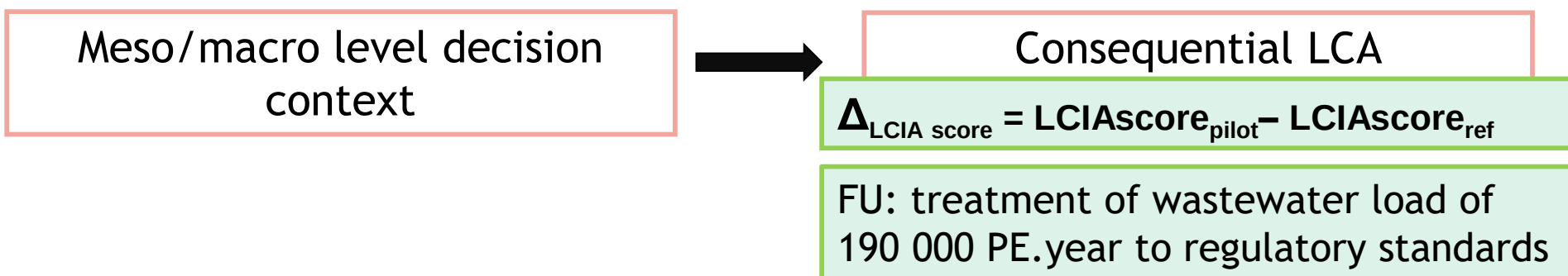
Research objective:

quantify the life cycle environmental impact changes with technology adoption on relevant scale

Assessment methodology

Goal & Scope

Quantify the environmental impacts of adopting HRAS + IEX technology on industrial scale in Flanders, Belgium



Uncertainty analysis

Adsorbent	Adsorption capacity	Inventory	Data source
resin	74.4 mg NH ₄ /g ads	ecoinvent 3.9.1	Huang et al. 2018
natural zeolite	70 mg NH ₄ /g ads	Chen et al. 2024	Shaban et al. 2017
synthetic zeolite	70 mg NH ₄ /g ads	Chen et al. 2024	Shaban et al. 2017
synth. zeolite ecoivent	70 mg NH ₄ /g ads	ecoinvent 3.9.1	Shaban et al. 2017
synth. zeolite ecoinvent	4 mg NH ₄ /g ads	ecoinvent 3.9.1	primary data

Assessment methodology

Use on land stage modelling

- Nuance the fertilizer substitution principle
- Emission factors and substitution rate based on specific agricultural context

Tier 3 agro-hydrological model integration

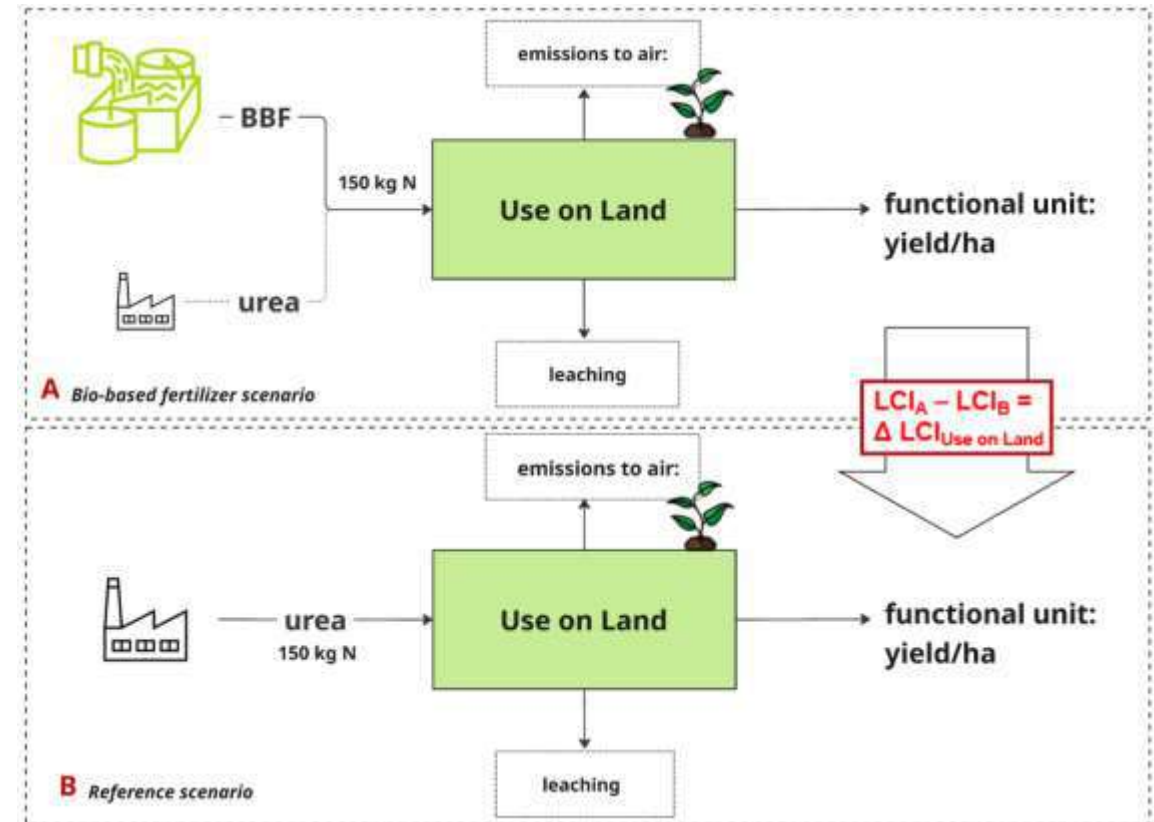


inputs

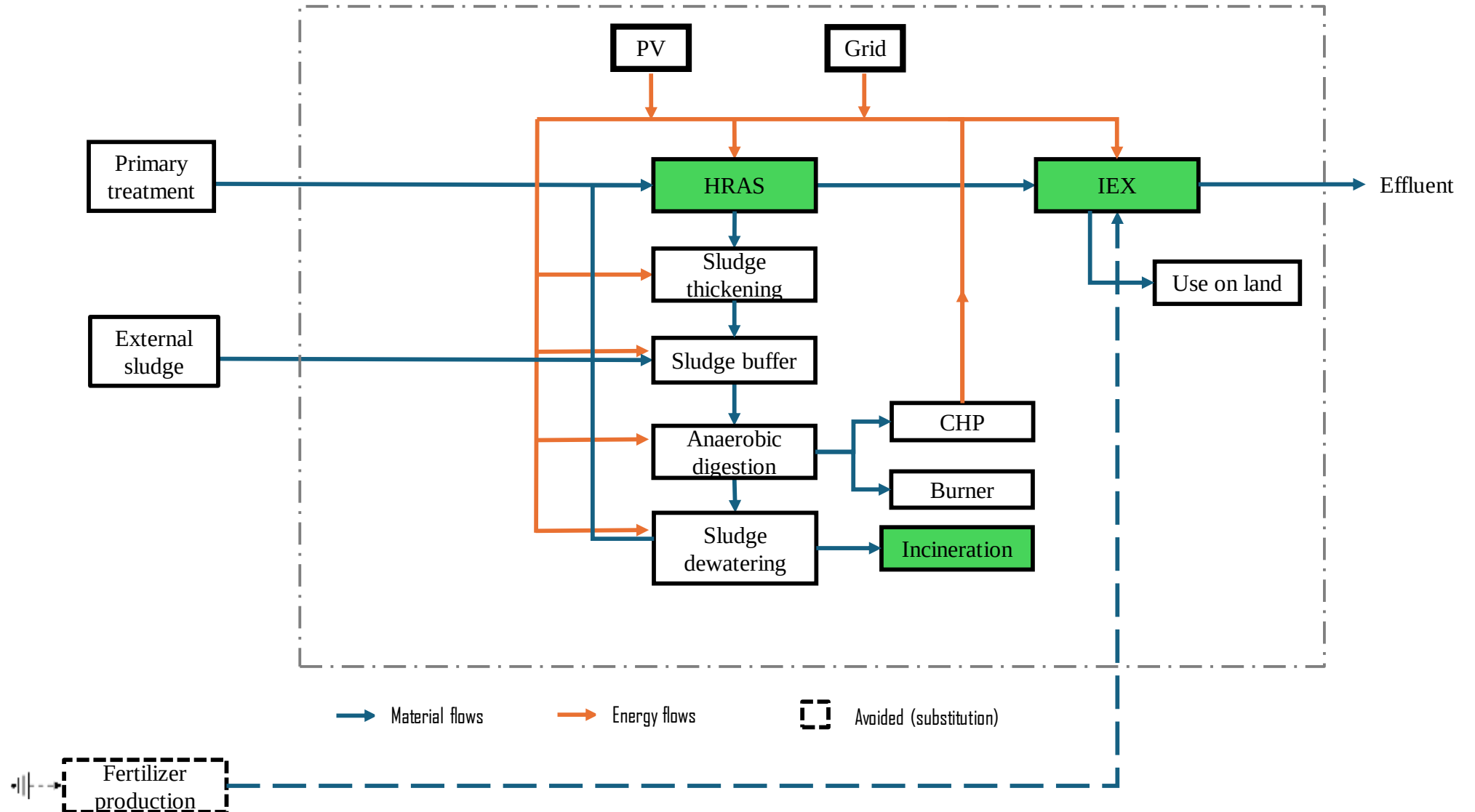
Soil properties
Management practices
BBF mineralization data

outputs

C, N flows and emissions
BBF/yield ratio



Municipal WWTP
190 000 PE



Results

Impact categories	Unit	Reference	IEX	Δ (IEX-RS)	Δ %	Normalized Δ
Acidification	mol H ⁺ -Eq	4.29E+03	6.91E+06	6.91E+06	+161108%	1.24E+05
Climate change - GWP	kg CO ₂ -Eq	2.90E+06	9.14E+08	9.11E+08	+31391%	1.21E+05
Ecotoxicity: freshwater	CTUe	4.53E+06	2.56E+10	2.56E+10	+56499930%	4.51E+05
Energy resources	MJ, net cal val	2.80E+07	9.91E+09	9.88E+09	+3523037%	1.52E+05
Eutrophication: fw	kg P-Eq	8.39E+02	7.85E+05	7.84E+05	+9345254%	4.88E+05
Eutrophication: m	kg N-Eq	2.26E+04	1.10E+06	1.08E+06	+476304%	5.51E+04
Eutrophication: T	mol N-Eq	1.22E+04	1.65E+07	1.65E+07	+13526335%	9.34E+04
Human tox: cancer	CTUh	6.38E-03	1.46E+00	1.46E+00	+2283180%	8.44E+04
Human tox: non-c	CTUh	1.32E-02	3.30E+01	3.30E+01	+24947431%	2.57E+05
Ioninising radiation	kBq U235-Eq	5.26E+03	-3.63E+07	-3.63E+07	-689743%	-8.60E+03
Land use	dimensionless	-3.47E+07	1.27E+10	1.28E+10	+3681690%	1.56E+04
Material resources	kg Sb-Eq	1.80E+01	2.74E+04	2.74E+04	+15226063%	4.30E+05
Ozone	kg CFC-11-Eq	1.26E-01	1.56E+01	1.55E+01	+1229200%	2.96E+02
Particulate matter	disease incidence	-5.47E-02	5.26E+01	5.27E+01	+9624747%	8.85E+04
Photochemical ox	kg NMVOC-Eq	5.83E+04	3.00E+06	2.94E+06	+504210%	7.19E+04
Water use	m ³ world eq. dep	5.91E+05	8.46E+08	8.46E+08	+14321480%	7.37E+04

manifold
increase in
impacts

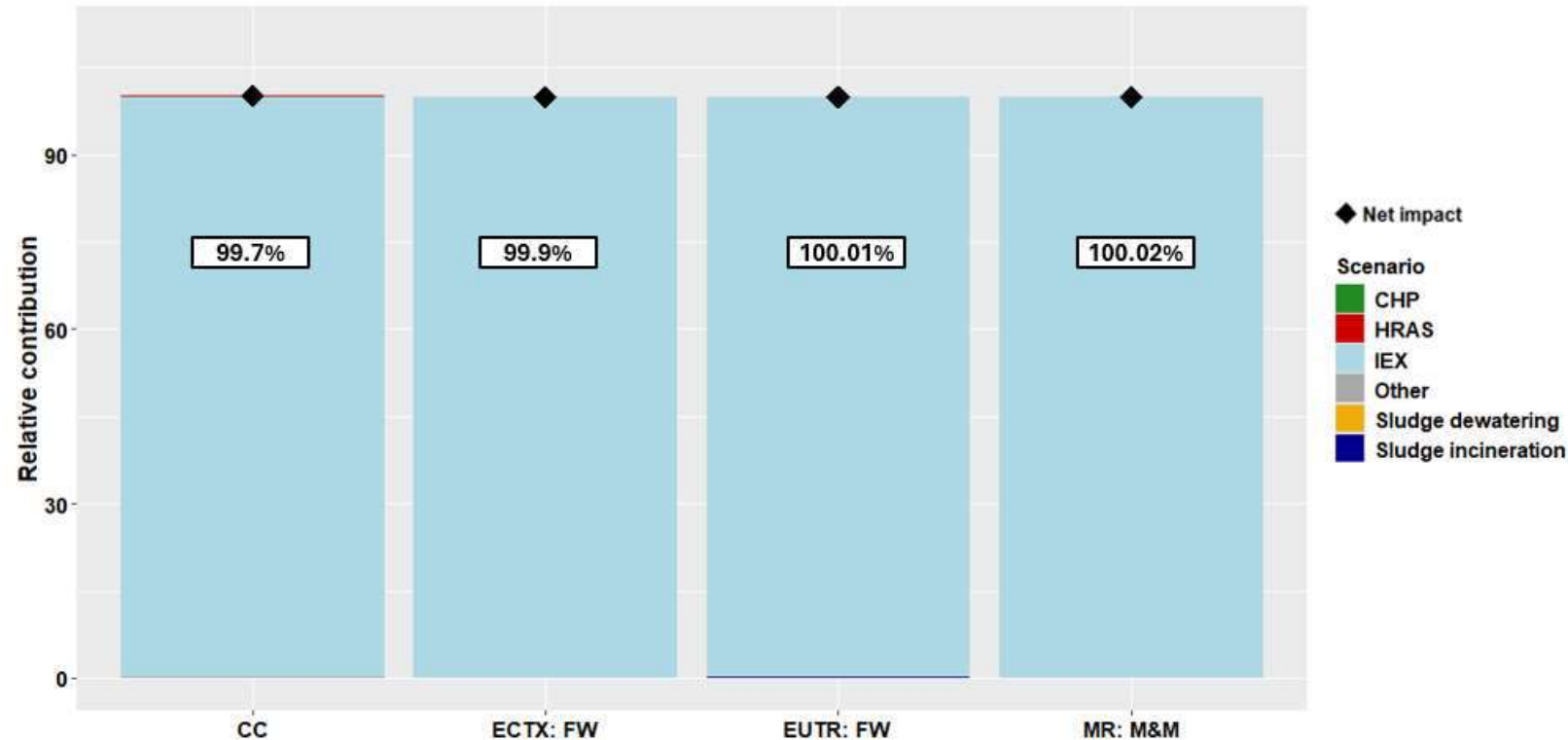
largest
normalized
impact scores

*Environmental Footprint (EF 3.1) method

Results

Process contribution analysis

Over 90% of impact contribution attributed to IEX process

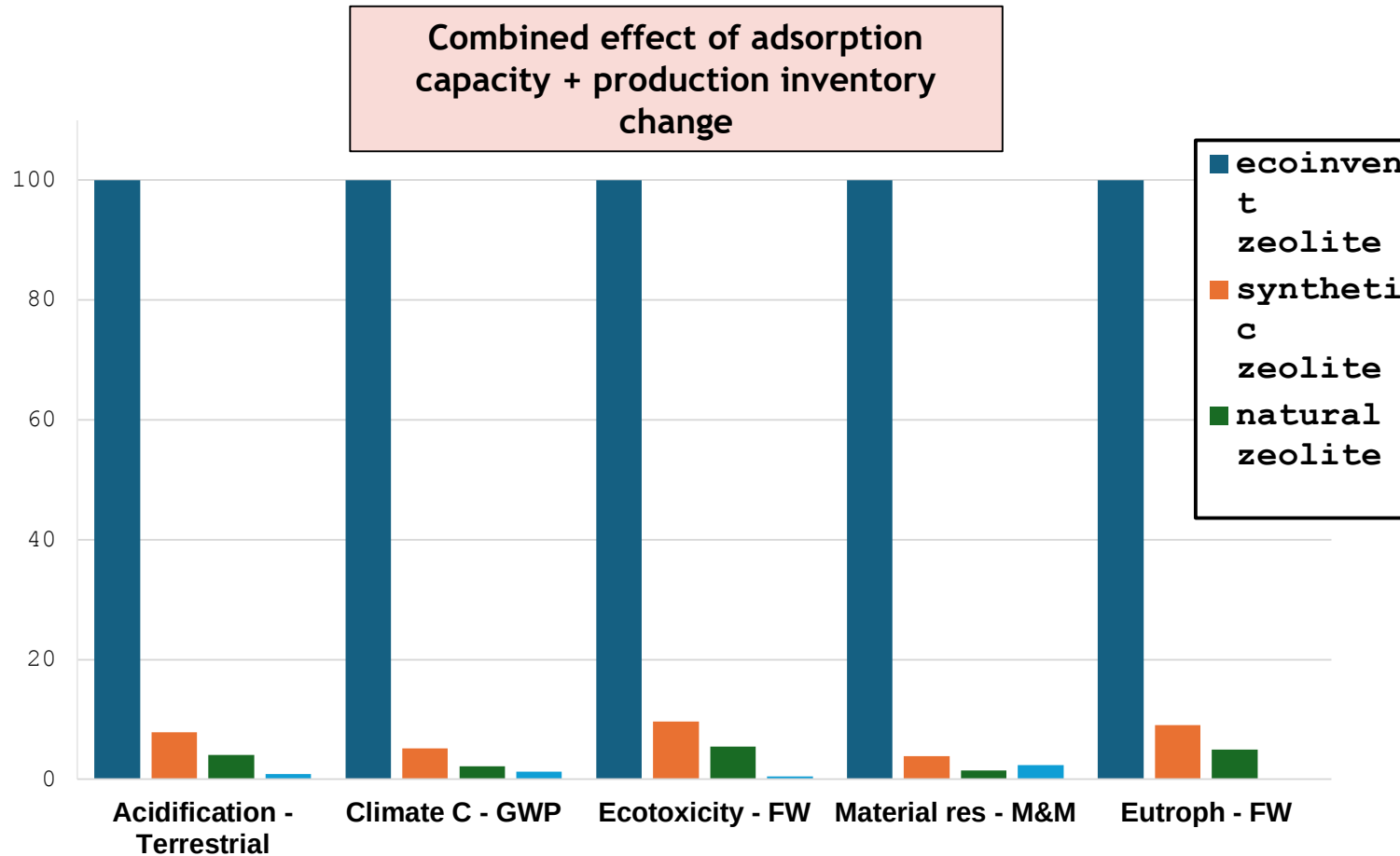


Causes

- low NH_4^+ concentration in mainline influent
- low adsorption capacity (4 mg N- NH_4^+ /g zeolite)
- impact-heavy outdated synthetic zeolite production process

Results

Uncertainty analysis - adsorbent trials

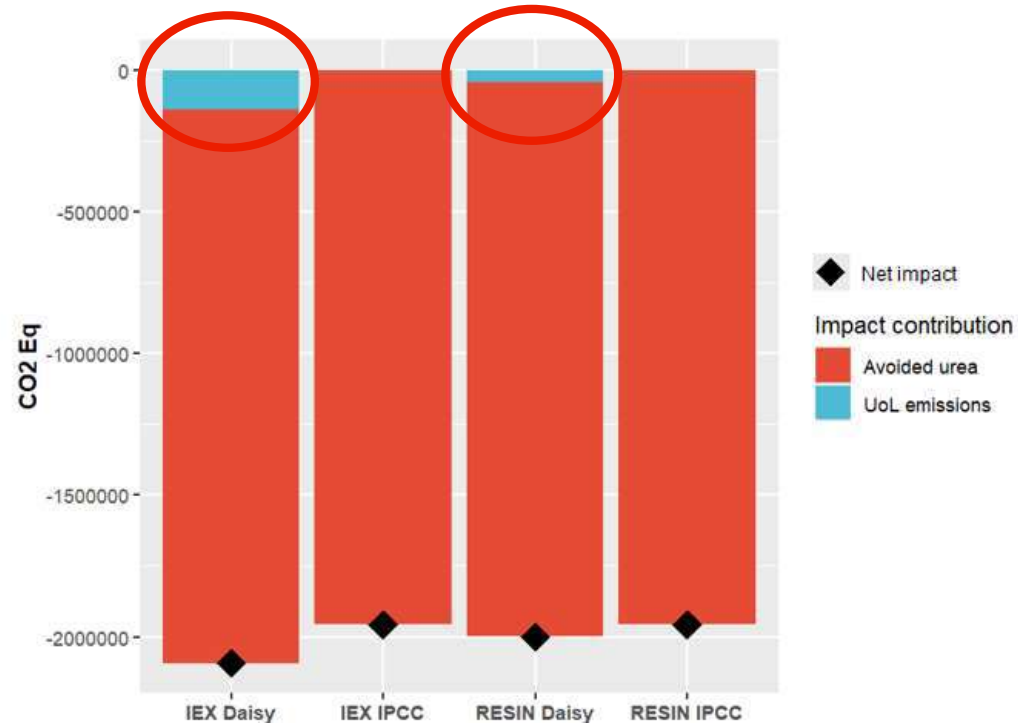


>90% reduction of process-related impacts with polymeric resin

Total system impact results were still not competitive with the reference scenario

Results

Use on Land stage impacts

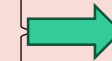


Climate change:

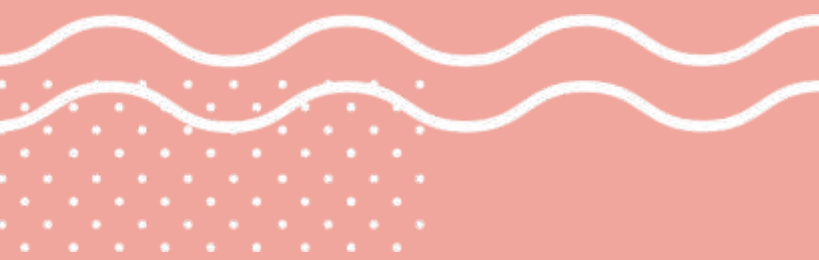
Impact reduction of 7.05% and 2.2% compared to 1:1 SR and IPCC emission factors in 4 mg/g zeolite and polymeric resin, respectively

Small difference

- mineralization rate
- management practices
- nutrient availability



**Similar
EFs
FER**

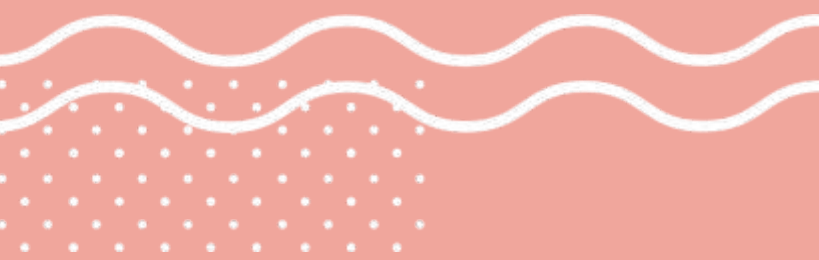


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LCA and TEA of ammonia stripping-scrubbing (Pilot 2b)

Jade Müller - University of Coimbra



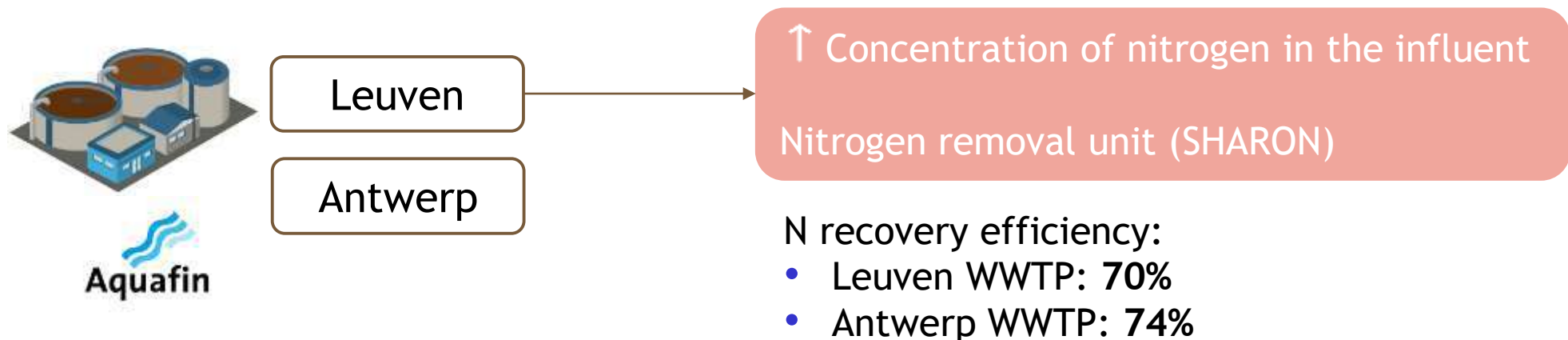
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Introduction

- N recovery from urban WW can reduce N_2O emissions and N discharges to water bodies
- Ammonia stripping-scrubbing (SS) is a mature technology, but not often applied in urban WWTPs, which may cause unintended consequences

SS (TRL 8) integration explored at two WWTPs in Belgium:



Goal & scope



To assess the environmental (LCA) & economic (TEA) performance

- Attributional LCA
- Consequential LCA

Urban WWTP



Ammonia stripping-
scrubbing (SS)

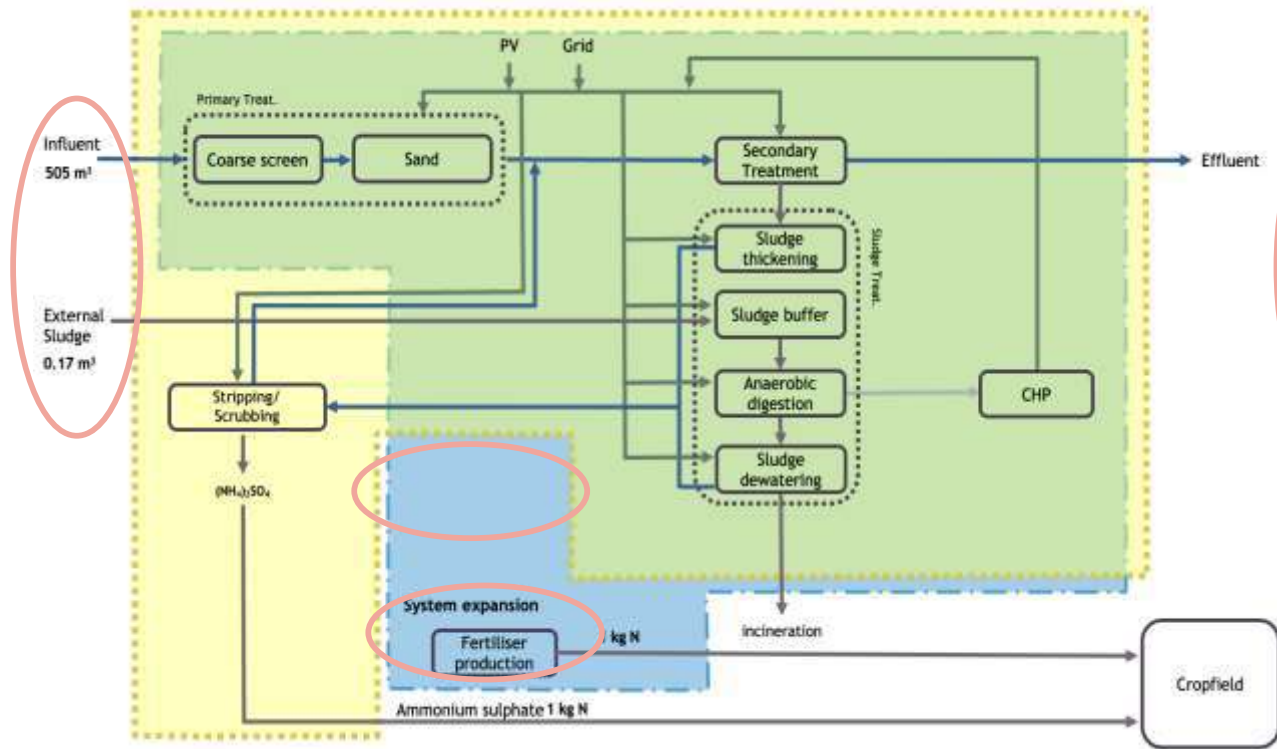
Functional unit:

- Attributional: 1 kg N recovery and the corresponding amount of wastewater influent and external sludge treated*
- Consequential: Annual amount of wastewater influent and external sludge treatment*

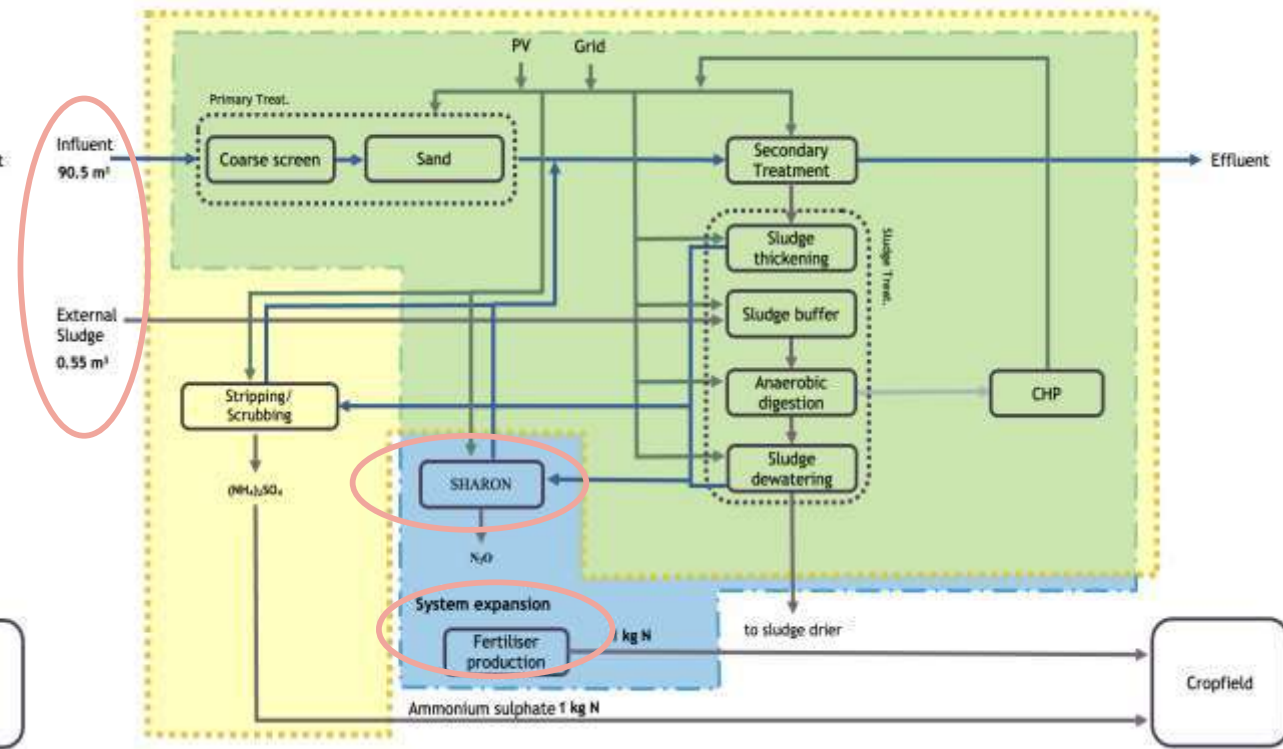
*Different for each WWTP

Attributional model

Antwerp WWTP

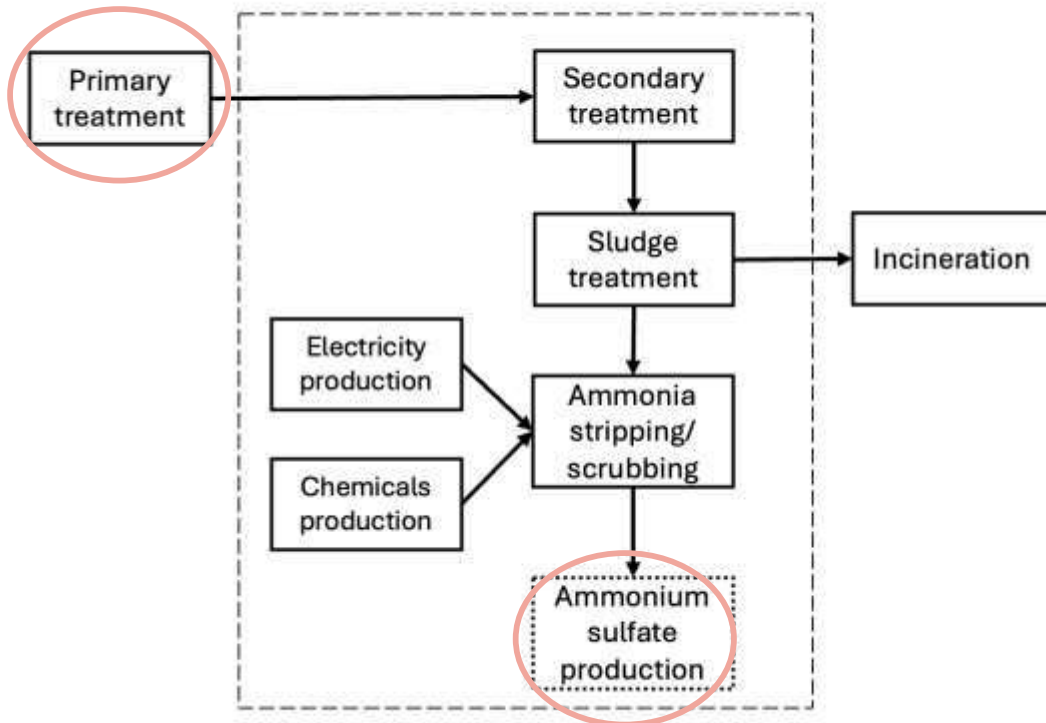


Leuven WWTP

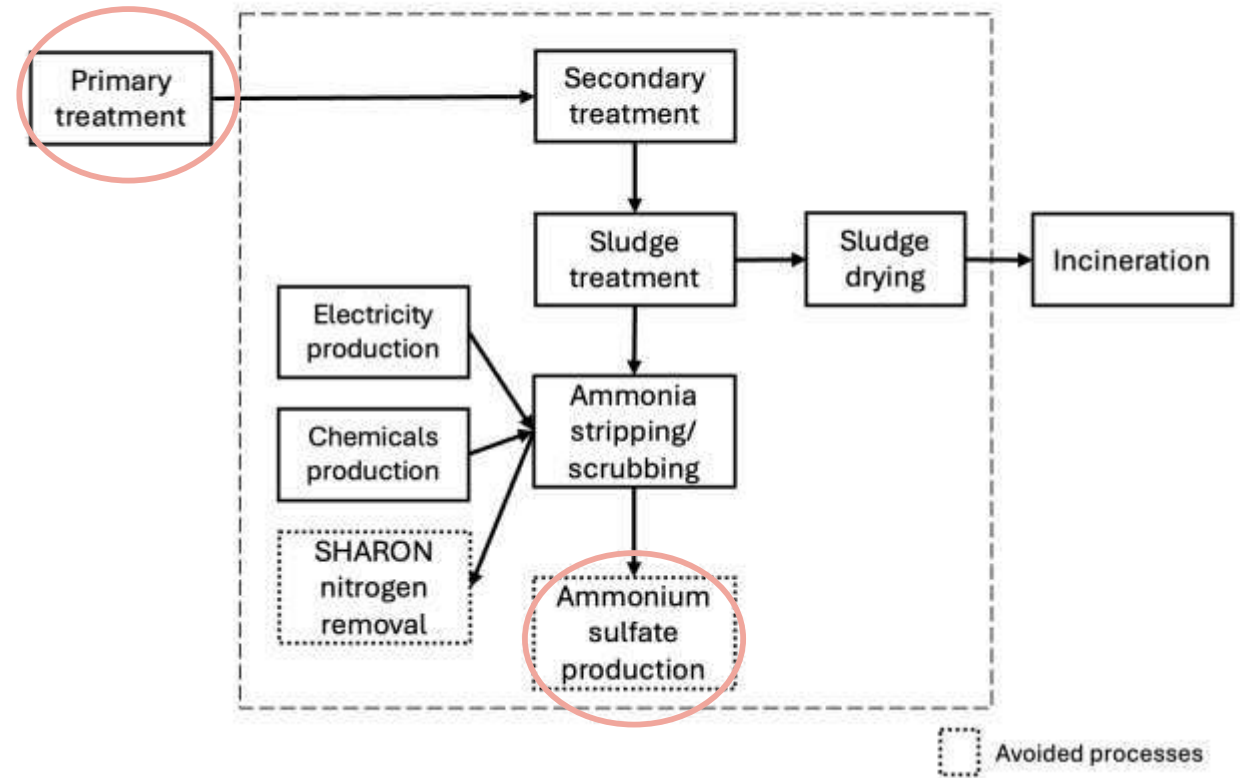


Consequential model

Antwerp WWTP



Leuven WWTP



Inventory analysis

Simulation data from Aquafin's internal CIS software (July 2025)

Antwerp WWTP: introduction of SS

- Reduction in N emissions to water and N_2O
- Increase in energy consumption

Leuven WWTP: substitution of SHARON by SS

- N recovery < N removal (SHARON)
- Increase in N emissions to water
- Reduction in energy consumption
- High N_2O emission reduction

Flows	Units	Δ Antwerp WWTP	Δ Leuven WWTP
Inputs			
Poly-electrolyte	kg/y	504	-2643
NaOH	kg/y	45892	316396
H ₂ SO ₄	kg/y	162281	654233
Electricity grid	kWh/y	230291	-276411
Electricity CHP*	kWh/y	4051	-12470
Natural gas combustion	kWh/y	-	-23327
Emissions			
Emission to water, BOD	kg/y	-165	804
Emission to water, COD	kg/y	-1667	1601
Emission to water, SS	kg/y		47
Emission to water, NO ₃	kg/y	-74163	-28263
Emission to water, NO ₂	kg/y	-1244	11483
Emission to water, KJN	kg/y	-2143	-671
Emission to air, CH ₄	kg/y	10	-120
Emission to air, N ₂ O	kg/y	-25	-25323
Emission to air, CO	kg/y	4	-
Emission to air, SO ₂	kg/y	0.3	-
Emission to air, NO _x	kg/y	6	-
Emission to air, NMVOC	kg/y	0.2	-
Emission to air, CH ₂ O	kg/y	0.2	-
Avoided products			
Ammonium sulphate	kg/y	218643	881459

Techno-economic assessment

- Indicator: **Net present value**
- **OPEX**
 - Material and energy inputs
 - Labour (SS maintenance)
 - Avoided costs - electricity & polyelectrolyte (SS_L)
- **CAPEX**
 - Estimated by technology developer
 - 10y-loan, 2% interest
 - 15y equipment lifespan
- **Revenue**
 - AS fertilizer sales

Parameter	Default value	Sensitivity ranges
Prices		
NaOH 30%	400 EUR/t	135-500 EUR/t
H ₂ SO ₄ 50%	30 EUR/t	24-90 EUR/t
Ammonium sulfate	150 EUR/t (SS_A); 110 EUR/t (SS_L)	120-390 EUR/t (SS_A); 88-285 EUR/t (SS_L)
Electricity	0.14 EUR/kWh	0.10-0.20 EUR/kWh
Salvage	0% CAPEX	10-20% CAPEX
Discount rate	5%	3-10%

Results

Attributional LCA

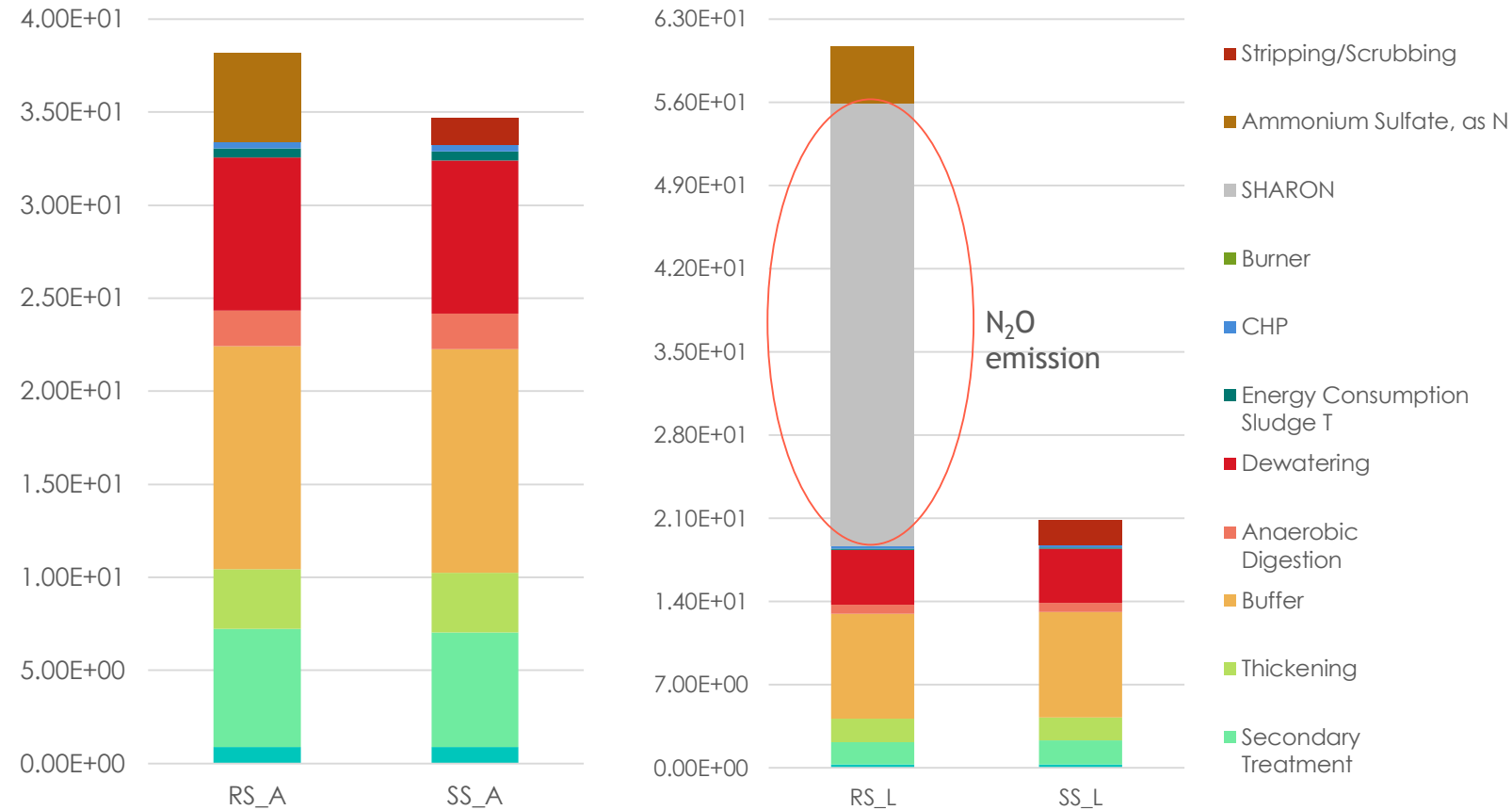
Antwerp WWTP:

- SS_A outperformed RS_A in **all 16** impact categories

Leuven WWTP:

- SS_L outperformed RS_L in **13/16** categories, except:
 - Ionising radiation (+17%)
 - Human toxicity, cancer (+4%)
 - Eutrophication, freshwater (+1%)

Climate change (kg CO₂-eq)



Environmental Footprint (EF 3.1) method

Results

Consequential LCA

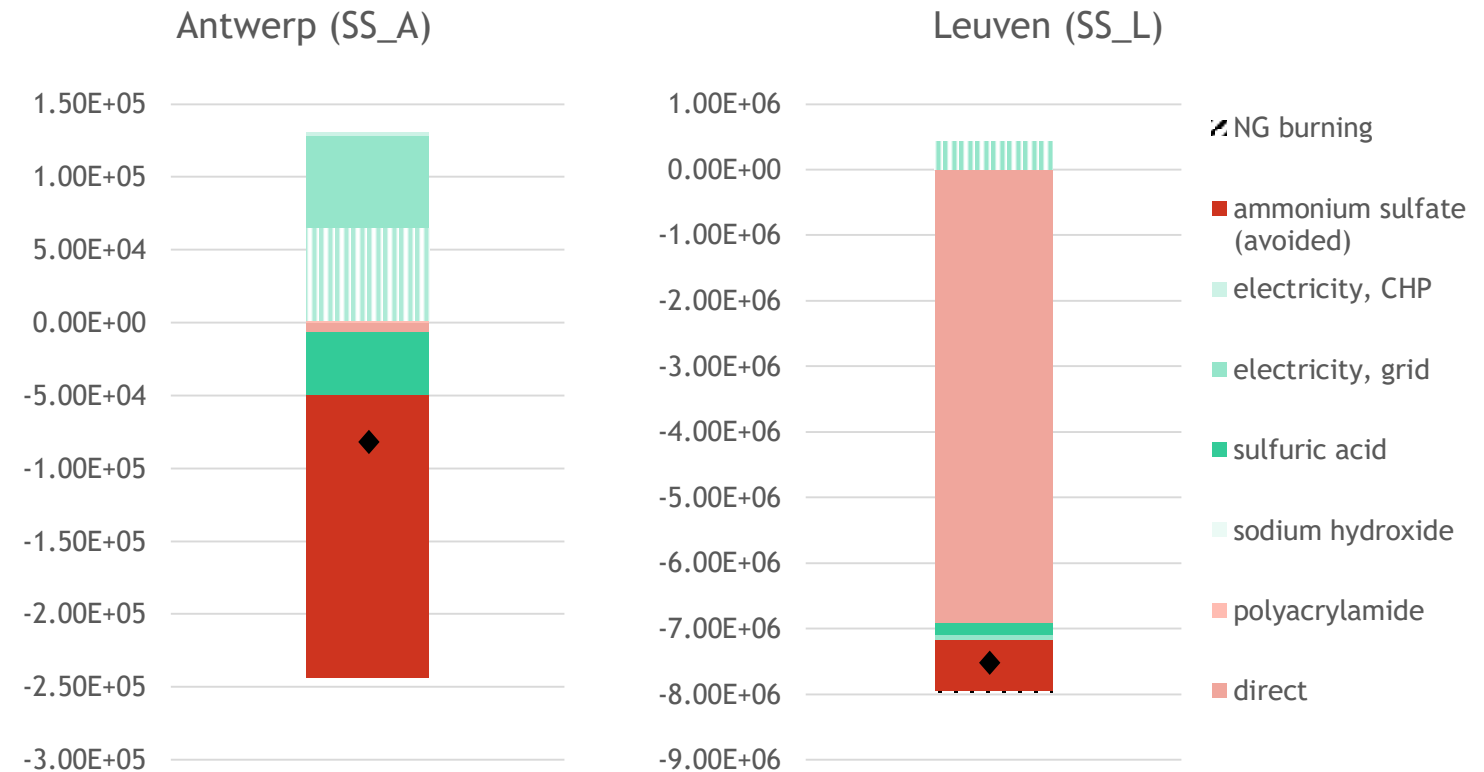
Antwerp WWTP

- SS outperformed RS in 14/16 impact categories, except:
 - Eutrophication, freshwater*
 - Land use*

Leuven WWTP

- SS outperformed RS in 12/16 impact categories, except:
 - Acidification*
 - Eutrophication, freshwater*
 - Land use*
 - Water use*

Net-impact - Climate change (kg CO₂-eq)



Environmental Footprint (EF 3.1) method

Sensitivity analysis: AS substitution rate

Normalised for one person*year, World average (EF3.1)

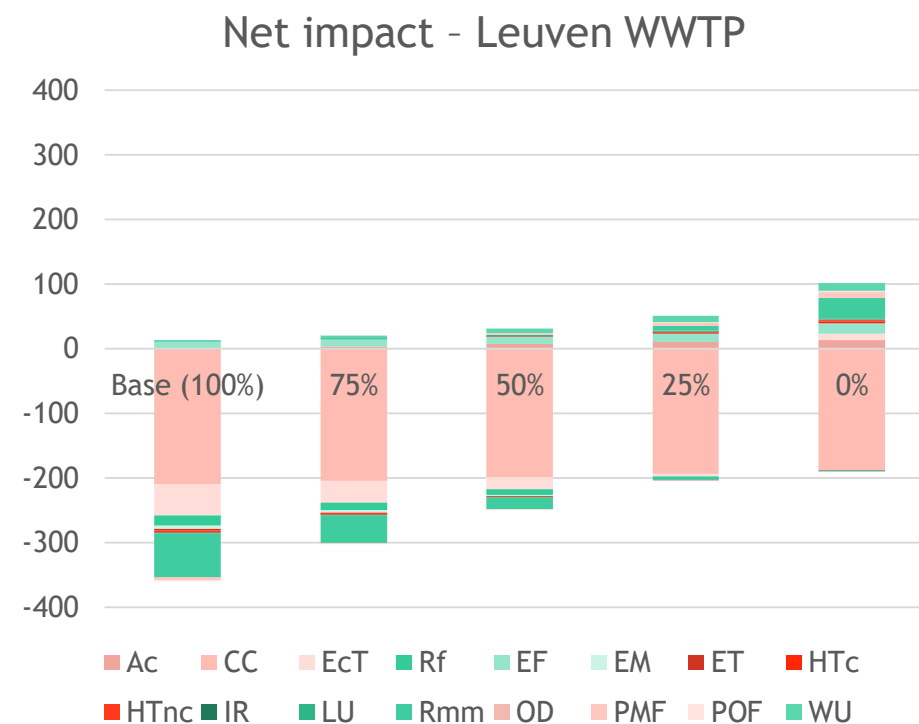
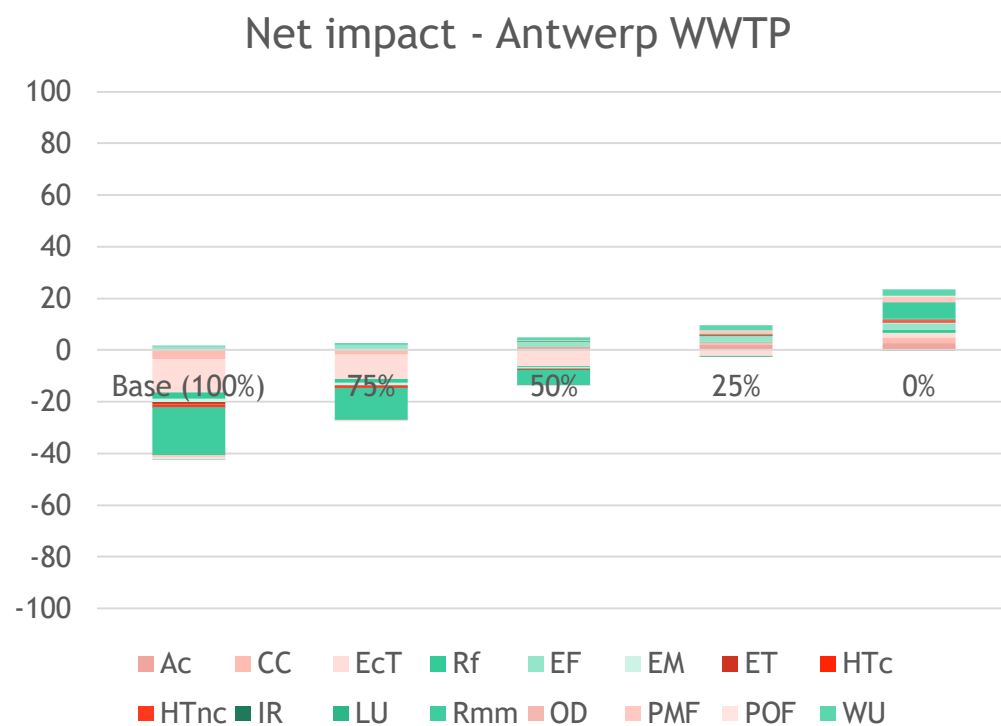
Normalized impact (EF 3.1)	Antwerp WWTP (SS_A - RS_A)					Leuven WWTP (SS_L - RS_L)				
	Sub_100%	Sub_75%	Sub_50%	Sub_25%	Sub_0%	Sub_100%	Sub_75%	Sub_50%	Sub_25%	Sub_0%
Ac	-6	7	19	32	44	11	61	111	162	212
CC	-15	-9	-2	4	11	-997	-971	-945	-919	-893
EcT	-676	-485	-295	-104	86	-2524	-1756	-987	-219	550
Rf	-28	-17	-7	4	14	-183	-140	-98	-55	-13
EF	48	59	70	81	92	335	380	424	468	513
EM	-46	-33	-20	-6	7	-184	-131	-78	-25	28
ET	-16	-8	0	8	16	-39	-7	25	57	90
HTc	-11	-7	-3	2	6	-47	-30	-13	4	20
HTnc	-54	-34	-14	7	27	-199	-118	-37	43	124
IR	-3.6	-3.1	-2.6	-2.1	-1.6	-19.2	-17.1	-15.0	-12.9	-10.8
LU	0.9	1.5	2.1	2.7	3.3	15.3	17.7	20.1	22.5	24.9
Rmm	-244	-161	-79	3	86	-905	-573	-240	92	424
OD	-0.05	-0.03	0.00	0.02	0.04	-0.62	-0.52	-0.42	-0.32	-0.22
PMF	-12	-4	5	13	22	-39	-5	29	64	98
POF	-11	-6	-1	4	9	-51	-30	-10	11	32
WU	-1	6	14	21	29	24	54	85	115	145

*Consequential model

Environmental Footprint (EF 3.1) method

Sensitivity analysis: AS substitution rate

Weighted impacts (EF3.1 factors)



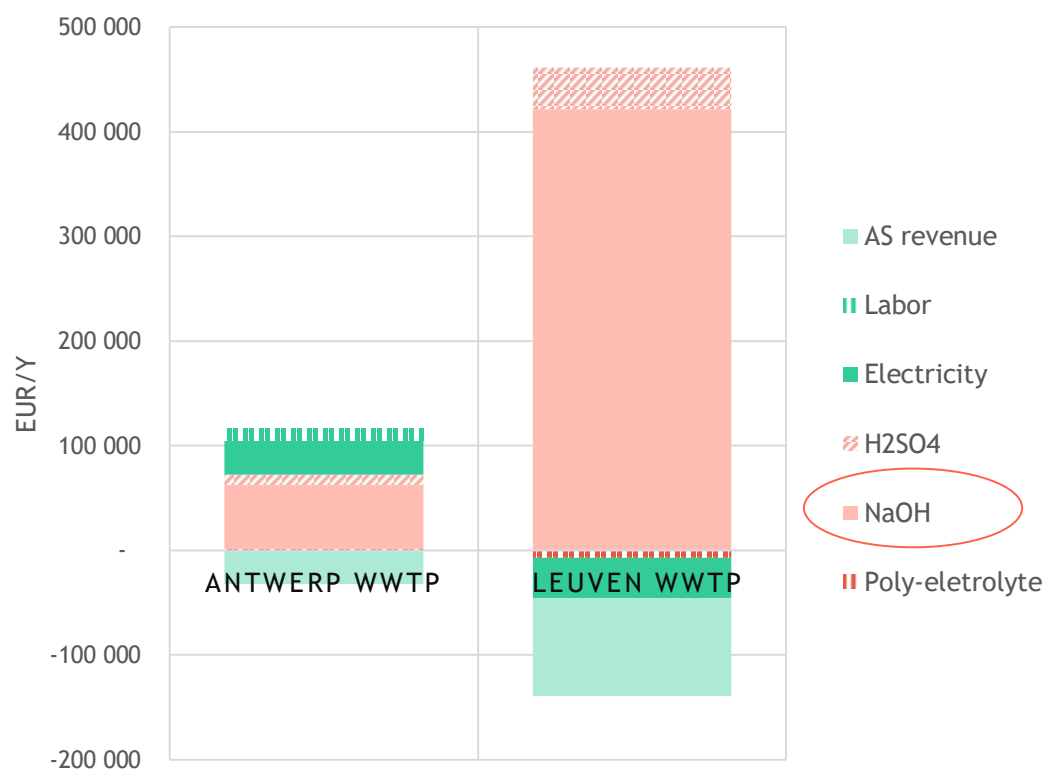
*Consequential model

Environmental Footprint (EF 3.1) method

Results

Techno-economic assessment

OPERATING COST AND REVENUES



Year	Discounted Cash Flow			
	Antwerp WWTP		Leuven WWTP	
1	-€	133 511	-€	385 382
2	-€	127 154	-€	367 031
3	-€	121 099	-€	349 553
4	-€	115 332	-€	332 908
5	-€	109 840	-€	317 055
6	-€	104 610	-€	301 957
7	-€	99 628	-€	287 578
8	-€	94 884	-€	273 884
9	-€	90 366	-€	260 842
10	-€	86 063	-€	248 421
11	-€	49 159	-€	187 383
12	-€	46 818	-€	178 460
13	-€	44 588	-€	169 962
14	-€	42 465	-€	161 868
15	-€	40 443	-€	154 160
NPV	-€	1 305 959	-€	3 976 442

Sensitivity analysis TEA

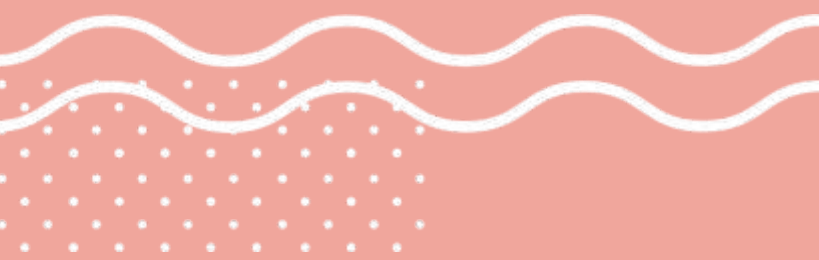
Parameter		SS_A	Change	SS_L	Change
NaOH price	low (135 €/kg)	-€ 885 194	32%	-€ 1 075 504	73%
	high (500 €/t)	-€ 1 416 252	-8%	-€ 4 962 406	-25%
Electricity price	low (0.1 €/kWh)	-€ 1 210 345	7%	-€ 4 090 066	-3%
	high (0.2 €/kWh)	-€ 1 449 380	-11%	-€ 3 806 007	4%
H2SO4 price	low (24 €/t)	-€ 1 286 757	1%	-€ 3 899 028	2%
	high (90 €/t)	-€ 1 508 089	-15%	-€ 4 791 328	-20%
AS price	low (120 €/t)				
		-€ 1 373 316	-5%	-€ 4 170 406	-5%
	high (390 €/t)	-€ 767 103	39%	-€ 2 424 730	41%
Salvage	medium (10% CapEx)	-€ 1 281 716	4%	-€ 3 940 077	3%
	high (20% CapEx)	-€ 1 257 472	2%	-€ 3 903 713	1%
Discount rate	low (3%)	-€ 1 482 338	-14%	-€ 4 543 895	-14%
	high (10%)	-€ 984 269	25%	-€ 2 954 804	26%
AS substitution rate	0%	-€ 1 642 744	-26%	-€ 4 946 262	-24%
	25%	-€ 1 558 548	-19%	-€ 4 703 807	-18%
	50%	-€ 1 474 352	-13%	-€ 4 461 352	-12%
	75%	-€ 1 390 155	-6%	-€ 4 218 897	-6%

Discussion: ALCA vs CLCA

Aspect	ALCA model	CLCA model
Scope	Broad (WWTP+SS), Share of SS impact within the WWTP	Net impact from baseline (WWTP+SS - WWTP - mineral AS)
Overall results	SS favorable	SS favorable
H ₂ SO ₄ impact	Major hotspot	Reduced - avoided NG heat co-produced with H ₂ SO ₄
NaOH impact	Relevant - NaOH production	Major hotspot - soda ash induced production as marginal supplier for NaOH (constrained product)

Conclusions

- SS implementation is environmentally favorable based on the findings both attributional and consequential LCAs, but not economically profitable
- At the Antwerp WWTP
 - SS reduces (weighted) impacts only if at least 50% of AS fertilizer replaces mineral AS production
 - Lower economic loss (higher NPV)
- At Leuven WWTP
 - SS reduces impacts even without mineral fertiliser substitution due to high CC mitigation potential (N₂O avoided emissions)
 - Higher economic loss (lower NPV)
- Decision-making requires balancing trade-offs and priorities.

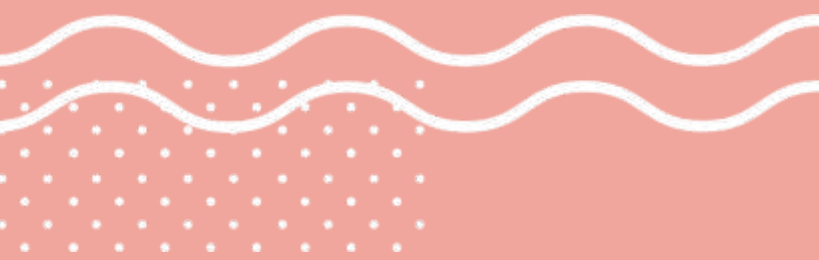


Thank you • Gracias • Grazie • Merci
Obrigado • Ευχαριστώ • Tak • Kösz • Bedankt



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101000752.





LCA of liquid/solid-state fermentation/animal bone char adsorption (Pilot 3)

Jade Müller - University of Coimbra



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101000752.



Introduction & background

- Phosphate rock is a finite, critical raw material essential for fertilizer production and food security
- Phosphorus recycling from waste streams can reinforce security of supply

3R-BioPhosphate Ltd. developed a pilot technology (TRL 5) to recover nutrients from:

- Acid whey - concent: 830-870 mg P/L
- Cow bone meal - concent: 91 g P/kg



Source: WalNUT / 3R-BioPhosphate Ltd.

Goal & scope



Goal: To assess the potential environmental impacts of a pilot-scale (TRL 5) technology that treats food industrial wastewater and recovers nutrients as bio-based fertilizer (BBF) from dairy wastewater and animal bones.

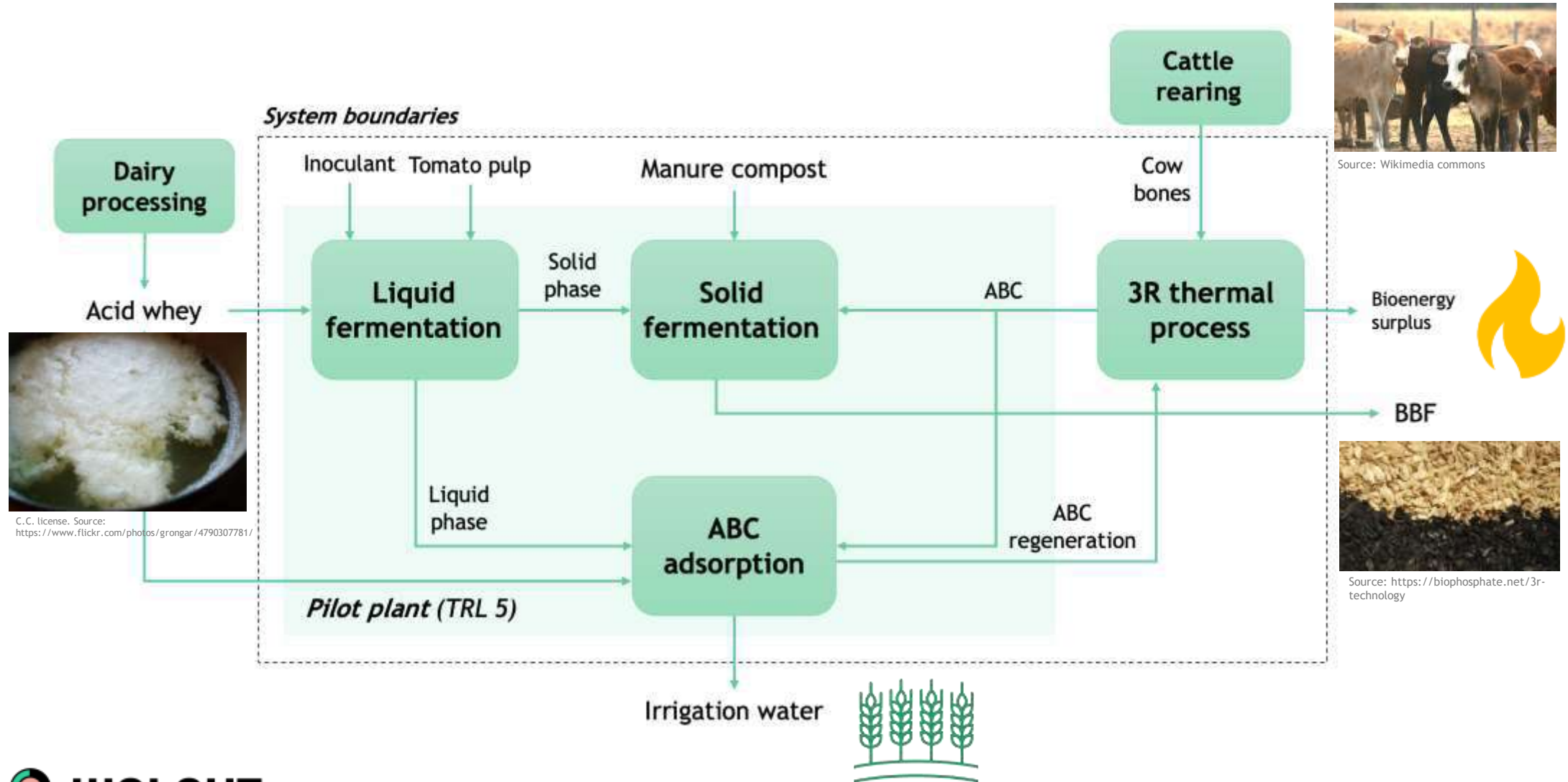
Functional unit: Production of 1 kg P, 0.096 kg N, and 0.030 kg K (in 14.4 kg of BBF)

Reference scenario:

Mineral NPK fertilizers production (1:1 substitution):

- P - Single superphosphate (SSP)
- N - Ammonium nitrate (AN)
- K - Potassium chloride (KCl)

System boundaries



Data & assumptions

- Cow bones considered burden-free - a recyclable by-product/waste (0€/kg) (consistent with ecoinvent cut-off system model) +
- Sensitivity analysis with varying prices (modified agri-footprint dataset)

Product Category	Mass fraction (%) ^a	Price (€/kg) ^a	Allocation factor (%)		
			Bone 0.0€	Bone 0.1€	Bone 0.2€
Fresh meat and edible offal	49	3	93.8	93.4	92.9
Food grade bones	8	0.0-0.2*	0	0.5	1
Food grade fat	7	0.4	1.8	1.8	1.8
Cat. 3 slaughter by-products	7	0.18	0.8	0.8	0.8
Hides and skins	7	0.8	3.6	3.6	3.5
Cat 1/2 material and waste	12	0	0	0	0

- Thermal process/pyrolysis (TRL9) modelled, considering:
 - Confidential primary data from the partner
 - Emissions from bio-oil/pyrolysis gas combustion - literature + stoichiometric calculations
 - Economic allocation for ABC and bioenergy (heat)

Life cycle inventory

- Foreground data provided by partner (TRL 5)
- Background data from ecoinvent v.3.10, cut-off

LCI	Unit	Batch	per FU
Product			
BBF	kg	275.0	14.4
Inputs			
Acid whey	kg	66.8	3.5
Animal bone char*	kg	170.0	8.9
Manure compost	kg	170.0	8.9
Tomato pulp	kg	32.5	1.7
Electricity, HU	kWh	1.5	0.1
Outputs			
Irrigation water	L	57.3	3.0

*3R thermal process (pyrolysis) model based on confidential data provided by the partner.

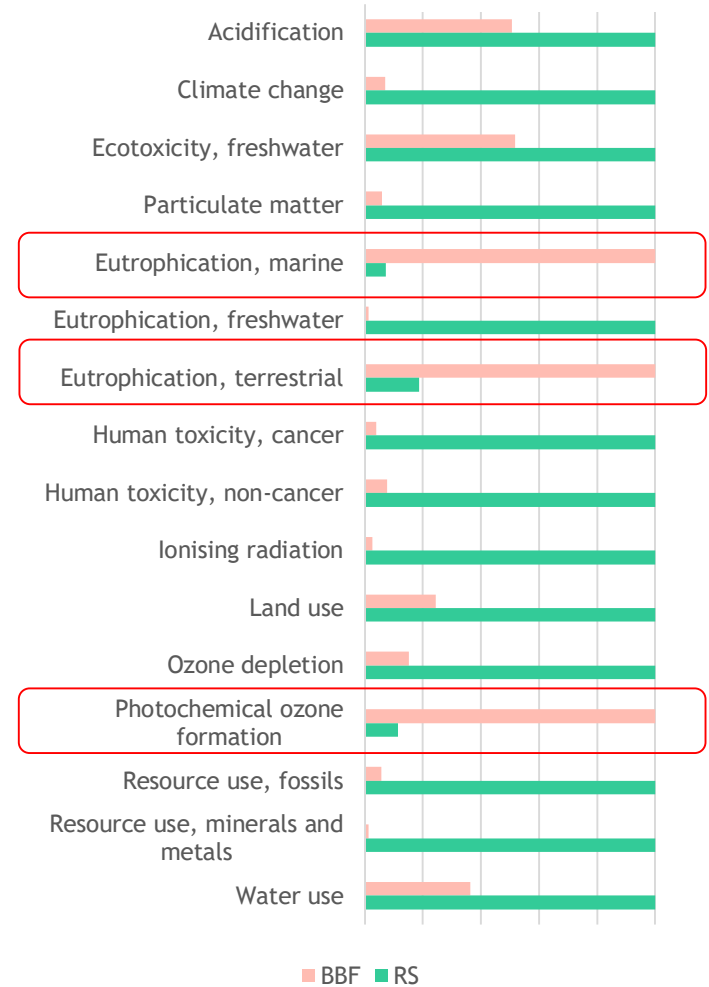
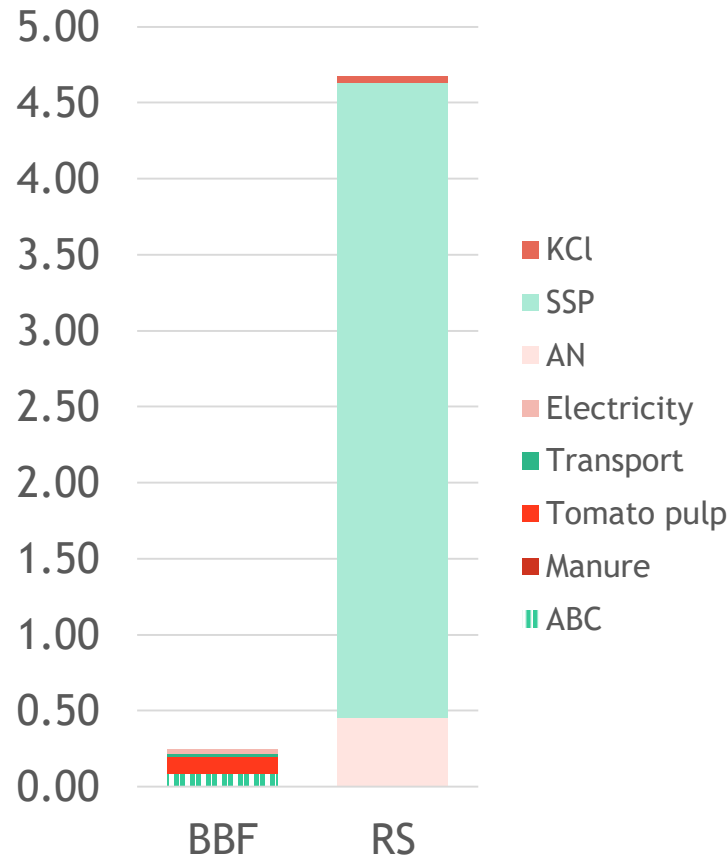
LCA Results

BBF (v. Mineral NPK)

- Overall lower impacts*
- >90% lower GWP
- Higher MEu, TEu, POF impact
↳ NO_x emissions (ABC thermal process)

*When bones are considered burden-free

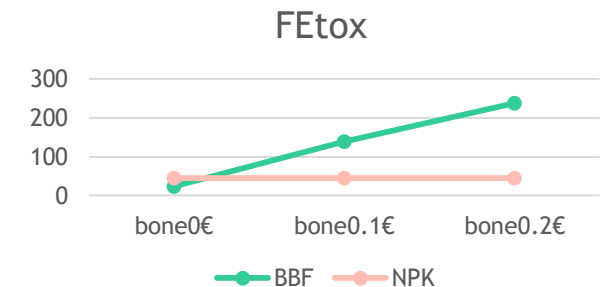
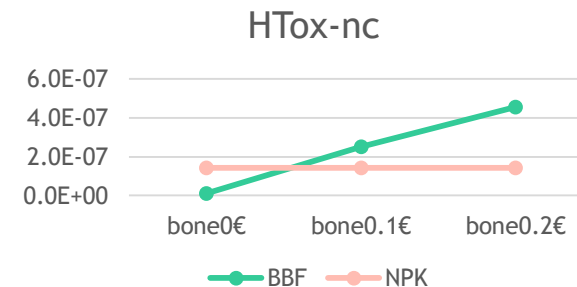
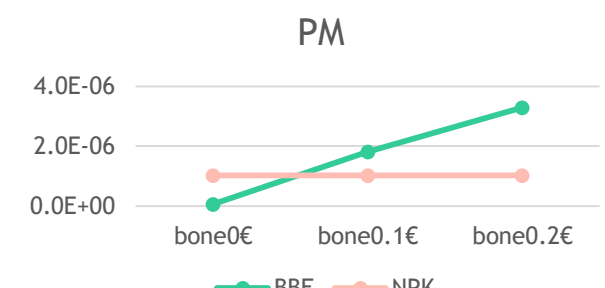
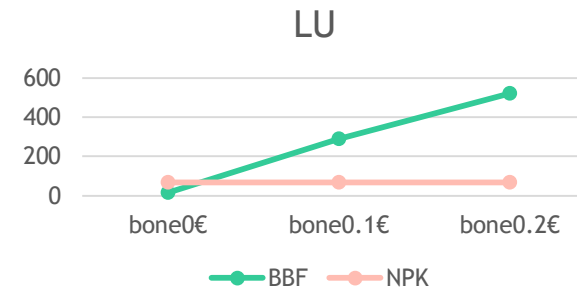
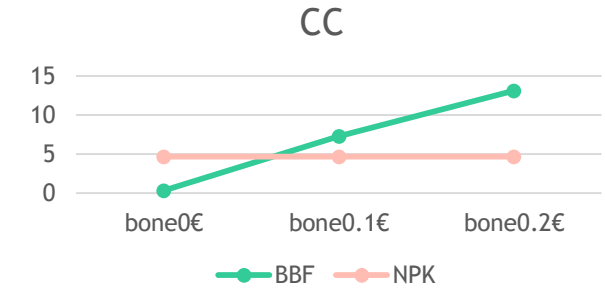
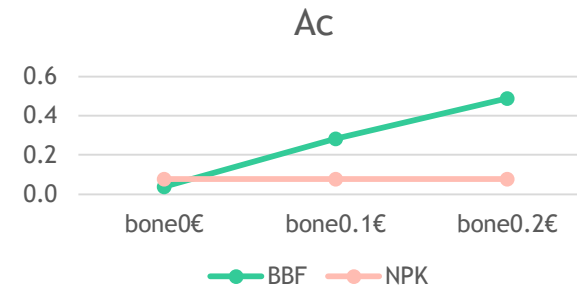
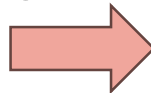
Climate change



Environmental Footprint (EF 3.1) method

Sensitivity analysis: bone price

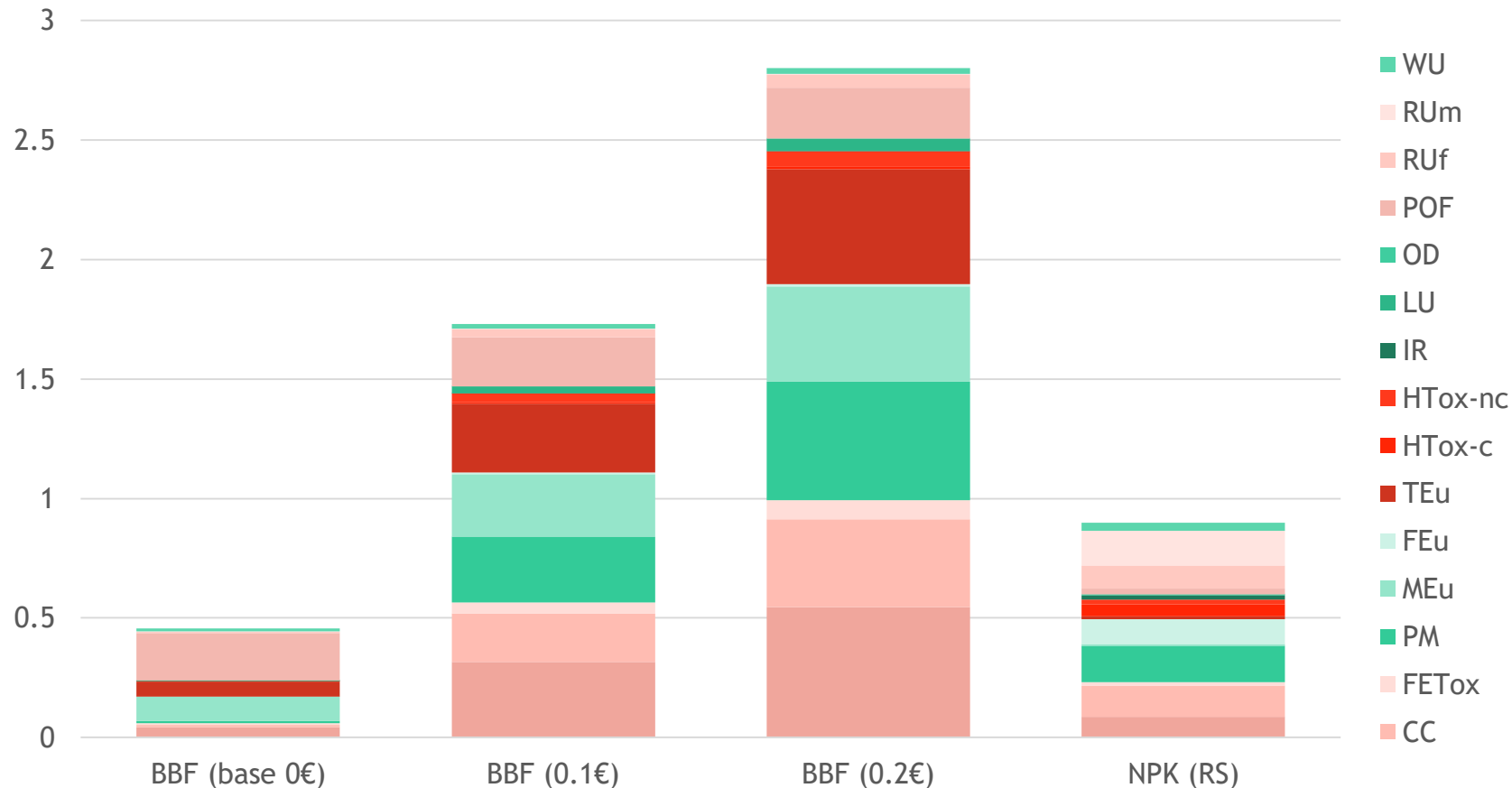
- BBF always outperforms Min.NPK in **7/16** impact categories (FEu, IR, HTox-c, OD, RUf, Rmm, WU)
- Min.NPK always outperforms NPK in **3/16** categories (MEu, TEu, POF)
- **6/16** categories depend on bone price/cattle-rearing burdens



Environmental Footprint (EF 3.1) method

Sensitivity analysis: bone price

Weighted impact results (EF 3.1)



Discussion: classification of cow bones

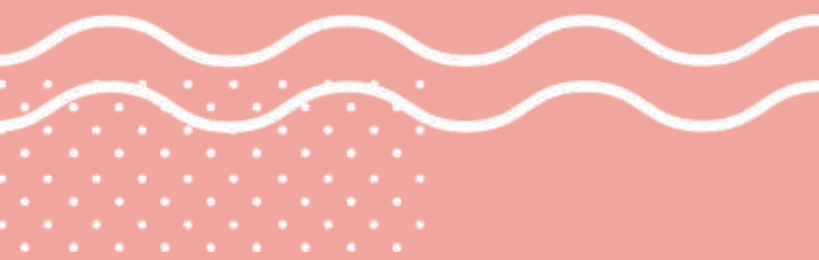
- ecoinvent cut-off: no burdens are attributed to 'waste' (0\$) or 'recyclable by-products' (>0\$), only to the 'reference product' and 'allocatable by-products'
- Classification based on judgment and a few criteria. For bones:

Criterion	Cattle bones
Intended product?	✗ No - slaughter exists for meat production
Drives production decisions?	✗ No
Economic value at slaughterhouse gate?	Low / secondary
Requires further processing?	✓ Rendering, crushing, degreasing
Sometimes waste?	✓ Yes
Fits waste/recycling logic?	✓ Yes

- In the specific case, cow bones are sourced at a 0 €/kg price - considered waste, thus not allocatable under the rules of ISO 14044.

Conclusions & limitations

- The pilot-scale LCA indicates overall lower environmental impacts of the BBF if considering cow bones burden-free.
- Cow bones classification as recyclable/waste and their price can change over time and across markets, which notably influence the impact attributed to the BBF.
- A 1:1 NPK substitution for the BBF was considered. Understanding the BBF's actual substitution effect on mineral NPK would make the LCA more robust, but it is not expected to alter the overall conclusions.

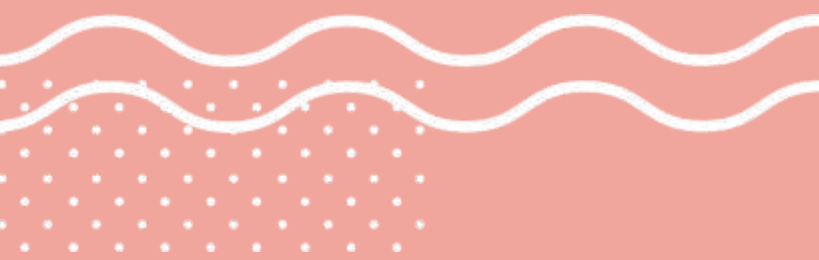


Thank you • Gracias • Grazie • Merci
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LCA of MLD SWRO brine treatment train (Pilot 4)

Lilla Simon - University of Southern Denmark



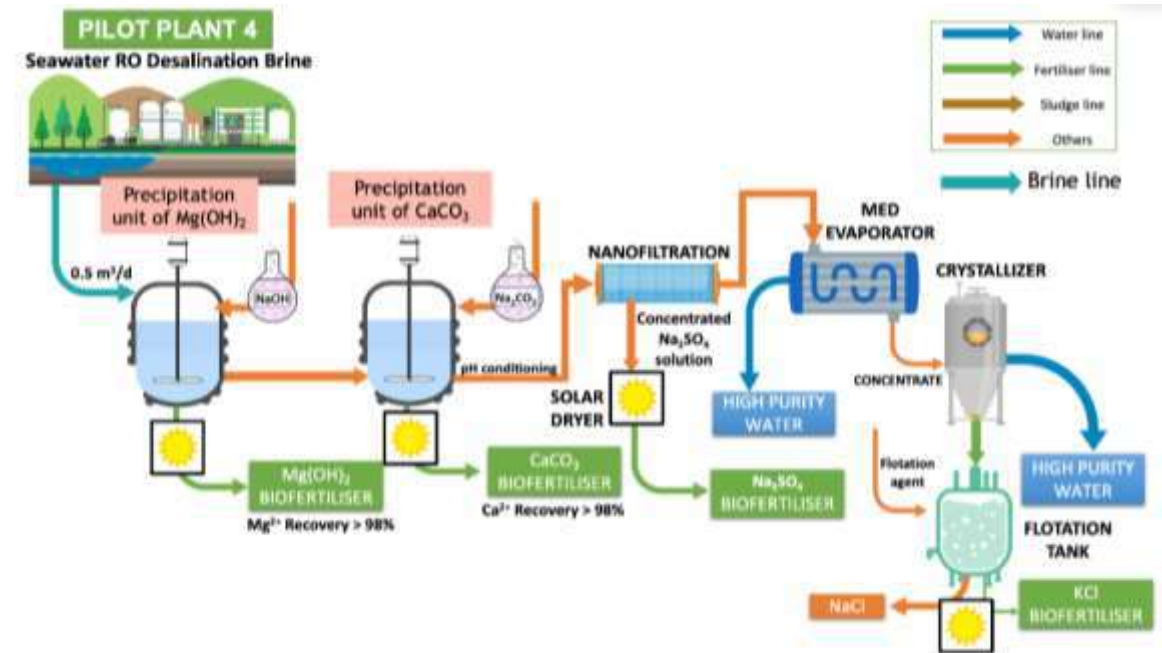
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101000752.



Introduction

Pilot description

- Wastewater type: SWRO brine
- Technologies: precipitation, NF, MED evap., crystallization, flotation
- Nutrients targeted: Mg, Ca, K, SO_4^{2-} (NaCl also recovered)
- Location: Cyprus
- Scale: lab-scale (200 ml) + pilot-scale (0.5 m³)
- Technology developer: NTUA



Research objectives:



- quantify the preliminary life cycle environmental impacts of the technology for in-house development and optimisation
- quantify the life cycle environmental impact changes with technology adoption on relevant scale

Assessment methodology



Goal & Scope

Lab-scale assessment Environmental impact assessment of technology train on bench-scale, hotspot optimization for in-house development Micro-level decision support Attributional LCA	Pilot-scale assessment Quantify the environmental impact effects of a decision: adopting MLD brine treatment train on full scale Meso/macro level decision support Consequential LCA
---	--

Functional unit:
management of 1 m³ of SWRO brine to regulatory standards

Assessment methodology

Bench-scale assessment

4 assessment scenarios:

	Sc1	Sc2	Sc3	Sc4
Mg precipitant		NaOH		Ca(OH) ₂
Calcination unit	-	✓	-	✓

Uncertainty & sensitivity analysis

Parameters:

- ✓ Influential
- ✓ High uncertainty data points
- ✓ Influence of background: 3 electricity providers: IEA Greece 2024 mix, ecoinvent 3.9.1 and NEPC projected 2050 Greek mix

Scenario analysis

Parameter	"Optimistic" scenario	"Pessimistic" scenario
Market substitution rate	1:1	2:1
MED evaporation electricity use	-20%	+20%
HCl use	-20%	+20%
NaOH/Ca(OH) ₂ use	-10%/-11%	+10%/+10%

$$\text{Sensitivity Ratio} = \frac{\frac{\Delta \text{result}}{\text{initial result}}}{\frac{\Delta \text{parameter}}{\text{initial parameter}}}$$

Assessment methodology

Pilot-scale assessment

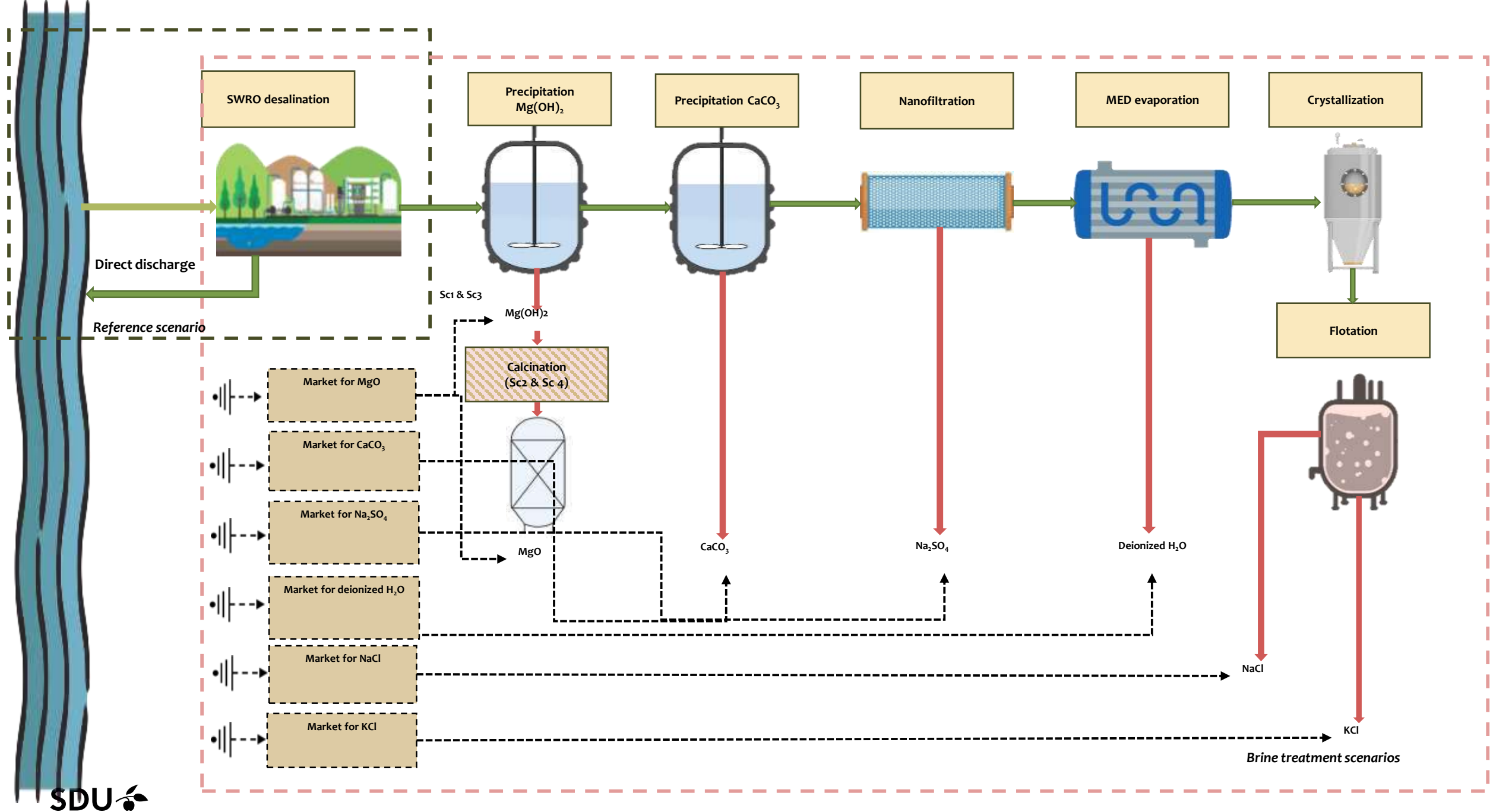
NaOH in $\text{Mg}(\text{OH})_2$ precipitation
No calcination step

Uncertainty & sensitivity analysis

Nanofiltration: added Na_2SO_4 recovered

Purity of recovered products

Recovered substance	Purity
$\text{Mg}(\text{OH})_2$	99.3%
CaCO_3	98%
KCl	94%
NaCl	99.6%



Results

Bench-scale assessment

Impact category	Unit	Ref	SC1	SC2	SC3	SC4
Acidification: Terrestrial	kg SO ₂ -Eq	1.4E-02 3.6E+0	2.2E-01	2.2E-01	2.0E-01	2.0E-01
Climate Change	kg CO ₂ -Eq	0	4.7E+01	4.6E+01	4.4E+01	4.2E+01
Ecotoxicity: Freshwater	kg 1,4-DCB-Eq	2.0E-01	5.6E-01	4.6E-01	-9.5E-02	-2.3E-01
Ecotoxicity: Marine	kg 1,4-DCB-Eq	2.7E-01	8.8E-01	7.4E-01	3.0E-02	-1.5E-01
Ecotoxicity: Terrestrial	kg 1,4-DCB-Eq	9.3E+0	2.4E+02	2.4E+02	2.0E+02	2.0E+02
Energy resources: fossil	kg oil-Eq	8.8E-01	1.3E+01	1.3E+01	1.1E+01	1.1E+01
Eutrophication: Freshwater	kg P-Eq	9.9E-04	8.4E-03	8.3E-03	3.3E-03	3.2E-03
Eutrophication: Marine	kg N-Eq	4.7E-04	2.4E-03	2.5E-03	1.9E-03	1.9E-03
Human toxicity: Carcinogenic	kg 1,4-DCB-Eq	3.3E-01	1.3E+00	1.1E+00	4.8E-01	2.7E-01
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	4.0E+0	1.4E+01	9.1E+00	-1.2E+00	-7.4E+00
Ionising radiation	kBq Co-60-Eq	2.2E-01	1.1E+00	1.1E+00	-1.8E-01	-1.6E-01
Land use	m ² *a crop-Eq	3.4E-02	1.6E+00	1.6E+00	1.5E+00	1.5E+00
Material resources	kg Cu-Eq	1.7E-02	-1.7E+00	3.4E+00	-3.9E+00	-6.1E+00
Ozone depletion	kg CFC-11-Eq	1.8E-05	6.2E-05	6.3E-05	5.3E-05	5.3E-05
Particulate matter formation	kg PM _{2.5} -Eq	7.2E-03	8.3E-02	8.2E-02	6.5E-02	6.3E-02
Photochemical oxidant formation: Human health	kg NO _x -Eq	7.8E-03	8.7E-02	8.5E-02	6.3E-02	6.0E-02
Photochemical oxidant formation: Terrestrial ecosystems	kg NO _x -Eq	8.0E-03	9.3E-02	9.0E-02	6.9E-02	6.5E-02
Water use	m ³	2.9E-02	2.8E-01	2.8E-01	-2.6E-03	-5.0E-03

*Recipe 2016 H LCIA method

FU = management of 1 m³ brine

- Sc4 impact < Reference scenario in 7/18 impact categories, net reduction of impacts in 6 impact categories

BUT 38.4 kg CO₂ Eq more than reference/FU

- Ca(OH)₂ preferred to NaOH as alkali
- Calcination step net negative impact score

Results

Bench-scale assessment - Process contribution analysis

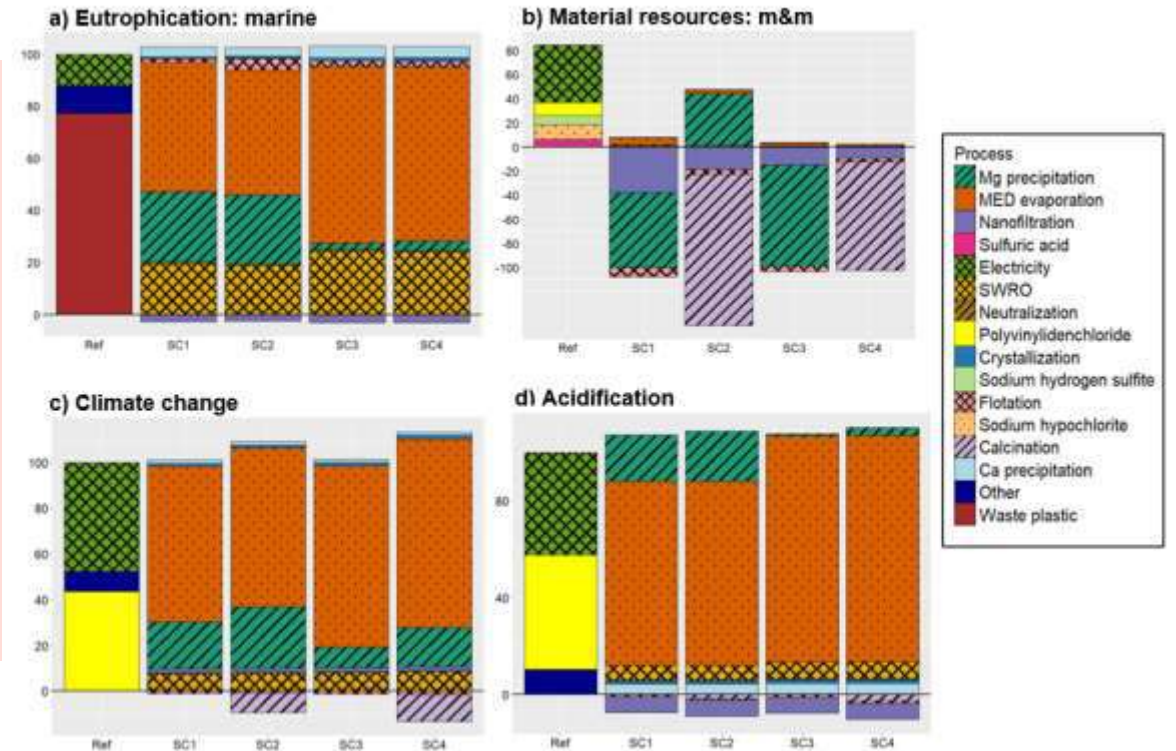
Main contributors:

MED evaporation, $\text{Mg}(\text{OH})_2$ precipitation and CaCO_3 precipitation, flotation

Main contributors to impact savings:

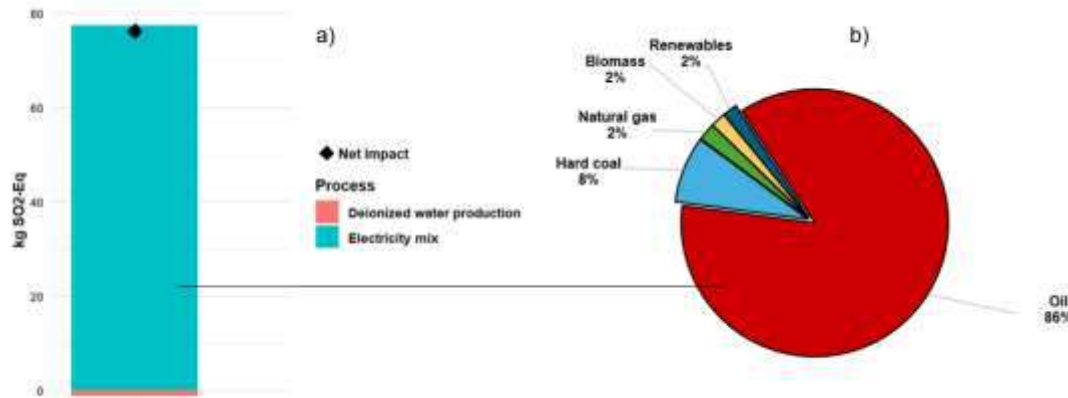
$\text{Mg}(\text{OH})_2$ and NaCl recovered

High-purity water recovery had a negligible effect on impact savings

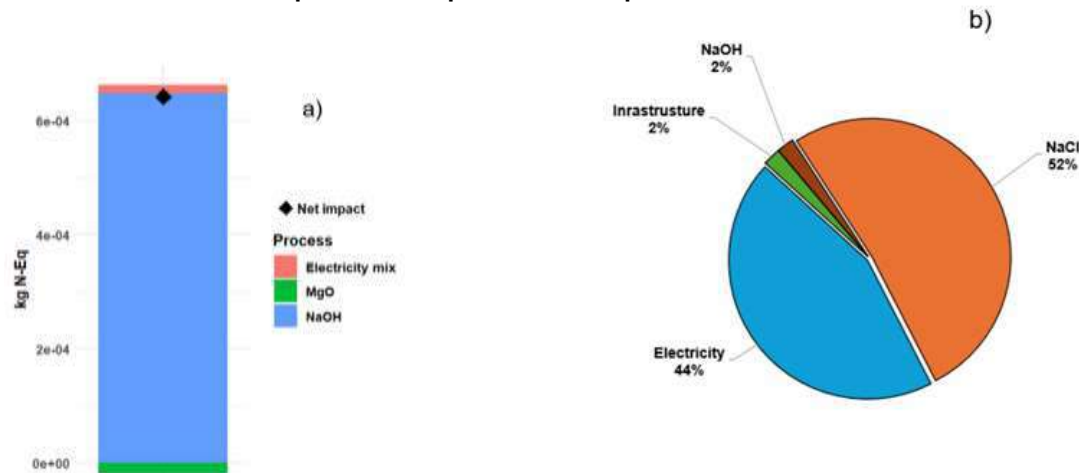


Results

Bench-scale assessment - Process contribution analysis



MED evaporation process impact shares



Mg(OH)₂ precipitation process impact shares

MED evaporation

- High specific electricity/m³ water retained
- High recovery rate (~90%)

Mg(OH)₂ precipitation

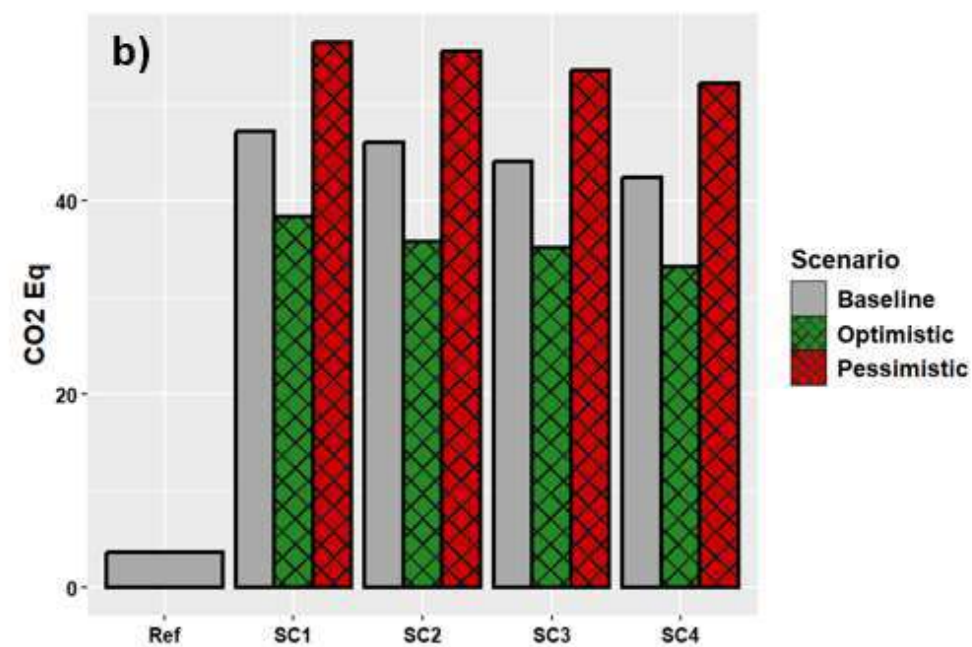
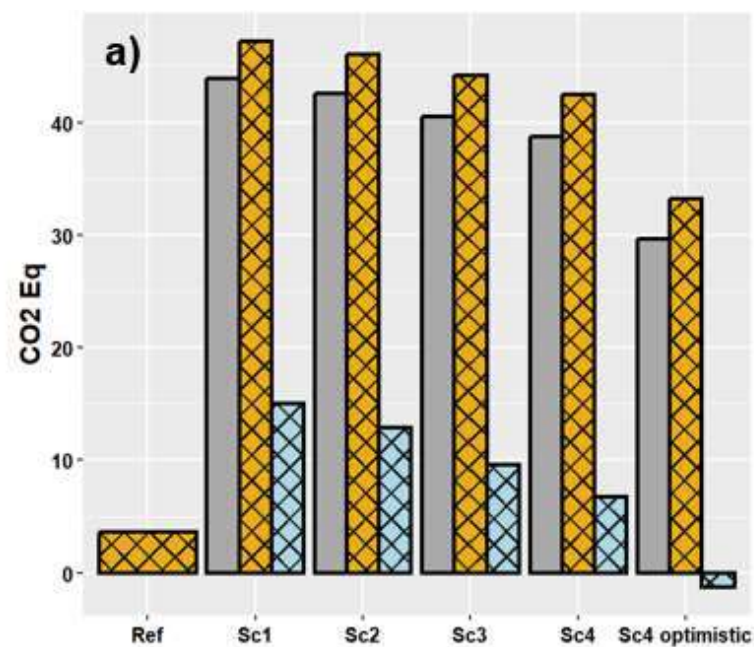
- Alkali production (NaOH/Ca(OH)₂)

Optimisation recommendation:

- Replacing NaOH with Ca(OH)₂ may lower climate change impacts by 59% (Sc1-Sc3)

Results

Bench-scale assessment - Uncertainty analysis



Results

Pilot-scale assessment

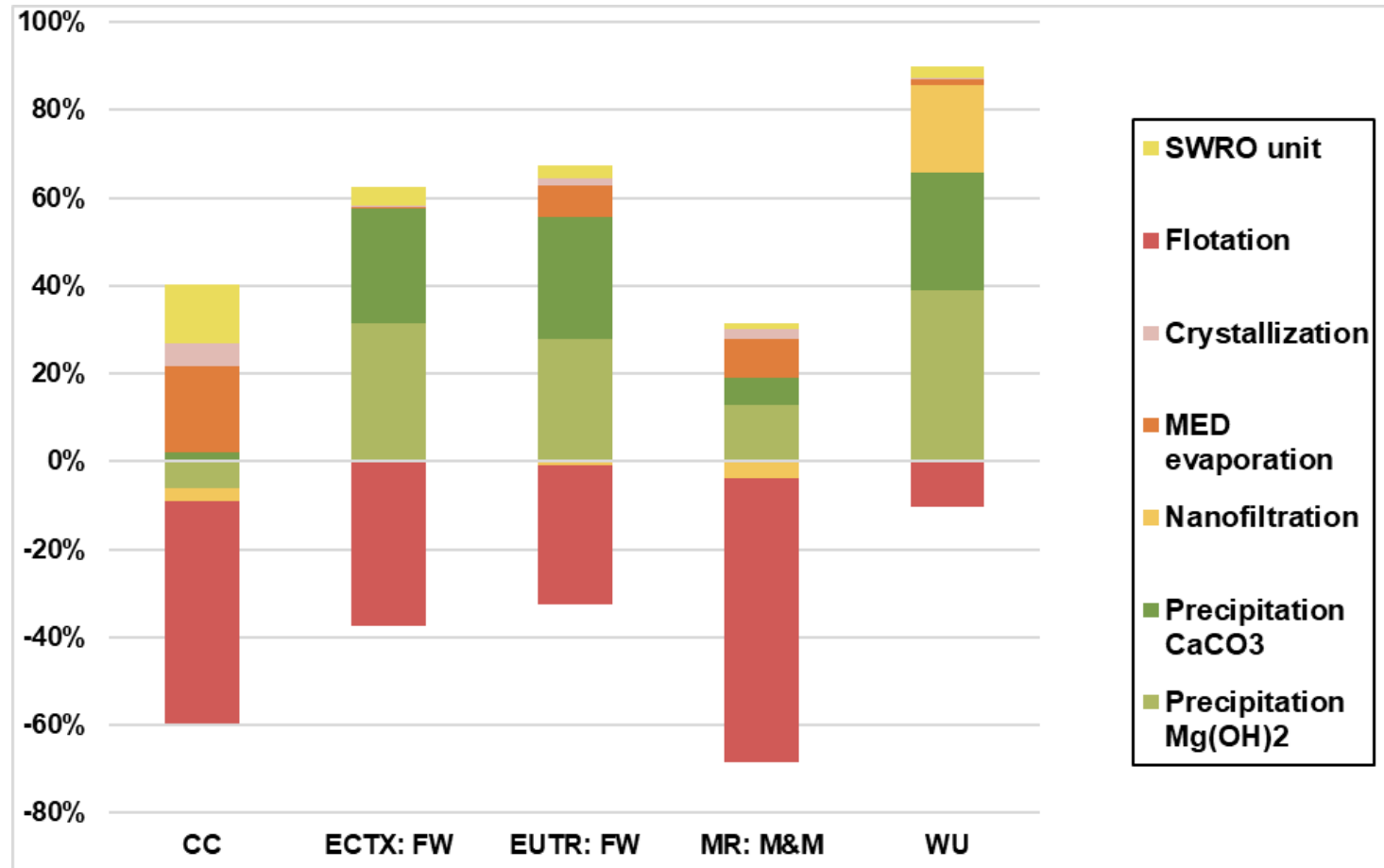
Impact category	Unit	Ref'	Pilot 4 - A	Pilot 4 - B	Δ results	Δ %	Normalized r.
Acidification	mol H ⁺ -Eq	1.67E-02	7.81E-02	8.02E-02	6.14E-02	367	1.10E-03
Climate change	kg CO ₂ -Eq	3.18E+00	-4.66E+00	-3.70E+00	-7.84E+00	-247	-1.04E-03
Ecotoxicity: freshwater	CTUe	4.98E+01	2.83E+02	2.85E+02	2.33E+02	468	4.11E-03
Energy resources: non-renewable	MJ, ncv	4.21E+01	-5.06E+01	-3.55E+01	-9.26E+01	-220	-1.42E-03
Eutrophication: freshwater	kg P-Eq	8.44E-04	1.03E-02	1.06E-02	9.44E-03	1119	5.88E-03
Eutrophication: marine	kg N-Eq	2.99E-03	-2.35E-03	-1.84E-03	-5.34E-03	-178	-2.73E-04
Eutrophication: terrestrial	mol N-Eq	2.69E-02	2.21E-01	2.25E-01	1.94E-01	721	1.10E-03
Human toxicity: carcinogenic	CTUh	1.14E-08	-1.97E-09	-1.65E-09	-1.34E-08	-117	-7.77E-04
Human toxicity: non-carcinogenic	CTUh	5.58E-08	-2.04E-07	-1.95E-07	-2.60E-07	-466	-2.02E-03
Ionising radiation: human health	kBq U235-Eq	1.87E-01	-1.23E+00	-1.19E+00	-1.41E+00	-757	-3.35E-04
Land use	dimensionless	3.80E+00	3.38E+02	3.38E+02	3.34E+02	8781	4.07E-04
Material resources: metals/minerals	kg Sb-Eq	2.73E-05	-8.42E-04	-7.49E-04	-8.69E-04	-3188	-1.37E-02
Ozone depletion	kg CFC-11-Eq	1.20E-05	1.63E-05	1.63E-05	4.27E-06	36	8.16E-05
Particulate matter formation	disease incid	4.64E-07	-3.94E-07	-3.83E-07	-8.58E-07	-185	-1.44E-03
Photochemical oxidant formation	kg NMVOC-Eq	9.15E-03	-1.82E-02	-1.58E-02	-2.74E-02	-299	-6.70E-04
Water use	m ³ world eq. depr.	1.10E+00	3.41E+01	3.42E+01	3.30E+01	2992	2.87E-03

FU = management of 1 m³ brine

* EF 3.1 LCIA method

Results

Pilot-scale assessment - Process contribution analysis

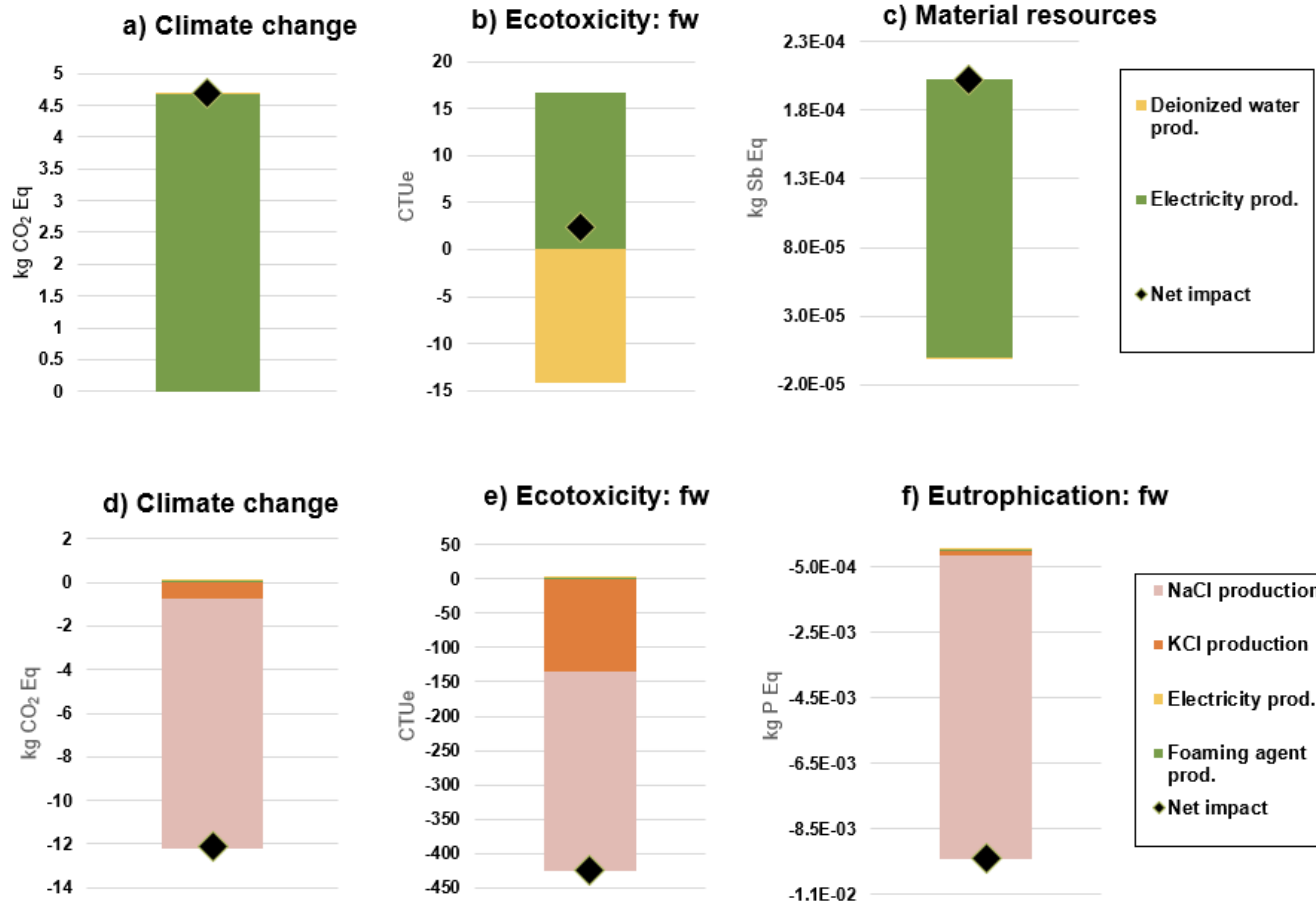


- Precipitation processes and MED evaporation still dominate, but impact share changed
- Flotation resulted in largest savings

* EF 3.1 LCIA method

Results

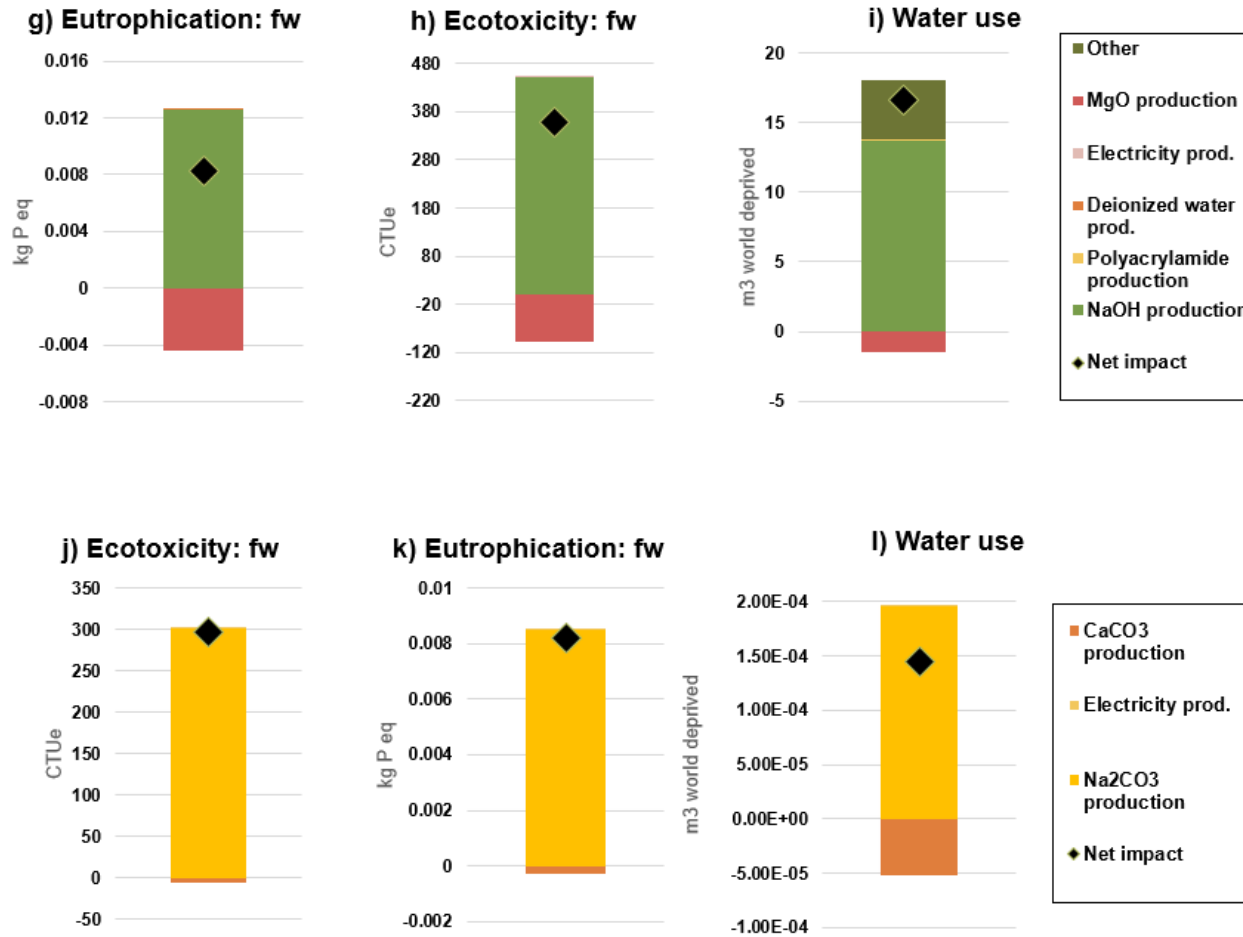
Pilot-scale assessment - Unit process level contribution analysis



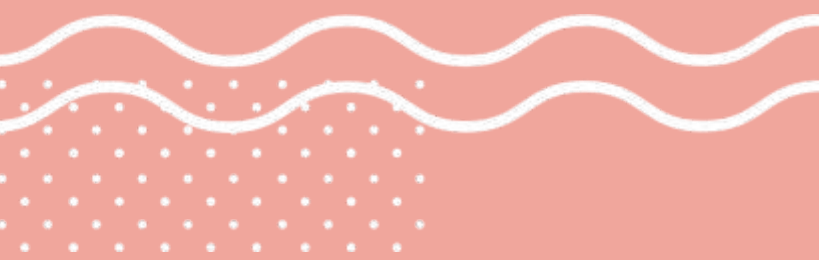
*EF 3.1 LCIA method

Results

Pilot-scale assessment - Unit process level contribution analysis



*EF 3.1 LCIA method

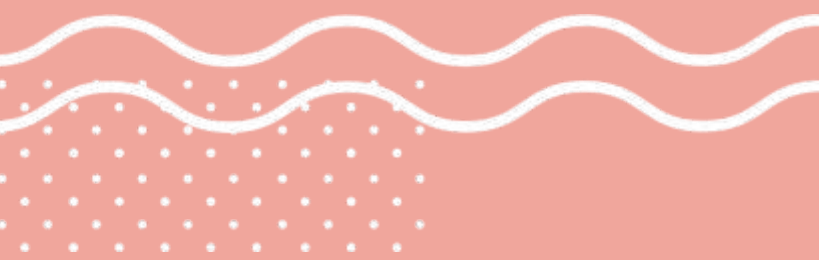


Thank you • Gracias • Grazie • Merci
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LCA and TEA of ion exchange/ membrane contactors (Pilot 5)

Ana Cordeiro - University of Coimbra



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101000752.



Introduction

Overview

Responsible partner: CETAQUA

Type of feedstock: Reject water

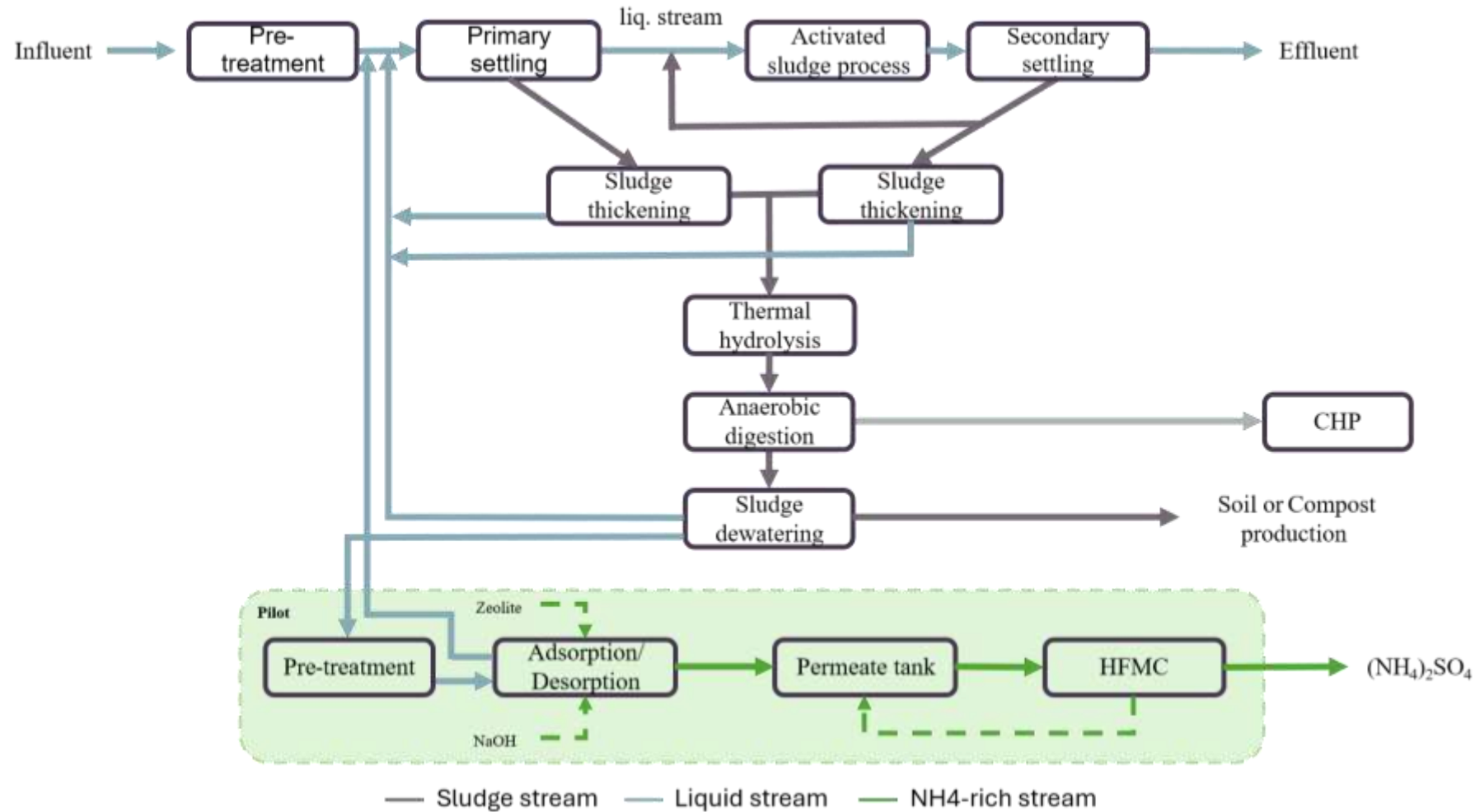
Nutrients recovered: Nitrogen as ammonium sulfate

Process technologies: Filtration unit; Ion exchange; Hollow Fibre Membrane Contactors



The primary goal of this LCA is to assess the environmental impacts of a pilot technology **(TRL 5)** system for recovering nitrogen as Ammonium Sulphate (AS) based on ion exchange and membrane contactors.

Goal & scope



Functional unit: production of 1 kg of nitrogen (in the form of AS)

Life cycle inventory

Inventory		Units	IEX-MC
Inputs			
	NaOH	kg	8.16
	H ₂ SO ₄	kg	3.51
	Zeolite	kg	3.115
	Electricity	kWh	2.577
Outputs			
	Recovered N (as Ammonium Sulphate)	kg N	1.00
	Zeolite waste treatment	kg	3.115

Reference scenario

Production of 1 kg of nitrogen (in the form of ammonium sulfate fertiliser*)

*This fertilizer is a mix of technologies that are used in the European market

- CETAQUA provided primary data for the pilot process (TRL 5).
- Background data for materials and energy were obtained from the ecoinvent v3.10 - Cut-off.

Techno-economic assessment (TRL5)

OPEX

- Material and energy inputs
- Labour (pilot)
- Zeolite

CAPEX

- Estimated by CETAQUA
- 20y equipment lifespan

Revenue

- AS fertiliser sales

OPEX	Cost (per unit)
Chemicals	
NaOH 50% (€/l)	€ 0.80
H ₂ SO ₄ 38% (€/l)	€ 1.00
Energy	
Electricity (€/kWh)	€ 0.14
Zeolites	
Zeolites (€/kg)	€ 1.00
Others	
Tap water (€/m ³)	€ 0.89
REVENUES	Selling Price (kg)
Ammonium sulfate	€ 0.30
CAPEX	Total Cost (€)
Pre-treatment	€ 4 990.00
Cation exchange system	€ 14 850.00
HFMC unit	€ 15 000.00
Blender	€ 7 900.00
Assembly	€ 3 990.00
Installation & construction	€ 13 470.00
N-NH ₄ analyzer	€ 12 500.00

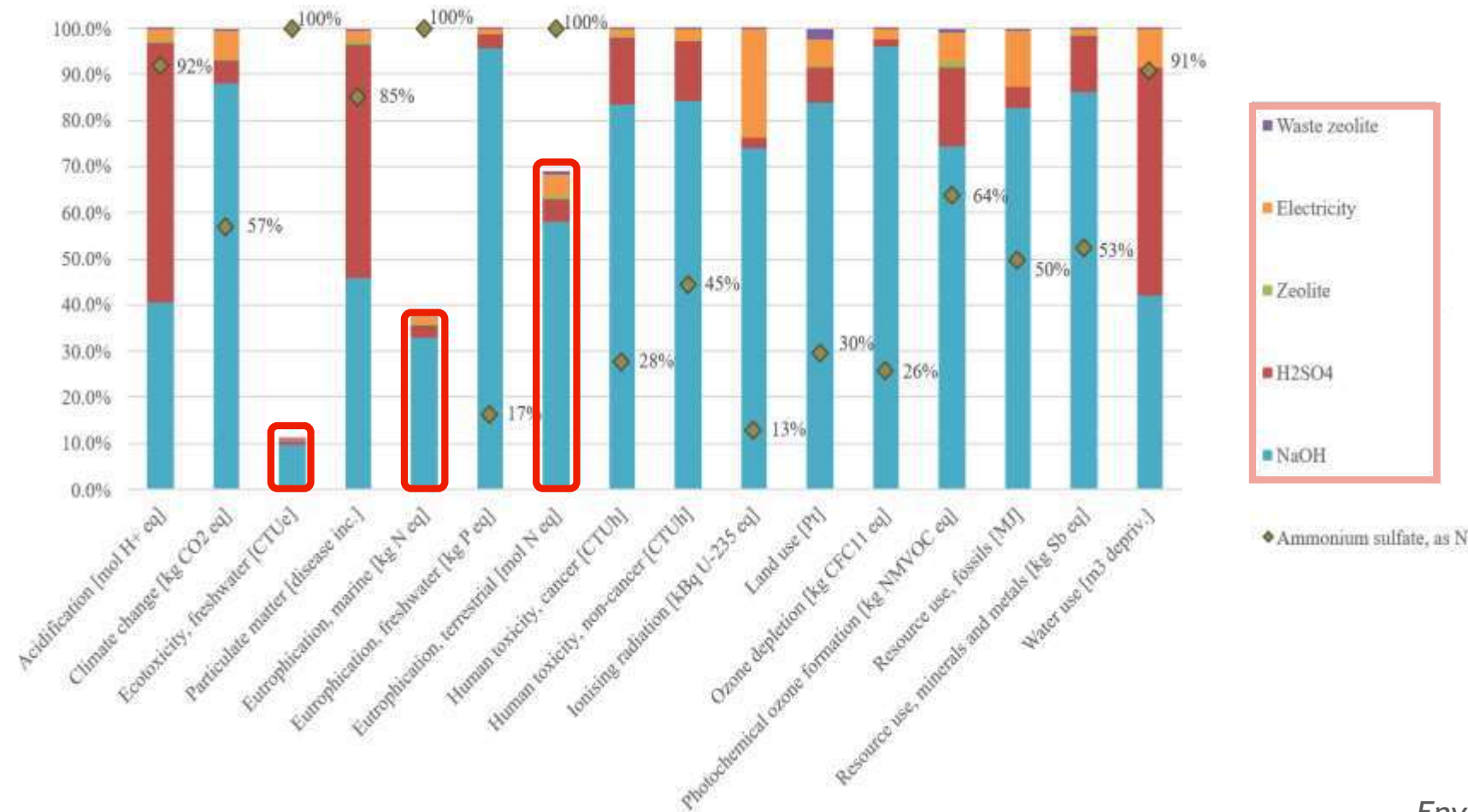
Results LCA

Damage category	Unit	IEX-MC	RS	Change
Acidification	mol H+ eq	8.30E-02	7.65E-02	8%
Climate change	kg CO2 eq	8.27E+00	4.73E+00	75%
Ecotoxicity, freshwater	CTUe	1.01E+02	9.32E+02	-89%
Particulate matter	disease inc.	5.89E-07	5.02E-07	17%
Eutrophication, marine	kg N eq	8.27E-03	2.16E-02	-62%
Eutrophication, freshwater	kg P eq	5.49E-03	9.07E-04	505.5%
Eutrophication, terrestrial	mol N eq	7.63E-02	1.11E-01	-31.1%
Human toxicity, cancer	CTUh	1.02E-07	2.83E-08	259.3%
Human toxicity, non-cancer	CTUh	1.19E-07	5.31E-08	124.3%
Ionising radiation	kBq U-235 eq	2.68E+00	3.52E-01	662.9%
Land use	Pt	4.18E+01	1.25E+01	235%
Ozone depletion	kg CFC11 eq	4.40E-07	1.15E-07	284%
Photochemical ozone formation	kg NMVOC eq	2.76E-02	1.77E-02	56%
Resource use, fossils	MJ	1.44E+02	7.22E+01	100%
Resource use, minerals and metals	kg Sb eq	1.25E-04	6.56E-05	90%
Water use	m3 depriv.	6.17E+00	5.62E+00	10%

- IEX-MC shows lower impact in 3 out of the 16 categories

Environmental Footprint (EF 3.1) method

Results LCA



Chemical balance



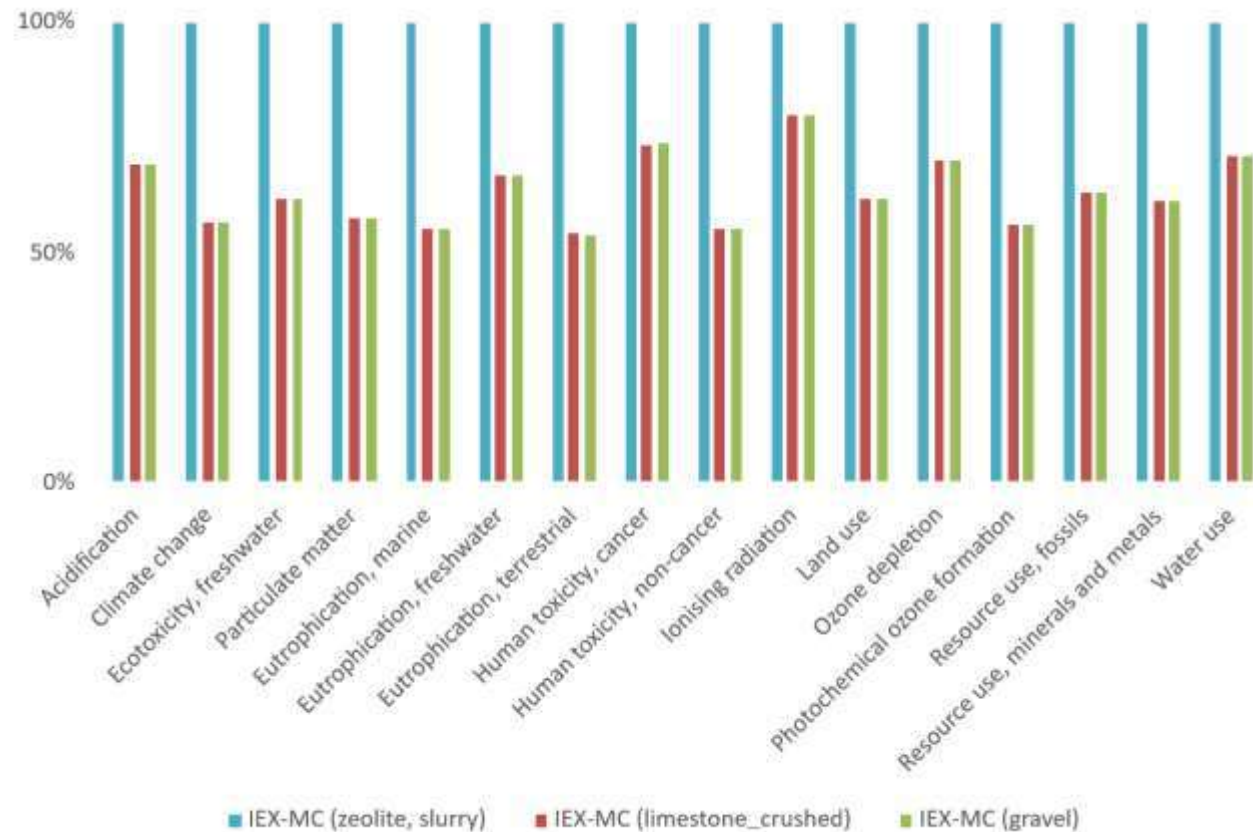
Minimal theoretical value



Three times the theoretical value

Environmental Footprint (EF 3.1) method

Sensitivity analysis LCA (zeolite)



Zeolite, slurry, without water, in 50% solution state {RER} | market for zeolite, slurry, without water, in 50% solution state | Cut-off, U

↳ (Mayor et al., 2023)

Limestone, crushed, washed {CH} | market for limestone, crushed, washed | Cut-off, U

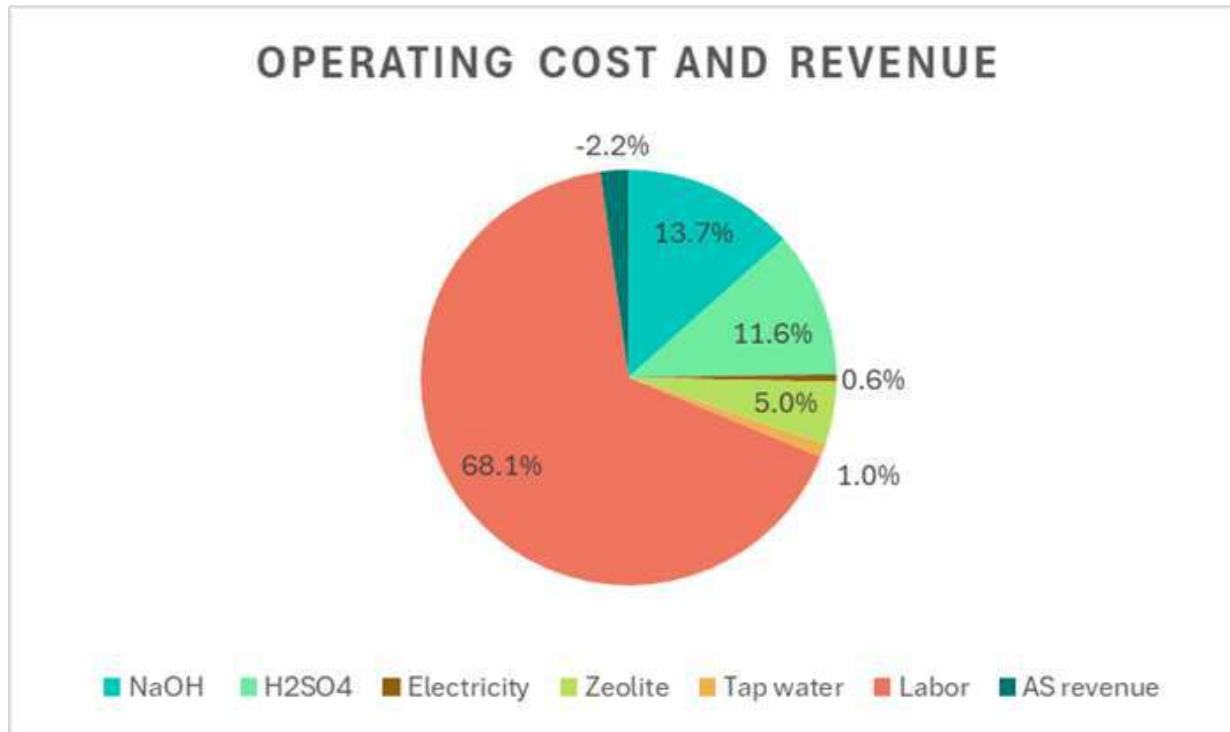
↳ (Salas et al., 2018)

Gravel, crushed {CH} | market for gravel, crushed | Cut-off, U

↳ (Amaraibi et al. 2024)

Results

Techno-economic assessment



Year	Discounted Cash Flow
1	-€ 10 995.64
2	-€ 10 472.04
3	-€ 9 973.37
4	-€ 9 498.45
5	-€ 9 046.14
6	-€ 8 615.37
7	-€ 8 205.12
8	-€ 7 814.40
9	-€ 7 442.28
10	-€ 7 087.89
11	-€ 6 750.37
12	-€ 6 428.92
13	-€ 6 122.79
14	-€ 5 831.22
15	-€ 5 553.55
16	-€ 5 289.09
17	-€ 5 037.23
18	-€ 4 797.36
19	-€ 4 568.92
20	-€ 4 351.35
NPV	-€ 143 881.51
NPV/ kgN	-€ 55.34

- Even if we disregard the labor cost, NVP would be negative as well

Conclusions

- Environmental benefits in reducing eutrophication and freshwater ecotoxicity impacts, it underperforms in most other categories;
- The main environmental burdens stem from the use of sodium hydroxide and sulfuric acid;
- Economically, the NPV is negative, as operating costs—dominated by labour and chemical expenses—far exceed revenues from recovered fertilizer.

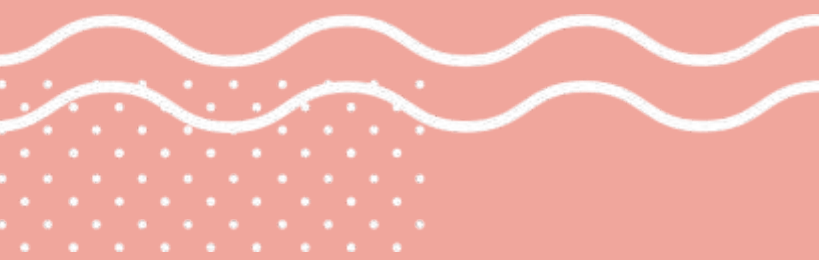
Limitations & Recommendations

Limitations

- These findings are preliminary and based on pilot-scale data (TRL 5);
- Minor reductions in N₂O emissions and energy use at the WWTP are possible. However, these are unlikely to significantly change the study's outcomes.

Recommendations

- Future full-scale implementations may improve performance and cost-effectiveness:
 - economies of scale;
 - process optimisation;
 - enhanced material efficiency.



Thank you • Gracias • Grazie • Merci
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