

Using water and wastewater decentralization to enhance the resilience and sustainability of cities

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Supplementary Information

Using Water and Wastewater Decentralization to Enhance the Resiliency and Sustainability of Cities

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682	probability of the hazard occurring, with H indicating high likelihood and L signifying low	
683	likelihood. Severity (Minor/Moderate/Major): Evaluates the potential consequences of	
684	the hazard, with Major representing significant impacts and Minor implying limited	
685	consequences. Risk Score (L/M/H): Combines likelihood and severity to categorize the	
686	overall risk level, highlighting areas needing prioritized action. Mitigation Strategies:	
687	Proposes specific actions and procedures to reduce the likelihood or severity of the	
688	hazard, ensuring system safety and reliability. Residual Risk: After considering mitigation	
689	strategies, this column indicates the remaining level of risk, aiming for minimal residual	
690	risk for optimal system performance. Cost Impact (%): Estimates the potential financial	
691	implications of implementing the mitigation strategies, providing a transparent view of	
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693	associated with water before or after a treatment process. Specific Human	
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1 System Overview: Decentralized Source Separation

Among the emerging paradigms for urban water systems, extreme decentralization based on the concept of source separation —the practice of integrating building-scale water recycling within cities with existing centralized water systems— is explored in this study.

Acknowledging the potential benefits of decentralized urban water systems (Larsen et al., 2013; Li et al., 2021; Rabaey et al., 2020; Singh et al., 2015; Sun et al., 2020. Sun et al., 2020; Yang et al., 2021), here we have extended previous analysis by providing a detailed techno-economic assessment of systems that are likely to be considered at the scale of individual homes, multi-family dwellings, all major main type of buildings (Garrido-Baserba et al., 2022), and finally, an urban development, as a city block, using standardized cost assessment methods, modelling approaches, LCA, etc.. To account for more complex types of distributed wastewater treatment technologies (e.g., anaerobic and membrane technologies that might be viable in multi-family buildings) as well as resource recovery approaches that require source-separation, we have included a range of new and emerging technologies under different housing scenarios.

While the current study will be focused on a specific treatment train corresponding to a city block of 2000 people equivalent, the technical and economic feasibility included six personalized treatment trains (Table S1-1). A city block of 2000 people equivalent has been evaluated (and the referenced dwellings ranging from a 2.3 to 300 people equivalent) through (i) a detailed economic analysis considering capital and operating expenditures and revenues for the in-house sewer system, pumps, and treatment modules; (ii) an estimation of the required space for tanks and technology; (iii) an assessment of the final water quality. The overall costs of implementing the systems in already existing buildings are presented, as well as the fraction of the total construction investment they represent for new buildings. This multidisciplinary effort illustrating the current state-of-the-practice and potential benefits of decentralization is meant to provide a rigorous baseline for further development of sustainable urban water systems, and it does not represent a conclusive case on extreme decentralisation. Rather, it is likely that new technologies and better controls will lead to other, more efficient configurations.

The system aims to sustainably treat different types of wastewater within a building by addressing them as separate flows for targeted solutions. Summary of the proposed concept:

Source Separation: Wastewater is divided into:

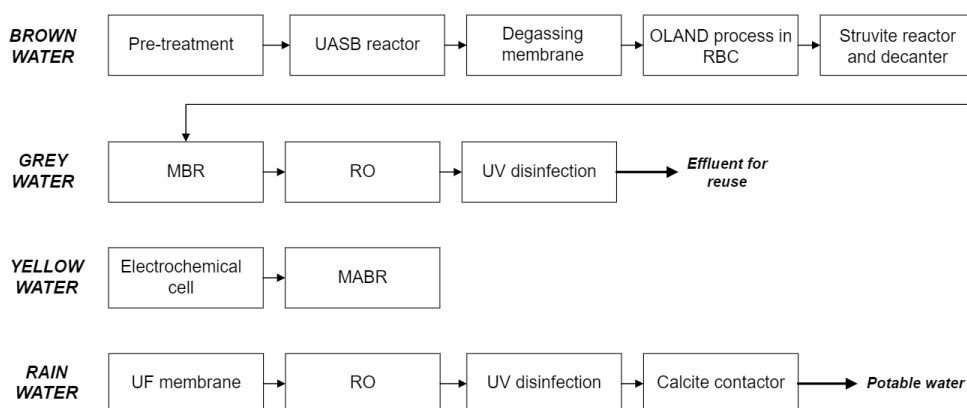
- **Brown Water (BrW):** From toilets, requiring nutrient and energy recovery.
- **Yellow Water (YW):** Urine, high in nitrogen and phosphorus
- **Grey Water (GW):** Less heavily soiled water from sinks, showers, etc.

Table S1-1: Summary of the proposed scenarios.

Study	Scenario	Toilet type	Stream types	Treatment train
Current Study	City Block	Urine-diverting	Yellow + Grey + Brown + Food Waste	electrochemical cell + MABR CoDigestion (UASSB) > OLAND reactor + struvite reactor MBR + RO + UV
Garrido-Baserba et al.,2022*	V1	Vacuum	Black + Grey (+ treated black)	UASB + OLAND reactor + struvite reactor MBR + RO + UV
Garrido-Baserba et al.,2022*	V2	Vacuum	Black + Grey (+ treated black)	OLAND reactor + struvite reactor anMBR + RO + UV
Garrido-Baserba et al.,2022*	C1	Conventional	Black + Grey (+ treated black)	OLAND reactor + struvite reactor MBR + RO + UV
Garrido-Baserba et al.,2022*	C2	Conventional	Black + Grey (+ treated black)	OLAND reactor + struvite reactor anMBR + RO + UV
Garrido-Baserba et al.,2022*	UD	Urine-diverting	Yellow + Grey + Brown	electrochemical cell + MABR anMBR + RO + UV

*Garrido-Baserba, M., Barnosell, I., Molinos-Senante, M., Sedlak, D. L., Rabaey, K., Schraa, O., Verdaguer, M., Rosso, D., & Poch, M. (2022). The third route: A techno-economic evaluation of extreme water and wastewater decentralization. *Water Research*, 218, 118408. <https://doi.org/10.1016/j.watres.2022.118408>

Table S1-2: Simplified flowchart of the described treatments..



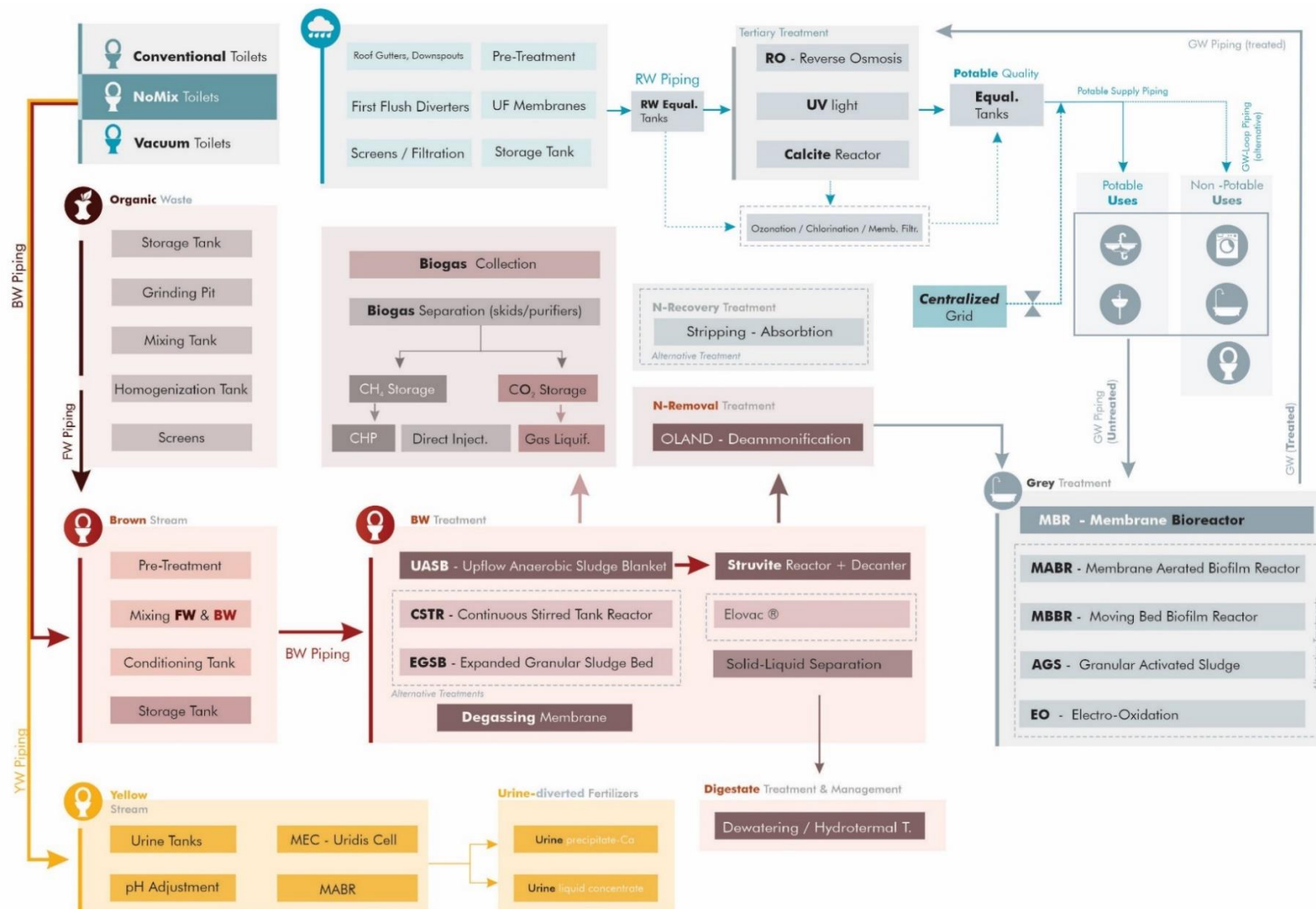


Table S1-3: Simplified flowchart of the described treatments. Process Flow Diagram encompassing all the main process included in the analysis. For the current paper only some of the alternatives are presented.

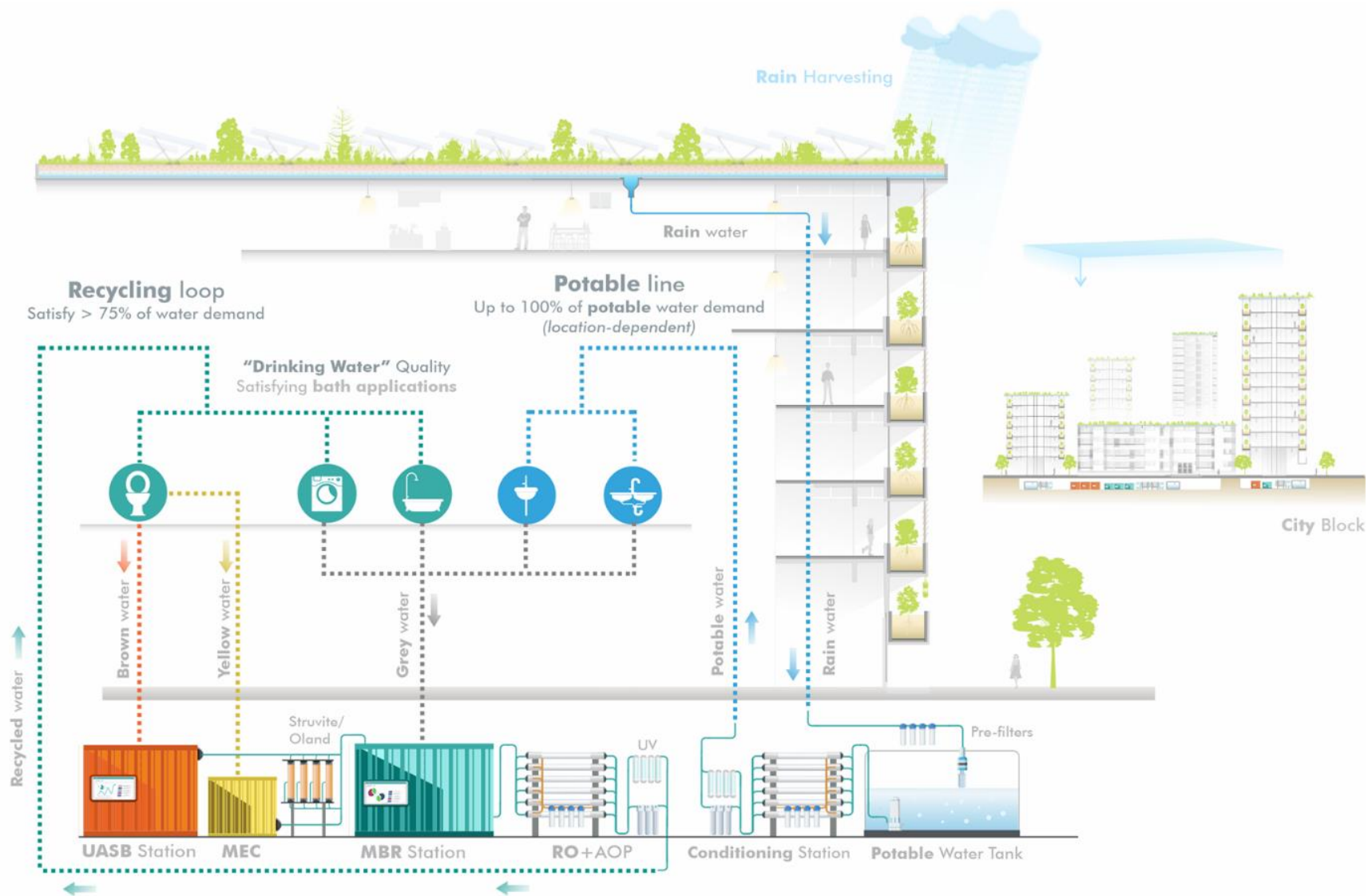


Figure 1-4. Conceptual representation of the decentralized source separation concepts.

1.1 Source Separation Enhances the Efficiency of Resource Recovery

Separation of wastewater into three different components, yellow water (i.e., urine), brown water (i.e., faeces and flush-water), and grey water (i.e., everything else), has the potential to reduce the costs of recovering water, energy, and nutrients relative to the conventional approach of treating the combined wastewater streams^{12–16}. Slowly but steadily, the number of initiatives taking advantage of this approach is increasing^{17–19}. Blackwater (combined brown- and yellow water), which constitutes roughly 20% of the volume of household wastewater, contains about 90% of the carbon and nitrogen and 80% of the phosphorus discharged by households. Treating this resource-rich stream separately (e.g., by anaerobic digestion) is a proven means of recovering energy and water^{2,12,16,20,21}. The grey water remaining after the black water is separated can be treated with less energy-intensive approaches to a point at which it is suitable for reuse within the home (e.g., for laundry) or irrigation of plants.

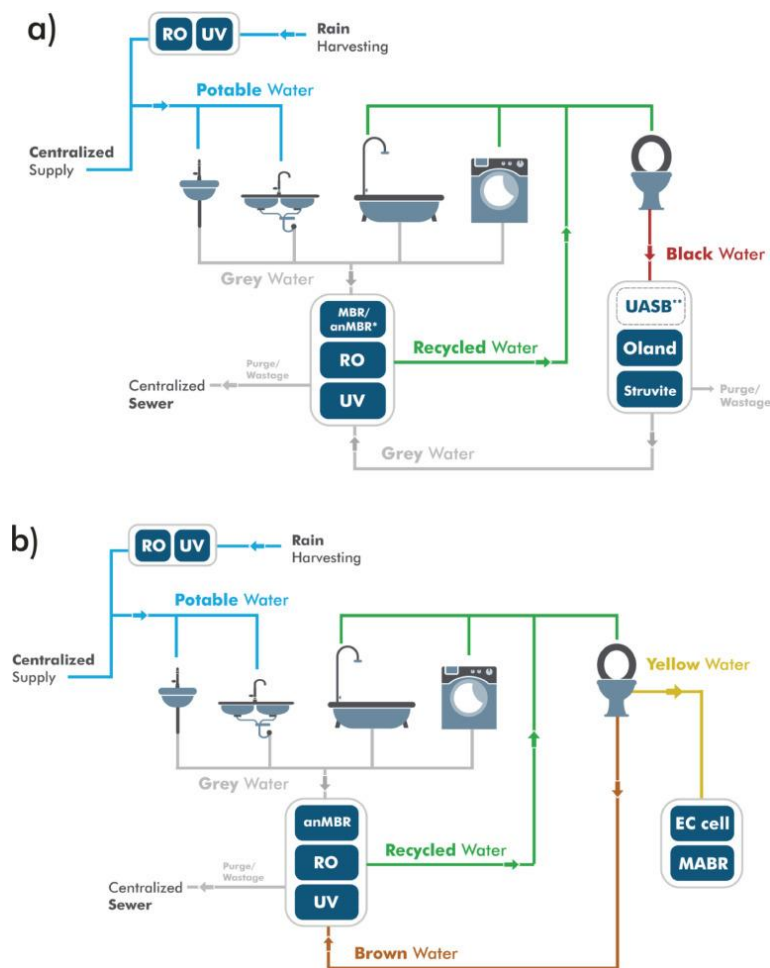


Fig. 1- 5. Flow diagrams of Garrido-Baserba, 2022, for the fully decentralized approach for both black and grey water streams. The upper flow diagram (a) corresponds to vacuum and conventional toilets while (b) corresponds to the urine-diverting layout. *Indicates that MBR will be used for scenarios V1 and C1 while anMBR will be considered in V2 and C2. **No UASB will be considered in those scenarios including anMBR (V2 and C2).

The system aims to sustainably treat different types of wastewater within a building by addressing them as separate flows for targeted solutions.

Source Separation: Wastewater is divided into:

- **Brown Water (BrW):** From toilets, requiring nutrient and energy recovery
- **Yellow Water (YW):** Urine, high in nitrogen and phosphorus
- **Grey Water (GW):** Less heavily soiled water from sinks, showers, etc.

Treatment Lines:

- **Brown Water:**
 - Anaerobic digestion in a UASB reactor (produces biogas)
 - Nutrient recovery (phosphorus removal, nitrogen treatment)
 - Blending with GW, then aerobic treatment in an MBR
 - Final filtration, reverse osmosis (RO), and UV disinfection
- **Yellow Water:**
 - Stabilization in an electrochemical cell (EC) and phosphorus recovery by crystallization
 - Nitrification (conversion of ammonia to nitrate) in a membrane aerated biofilm reactor (MABR), producing liquid fertilizer
- **Grey Water:** Combined with treated BrW in the MBR.
- **Rainwater (RW):** Captured, treated with RO and UV, and blended to supplement recycled water.

Advantages of Source Separation

- **Tailored Treatment:** Addressing specific pollutants in each stream makes treatment more efficient.
- **Resource Recovery:** Nutrients like phosphorus and nitrogen can be recovered, along with biogas from BrW.
- **Sustainability:** Reduces footprint, and lessens reliance on freshwater.
- **Water Quality:** The multi-stage process and blending ensure a high quality of end product suitable for non-potable use.

Goals

- **Water Conservation:** Reducing the building's dependence on external potable water sources.
- **Resource Recovery:** Capturing valuable nutrients for fertilizer and biogas for energy.
- **Environmental Sustainability:** Decreasing the strain on local water supplies and wastewater treatment infrastructure.

2 Residential and Urban development information

To evaluate the technical and economic feasibility of implementing decentralized urban water facilities, we considered seven housing types (i.e., single-family homes, low-rise dwellings, low/medium-rise, medium-rise, medium/high-rise, high-rise building, and city block) representative of residential housing in many cities (Fig. 1-1). This paper will be focused on the city block to represent a typical urban environment, nevertheless, the supplementary information has been extended to further show the extend of the techno-economic analysis. Building upon those initial findings, we focused on a typical city block designed to accommodate 2,000 population equivalents (PE), consisting of eight high-rise buildings, each with 12 stories and 250 PE, following the typical occupancy rate found in Europe (i.e., 2.3 inhabitants per dwelling) and an average apartment floor space of 30 m² per capita.

An occupancy rate typical of Europe (i.e., 2.3 inhabitants per dwelling) was assumed, with an average apartment floor space per capita of 30 m² (Negro and Economidou, 2014; Roefs et al., 2016). The assumed area per story (i.e., the area available for rooftop rainwater collection) representing the total floor space (i.e., including the space for staircases, lifts, hallways) was estimated for typical European buildings through Eq. 1, where A_s and A_{hh} are the areas per story and household, respectively [m²], γ is a constant (equal to 1.15), and N_{hh} is the number of households in the designed building. The extra surface assigned to the average area destined to common spaces is that of 30 m² per story. The total floor space of each building is calculated to encompass the area destined to stairs, lifts, corridors, and walls in each storey, to obtain a realistic estimation of the total water catchment area at the roof of each apartment type. An additional floor is added to the number of storeys destined to housing to store equipment and technologies.

$$A_s = \gamma * A_{hh} * N_{hh} + 30 \quad (1)$$

Low-rise housings are designed to represent the average terraced house, using floor space requirements per capita which are specific for houses instead of apartments, thus the final floor space per capita is larger than those of the rest of building types. It is assumed each house has two floors plus the basement where technologies are kept. House and apartment floor space per capita are averages for South Europe. Shape factors (f_2) used in the UWIM model are also presented below.

Most common residential and urban developments

The seven most common residential and urban developments types were evaluated according to **rain harvesting potential**, capacity to **recycle grey and black/brown water**, **space available** for treatment units, **environmental impacts** and **costs**.

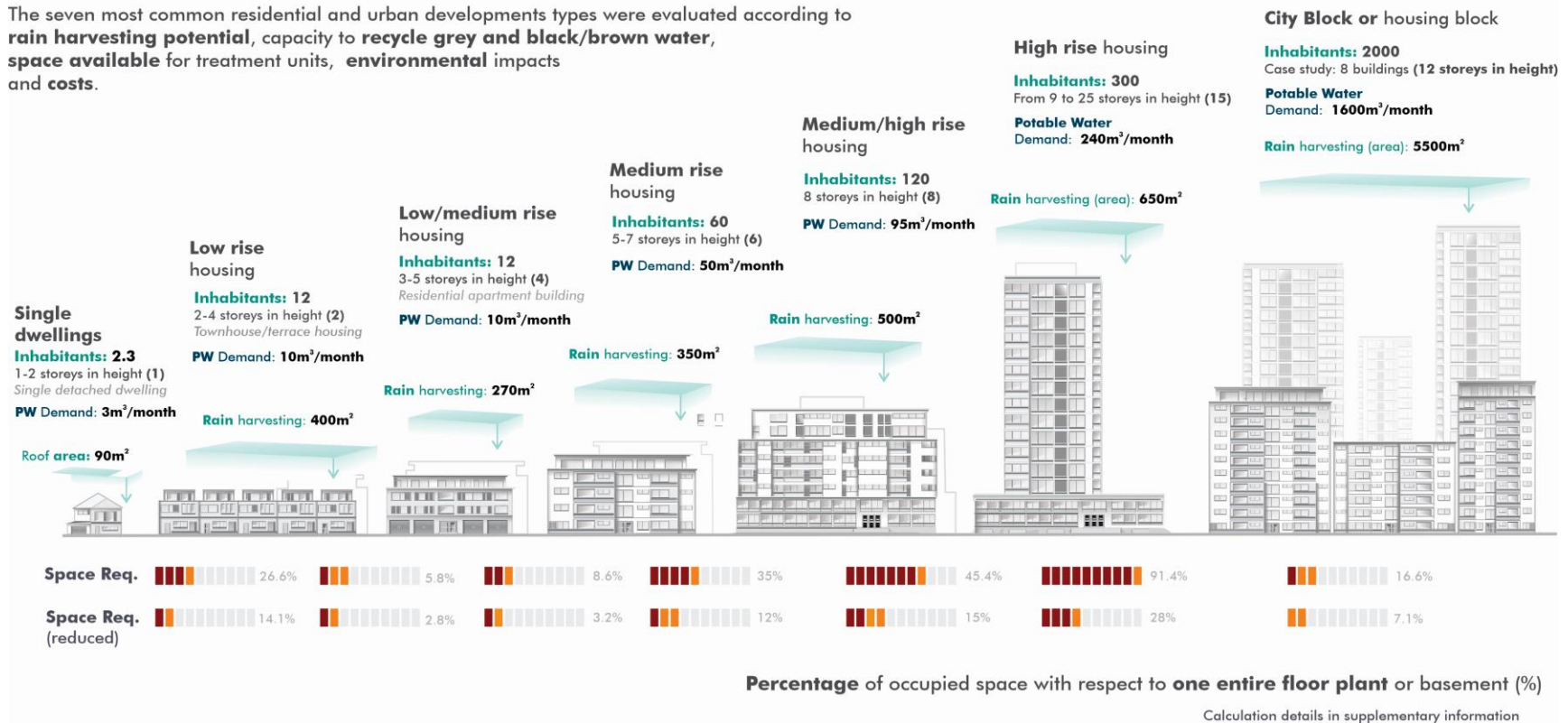


Figure 2-1. Characterization of the most common residential and urban developments according to their number of inhabitants (using an average of 2.3 habitants per household), number of stories (12 floors in this study), total potable water demand (estimating 26/l per person per day); available roof area that could be used for rain harvesting (90% of available roof area), and total space (as volume) of a typical basement or underground floor for each type of development.

Most common residential and urban developments

The seven most common residential and urban developments types were evaluated according to **rain harvesting potential**, capacity to **recycle grey and black/brown water**, **space available** for treatment units, **environmental impacts** and **costs**.

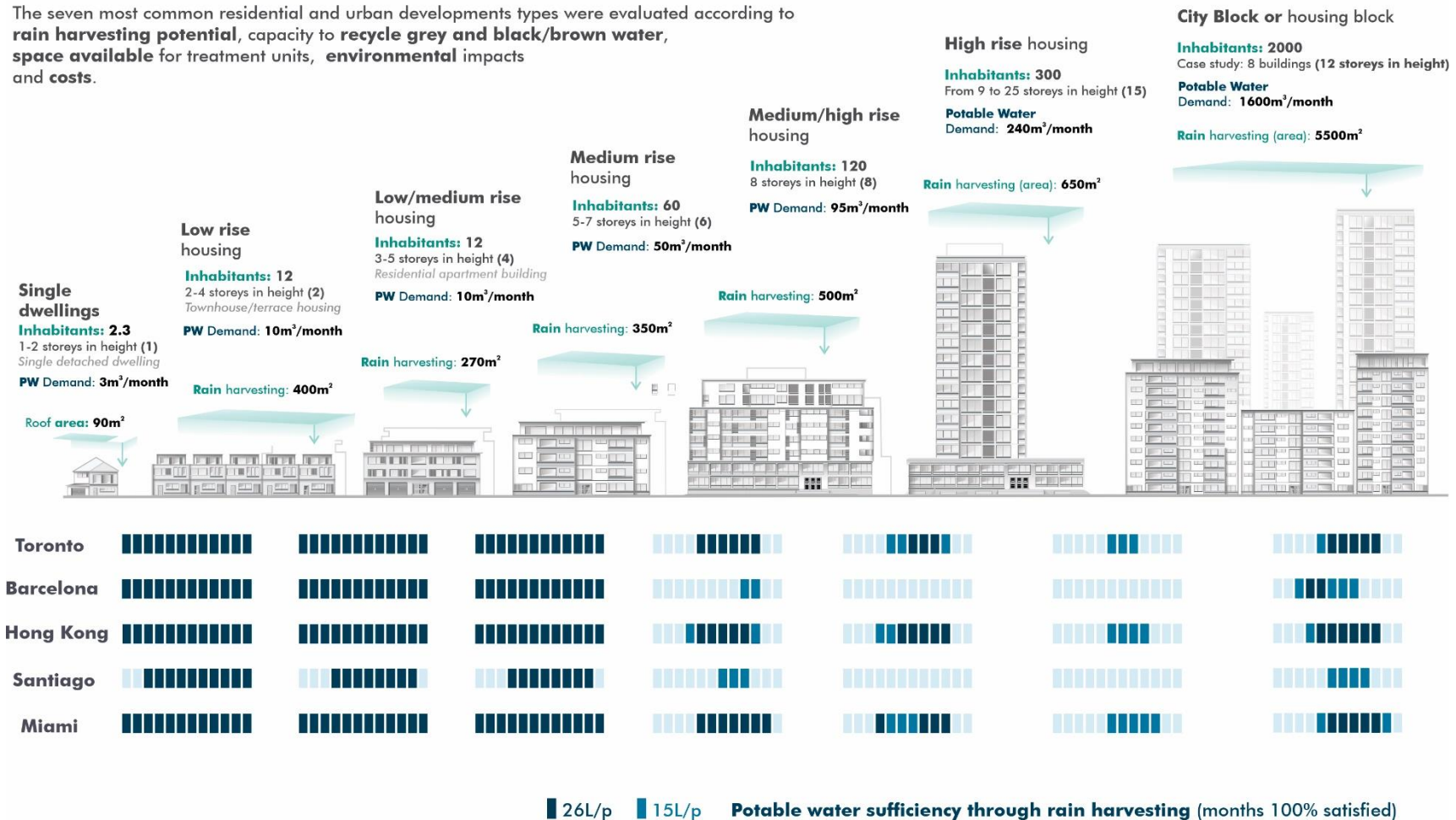


Figure 2-2. Rainwater collection potential per type of building is depicted using colored bars where each fraction represents a month of the year (from January to December), when demand can either be satisfied or not depending on the location and total monthly rainfall.

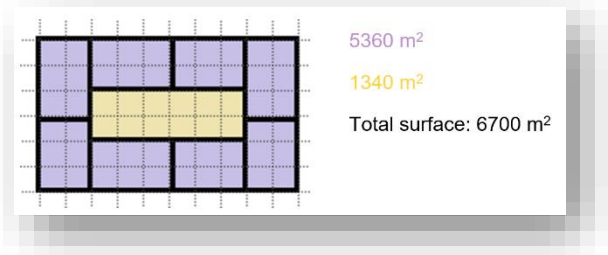
Table S2-1: Information on each building type considered.

Building type	Low-rise	Low/Mid-rise	Mid-rise	Mid/high-rise	High-rise	City Block
Abbreviation	LR	ST	MR	MHR	HR	CB
Number of storeys (housing)	2	2	6	8	15	96
Number of units per floor	0.5	3	4	6	8	8
PE per floor (house)	2.4	6	10	15	20	250 X 8 (building)
Total PE	12	12	60	120	300	2000
Floor surface per storey (m ₂)	80	270	350	510	670	670
Total water catchment area (m ₂)	400	270	350	510	670	5360
f ₂	2.29	1.44	1.44	1.44	1.44	1.44

The total area available for rainwater collection per building, or rainwater catchment surface, was calculated to be 670 m². These buildings were arranged around a central rectangular space and shared a common basement with a standard floor height of 3 for the storage of technology, resulting in a total rainwater collection area of 5,360 m²

Table S2-2: Information on each building type considered.

Hab	2,000.00
Hab/building	250.00
Number eq household	104.17
A (floor surface per storey)	670.00
p	0.16
f ₂	1.44
HH/storey	9.31
Number of storeys	11.19
N° of buildings	898
Area per building	670
Area inside	1340
Width	21.1356
Lenght	31.702
PE/house	2.40
m ² /PE	30.00
m ² /HH	72.00



3 Scenarios Description

For this study, both the solar energy potential and the rainwater harvesting potential were evaluated across five geographically diverse cities. These cities were selected to represent a variety of climates based on the Köppen-Geiger classification: Miami (North America, equatorial), Santiago de Chile (South America, arid), Barcelona (Europe, Mediterranean with dry summer), Hong Kong (Asia, warm with dry winters), and Toronto (North America, temperate). To facilitate analysis, average monthly precipitation patterns and average solar irradiance were included for each case study.

Table S3-1: A table comparing average annual rainfall (mm) and average solar irradiance (kWh/m²/day) across diverse locations selected to represent a variety of climates based on the Köppen-Geiger classification.

Location	Avg. Annual Rainfall (mm)	Avg. Solar Irradiance (kWh/m ² /day)
World	1000 (range: 500-2000+)	4-5
EU	600-1000	3-4
Barcelona	600-700	4.5-5.5
Amsterdam	800-900	3-4
Chile (Santiago)	300-400	6-7
Hong Kong	2200-2500	3.5-4.5
Seoul	1300-1500	4-5
Toronto	800-900	3-4.5
Miami	1500-1800	5-6

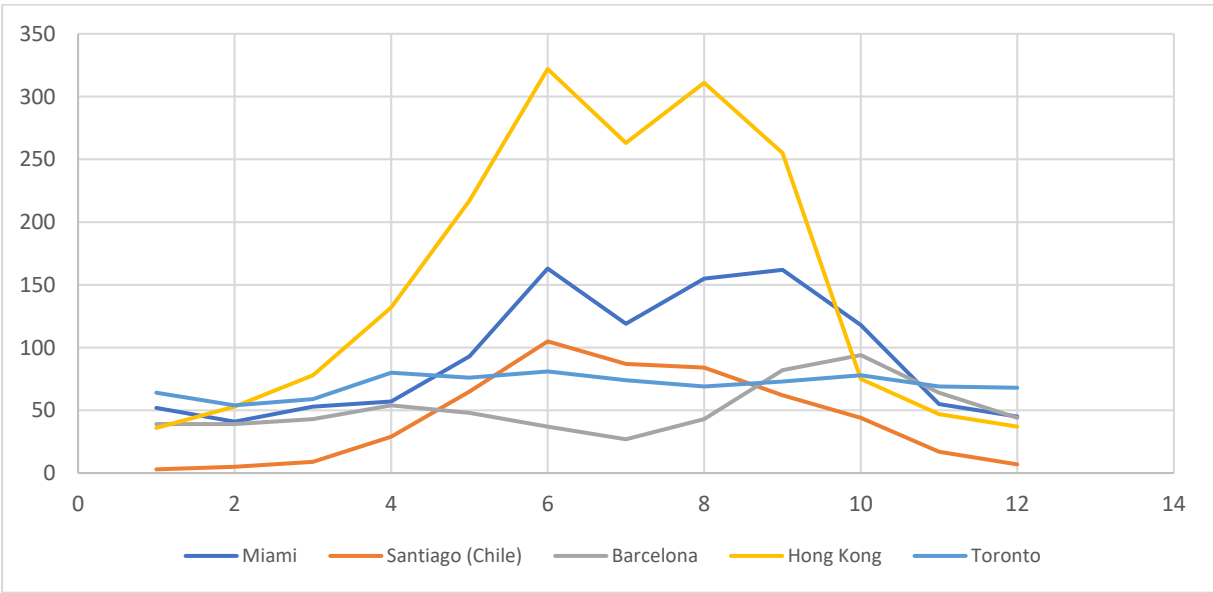
3.1.1 Rain harvesting Potential.

To estimate the supply of rainwater (m³/month), average monthly rainfall (mm) data was extracted from Climate Data Org (2021). The authors acknowledge that rainfall regimes and overall extreme variability are being impacted by climate change (IPCC, 2022, IPCC, 2021; Slater et al., 2021; UNEP, 2021) and that estimates based on historic averages or return periods might be inaccurate in the coming decades. To assess the potential of rainwater systems to complement the existing access to a centralized water supply, it would be more appropriate to consider a particularly dry period (e.g., the driest year in a 20- or 50-year period). Nevertheless, according to the latest IPCC report, this approach could be very short-lived as extreme variability is expected to change drastically in the upcoming decades (IPCC, 2022). Future studies on rainwater capture capacity should include these most recent forecasts. Furthermore, other options for

storing precipitation generated by shorter, more intense storms (e.g., managed aquifer recharge) should be considered.

Rainfall values were multiplied by the roof surface of each dwelling type (m²), and a correction factor for roof losses of 0.9 was included. Drinking water demands and rainwater accumulations were estimated for each type of building and location. Rainwater accumulated in the storage tanks was carried over to between months. The total demand of drinking water (m³/month) for potable uses (i.e., drinking and cooking) for each type of building was calculated considering a per capita water consumption of 26.5L/day (Rabaey et al., 2020) multiplied by the number of building inhabitants for 31 days per month. The daily amount of 26.5L represents an approximate 30% of the overall water usage (80 L/day) and does not consider other uses such as flushing toilets (25%), cleaning (20%), washing clothes (15%), gardening, etc.

Table S3-2: Monthly rainfall (Climate Data Org) (mm). Detailed analysis for each city depending on the different rain patterns in the various climatic regions



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Table S3-3: Captured water/month (m3).

City	Jan	February	March	April	May	June	July	August	September	October	November	December
Concepción (Chile)	28.94	57.89	101.30	250.85	675.36	882.79	699.48	607.82	323.21	226.73	110.95	82.01
Temuco (Chile)	149.54	173.66	294.26	511.34	940.68	1,283.18	1,056.46	979.27	588.53	530.64	347.33	294.26
Santiago (Chile)	14.47	24.12	43.42	139.90	313.56	506.52	419.69	405.22	299.09	212.26	82.01	33.77
Barcelona	188.14	188.14	207.43	260.50	231.55	178.49	130.25	207.43	395.57	453.46	308.74	212.26
Amsterdam	332.86	274.97	279.79	274.97	328.03	352.15	424.51	414.86	366.62	337.68	328.03	356.98
Hong Kong	173.66	255.67	376.27	636.77	1,046.81	1,553.33	1,268.71	1,500.26	1,230.12	361.80	226.73	178.49
Toronto	308.74	260.50	284.62	385.92	366.62	390.74	356.98	332.86	352.15	376.27	332.86	328.03
Seoul	101.30	135.07	197.78	352.15	477.58	694.66	1,538.86	1,201.18	631.94	265.32	231.55	120.60
Miami	250.85	197.78	255.67	274.97	448.63	786.31	574.06	747.72	781.49	569.23	265.32	217.08

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Table S3-4: Captured water/month (m3).

Koppen Geiger scale	City	Jan	February	March	April	May	June	July	August	September	October	November	December	Total/yr
Csb	Concepción (Chile)	6	12	21	52	140	183	145	126	67	47	23	17	839
Csb	Temuco (Chile)	31	36	61	106	195	266	219	203	122	110	72	61	1482
Csa	Santiago (Chile)	3	5	9	29	65	105	87	84	62	44	17	7	517
Csa	Barcelona	39	39	43	54	48	37	27	43	82	94	64	44	614
Cfb	Amsterdam	69	57	58	57	68	73	88	86	76	70	68	74	844
Cfa	Hong Kong	36	53	78	132	217	322	263	311	255	75	47	37	1826
Dfb	Toronto	64	54	59	80	76	81	74	69	73	78	69	68	845
Dwa	Seoul	21	28	41	73	99	144	319	249	131	55	48	25	1233
Am	Miami	52	41	53	57	93	163	119	155	162	118	55	45	1113

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[illegible]

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970 Table S3-6: Screen capture of the detailed analysis for each city depending on the different rain patterns in the various
971 climatic regions



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974 Table S3-7: Screen capture of the detailed analysis for each city depending on the different rain patterns in the various
975 climatic regions [in Spanish, produced through a collaboration with the University of Chile].
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984 *3.1.2 Rain harvesting Capacity – Tank Sizing.*

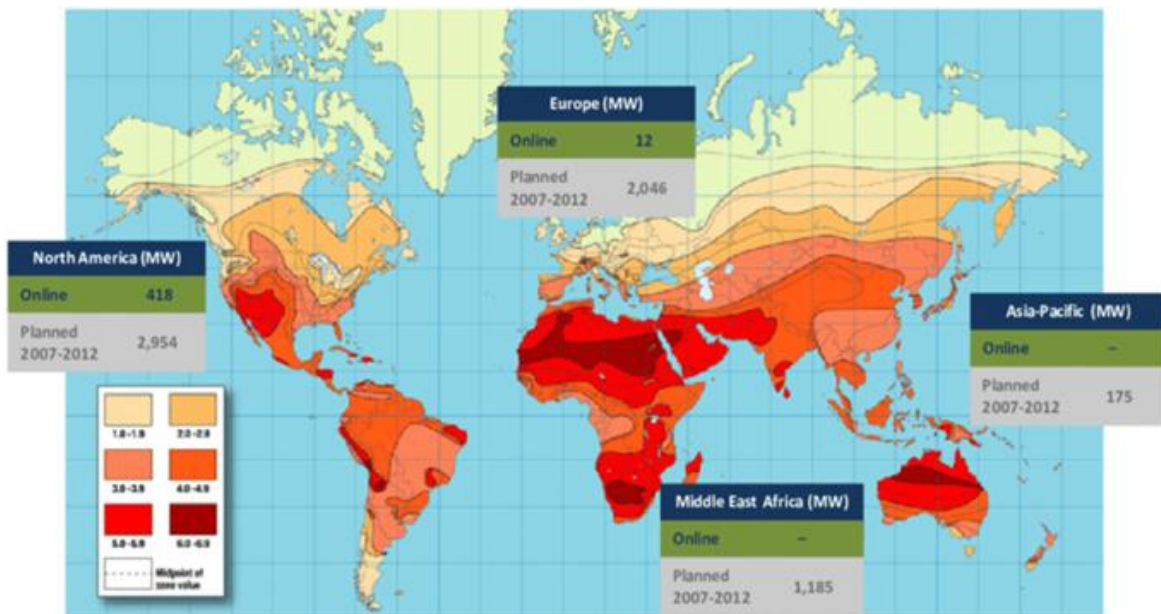
985 The ideal tank size for a rain harvesting system depends heavily on the specific goals and circumstances,
986 and parameter like catchment area, rainfall patterns, water usage, regulations, etc. might impact the final
987 design. Nevertheless, as rule of thumb, the general volumes are within the following ranges: For a small
988 garden, a tank ranging from a few hundred litres (0.2 - 1 m³) might be enough. For household needs like
989 toilets or laundry, tanks between 1 m³ and 5 m³ are typical. Commercial operations or community projects
990 might require much larger tanks, exceeding 10 m³ or even utilizing underground storage. Therefore, the
991 estimated 30 m³ is within the upper range of commercial operations or community projects. The 30 m³
992 corresponds to the approximate volume required for a high-rise building. The current study which is based
993 in a city block including 2,000 people equivalent it's an approximated equivalent of 7high rise blocks.
994 Therefore, the total required volume would be 30 m³ x 7 = 210m³

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3.1.1 Solar Energy Potential.

This study investigates the capacity for solar energy to power critical urban infrastructure. Specifically, it examines the potential of solar panels to offset energy needs within a multi-use block. This block integrates a water reuse system, vertical farm, and domestic energy components. The analysis covers the cited diverse cities under various Köppen-Geiger climate classifications (Barcelona, Amsterdam, Santiago de Chile, Hong Kong, Seoul, Toronto, and Miami), suggesting an exploration of solar viability across varying geographical and climatic conditions.

Table S3-8: Average solar irradiance (kWh/m²/day) across diverse locations selected to represent a variety of climates based on the Köppen-Geiger classification.



1009 *Table S3-9: Solar energy analysis for each city depending in the various climatic regions.*

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	Electricity consumption per capita (average)	For All (2000 PE) kWh/yr	Monthly req (kWh)	Sun hours/ mo	kWh system/ hh [load sizing]	kW system/ house [consu mption]	Total kW system	Nº 400Wp panels	Nº 425Wp panels	kwh/yr produced
World	3,128	6,256,000	521,333							
EU	6,022	12,044,000	1,003,667							
Barcelona	5,356	10,712,000	892,667	105	8	10	1,063	2,657	2,501	1,135,260
Amsterdam	6,713	13,426,000	1,118,833	45	18	30	3,108	7,770	7,313	486,540
Chile (Santiago)	3,880	7,760,000	646,667	90	9	9	898	2,246	2,114	973,080
Hong Kong	6,083	12,166,000	1,013,833	105	8	12	1,207	3,018	2,840	1,135,260
Seoul	10,497	20,994,000	1,749,500	165	5	13	1,325	3,314	3,119	1,783,980
Toronto	15,588	31,176,000	2,598,000	75	11	42	4,330	10,825	10,189	810,900
Miami	12,994	25,988,000	2,165,667	263	3	10	1,031	2,579	2,427	2,838,150

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4 Influent composition

Per capita water production is assumed 108 L/day, 15 L/day, and 1.5 L/day for grey, black, and yellow water, respectively, considering the use of urine-diverting toilets capable of recovering 70% of urine (de Graaff et al., 2010; Larsen et al., 2013; Rabaey et al., 2020). Non-recovered urine leaks to the brown water sewer. The daily average of organic food waste is 150 g/PE.

Whilst the possibility of deviations due to specific events is acknowledged, an average composition of wastewater in the system is assumed as shown in Table S4-1. Concentrations are calculated from daily constituent load per capita and are in concordance with previous studies (Dhadwal, 2020; Dhadwal et al., 2021; Gao et al., 2019; Garrido-Baserba et al., 2022; Kujawa-Roeleveld et al., 2006; Larsen et al., 2013; Lienert & Larsen, 2010; Rossi et al., 2009; Sun et al., 2020). Food waste composition allows to calculate the final composition of the treatment train influent (Gao et al., 2020; M. Kim et al., 2015; Rajagopal et al., 2013).

Table S4-1 shows the compositions the different wastewater flows used to calculate the treatment requirements of the building, as well as the influents to the BrW and GW treatment lines calculated considering daily constituent loads per capita and food waste composition in concordance with literature and the volumes presented in SI. Food waste is mixed with BrW and its composition is expressed in mg/g wet basis considering a water content of 76% (Dhadwal, 2020; Dhadwal et al., 2021; Gao et al., 2020, 2020; Garrido-Baserba et al., 2022; Kim et al., 2015; Kujawa-Roeleveld et al., 2006; Larsen et al., 2013; Lienert and Larsen, 2010; Rajagopal et al., 2013; Rossi et al., 2009; Sun et al., 2020).

Composition of black water (BW) [mg/l], undiluted fresh urine (YW) considering urea hydrolysis [mg/l], GW [mg/l], the organic fraction of municipal solids waste (OFMSW) [mg/g wet basis], Brown water (BrW) from urine-diverting toilets, the mixture entering the BrW line combining BrW, non-recovered, nonhydrolyzed YW, and OFMSW [mg/l], and the influent to the grey water (GW) line combining the treated effluent of the BrW line and GW [mg/l]. COD: chemical oxygen demand; BOD: biological oxygen demand, TN: total nitrogen; TAN: total ammonia nitrogen; TP: total phosphorus; TSS: total suspended solids; VSS: volatile suspended solids.

The highest uncertainty in the presented compositions is associated with the organic fraction of municipal solid waste (OFMSW), as it is directly related with diet and can therefore vary significantly depending on the region. The considered composition refers to a western diet. While acknowledging individual habits, socioeconomic factors, and even how different studies categorize "food waste", a ballpark could be about 0.5 - 1 kg per person per day, which could correspond to a COD concentration that can range from around 5,000 mg/L to upwards of 10,000 mg/L.

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1064 *Table S4-1: Composition of blackwater, undiluted fresh urine considering urea hydrolysis, greywater, organic food*
1065 *waste, and the mixture of brown water, non-recovered urine, and food waste.*

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mg/L	BW	YW	GW	FW*	BrW	BrW+non-recovered YW+FW
COD	10,500	10,400	472	286	2,490	5,437
BOD	3,560	3,870	175	218	800	2,987
TN	2,000	8,800	8	6	80	335
NH ₄ -N	1,800	463	3	0.8	72	88.5
TP	260	800	5	3.2	34	82.4
TSS	8,360	0.0	175	189.5	2,790	4,560
VSS	6,690	0.0	64	179.8	2,230	3,925

1067 **mg/g wet basis*

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1070 *Table S4-2: Detailed Composition of blackwater, undiluted fresh urine considering urea hydrolysis, greywater, organic*
1071 *food waste, and the mixture of brown water, non-recovered urine, and food waste.*

Concentration data				g/p*d	
Concentrations BrW, FW, nrcYW	mg/L	mg/L	mg/g wet basis 76% w water/w	mg/L	
	BrW (15 L/p*d)	BrW + non-recovered YW (recovery efficiency of 75%; 15.45 L/p*d)	Food waste (FW) Rajagopal et al 2013; Gao et al 2020; Kim et al 2015	Br + nrc YW + FW (150 g/p*d Rajagopal et al 2013)	g/L
COD	2490.00	2660.00	286.00	5436.70	5.4
BOD	800.00	869.00	218.18	2987.25	2.9
TN	80.00	278.00	5.90	335.28	0.3
NH ₄ -N (TAN: Total ammonia N, NH ₃ +NH ₄ +))	72.00	80.90	0.78	88.48	0.08
TP	34.00	51.50	3.18	82.37	0.08
TSS	2790.00	2720.00	189.50	4559.81	4.55
VSS	2230.00	2180.00	179.77	3925.34	3.92

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4.1 Influent: Co-digestion with food waste

The highest uncertainty in the presented compositions is associated with the organic fraction of municipal solid waste (OFMSW), as it is directly related with diet and can therefore vary significantly depending on the region. The considered composition refers to a western diet. While acknowledging individual habits, socioeconomic factors, and even how different studies categorize "food waste", a ballpark could be about 0.5 - 1 kg per person per day, which could correspond to a COD concentration that can range from around 5,000 mg/L to upwards of 10,000 mg/L. Food waste values in literature can be very high, especially for specialized food-waste facilities or high-strength anaerobic digesters. Our study focuses on household food waste combined with brown and/or black water. The COD for the food waste considered in this study is around 3,000 mg/l.

For this context, we employed data supported by widely adopted literature on the topic:

- Kim, M., Chowdhury, M.M.I., Nakhla, G. and Keleman, M., 2015. Characterization of typical household food wastes from disposers: fractionation of constituents and implications for resource recovery at wastewater treatment. *Bioresource technology*, 183, pp.61-69.
- Rajagopal, R., Lim, J.W., Mao, Y., Chen, C.L. and Wang, J.Y., 2013. Anaerobic co-digestion of source segregated brown water (feces-without-urine) and food waste: for Singapore context. *Science of the Total Environment*, 443, pp.877-886.
- Gao, M., Zhang, L. and Liu, Y., 2020. High-loading food waste and blackwater anaerobic co-digestion: Maximizing bioenergy recovery. *Chemical Engineering Journal*, 394, p.124911.

While the authors don't provide the exact list of edible products or the relative fraction of meat and dairy on those totals, acknowledge the usual presence of meat and some dairy within household food waste. We employed conservative FW quantities to prioritize focus on the core comparison between centralized and decentralized systems, and avoid deviating the reader attention from brown and food waste co-digestion towards a highly specialized high-strength food waste facility.

Table S4-3: Values in mg/l for column [Food waste (FW) - Rajagopal et al 2013; Gao et al 2020; Kim et al 2015. When converted to mg/l the results for FW are as follows.

Concentrations BrW, FW, nrcYW	mg/L	mg/L	mg/L	mg/L		
	BrW (15 L/p*d)	BrW + non-recovered YW (recovery efficiency of 75%; 15.45 L/p*d)	Food waste (FW) Rajagopal et al 2013; Gao et al 2020; Kim et al 2015	Br + nrc YW + FW (150 g/p*d Rajagopal et al 2013)	g/L	g/L 2L
COD	2490.0	2660.0	2776.7	5436.7	5.4	24.1
BOD	800.0	869.0	2118.3	2987.3	3.0	17.2
TN	80.0	278.0	57.3	335.3	0.3	0.7
NH4-N (TAN: Total ammonia N, NH3+NH4+)	72.0	80.9	77.6	88.5	0.1	0.1
TP	34.0	51.5	30.9	82.4	0.1	0.3
TSS	2790.0	2720.0	1839.8	4559.8	4.6	16.9
VSS	2230.0	2180.0	1745.3	3925.3	3.9	15.7

1101 Table S4-4: Food waste composition according to Rajagopal et al 2013 and Gao et al 2020.

	Unit	BW + FW (Phase III)	Parameter	Unit	Feed mixture (2-L BW + 150 g FW)
BW:FW VS mixing ratio		1:1	TS	[g/kg, wet basis]	18.26 ± 3.49
Operation duration	day	61–98	VS	[g/kg, wet basis]	16.9 ± 3.19
Initial pH		8.0 (± 0.2)	VS/TS	[%]	93
tCOD ^a	g/L	25.4 (± 1.2)	pH	–	6.18 ± 0.55
sCOD	g/L	9.5 (± 0.8)	CODt	[gCOD/L]	35.21 ± 10.41
sCOD /tCOD	%	37.4	CODs	[gCOD/L]	13.02 ± 4.36
Acetate	g COD/L	1.32 (± 0.20)	VFA-COD		
Propionate	g COD/L	0.66 (± 0.07)	Acetic	[gCOD/L]	0.67 ± 0.04
Butyrate	g COD/L	0.32 (± 0.05)	Propionic	[gCOD/L]	0.31 ± 0.09
TN ^b	g/L	2.7 (± 0.0)	Isobutyric	[gCOD/L]	0.05 ± 0.01
TAN ^c	g/L	1.1 (± 0.0)	Butyric	[gCOD/L]	0.19 ± 0.06
PO ₄ ³⁻ -P	mg/L	34.1 (± 8.5)	Isovaleric	[gCOD/L]	0.14 ± 0.02
Alkalinity	g CaCO ₃ /L	1.72 (± 0.06)	Valeric	[gCOD/L]	0.06 ± 0.01
COD/TN		9.4:1			
TS ^d	g/L	20.6 (± 0.9)			
VS ^e	g/L	17.5 (± 0.6)			

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Table S4-5: Conversion of the source separated concentrations and flows to SIMBA# influent. Influent fractionation and main characteristics of the brown water stream plus the addition of organic waste flows (co-digestion influent) as in SIMBA#

Parameter block BROWN Water_NoMIX+nrYW+FW1

Parameter

Model or signal type

inCTRL_ASM

VFAs S_VFA	0	g COD/m³
Fermentable substrate S_F	5436*0.05	g COD/m³
Methanol S_MEOL	0	g COD/m³
Colloidal biodegradable substrate C_B	0	g COD/m³
Slowly biodegradable substrate X_B	5436*0.7	g COD/m³
Soluble unbiodegradable organics S_U	5436*0.05	g COD/m³
Colloidal unbiodegradable organics C_U	0	g COD/m³
Particulate unbiodegradable organics X_U	5436*0.1	g COD/m³
Stored PHA X_PHA	0	g COD/m³
Endogenous decay products X_E	0	g COD/m³
Ordinary heterotrophs X_OHO	5436*0.1	g COD/m³
Anoxic methanol utilizers X_MEOL	0	g COD/m³
Phosphorus accumulating organisms X_PAO	0	g COD/m³
Aerobic ammonia oxidizers X_AOO	0	g COD/m³
Nitrite oxidizing organisms X_NOO	0	g COD/m³
Total ammonia S_NHx	88.4	g N/m³
Nitrite S_NO2	0.2	g N/m³
Nitrate S_NO3	10	g N/m³
Dissolved Nitrogen S_N2	0	g N/m³
Soluble biodegradable organic N (from S_F) S_N_F	5436*0.05*0.1	g N/m³
Particulate biodegradable organic N X_N_B	5436*0.7*0.1	g N/m³
	< >	
Soluble unbiodegradable organic N S_N_U	5436*0.05*0.03	g N/m³
Particulate unbiodegradable organic N X_N_U	5436*0.1*0.03	g N/m³
Orthophosphate S_PO4	82*0.5	g P/m³
Releasable stored polyphosphate X_PP_LO	0	g P/m³
Non-releasable stored polyphosphate X_PP_HI	0	g P/m³
Soluble biodegradable organic P (from S_F) S_P_F	5436*0.05*0.01	g P/m³
Particulate biodegradable organic P X_P_B	5436*0.7*0.01	g P/m³
Soluble unbiodegradable organic P content S_P_U	5436*0.05*0.01	g P/m³
Particulate unbiodegradable organic P content X_P_U	5436*0.1*0.01	g P/m³
Dissolved oxygen S_O2	0	g O2/m³
Inorganic suspended solids X_IG	4559-3925	g TSS/m³
Metal hydroxide compounds X_MeOH	0	g Me/m³
Metal phosphate compounds X_MeP	0	g Me/m³
Alkalinity S_alk	4	eq/m³
Fermentative and Methanogenic Biomass from Digester X_DIG	0	g COD/m³
Calcium ions S_Ca	140	gCa/m³
Magnesium ions S_Mg	50	gMg/m³
Potassium ions S_K	100	gK/m³

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1112 Table S4-6: Conversion of the source separated concentrations and flows to SIMBA# influent. Influent fractionation and
 1113 main characteristics of the grey water stream as in SIMBA#:

Parameter block GREY Water INFLUENT

Parameter

Model or signal type	inCTRL_ASM	
VfAs S_VfA	0	g COD/m ³
Fermentable substrate S_F	14	g COD/m ³
Methanol S_MEOL	0	g COD/m ³
Colloidal biodegradable substrate C_B	0	g COD/m ³
Slowly biodegradable substrate X_B	400	g COD/m ³
Soluble unbiodegradable organics S_U	15	g COD/m ³
Colloidal unbiodegradable organics C_U	0	g COD/m ³
Particulate unbiodegradable organics X_U	15	g COD/m ³
Stored PHA X_PHA	0	g COD/m ³
Endogenous decay products X_E	0	g COD/m ³
Ordinary heterotrophs X_OHO	15	g COD/m ³
Anoxic methanol utilizrs X_MEOL	0	g COD/m ³
Phosphorus accumulating organisms X_PAO	0	g COD/m ³
Aerobic ammonia oxidizers X_AOO	0	g COD/m ³
Nitrite oxidizing organisms X_NOO	0	g COD/m ³
Total ammonia S_NHx	8	g N/m ³
Nitrite S_NO2	0.2	g N/m ³
Nitrate S_NO3	0	g N/m ³
Dissolved Nitrogen S_N2	0	g N/m ³
Soluble biodegradable organic N (from S_F) S_N_F	8	g N/m ³
Particulate biodegradable organic N X_N_B	5	g N/m ³
Soluble unbiodegradable organic N S_N_U	0	g N/m ³
Particulate unbiodegradable organic N X_N_U	0	g N/m ³
Orthophosphate S_PO4	4.6	g P/m ³
Releasable stored polyphosphate X_PP_LO	2	g P/m ³
Non-releasable stored polyphosphate X_PP_HI	0	g P/m ³
Soluble biodegradable organic P (from S_F) S_P_F	0	g P/m ³
Particulate biodegradable organic P X_P_B	0	g P/m ³
Soluble unbiodegradable organic P content S_P_U	0	g P/m ³
Particulate unbiodegradable organic P content X_P_U	0	g P/m ³
Dissolved oxygen S_O2	0	g O2/m ³
Inorganic suspended solids X_IG	150	g TSS/m ³
Metal hydroxide compounds X_MeOH	0	g Me/m ³
Metal phosphate compounds X_MeP	0	g Me/m ³
Alkalinity S_alk	4	eq/m ³
Fermentative and Methanogenic Biomass from Digester X_DIG	0	g COD/m ³
Calcium ions S_Ca	140	gCa/m ³
Magnesium ions S_Mg	50	gMg/m ³
Potassium ions S_K	100	gK/m ³
Calcium rhosphate X_CaPO4	1	gCaPO4/m ³

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5 Overview: Treatment Layout and Technologies

Decentralized wastewater treatment layouts including not only source-separation but also urine diversion offer the highest potential in cost-effectiveness and resource recovery (Garrido-Baserba et al., 2022) due to the high nutrient loads of yellow water.

The proposed layout separates black and grey water and further divides the former between yellow and brown water employing urine diverting toilets. Even if quality standards for drinking water are met, flows are treated and reused as grey water within the block for non-potable applications. Potable water is supplied by the collection and treatment of rainwater by reverse osmosis (RO), ultraviolet filtration (UV), and remineralization (e.g., Water-dropfilter, 2021). Two main treatment trains are installed in series for brown and grey water, while urine is directed towards additional equipment designed to harvest N-based and P-based fertilizers from the flow.

The incorporation of kitchen food waste (KFW) into the brown water flow is assumed in order to achieve higher loads of organic matter and consequently increased biogas production in the UASB reactor. An organic loading rate (OLR) of 10 g/m^3 is desired for co-digestion as it offers the optimum methane conversion rate, of around 62% (Gao et al., 2020). The installed reactor is expected to operate at an OLR of 10.4 g/m^3 , a temperature of 35°C , and a short HRT of 2.6 days (de Graaff et al., 2010; Gao et al., 2020; Kujawa-Roeleveld et al., 2005, 2006; Luostarinen & Rintala, 2007; Ma et al., 2018; Mohammadi, 2022; Mukherjee et al., 2016; Rajagopal et al., 2013; Silvestre et al., 2015; Wendland, 2008; Zeeman et al., 2008). The described operation allows the reactor to cover 55% of its energy consumption through biogas. Reactor volume of 16 m^3 is calculated from HRT.

A single stage OLAND process is installed in series with the UASB reactor to perform nitrogen removal from the brown water stream. Biofilm surface and RBC volume are sized according to the influent nitrogen load. Phosphorus is recovered in a struvite reactor composed of a crystallizer and a decanter where supersaturation is achieved through the maintenance of reactor pH at 8 by the addition of $\text{Mg}(\text{OH})_2$. See Supplementary Information for calculations of effluent nutrient concentrations, struvite production, consumption of $\text{Mg}(\text{OH})_2$, electricity demand, and reactor and decanter volume.

After nutrient removal treatment, brown and grey water are mixed and aerobic treatment is performed in a side-stream membrane bioreactor (MBR) coupling an aerated biological treatment tank and a crossflow, multi-tube membrane loop (Garrido-Baserba et al., 2022). An HRT of 16.2h and a reactor volume of 164 m^3 are calculated. Even if the incorporation of an MBR in the treatment layout substantially increases operational costs, the inclusion of an aerobic stage ensures adequate effluent quality.

Difficulty of the proposed treatment train to meet phosphorus concentration guidelines for wastewater reuse is solved by the incorporation of a final stage composed of a flat sheet RO membrane and a UV filter which also helps damper pathogen risks.

1170 The following table summarizes some of the selected literature considered for the modelling of each
 1171 treatment unit from which removal efficiencies, design parameters or costing methods were obtained.
 1172 Additionally, some data has also been obtained from various suppliers, which have been cited along the
 1173 paper.

1174 *Table S5-1: Selected literature and software employed for the modelling of each treatment.*

References		
UASB	<i>de Graaf et al., 2010</i>	<i>Kujawa-Roeleveld and Zeeman, 2006</i>
	<i>Metcalf and Eddy, 2013</i>	<i>CapdetWorks</i>
	<i>Oteng-Peprah et al., 2018</i>	<i>SIMBA</i>
OLAND	<i>Courstens et al., 2014</i>	<i>Lozano et al., 2007</i>
	<i>Clippeleir et al., 2011</i>	<i>Oteng-Peprah et al., 2018</i>
	<i>Roefs et al., 2017</i>	<i>SIMBA</i>
Struvite reactor	<i>De Graaf et al., 2010</i>	<i>Etter et al., 2011</i>
	<i>Siciliano et al., 2020</i>	<i>Pastor Alcañiz, 2008</i>
	<i>Tarragó et al., 2016</i>	<i>SIMBA</i>
MBR	<i>Fletcher et al., 2007</i>	<i>Lo et al., 2015</i>
	<i>Wen et al., 1999</i>	<i>Atasoy et al., 2007</i>
	<i>Xing et al., 2001; 2003</i>	<i>Bani-Melhem et al., 2015</i>
	<i>Liu et al., 2005</i>	<i>Lesjean and Gnirss, 2006</i>
	<i>Merz et al., 2007</i>	<i>Oteng-Peprah et al., 2018</i>
		<i>SIMBA</i>
anMBR (only in Garrido-Baserba, 2022)	<i>Ariunbaatar et al., 2021</i>	<i>Shoener et al., 2016</i>
	<i>Foglia et al., 2020</i>	<i>Wang et al., 2018a, 2018b</i>
	<i>Gouveia et al., 2015</i>	<i>Lin et al., 2011</i>
	<i>Ribera-Pi et al., 2020</i>	<i>Verrecht et al., 2010</i>
	<i>Shin et al., 2014</i>	<i>Fletcher et al., 2007</i>
	<i>Pretel et al., 2014</i>	<i>SIMBA</i>
MABR	<i>Casey et al., 2008</i>	
	<i>Gritti, 2019</i>	
	<i>De Paepe et al., 2020</i>	<i>Chipako and Randall, 2020</i>
	<i>De Paepe et al., 2018</i>	
RO	<i>Van Voorthuizen et al., 2005</i>	
UV	<i>Mazuki et al., 2020</i>	
Uridis cell	<i>Personal communication (K. Rabaey)</i>	
	<i>De Paepe et al., 2020</i>	
	<i>Etter et al., 2011</i>	

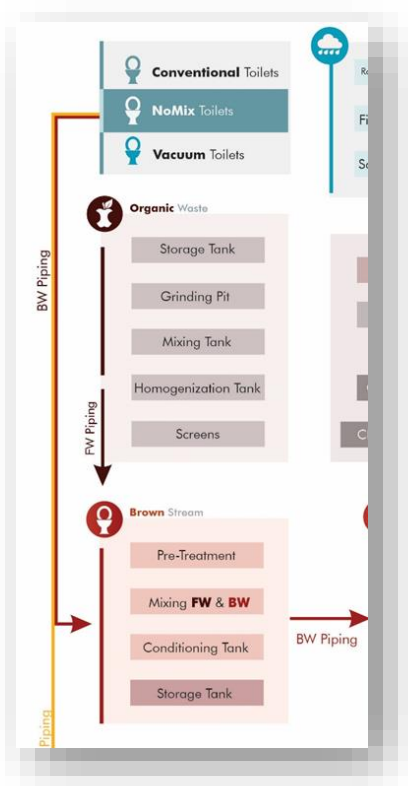
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6 Co-digestion (Food Waste)

Anaerobic digestion (AD) broadly refers to the biological process where microorganisms break down organic matter without oxygen. It's applicable to various feedstocks, including brown water and food waste. Both the brown water and the food waste will be mixed and treated through Anaerobic digestion (AD). Nevertheless, food waste and brown water constitute distinct feedstocks with different characteristics.

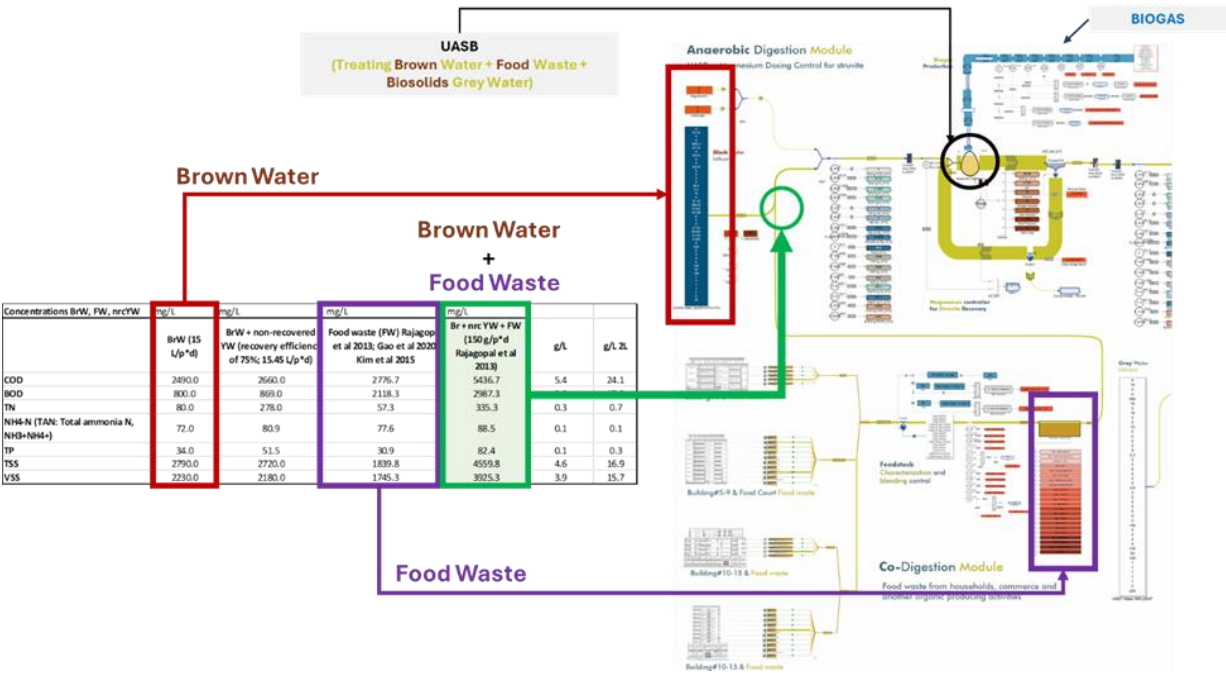
Co-digestion Module's Role is to ensure food waste stream is compatible with the process happening in the UASB reactor. This might involve pretreatment steps like shredding, mixing or nutrient balancing to optimize the combined feedstock entering the reactor. Food waste could represent the combination of different food waste sources, such as households, food courts, restaurants, supermarkets, specialized shops, food processing, etc.

Table S6-1: Main processes involved in the co-digestion module



Why "Co-digestion": When the UASB receives both pretreated food waste and brown water, the anaerobic digestion process is termed "co-digestion." It signifies the simultaneous treatment of multiple feedstocks within the same reactor. Combining feedstocks can create synergies, such as improved nutrient balance for microorganisms, potential for higher biogas yields, dilution of potential inhibitors present in individual feedstocks, etc.

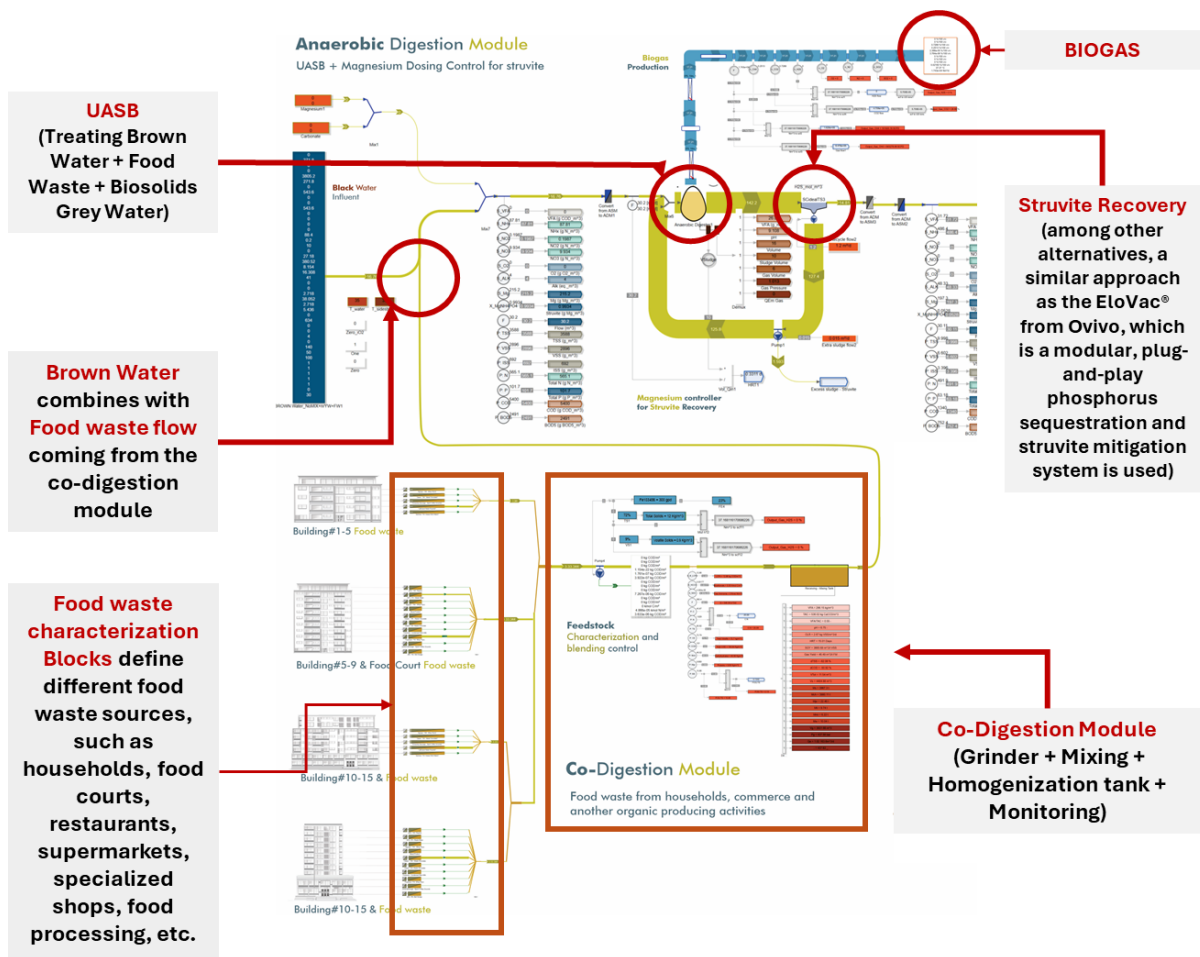
Table S6-2: Conversion of the source separated concentrations and flows to SIMBA# influent. Influent fractionation and main characteristics of the grey water stream as in SIMBA#:



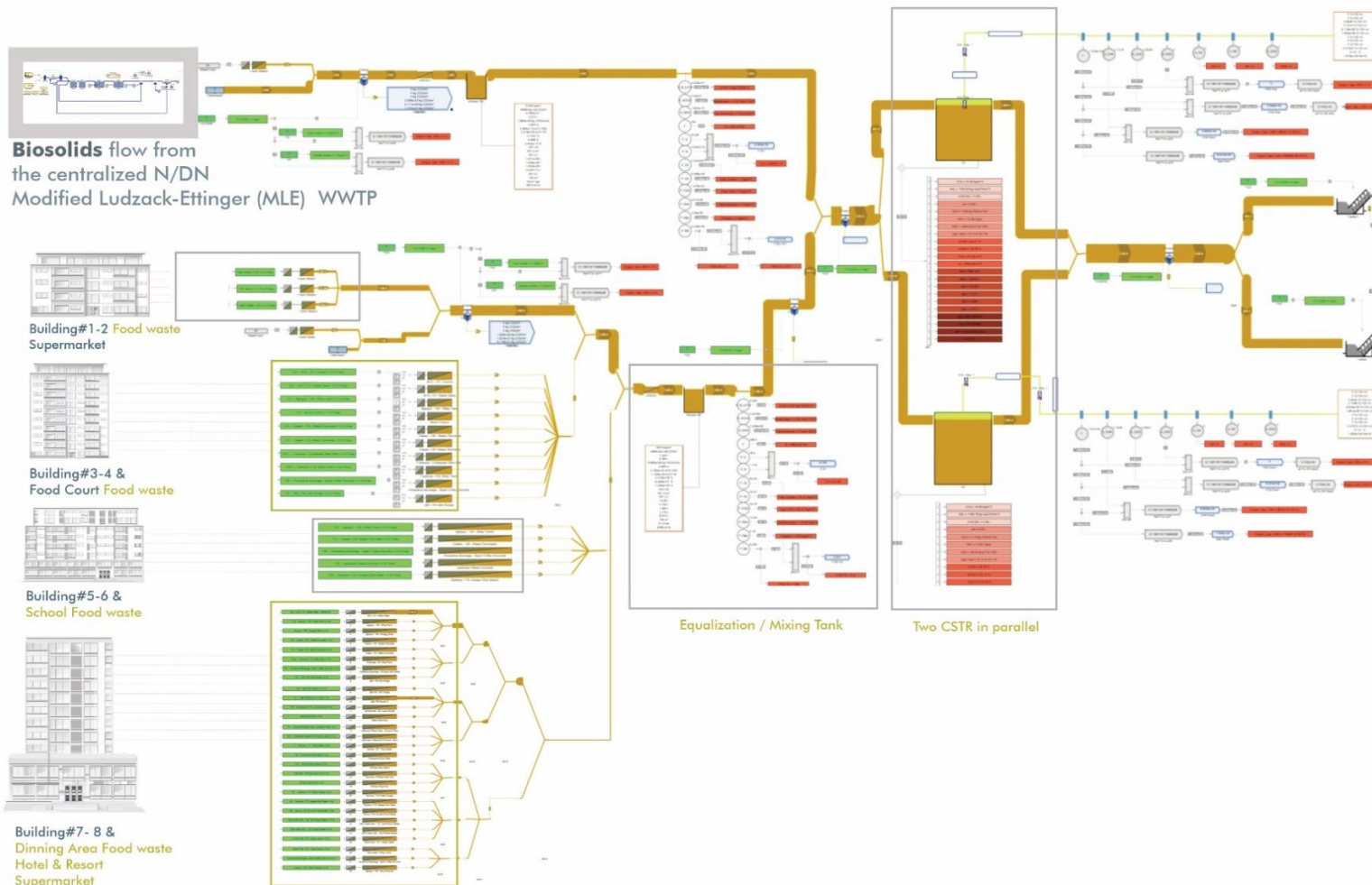
Food waste passes through the UASB in this process and food waste produces biogas. The figure shows the food waste stream entering the main treatment stream after the co-digestion module. The inclusion of food waste is a potent source of biogas in this Anaerobic Digestion (AD) system. Specifically, for this conservative scenario, the introduction of food waste increases biogas production by approximately 36±4% for the DSS, approximately 28±3% for CAS with PC, and 19±6% for CAS with no PC (when using MBR as main secondary treatment). While different anaerobic digestion (AD) alternatives are possible beyond the UASB configuration [e.g., Expanded Granular Sludge Bed (EGSB); Complete mix tank reactors (CSTRs), Anaerobic Membrane Bioreactors (AnMBRs), etc.]. The selected AD alternative: UASB, specifically plays a crucial role in breaking down the organic matter and generating biogas from the combination of brown water and food waste during its anaerobic digestion process. The produced biogas stream can be seen at the top of the diagram, right above the UASB block representing the AD process.

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Table S6-3: Conversion of the source separated concentrations and flows to SIMBA# influent. Influent fractionation and main characteristics of the grey water stream as in SIMBA#:



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Table S6-4.: The modeled anaerobic digestion process corresponds to two CSTR in parallel. The anaerobic digestion system is both fed from the WWTP facility biosolids (the NDN – MLE process depicted above) and from the same co-digestion materials and regime used for the decentralized (DSS) model. The planned operation of the co-digestion modules basically consists of an equalization tank that will achieve partial degradation of hauled-in waste, while allowing time for mixing and nutrient/composition balance. Other necessary equipment as grinders, storage tanks, etc. were not modeled but considered in the technoeconomic assessment. Effluent from these two digesters will flow into screw presses, which are modelled with a single separator block operating at a fixed 40% (w/v) TSS concentration in the centrifuge solids (Figure 19). The screw press solids flow rate was assuming that the specific gravity of the solids was approximately equal to water. A gas analysis subsystem was added to calculate the production rate of total gas, methane, and carbon dioxide.

6.1 Influent: Co-digestion with food waste

The highest uncertainty in the presented compositions is associated with the organic fraction of municipal solid waste (OFMSW), as it is directly related with diet and can therefore vary significantly depending on the region. The considered composition refers to a western diet. While acknowledging individual habits, socioeconomic factors, and even how different studies categorize "food waste", a ballpark could be about 0.5 - 1 kg per person per day, which could correspond to a COD concentration that can range from around 5,000 mg/L to upwards of 10,000 mg/L. Food waste values in literature can be very high, especially for specialized food-waste facilities or high-strength anaerobic digesters. Our study focuses on household food waste combined with brown and/or black water. The COD for the food waste considered in this study is around 3,000 mg/l.

For this context, we employed data supported by widely adopted literature on the topic:

- Kim, M., Chowdhury, M.M.I., Nakhla, G. and Keleman, M., 2015. Characterization of typical household food wastes from disposers: fractionation of constituents and implications for resource recovery at wastewater treatment. *Bioresource technology*, 183, pp.61-69.
- Rajagopal, R., Lim, J.W., Mao, Y., Chen, C.L. and Wang, J.Y., 2013. Anaerobic co-digestion of source segregated brown water (feces-without-urine) and food waste: for Singapore context. *Science of the Total Environment*, 443, pp.877-886.
- Gao, M., Zhang, L. and Liu, Y., 2020. High-loading food waste and blackwater anaerobic co-digestion: Maximizing bioenergy recovery. *Chemical Engineering Journal*, 394, p.124911.

While the authors don't provide the exact list of edible products or the relative fraction of meat and dairy on those totals, acknowledge the usual presence of meat and some dairy within household food waste. We employed conservative FW quantities to prioritize focus on the core comparison between centralized and decentralized systems, and avoid deviating the reader attention from brown and food waste co-digestion towards a highly specialized high-strength food waste facility.

Table S6-5: Values in mg/l for column [Food waste (FW) - Rajagopal et al 2013; Gao et al 2020; Kim et al 2015. When converted to mg/l the results for FW are as follows.

Concentrations BrW, FW, nrcYW	mg/L	mg/L	mg/L	mg/L		
	BrW (15 L/p*d)	BrW + non-recovered YW (recovery efficiency of 75%; 15.45 L/p*d)	Food waste (FW) Rajagopal et al 2013; Gao et al 2020; Kim et al 2015	Br + nrc YW + FW (150 g/p*d Rajagopal et al 2013)	g/L	g/L 2L
COD	2490.0	2660.0	2776.7	5436.7	5.4	24.1
BOD	800.0	869.0	2118.3	2987.3	3.0	17.2
TN	80.0	278.0	57.3	335.3	0.3	0.7
NH4-N (TAN: Total ammonia N, NH3+NH4+)	72.0	80.9	77.6	88.5	0.1	0.1
TP	34.0	51.5	30.9	82.4	0.1	0.3
TSS	2790.0	2720.0	1839.8	4559.8	4.6	16.9
VSS	2230.0	2180.0	1745.3	3925.3	3.9	15.7

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1250 *Table S6-6: Food waste composition according to Rajagopal et al 2013 and Gao et al 2020.*

	Unit	BW + FW (Phase III)	Parameter	Unit	Feed mixture (2-L BW + 150 g FW)
BW:FW VS mixing ratio		1:1	TS	[g/kg, wet basis]	18.26 ± 3.49
Operation duration	day	61–98	VS	[g/kg, wet basis]	16.9 ± 3.19
Initial pH		8.0 (± 0.2)	VS/TS	[%]	93
tCOD ^a	g/L	25.4 (± 1.2)	pH	–	6.18 ± 0.55
sCOD	g/L	9.5 (± 0.8)	COD _t	[gCOD/L]	35.21 ± 10.41
sCOD /tCOD	%	37.4	COD _s	[gCOD/L]	13.02 ± 4.36
Acetate	g COD/L	1.32 (± 0.20)	VFA-COD		
Propionate	g COD/L	0.66 (± 0.07)	Acetic	[gCOD/L]	0.67 ± 0.04
Butyrate	g COD/L	0.32 (± 0.05)	Propionic	[gCOD/L]	0.31 ± 0.09
TN ^b	g/L	2.7 (± 0.0)	Isobutyric	[gCOD/L]	0.05 ± 0.01
TAN ^c	g/L	1.1 (± 0.0)	Butyric	[gCOD/L]	0.19 ± 0.06
PO ₄ ^{3–} -P	mg/L	34.1 (± 8.5)	Isovaleric	[gCOD/L]	0.14 ± 0.02
Alkalinity	g CaCO ₃ /L	1.72 (± 0.06)	Valeric	[gCOD/L]	0.06 ± 0.01
COD/TN		9.4:1			
TS ^d	g/L	20.6 (± 0.9)			
VS ^e	g/L	17.5 (± 0.6)			

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1254 6.2 Kitchen food waste (KFW) incorporation into the brown water flow

1255 A dedicated KFW collection system is considered, and could involve separate bins, under-sink disposals,
 1256 or other collection methods suited to the building or community context. The incorporation of kitchen food
 1257 waste (KFW) into the brown water flow was to achieve higher loads of organic matter and consequently
 1258 increased biogas production in the UASB reactor. An organic loading rate (OLR) of 10 g/m³ was targeted
 1259 for co-digestion because it offers the optimum methane conversion rate of around 62% (Gao et al., 2020)."

1260 The KFW incorporated into brown water through the previously addressed units or processes:

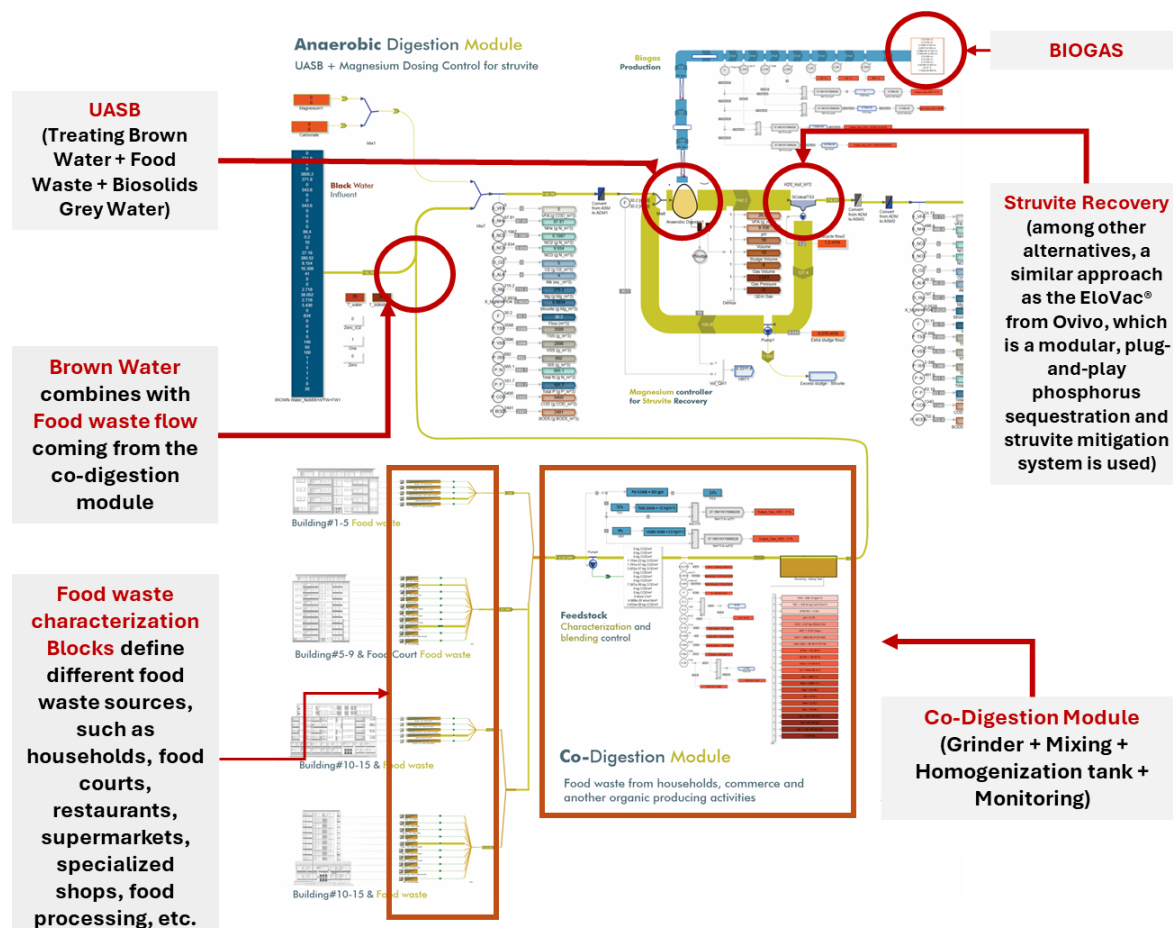
1261 **Separate Collection:** KFW will not be simply disposed of through kitchen grinders into the greywater
 1262 stream. A dedicated KFW collection system will be in place, using methods like separate bins or under-sink
 1263 disposals. To emphasize, KFW will NOT be disposed of through toilets, as this would contaminate the
 1264 brown water stream and disrupt the treatment process.

1265 Co-Digestion Module: Collected KFW enters a specialized co-digestion module with brown water. This
 1266 module features:

- 1267 ▪ **Homogenization tanks:** These tanks buffer the intermittent nature of KFW input and create a
- 1268 consistent feedstock for digestion.
- 1269 ▪ **Pretreatment:** KFW may require steps like grinding or shredding to prepare it for optimal
- 1270 digestion.
- 1271 ▪ **Nutrient Balancing:** KFW will be combined with brown water to achieve a balanced nutrient
- 1272 profile for anaerobic microbes.

While screens are not absolutely essential in all scenarios, they offer significant benefits, especially with intermittent flows. They can effectively remove foreign objects like plastic bags, utensils, or packaging materials that can damage digester components and cause operational disruptions (Mata-Alvarez et al., 2009; Zhang et al., 2005). Furthermore, screens help to ensure manageable particle size for efficient mixing and digestion, maintaining a suitable particle size distribution, as large food particles can hinder mixing and reduce biogas production (Amon et al., 2007; Fernández et al., 2012). Therefore, while not accounted for in the current study, this should be an element that we would strongly recommend for this type of operation.

Table S6-7: Kitchen food waste (KFW) incorporation into the brown water flow.



6.3 Intermittent food waste flow

Homogenization tanks are key to what we call the co-digestion module. The intermittent nature of food waste flow is a valid concern and can indeed impact digester performance. The impact of intermittent food waste flow on digester performance is a valid and crucial point that need in-depth consideration to ensure the system feasibility. Our study comprehensively addresses this challenge through several strategies:

Consideration of Homogenization Tanks (Buffering and Blending). These tanks act as buffers, storing and blending incoming waste to create a more consistent feedstock for the digester. This minimizes performance fluctuations caused by variations in flow and composition (Cueto-Vázquez et al., 2020; Amon et al., 2007), and smoothens digester operation, while optimizing microbial activity and enhancing biogas production (Fernández et al., 2012; Zhang et al., 2017).

Inventory of stable waste streams. The food waste sources could widely vary in the urban landscape (i.e., households, food courts, restaurants, supermarkets, specialized shops, etc.), and understanding its availability and frequency will be key to the correct management of these systems. We are inclined to think that household food waste (leftovers from food) should be fairly constant throughout the year, so understanding the relationship between the different feedstock sources and combining food waste from other sources (like restaurants, supermarkets, et.c) with household food waste, which has more stable flows, could buffer the intermittent nature of some of the food waste sources and stabilize digester performance. On those lines, this study considers the use of a storage tank than obviously will depend for each given scenario and food availability, characteristics of the feedstock, packaging-related issues, seasonal patterns, etc. There is an extensive body of research addressing the correct management of intermittent feedstock flows that shows important aspects to be considered for similar cases using co-digestion (Appels et al., 2018; Nayak et al., 2020; Monroy-Ramírez et al., 2020; Wang et al., 2017).

Operational strategies. Implementing operational adjustments like variable feeding rates, targeted pH control, or temperature regulation allows the digester to adapt to inconsistent influent flows and maintain optimal performance and mitigates operational disruptions, ensures stable biogas production throughout varying flow periods (Nistor et al., 2019; Singh et al., 2018; El-Bassam et al., 2016; Mao et al., 2015).

References:

- Cueto-Vázquez, M., et al. (2020). Anaerobic co-digestion of food waste and sewage sludge in mesophilic and thermophilic conditions: Effect on the microbial community. *Journal of Environmental Management*, 262, 110270.
- Amon, T., et al. (2007). Methane production potential of low-amylose maize silages harvested at different maturity stages. *Bioresource Technology*, 98(13), 2408-2418.
- Fernández, B., et al. (2012). Effect of pre-treatment on dry anaerobic digestion of sunflower oil cake. *Fuel*, 94(1), 84-91.
- Zhang, L., et al. (2017). Effect of pre-treatment on the anaerobic digestion of food waste with high chicken manure content. *Waste Management*, 79, 816-823.

- 1320 ▪ Appels, X., et al. (2018). Enhanced methane production from co-digestion of organic wastes with
1321 microalgal residue: Impact of inoculum source and pretreatment. *Renewable Energy*, 129, 709-
1322 718.
- 1323 ▪ Nayak, L., et al. (2020). A review on co-digestion of food waste and other organic substrates for
1324 enhancing biogas production. *Journal of Environmental Management*, 260, 110106.
- 1325 ▪ Monroy-Ramírez, G., et al. (2020). Anaerobic co-digestion of sewage sludge and food waste in
1326 horizontal and vertical flow digesters: Comparison of hydraulic retention times and performance
1327 parameters. *Journal of Cleaner Production*, 275, 123205.
- 1328 ▪ Wang, W., et al. (2017). Enhanced methane production from co-digestion of food waste and
1329 sewage sludge with different pretreatment methods. *Journal of Environmental Management*, 201,
1330 155-162.

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1332 6.4 Mixing and total solids requirements

1333 All the necessary equipment to ensure the brown water loaded with food waste can have enough sheer
1334 force to be moved/flushed to UASB was considered in the techno economic analysis (i.e., Grinding
1335 equipment, mixing tank, equalization tank, storage and plumbing) as detailed below. Managing high loaded
1336 stream deriving food waste and the brown water to a UASB demands a strategic approach.

1337 The co-digestion module would consist, as existing larger food waste facilities, mixing tank in coordination
1338 with an influent pit which are meant to manage and monitor the required pre-treatment processes.

- 1339 ▪ **Grinding:** Reduce particle size to manageable chunks (< 5 mm) for smoother pumping and
1340 improved mixing. Consider hammer mills or disc mills (Ferreira et al., 2015; Lettinga et al., 1997).
- 1341 ▪ **Hydrolysis:** Unlock the energy potential of complex carbohydrates for enhanced biogas
1342 production. Explore enzymatic (Neybert et al., 2017) or thermal hydrolysis (Monroy-Pérez et al.,
1343 2020). Microwave (Wang et al., 2009) or ultrasonic (Nishio et al., 2013) options offer efficient
1344 breakdown.
- 1345 ▪ **The equalization tank:** should employ well-mixed mechanical equipment or airlift mixers for flow
1346 homogenization and sedimentation prevention (Lettinga et al., 1997; Silva et al., 2020), and total
1347 solids (TS) levels for optimal dilution (Gómez et al., 2020) should be always monitored. Similarly,
1348 it's expected that there is a need for in-feed dilution. The expected high-TS food waste stream
1349 should accordingly be diluted with the low-TS brown water streams before UASB entry to reduce
1350 density and viscosity (Lettinga et al., 1997). Aiming for influent TS below 6% (Van Lier et al.,
1351 2008).

1352 Pumps and Piping should suited for high-TS slurries, like progressive cavity (PC) or macerator pumps
1353 (Lettinga et al., 1997; Monroy-Pérez et al., 2020, even energy-efficient options like variable-speed drives
1354 could be considered (Ferreira et al., 2015). Pipe diameters should always maintain sufficient flow velocities
1355 (0.5-1 m/s) to prevent blockages (Lettinga et al., 1997; Monroy-Pérez et al., 2020), while paying especial
1356 attention to optimized bends and minimize elbows for smooth flow.

Increase SRT could be also an alternative, by proving longer sludge retention time (SRT) (up to 40 days) compared to conventional UASBs the UASB could accommodate slower digestion of complex food waste (Lettinga et al., 1997; Van Lier et al., 2008), while maintaing a dense and active sludge blanket for optimal microbial activity and organic matter conversion (Lettinga et al., 1997; Silva et al., 2020). Monitor settleability to avoid bulking problems (Gómez et al., 2020). Similarly, it could be also possible to consider a two-stage UASB setup, with the first stage focusing on hydrolysis and acidification followed by methanogenesis in the second stage (Lettinga et al., 1997; Van Lier et al., 2008). This can improve performance for complex substrates. Design the UASB influent pipe and feedwell to create internal turbulence and prevent settling (e.g., chimney inlets) (Lettinga et al., 1997; Silva et al., 2020).

Also, especial monitoring and Control could be necessary, from regular TS Monitoring, to track influent and effluent TS to ensure optimal operating conditions and prevent overloading (Gómez et al., 2020) to regular backwashing routines for pipes and pumps could be implemented to clear accumulated solids (Silveira et al., 2009) to conducting periodic sludge activity and settleability tests to identify potential issues like bulking or unexpected flocculation issues (Gómez et al., 2020).

References:

- Ferreira, L. F., Ometto, A. R., Nogueira, N. G., & Oliveira, R. A. (2015). Influence of pre-treatment on UASB reactor performance treating high-strength cassava wastewater. *Journal of environmental management*, 150, 155-162.
- Lettinga, G., Rebac, S., & Zeeman, G. (1997). Upflow anaerobic sludge blanket (UASB) process for biological wastewater treatment. *Water Science and Technology*, 35(10), 225-234.
- Neybert, K. H., Heiermann, M., & Welz, G. (2017). Enhanced biogas production from lignocellulose using enzymatic pretreatment and two-stage up-flow anaerobic sludge blanket (UASB) digestion. *Water research*, 120, 352-364.
- Monroy-Pérez, L. T., García-Peña, R., & Rojano-Barrón, R. E. (2020). Effect of thermal and ultrasonic pretreatment on the anaerobic digestion of food waste. *International Journal of Hydrogen Energy*, 45(37), 19441-19450.
- Wang, L., Sun, J., Yuan, M. X., Yang, Y., & Li, X. (2009). Microwave pretreatment of sewage sludge for enhancing anaerobic digestion in the upflow anaerobic sludge blanket (UASB) reactor. *Water research*, 43(15), 3779-3785.
- Nishio, N., Lee, Y. J., & Urano, K. (2013). Pretreatment of food waste by ultrasonic irradiation for efficient methane fermentation. *Waste management*, 33(10), 2105-2110.
- Silva, A. G., Ribeiro, T. A., Pereira, F. V., & Van Loosdrecht, M. C. (2020). Single-stage and two-stage UASB reactors for the treatment of domestic wastewater under low organic loading rates. *Environmental technology & innovation*, 9(3), 100801.
- Gómez, M. A., Montoya, M. I., Ruiz, E., & Martín, A. (2020). Impact of total solids content on UASB reactor performance treating cheese whey. *Journal of cleaner production*, 242, 118406.
- Ferreira, L. F., Ometto, A. R., Nogueira, N. G., & Oliveira, R. A. (2015). Influence of pre-treatment on UASB reactor performance treating high-strength cassava wastewater. *Journal of environmental management*, 150, 155-162.
- Silveira, A. G., Lettinga, G., & van der Meer, R. R. (2009). Reflux of sludge and scum in UASB reactors for the treatment of sewage and industrial wastewater. *Water research*, 43(13), 3425-3432.

- Van Lier, J. B., Mahmoud, N., Zeeman, G., & Samani, Z. A. (2008). Biological wastewater treatment of domestic sewage: upgrading of high.

6.5 Co-digestion: centralized vs decentralized.

The specific quantities and quality of food waste (FW) used in this study were based on [SI 6.1 - Influent: Co-digestion with food waste]. These figures represent conservative estimates, prioritizing the demonstration of the synergy that decentralized source separation within the current urban water cycle. We believe that by implementing close-proximity FW collection points, diversion rates within the urban waste cycle can significantly increase. FW's readily decomposable nature often leads to its improper disposal as regular garbage. Convenient collection points directly address this issue and maximize resource utilization.

While acknowledging the limitations of centralized treatment in effectively collecting and utilizing FW, as current rates worldwide are clearly underwhelming, we included anyway its theoretical impact on biogas production in this analysis to ensure direct comparison under identical conditions. This allows us to clearly highlight the benefits of decentralized source separation despite the established drawbacks of centralized systems.

It's crucial to recognize that biogas gains across the two different systems will vary significantly due to the different utilization pathways of the VSS (volatile suspended solids). In the decentralized system, a highly enriched VSS stream is obtained by combining brown water, food waste, and biosolids. This stream feeds directly into the anaerobic digester, ensuring efficient conversion to biogas and, in this specific scenario, potentially enhancing biogas production by up to 42%. In contrast, centralized systems face an inherent disadvantage: the aeration process inevitably consumes part of the VSS, reducing its potential biogas contribution. A typical WWTP, diverting up to 60% of the VSS to AD through primary biosolids, would fall short of the decentralized system's potential (increasing biogas by $28\pm3\%$ instead of 35-40%). Furthermore, space-constrained contexts and seeking to minimize sludge handling would likely omit primary clarifiers. Therefore, the biogas production due to co-digestion would plunge to approximately less than 20%. Furthermore, introducing food waste, especially in cases with limited VSS diversion from primary clarifiers, can have additional consequences. The increased organic load in the centralized approach can boost air demand by up to 30%, potentially impacting the overall energy net balance of the system. Therefore, it is of the utmost importance to consider these nuanced differences in VSS availability and potential side effects so that both system design and food waste integration can be optimized to improve biogas production and energy efficiency for each specific context or treatment configuration. It is also important to mention that we employed conservative FW quantities to prioritize focus on the core comparison between centralized and decentralized systems. The different energy demand and energy production simulations and assessments can be available upon request.

On those lines, studies by Agrawal (2009) and Hansen et al. (2016) demonstrate that co-digestion of brown water with fruit and vegetable waste or food waste, respectively, significantly increases biogas production compared to sludge-only digestion. Similarly, Anjum et al. (2023) highlight the synergistic effect of co-digestion when using brown water, as it provides essential nutrients like nitrogen and phosphorus for microbial activity, while organic waste adds carbon, balancing the C:N ratio for optimal biogas production. This synergy, was also observed by Luostarinen et al. (2009) and Wang et al. (2022) and it can aligns with the principles of a circular economy, minimizing waste and closing nutrient loops (El-Fadel et al., 2010).

References:

- Agrawal, N. K. (2009). Increased biogas production in a wastewater treatment plant by anaerobic co-digestion of fruit and vegetable waste and sewer sludge - a full scale study. *Water Science and Technology*, 64(9), 1851-1856.
- Anjum, M., Ahmed, A., Shah, N., Sial, F., & Qureshi, N. A. (2023). Opportunities and challenges in the anaerobic co-digestion of municipal sewage sludge and fruit and vegetable wastes: A review. *Environmental Technology & Innovation*, 14(3), 100317.
- El-Fadel, M., Abou Eleila, M. A., & Alaerts, G. J. (2010). Anaerobic Co-Digestion of Wastes: Reviewing Current Status and Approaches for Enhancing Biogas Production. *Journal of Chemical Technology & Biotechnology*, 85(7), 906-918.
- Fernandez, J., Molinuevo, J., & Gomez, C. (2016). Feasibility of OFMSW co-digestion with sewage sludge for increasing biogas production at wastewater treatment plants. *Euro-Mediterranean Journal for Environmental Integration*, 1(1), 1-11.
- Hansen, T., Angelidaki, I., & Sørensen, K. B. (2016). Biogas production from food waste via co-digestion and digestion- effects on performance and microbial ecology. *Scientific Reports*, 6(1), 30253.
- Luostarinen, S., Riekkola, R., & Lonka, E. (2009). Co-digestion of cow manure and food waste for biogas enhancement and nutrients revival in bio-circular economy. *ScienceDirect*, 262, 811-817.
- Wang, W., Ma, W., Liu, B., Chen, Y., & Wang, R. (2022). Co-digestion of cow manure and food waste for biogas enhancement and nutrients revival in bio-circular economy. *Bioresource Technology*, 350, 126705.
- Zhang, R., Wang, F., Wang, W., & Ren, Y. (2018). Process parameters optimization for improved methane production from anaerobic co-digestion of corn straw and sewage sludge. *Bioresource Technology*, 259, 152-157.

7 Brown Water

7.1 Brown Water (BrW) Line: Overview

The BrW line features more intensive treatment to handle high pollutant concentrations and maximize resource recovery. We prioritize anaerobic treatment in a UASB reactor due to several advantages for a decentralized scheme:

- **Low Excess Sludge, Smaller Footprint:** Reduces waste sludge and overall system size.
- **Flexibility:** Allows operation at varying SRT and HRT durations.
- **Circular Economy Fit:** Produces energy (methane) from waste.
- **Avoid energy-intensive aeration** from traditional aerobic treatment

UASB reactors are proven for robust COD removal in wastewater treatment (Cecconet et al., 2022). To boost system efficiency, we propose co-digestion of Organic Fraction of Municipal Solid Waste (OFMSW) with BrW. This increases organic matter input for greater methane production (Adami et al., 2020; Gao et al., 2020; et al., 2018; Mohammadi, 2022; Mu et al., 2020). We ensure a reactor temperature of 35°C (optimal for methanogenesis) by pre-heating the influent and utilize methane energy to contribute towards process needs.

For decentralization benefits, we operate at a short HRT (2.6 days, based on Gao et al., 2020). This aligns with a small reactor volume and a higher organic loading rate (OLR) to promote methanogenesis. For consistency, hydrolysis level, effluent/influent ratio, and other parameters have been verified using SIMBA# wastewater simulation software. Note that pretreatment of OFMSW (grinding & mixing) is needed for homogenous UASB reactor feed.

After significant COD reduction in the UASB, we target nitrogen in the BrW flow via a one-stage nitrification/anammox system within a rotating biological contactor (RBC). Also known as the OLAND process, it relies on specialized anammox bacteria (Hu et al., 2011; Laurenzi et al., 2016; et al., 2013; Wongkiew et al., 2020). Anammox bacteria oxidize ammonium and nitrite into harmless nitrogen gas and water. This system is cost-effective, avoids GHG emissions of typical nitrogen removal methods. RBC design supports simple operation and maintenance, crucial for decentralization. We've calculated biofilm surface area based on influent nitrogen, leading to a compact tank volume.

Post-RBC, a fluidized bed crystallizer/decanter setup promotes struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) formation. To avoid air, we follow the design by Bhuiyan et al. (2008) to regulate velocity (Kumar & Pal, 2015). Materials selected (stainless steel, PVC) resist pH variation and clogging concerns. Reactor and decanter sizing considers Stokes' law and optimal retention times.

7.2 Energy Recovery

Black water (BW) treatment offers a potential solution for sustainable wastewater management. It involves separating black water (toilet wastewater) from greywater (other wastewater sources) for targeted treatment.

In BW treatment, methane from biogas production can generate 56 MJ/p/y of electricity and 84 MJ/p/y of heat. This demonstrates the potential for significant energy recovery in this process. On the other hand, traditional wastewater treatment plants (WWTPs) are energy-intensive, consuming around 96 MJ/p/y.

BW treatment concepts offer a net energy gain of 22.5 MJ/p/y in contrast to the energy loss of 107 MJ/p/y in conventional WWTPs. Note that these figures don't factor in energy used for hardware production or heat losses, providing an optimistic estimate.

Table S7-1: Energy Production and Consumption in BW Treatment vs. Conventional WWTPs (Graaf et al. 2011)

Black water (5 L/p/d)	Electricity (MJ/p/y)	Heat (MJ/p/y)	Conventional WWTP, domestic sewage (124 L/p/d)	Heat (MJ/p/y)
Vacuum transport ^a	-14		Sewerage	-43
BW heating ^b		-80	WWTP	-96
Biogas production ^c	+56	+84	Biogas Production from AD	+32
P removal by struvite precipitation ^d	-3.5			
N removal by nitrification-anammox ^d	-16			
Total	+22.5			-107
Savings				
Drinking water production^e	+19			

^a4 kWh/p/y, most energy efficient vacuum toilet (WRS 2001).

^bIncrease of 9 W (worst case), transfer efficiency of 85%.

^c12.5 L CH₄/p/d, 35.6 MJ/m³ CH₄, 85% efficiency (40% electricity and 60% heat).

^dMaurer et al. (2003).

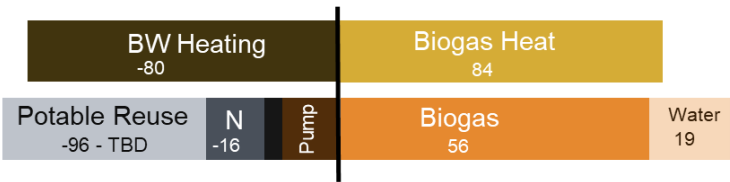
^e0.47 kWh/m³ (Vewin 2006).

^fIncluding N and P removal (Frijns et al. 2008).

De Graaff, M.S., Temmink, H., Zeeman, G. and Buisman, C.J.N., 2011. Energy and phosphorus recovery from black water. *Water Science and Technology*, 63(11), pp.2759-2765.

Table S7-2: Energy Production and Consumption in BW Treatment vs. Conventional WWTPs (Graaf et al. 2011)

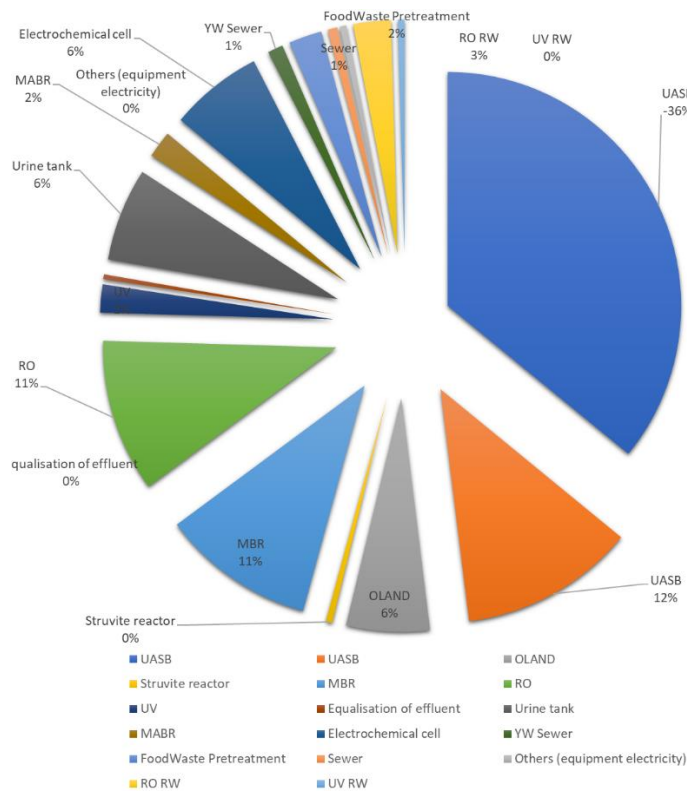
Black water (5 L/p/d)



Conventional WWTP, domestic sewage (124 L/p/d)



Table S7-3: Energy Production and Consumption in the decentralized source separation treatment (city block).



1532 Table S7-4: Energy Production and Consumption of the different processess in the decentralized source separation
 1533 treatment (city block).

Energy Demand (kWh/year)		Energy recovery
UASB	-150,515	AD: 68.4 (%)
	50,809	Whole System: 44.4 (%)
UASB	-79,361	kWh/yr
OLAND	24,178	kWh/yr
Struvite reactor	1,858	kWh/yr
MBR	44,486	kWh/yr
RO	44,377	kWh/yr
UV	8,136	kWh/yr
Equalization of effluent	1,392	kWh/yr
Urine tank	15,000	kWh/yr
MABR	7,760	kWh/yr
Electrochemical cell	27,000	kWh/yr
YW Sewer	4,467	kWh/yr
Food Waste Pretreatment	9,636	kWh/yr
Sewer	2,784	kWh/yr
Others (equipment electricity)	2,026	kWh/yr
RO RW	10,923	kWh/yr
UV RW	1,885	kWh/yr
Total	138,548	kWh/yr

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1538 **7.3 Upflow anaerobic sludge blanket reactor (UASB)**

1539 The UASB reactor considered enabled the uncoupling of the solids retention time (SRT) from the hydraulic
1540 retention time (HRT). The system was assured to operate with an HRT of 7.15 days and a SRT of 30 days.
1541 The common practice in full-scale anaerobic digestion facilities is to convert a fraction of the produced
1542 biogas into heat to satisfy heat requirements (while producing energy) via gas microturbines or combined
1543 heat and power (CHP). We adopted this approach because it also has been employed in small-scale
1544 applications (Adami et al., 2020; Baccioli et al., 2018; Zhang et al., 2021). One of the challenges when
1545 operating UASBs and anMBRs is the high percentage (up to 50%) of methane gas dissolved in the effluent
1546 that could escape, which could lower energy recovery efficiencies and increase greenhouse gas (GHG)
1547 emissions (Cookney et al., 2016; Shin et al., 2014; Shoener et al., 2016; Velasco et al., 2018a). Thus, a
1548 degassing membrane contactor was included in the treatment train, with a separated reactor separating
1549 the gas and liquid phases (Henares et al., 2016; Velasco et al., 2018b). UASB design calculations, removal
1550 efficiencies, and costs can be found in supplementary information section 4.1.

1551 Depending on scenario conditions (e.g., location, space availability, budget constraints, legislation),
1552 different biogas management options are possible (Rodero et al., 2018; Salihu and Alam, 2015; Yentekakis
1553 and Goula, 2017). Arguably the most common solution in biogas-producing treatment plants involves
1554 upgrading (i.e., purifying) the biogas to achieving 99% methane purity and selling it as fuel for electricity
1555 production or transport applications (gas or liquified). Both natural gas and CO₂ have a value market that
1556 could allow additional revenues to offset some of the system operating costs.

1557

1558 **7.4 Resource Recovery (UASB)**

1559 *7.4.1.1 A Circular Approach to Wastewater Management*

1560 A central goal of this decentralized system is to embrace the principles of a circular economy. With our
1561 natural resources under increasing strain, identifying ways to close material loops becomes essential.
1562 Recovering nitrogen and phosphorus – two critical nutrients in wastewater and fertilizers – presents an
1563 opportunity to decrease phosphate rock mining and the reliance on energy-intensive fertilizer production
1564 processes (Ostermeyer et al., 2022). Additionally, the energy stored in wastewater as COD offers a source
1565 of electrical and thermal energy. This can be used to reduce wastewater treatment reliance on non-
1566 renewable sources (Ostermeyer et al., 2022). Our focus in this decentralized setup is on recovering both
1567 biogas and nutrients using source-separation and targeted treatments designed for minimal resource loss.

1568

7.4.1.2 Addressing Methane Loss

Anaerobic treatment transforms organic matter into biogas, however, a significant portion of dissolved methane may still be lost in the effluent. Due to supersaturation, this loss can exceed 50% of the total gas produced, particularly in UASB reactors (Cookney et al., 2016; Velasco et al., 2018). This inefficiency not only compromises process yields but also creates a source of greenhouse gas emissions. Various techniques mitigate dissolved methane loss, but membrane-based recovery stands out as a low-energy solution. Notably, non-porous hollow fiber membrane contactors (HFMC) offer the further benefit of being easily retrofitted to existing reactor systems.

7.4.1.3 Why HFMCs Offer Advantages

The design proposed here involves an out-in HFMC made from polydimethylsiloxane (PDMS) operated with a vacuum. The rationale is as follows: PDMS, as a material, provides high membrane permeability, and the out-in configuration helps avoid clogging, a potential issue with effluents containing suspended solids. Systems of this type can achieve over 92% methane recovery (Bandara et al., 2011; Cookney et al., 2016; Crone et al., 2016; Gabelman and Hwang, 1999; Velasco et al., 2018). Importantly, integrating a degassing system like this into the UASB reactor boosts the system's overall COD removal efficiency by improving thermodynamic conditions within the reactor (Bandara et al., 2013; Crone et al., 2020).

7.4.1.4 Quantifying Energy Requirements

To calculate the energy needed for the degassing equipment, Eq. 1 will be utilized [provide equation]. Key input variables include heat capacity ratio, molar flow rate, gas constant, temperature, and pressure differential (Crone et al., 2016).

$$W_{deg} = \frac{kWRT}{k-1} * \left[\left(\frac{p_{out}}{p_{in}} \right)^{\left(\frac{k-1}{k} \right)} - 1 \right] \quad \text{Eq. 1}$$

Power demand of 0.052 kWh per m³ of treated effluent.

1599 Table S7-5: Parameters regarding energy consumption of dissolved methane recovery. Constants are obtained from
1600 Crone et al. (2016).

Parameter	Value
Heat capacity ratio (k)	1.295
Influent molar flow rate (mol/s)	0.002
Gas constant R (J/molK)	8.314
Inlet temperature (K)	308.000
Inlet pressure (p_{in})	101.300
Discharge pressure (p_{out})	21.300

1601

1602 *7.4.1.5 Harnessing Biogas for Efficient Energy Use*

1603 Once biogas is captured, converting it directly into heat offers an efficient strategy to cover heat
1604 requirements of both the reactor and the degassing membrane, thus, lowering overall energy demand. Gas
1605 microturbines or combined heat and power generators are commonly used for this (Garrido-Baserba et al.,
1606 2022). Generator efficiencies around 40% are typical for electricity conversion to the grid. However, as
1607 this UASB operates with high organic matter loads and subsequently has substantial heat demands, there
1608 is no energy surplus from biogas. Instead, all energy generated is used as heat after combustion.

1609 *7.4.1.6 Quantifying Energy Needs and Biogas Output*

1610 We can calculate the percentage of the anaerobic system's total energy demand covered by biogas by
1611 looking at reactor operation consumption and methane production.

1612 **UASB Energy Demand:** This primarily involves pre-heating influent to the 35°C operating temperature
1613 required for digesting high-loaded BrW, including food waste. We assume a specific heat (W) of 4.2 kJ*kg-
1614 1 (Adami et al., 2020; de Graaff, 2010; Metcalf and Eddy, 2013) and an 80% reactor heating efficiency
1615 (Metcalf and Eddy, 2013). Using Eq. 2, annual energy for preparing influent is calculated as 38,200 kWh.

1616 **Biogas Production:** Thanks to the OFMSW in the feed, this UASB achieves a 60% COD-methane
1617 conversion rate operating at a 10.55 kg CODm-3day-1 OLR. This significantly exceeds the typical 40-50%
1618 achieved with BW digestion alone (Gao et al., 2020; Kujawa-Roeleveld et al., 2005; Vinardell et al., 2020;
1619 J. Zhang et al.,

1620

1621 7.5 UASB – Design and Costs

1622 UASB units were sized according to the calculated HRT and operation flow, with assumed removal
 1623 efficiencies were those of 78% COD, 100% BOD, 9% TN, 39% TP, 93% TSS and 95% VSS (De Graaff et
 1624 al., 2010).

1625 The calculations to size the UASB reactor, find its biogas production and solve its energy balance were the
 1626 following (an example of the procedure is given for the MHR building; the same steps were repeated for all
 1627 buildings):

1628 7.5.1 Calculation of the BW flow

$$5 \frac{L}{PE * day} * \frac{120 ppl}{building} = 600 \frac{L}{building * day} = 0.6 \frac{m^3}{building * day} \quad Eq. 1$$

1629

1630 7.5.2 Estimation of the UASB's effluent flow

1631 The effluent from the UASB is estimated by using literature COD concentrations and removal efficiencies
 1632 (de Graaff et al., 2010).

1633 COD in influent: $9800 \text{ mg/L} = g/m^3$

1634 COD in effluent: $2400 \text{ mg/L} = g/m^3$

$$0.6 \frac{m^3}{day} * 9800 \frac{g}{m^3} = 5880 \frac{g COD}{day} \quad Eq. 2$$

$$5880 \frac{g COD}{day} * (1 - 0.78) = 1293,6 \frac{g COD}{day} \quad Eq. 3$$

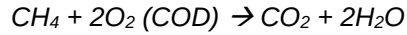
$$\frac{1293,6 \frac{g COD}{day}}{2400 \frac{g}{m^3}} = 0.539 \frac{m^3}{day} \quad Eq. 4$$

1635 The remaining flow corresponds to the produced sludge: $0.6 - 0.539 = 0.061 \text{ m}^3/day$

1636 7.5.3 Calculation of the biogas production

1637 Biogas production is calculated from COD removal knowing $1g \text{ DQO} = 0.35 \text{ L CH}_4$ in STP. A conversion of
 1638 49% of total COD into methane is taken (de Graaff et al., 2010; Metcalf and Eddy, 2013).

1639 However, since biogas is obtained at 1 atm and 25°C, the data must be adapted to this temperature. Eq. 5
 1640 shows the reaction between methane and oxygen.



1641 Thus,
Eq. 5

1642 knowing that 24.45 L of methane at 25°C (298.15 K) equivaile to one mole of methane (ideal gas law), the
1643 litres of methane obtained per gram of COD can be calculated through Eq. 6:

$$24.25 \frac{L CH_4}{mole CH_4} * \frac{mole CH_4}{2 moles COD} * \frac{1 mole COD}{32 g COD} = 0.382 \frac{L CH_4}{g COD}$$

Eq. 6
1644 Finally,
1645 since

1646 78% of biogas is CH₄:

$$6336 \frac{g COD}{day} * 0.49 = 3104.64 \frac{g COD eliminated}{day}$$

Eq. 7

$$3104.64 \frac{g COD}{day} * 0.38 \frac{L CH_4}{g COD} = 1185.97 \frac{L CH_4}{day}$$

Eq. 8

$$\frac{1185.97}{0.78} = 1520.48 L \frac{biogas}{day}$$

Eq. 9

1647 7.5.4 Energy balance

1648 The used data were the following (de Graaff et al., 2010; Metcalf and Eddy, 2013):

- 1649 • Density of BW: 1,020 kg/m³
- 1650 • Specific heat capacity BW: 4.2 KJ/kg °C
- 1651 • Heat of combustion CH₄: 38,846 KJ/m³
- 1652 • Operation temperature: 25°C
- 1653 • BW temperature: 20°C
- 1654 • Efficiency: 0.8

1655 The energy consumption, energy from biogas and remaining energy are calculated as follows. The
1656 produced biogas is used to supply the necessary energy in the reactor.

$$0.6 \frac{m^3}{day} * 1020 \frac{kg}{m^3} * 4.2 \frac{KJ}{kg^\circ C} * (25 - 20)^\circ C = 12,85 \frac{KJ}{day}$$

Eq. 10

$$thus, \frac{12852}{0.8} = 16065 \frac{KJ}{day}$$

1657 a. Consumption

1658

1659

$$16065 \frac{KJ}{day} * \frac{1 day}{3600s} * 365 days = 1628.81 \frac{KWh}{yr}$$

Eq. 11

1660

b. Biogas

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \rightarrow \frac{1.18}{298.15} = \frac{V_2}{273.15} \rightarrow V_2 = 1.09 \frac{m^3 CH_4}{day} STP \quad Eq. 12$$

$$1.09 \frac{m^3 CH_4}{day} STP * 38,846 \frac{KJ}{m^3} = 42,225.6 \frac{KJ}{day} \quad Eq. 13$$

$$42,225.6 \frac{KJ}{day} * \frac{1 day}{3600s} * 365 days = 4281.2 \frac{KWh}{yr} \quad Eq. 14$$

1661

c. Balance

$$4281.2 - 1628.8 = 2652.4 \frac{KWh}{yr} \quad Eq. 15$$

1662 7.5.5 Remaining biogas

1663 The surplus biogas which can be sold to obtain benefits is also calculated as production per year which is
1664 not consumed by the same UASB:

$$2652.39 \frac{KWh}{yr} * \frac{3600 s}{1 h} * \frac{1 m^3 CH_4 STP}{38,846 KJ} = 245.8 \frac{m^3 CH_4 STP}{yr} \quad Eq. 16$$

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \rightarrow \frac{245.8}{273.2} = \frac{V_2}{298.2} \rightarrow V_2 = 268.3 \frac{m^3 CH_4}{yr} \quad Eq. 17$$

$$\frac{268.3 \frac{m^3 CH_4}{yr}}{0.78} = 343.6 \frac{m^3 biogas}{yr} \quad Eq. 18$$

1665 7.5.6 Reactor volume

1666 The volume of the reactor is calculated from its hydraulic residence time using *Eq. 19* and *Eq. 20*, where
1667 UASB_{volume} is the reactor's volume [m³], HRT is the hydraulic retention time [hours], and the flow rate must
1668 be in m³/h.

1669 The rest of design parameters can be found in

1670

1671

1672

1673

1674 Table S7-6.

$$UASB_{volume} = HRT * Flow\ rate \quad Eq. 19$$

$$HRT = \left(C * \frac{SS}{X} \right) * R * (1 - H) * SRT \quad Eq. 20$$

Table S7-6: Design parameters for the UASB reactor.

UASB reactor		Units	Value
Solids retention time	SRT	days	75.00
Hydrolysis level	H	-	0.49
SS influent	SS	g/l	0.65
Total DQO influent	C	g/l	10.56
Sludge concentration	X	g COD/l	34.20
Fraction of eliminated solids	R	-	0.93
Hydraulic retention time	HRT	days	7.16

The obtained volumes are the following:

Table S7-7: Volumes of UASB reactors (V1).

UASB reactor	Units	LR	ST	MR	MHR	HR
Volume	m³	0.43	0.43	2.15	4.29	10.73

Data on energy consumption and biogas production for all building types is shown in Table S7-8.

Table S7-8: UASB energy consumption and biogas production (V1).

	LR	ST	MR	MHR	HR
L biogas/day 25°C	152.05	152.05	760.24	1520.48	3801.19
Energy consumption (kWh/yr)	162.88	162.88	814.41	1628.81	4072.03
Energy from biogas (kWh/yr)	427.93	427.93	2139.67	4279.35	10698.37
Net energy production	265.05	265.05	1325.27	2650.54	6626.34
m³ CH₄/day STP	0.11	0.11	0.54	1.09	2.72
m³ CH₄/yr STP	39.66	39.66	198.29	396.58	991.46
Remaining m³ CH₄/yr STP	24.56	24.56	122.82	245.63	614.09
Remaining m³ biogas/yr 25°C	34.37	34.37	171.87	343.74	859.35

7.5.7 CAPEX and OPEX

As for the UASB's CAPEX and OPEX, they are obtained through data from simulation software CapdetWorks. Table S7-9 shows the final costs for all types of buildings.

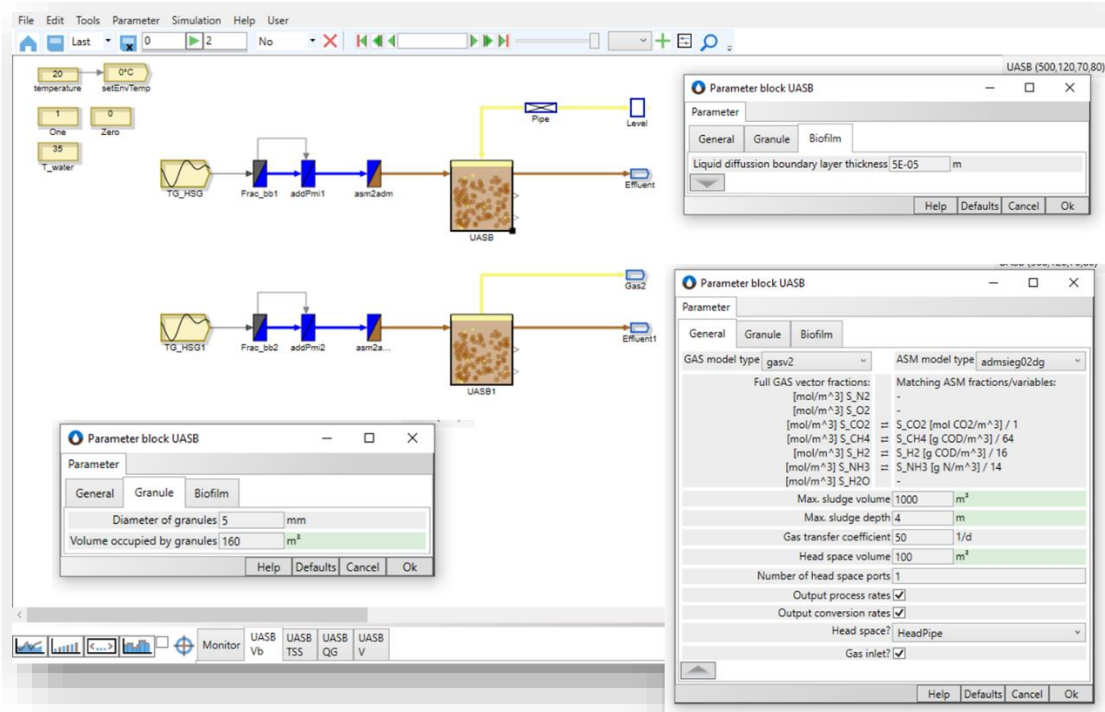
Table S7-9: Total CAPEX and OPEX for the UASB reactors (V1).

	Construction costs (\$)	Other construction costs (\$)	Total CAPEX (\$)	Labour costs (\$/yr)	Energy and material costs (\$/yr)	Total OPEX (\$/yr)
LR	801.00	2540.00	3341.00	123.00	10.82	133.82
ST	801.00	2540.00	3341.00	123.00	10.82	133.82
MR	4005.00	12700.00	16705.00	615.00	54.10	669.10
MHR	8010.00	25400.00	33410.00	1230.00	108.20	1338.20
HR	20025.00	63500.00	83525.00	3075.00	270.50	3345.50

7.6 Brown Water - Modelling

The models were built following the recommendations of the IWA Guidelines for Using Activated Sludge Models 145 using the advanced modelling platform SIMBA# [v4.2]. All the models were designed with an energy-producing anaerobic co-digestion process as the main biological treatment with the influent flows derived from a source separation approach (i.e., organic waste and brown, yellow, and grey water) instead of using energy-intensive conventional aeration-based treatment (i.e., activated sludge), which do not follow a source separation approach. The developed models for the mainstream process were built on an adapted biokinetic model based on the ADM1 (Anaerobic Digestion Model) of the International Water Association. The adapted models were specifically built to allow the consideration of adding additional substrates (e.g., food waste) to the brown and black water streams. The model was modified to consider pH changes by using a specific algebraic equation solver.

Table S7-10: Design parameters for the UASB reactor.



1705

1706

Block UASB

Block of type xasmLib.biofilm_ag, Assembly= xasmLib.dll, Class= xasmLib.biofilm_ag, subtype= gasv2|admsieg02dg

Gas phase (head space)

Cont. state	Value	Unit	Description
S_N2(h)	-9.051e-14	-	Dinitrogen
S_O2(h)	-2.437e-14	-	Oxygen
S_CO2(h)	0.3189	-	Carbone dioxide
S_CH4(h)	0.6799	-	Methane
S_H2(h)	3.917e-06	-	Hydrogen
S_NH3(h)	1.228e-06	-	Ammonia
S_H2O(h)	0.001197	-	Water vapour
theta(h)	35	°C	Temperature
Vg(h)	79.59 (88.65)	Nm³3 (m³3)	Volume gas

Gas phase (bubbles)

Cont. state	Value	Unit	Description
S_N2(b)	-6.045e-08	-	Dinitrogen
S_O2(b)	-1.627e-08	-	Oxygen
S_CO2(b)	0.3245	-	Carbone dioxide
S_CH4(b)	0.6743	-	Methane
S_H2(b)	4.123e-06	-	Hydrogen
S_NH3(b)	1.149e-06	-	Ammonia
S_H2O(b)	0.001173	-	Water vapour
theta(b)	35	°C	Temperature
GTR(b)	50	1/d	Gas transfer rate
Vg(b)	0.3888 (0.3655)	Nm³3 (m³3)	Volume gas

Sludge and biofilm phases

Cont. state	B3	B2	B1	Bulk	Diff: kg/d	Unit	Description
S_H	0.00043141	0.00043002	0.00042757	0.00042731	-0.0003266	mol/m³3	Protons
S_H2	7.1453e-05	0.00015546	0.00018334	0.00017906	-0.005331	g COD/m³3	Dissolved hydrogen
S_CH4	197.04	173.25	141.48	138.24	-3453	g COD/m³3	Dissolved methane
S_CO2	11.441	11.248	10.886	10.849	-39.16	mol CO2/m³3	Dissolved carbon dioxide 15
S_HCO3	18.119	18	17.93	17.922	-8.254	mol HCO3/m³3	Bicarbonate
S_NH4	294.66	293.99	292.67	292.53	-147.1	g N/m³3	Ammonium
S_NH3	0.68627	0.68777	0.69049	0.6908	0.323	g N/m³3	Free ammonia
S_AC	50.583	60.265	54.405	53.84	-200.9	g COD/m³3	Acetate
S_HAC	0.91789	1.0481	0.93721	0.92561	-4.13	g COD/m³3	Acetic acid
S_PRO	8.2002	12.952	11.849	11.743	-37.86	g COD/m³3	Propionate
S_HPRO	0.20323	0.28994	0.2682	0.2656	-0.9261	g COD/m³3	Propionic acid
S_AA	13.977	29.957	64.904	68.419	1251	g COD/m³3	Amino acids
S_SU	14.322	33.704	78.149	82.658	1605	g COD/m³3	Sugars
S_FA	328.03	340.72	356.33	357.99	590.9	g COD/m³3	Long chain fatty acids
S_I	523.06	521.47	518.94	518.63	-110.1	g COD/m³3	Inert soluble matter
X_S	28105	6670	0.58147	1.6026e-05	-0.000345	g COD/m³3	Biodegradable particulate organic matter
X_D	25231	16332	1055.2	42.239	-0.601	g COD/m³3	Desintegrable particulate organic matter
X_BAA	2549.7	1357.4	0.12778	3.6331e-06	-7.581e-05	g COD/m³3	Amino acids fermenting biomass
X_BSU	2048.3	1328	0.12632	3.6078e-06	-7.494e-05	g COD/m³3	Sugar fermenting biomass
X_BFA	6046.3	1440.2	0.1256	3.4622e-06	-7.451e-05	g COD/m³3	Long chain fatty acids oxidising biomass
X_BPRO	4648	1152.7	0.10046	2.7685e-06	-5.96e-05	g COD/m³3	Biomass transforming propionate into acetate
X_BAC	6352.6	1546.2	0.13476	3.714e-06	-7.995e-05	g COD/m³3	Biomass undergoing acetotrophic methanogenesis
X_BH2	3137.3	854.52	0.074936	2.0697e-06	-4.446e-05	g COD/m³3	Biomass undergoing hydrogenotrophic methanogenesis
X_I	2.3456e+05	58656	242.58	9.1897	-0.1385	g COD/m³3	Inert particulate matter
X_MI	58558	18721	422.51	15.771	-0.2413	g/m³3	Particulate mineralic fration
T	35.01	35.01	35.01	35.002		°C	Temperature

1710 Table S7-12: Parameters, design and another key modelling aspects of the UASB reactor.

Info	Value	Unit	Description
A	1.92e+05	m ²	Biofilm base surface area per reactor (A)
Aextra	0	m ²	Biofilm extra surface area for diffusion per reactor (Aextra)
A_Vreactor	192	m ² /m ³	Biofilm base surface area per volume of reactor (A/Vreactor)
A_Aextra_Vreactor	192	m ² /m ³	Total biofilm base surface per reactor volume ((A+Aextra)/Vreactor)
TSbf	3e+05	g/m ³	Total solids concentration in biofilm (TSbf)
Vbiof	197.9	m ³	Volume of biofilm (Vbiof)
R	1.031	mm	Actual biofilm thickness (R)
LTSStot	2.583e+04	kg	Biofilm mass (LTSStot)
LTss	49.36	kg	Suspended mass (LTss)
Tss	60.68	g/m ³	Total suspended solids concentration (Tss)
Tss_tot	2.588e+04	g/m ³	Total solids concentration (suspended and attached, (Mass/Liquide Volume), Tss_tot)
LTss_A	134.8	g/m ²	Total solids mass per total biofilm surface area (LTss_A)
BSRT	397.1	d	Biofilm reactor solids SRT (SRT)
TSRT	397.8	d	Total reactor solids SRT (SRT)
R_Att	6.068	g/m ² /d	Solids attachment rate (R_Att)
R_Det	-7.736	g/m ² /d	Solids detachment rate (last biofilm layer) (R_Det)
fVI	0	%	Reactor media fill fraction (fVI)
V_tot	1011	m ³	Recent total volume (V_tot)
V_bulk	813.4	m ³	Bulk liquid volume (V_bulk)
Vi	0	m ³	Volume displaced by media (Vi)

1711

1712

1713 Table S7-13: Parameters, design, and another key modelling aspects of the UASB reactor.

1714

Parameter	Value	Unit
GAS model type (GASModel)	gasv2	
ASM model type (ASMModel)	admsieg02dg	
Full GAS vector fractions:	GPL	
[mol/m ³] S_N2		
[mol/m ³] S_O2		
[mol/m ³] S_CO2		
[mol/m ³] S_CH4		
[mol/m ³] S_H2		
[mol/m ³] S_NH3		
[mol/m ³] S_H2O (GPL)		
	GPM	
(GPM)		
Matching ASM fractions/variables:	GPR	
-		
-		
S_CO2 [mol CO2/m ³] / 1		
S_CH4 [g COD/m ³] / 84		
S_H2 [g COD/m ³] / 16		
S_NH3 [g N/m ³] / 14		
- (GPR)		
Max. sludge volume (V)	1000	m ³
Max. sludge depth (h)	4	m
Gas transfer coefficient (kLa)	50	1/d
Head space volume (Vh)	100	m ³
Number of head space ports (nhp)	1	-
Excess pressure (pset)	2	mbar
Elevation above sea level (hgeo)	0	m
Output process rates (PRI)	False	
Output conversion rates (CRI)	False	
Diameter of granules (D_G)	5	mm
Volume occupied by granules (V_G)	160	m ³
Liquid diffusion boundary layer thickness (Rd)	5E-05	m
Thickness of minimum water layer (RWL)	0.0001	m
Fraction of biofilm volume that is water (<1) (epsL)	0.7	-
Density of particulate fraction of biofilm (rho)	1000000	g/m ³
Number of biofilm layers (nlay)	3	-
Diffusion coefficient for soluble matter (if set to 0 in ASM) (D)	2E-05	m ² /d
Diffusion coefficient for particulate matter (if set to 0 in ASM) (Dx)	1E-10	m ² /d
Ratio of Diffusion in biofilm to diffusion in pure water (<1) (fD)	0.7	-
Temperature dependency of diffusion (f_T_D)	0.029	-
Attachment velocity of flocs to biofilm (vAtt)	0.1	m/d
Erosion velocity (vEro)	5E-05	m/d
Artificial erosion/att. velocity for TSS balancing (vEroArt)	0.005	m/d
Erosion velocity exponent (vEroEx)	2	
Head space? (hsp)	HeadPipe	
Gas inlet? (gi)	False	

1715

1716 7.7 Brown Water - LCA

1717 In this wastewater treatment system, electricity consumption is the primary source of
1718 environmental impact during the operational phase. Here's a breakdown of how electricity is used
1719 and the associated impacts:

- 1720 ▪ **Pre-treatment:** The pre-treatment process (grinding and mixing) requires 4.5 kW of power and
1721 operates twice a day for 3 hours each cycle.
- 1722 ▪ **UASB Reactor:** The UASB reactor partially offsets its energy needs by recovering biogas that's
1723 used to cover roughly 51% of its energy consumption. The remaining electricity demand (18,755
1724 kWh*yr⁻¹) must be sourced externally. This reactor also releases methane and carbon dioxide
1725 into the air as byproducts of uncaptured dissolved biogas. Additionally, sodium hypochlorite is
1726 used during the process.
- 1727 ▪ **RBC:** The rotating biological contactor (RBC) draws its power primarily from an electric motor
1728 with an estimated consumption of 0.14 kWh*m⁻³. During operation, the RBC releases nitrous
1729 oxide (N₂O) emissions, but doesn't produce direct CO₂ emissions.
- 1730 ▪ **Struvite Reactor:** This reactor has an energy consumption of 2.2 kWh per kilogram of total
1731 phosphorus removed (kWh*(kg TP)⁻¹). Magnesium hydroxide is a necessary chemical input for
1732 the struvite precipitation process.
- 1733 ▪ **Degassing Membrane:** The degassing membrane consumes relatively low amounts of energy –
1734 about 0.052 kWh per cubic meter of treated effluent.

1735 The system is installed within a building's infrastructure and operates on low voltage.

1736 The hollow fiber membrane contactor (HFMC) uses a vacuum approach, eliminating the need for
1737 sweep gas or solvents.

1738

1739 7.7.1 Brown Water LCA - Construction

1740 The ecoinvent dataset for the construction of an anaerobic digestion plant is taken as the material inventory
1741 reference for the UASB reactor as immobile infrastructure including everything needed for the installation
1742 of the reactor such as sludge and digestion tanks, gasholder, land occupation and land transformation. The
1743 ecoinvent lifespan of 30 years is considered in concordance with references (Herman et al., 2017).

1744 The OLAND reactor consists of a RBC made of a PVC tank of 1,5 cm wall thickness and 2 mm thick PE
1745 rotating submerged by 45%. A lifespan of 10 years for the total reactor is considered (Mohammed and Sills,
1746 2022). Tank dimensions are assumed to be 0.7x0.7x0.7 m to obtain a total volume of 343 L sized according
1747 to influent nitrogen load through Eq. 1 and Eq. 2, where BFS is the biofilm surface in the reactor in m².
1748 Influent is the concentration of total nitrogen in the influent in kg/day, and N_{surface} load and A_{carrier} are
1749 design parameter which take values of 0.015 kg N/m²day and 350 m²/m³ (Roefs et al., 2017).

$$BFS = \frac{N_{influent}}{N_{surface\ load}} \quad Eq. 1$$

$$V_{reactor} = \frac{BFS}{S_{carrier\ material}} \quad Eq. 2$$

1750

1751 Rotating is achieved with an electric motor of 0.75 kW sized according to required rotation velocity and a
1752 stainless-steel shaft (lifespan of 15 years is considered for steel components in the OLAND reactor).

1753 The struvite precipitation process is composed solely of a reactor and crystallizer and has an estimated
1754 lifespan of 30 years (Kjerstadius et al., 2017). These are made of stainless steel, due to the capacity of this
1755 material to resist pH variations. Accessories including the chemical dosing tank are made of PVC (Bisinella
1756 de Faria et al., 2015; Igos et al., 2017; Kjerstadius et al., 2017; Mbaya et al., 2017; Sena and Hicks, 2018).
1757 Reactor height is 4.35 m and wider diameter is 1.09 m (maintaining a diameter:height ratio of 1:4 for optimal
1758 precipitation). Decanter height and diameter are 0.05 m and 2.18 m, respectively, and wall thickness is
1759 assumed to be 1 cm for the calculation of material requirements.

1760 Total volumes are 640 L and 180 L sized though Eq. 3 assuming a retention time (RT) of 3.5 hours for
1761 struvite precipitation in the reactor and 1 hour in the decanter, respectively (Tarragó et al., 2016).

$$V = Influent\ flow * RT * \frac{1\ day}{24\ h} \quad Eq. 3$$

1762

1763

1764 The decanter height:diameter correlation is obtained from Stroke's law by calculating the terminal particle
1765 diameter of precipitated struvite particles using Eq. 4, Eq. 5, and Eq. 6 assuming all particles with diameters

1766 <0.5*dp are recirculated. Ascensional velocity (vasc) in the reactor is calculated from its diameter and flow,
 1767 viscosity (μ), and solid (ps) and liquid (pl) densities take values of 7.978E-4 kg*m-1*s-1, 1700 kg/m3, and
 1768 995.65 kg/m3, respectively. Gravity (g) is 9.81 m*s2.

$$d_p = \left(\frac{v_{asc} * 18 * \mu}{g * (\rho_s - \rho_l)} \right)^{\frac{1}{2}} \quad Eq. 4$$

$$u_T = \frac{1}{18} * \frac{\left(\frac{d_p}{2} \right)^2 * g * (\rho_s - \rho_l)}{\mu} \quad Eq. 5$$

$$h_{reactor} = v_{asc} * RT \quad Eq. 6$$

1769

1770 Pre-treatment of organic waste involving grinding and mixing requires a steel mixing tank with a 3.5 kW
 1771 motor for grinding and a 1 kW motor for mixing with BrW. Tank size is 3 m3 considering treatment of influent
 1772 in two daily batches and wall thickness is 1.2 cm is assumed. Total life span of the pre-treatment equipment
 1773 is 15 years, except for the motor in charge of grinding, which is expected to last 7 years due to higher
 1774 stress.

1775

1776 Table S7-14: Inventory details for the construction of the treatments and processes included in the BrW line. Tables in
 1777 the construction inventory refer to the total amount of materials of components needed to build the decentralized system
 1778 for the water treatment for the reference population of 300 people.

Element	Amount	Unit	Material	Life span (years)	Ecoinvent dataset	
UASB reactor	0.01	unit	-	30	anaerobic digestion plant construction, for sewage sludge	GLO
OLAND reactor, tank	48.90	kg	PVC	10	market for polyvinylchloride, suspension polymerised	GLO
OLAND reactor, disks	206.00	kg	PE	10	market for polyethylene, high density, granulate	GLO
OLAND reactor, motor	9.00	kg	-	10	market for electric motor	GLO
OLAND reactor, shaft	2.33	kg	Steel	30	market for steel, low-alloyed	GLO
Struvite reactor, steel	186.00	kg	Stainless steel	30	market for steel, chromium steel 18/8	GLO
Struvite decanter, steel	26.11	kg	Stainless steel	30	market for steel, chromium steel 18/8	GLO
Struvite reactor and decanter, PVC	66.00	kg	PVC	30	market for polyvinylchloride, suspension polymerised	GLO
Pre-treatment, grinding	12.50	kg	-	7	market for electric motor	GLO
Pre-treatment, mixing	10.00	kg	-	15	market for electric motor	GLO
Pre-treatment, tank	150.00	kg	Stainless steel	30	market for steel, chromium steel 18/8	GLO
HFMC, membrane	0.13	kg	PDMS	7	market for polydimethylsiloxane	GLO
HFMC, pump	0.4	unit		18	market for pump, 40W	GLO
HFMC, shell and caps	0.03	kg	Polycarbonate	7	market for polycarbonate	GLO
HFMC, potting	0.02	kg	Polycarbonate	7	market for polycarbonate	GLO

1779
 1780

7.7.1 Brown Water LCA - Operation

Electricity consumption is the main source of impacts during the operation phase. As the installation is in buildings, low voltage is assumed. Pre-treatment has a total power of 4.5 kW and is expected to be in operation twice daily during a grinding and mixing time of 3 hours (Chowaniec and Fryzlewicz, 2014). In the UASB reactor, energy from biogas (not including sludge digestion to focus on the self-sufficiency capacity of the on-site treatment train) is accounted for as a recovered resource employed to cover 51% of consumption of the own reactor. An additional 18,755 kWh*yr⁻¹ still need to be provided (see the Resource recovery section in the main document). Regarding the RBC, power consumption originates mainly from the motor and is estimated at 0.14 kWh*m⁻³ (Irfan et al., 2022). The struvite reactor's energy consumption is 2.2 kWh*(kg TP)⁻¹ (Ostara Nutrient Recovery Technologies Inc., Vancouver, Canada), while the decanter has no consumption. Finally, the degassing membrane uses 0.052 kWh per m³ of treated effluent as calculated in the Resource recovery section of the main document.

Additional operational exchanges for the UASB are the methane and carbon dioxide emissions to air originating from uncaptured dissolved biogas in the effluent, and 3E-02 kg*m⁻³ of sodium hypochlorite (Boldrin et al., 2022; do Amaral et al., 2018; Isola et al., 2018). The RBC causes N₂O emissions estimated at 1.72 kg*yr⁻¹ calculated considering an emission factor of 0,36% of influent nitrogen; and no direct CO₂ emissions (Hauck et al., 2016; Joss et al., 2009; Vineyard et al., 2021). In the struvite reactor, addition of magnesium is required. Consumption of Mg(OH) is calculated from input moles of TP and TN and a 1.5 Mg²⁺:PO₄³⁻ molar ratio (Siciliano et al., 2020). The HFMC is operated with vacuum since it is the recommended approach with non-porous membranes (Crone et al., 2016); therefore, no sweep gas or solvent is needed.

1803

1804 *Table S7-15: Inventory details for the annual operation of the brown water line (FU: water treatment for 300 people*
 1805 *during a year).*

1806

Element	Amount	Unit	Ecoinvent dataset	
Pre-treatment, electricity	9,720.00	kWh	market group for electricity, low voltage	RER
UASB reactor, electricity	18,755.04	kWh	market group for electricity, low voltage	RER
UASB reactor, CH ₄ emissions to air	148.00	kg	Methane, from soil or biomass stock, emissions to air	-
UASB reactor, CO ₂ emissions to air	6.56	kg	Carbon dioxide, fossil, emissions to air	-
UASB, sodium hypochlorite	50.75	kg	market for sodium hypochlorite, without water, in 15% solution state	RER
RBC, electricity	225.01	kWh	market group for electricity, low voltage	RER
RBC, N ₂ O emissions to air	1.72	kg	Dinitrogen monoxide, emissions to air	-
Struvite reactor, electricity	118.00	kWh	market group for electricity, low voltage	RER
Struvite reactor, magnesium	76.74	kg	market for magnesium	GLO
HFC, electricity	84.67	kWh	market group for electricity, low voltage	RER

1807

1808

7.8 anMBR [Not included in the current study]

Although anMBR technology is not directly referenced in the current study, we have included this supplementary techno-economic assessment based on this technology, as the techno-economic assessment carried out for the smaller urban development had include the technology. This decision highlights our commitment to investigating a wide range of process flow diagrams and our openness to supporting diverse technological solutions.

Alternative configurations were considered in which anMBRs were employed. These systems provide the advantages of anaerobic wastewater treatment (e.g., production of biogas, lower energy consumption, and less excess sludge production) while overcoming the technology's main challenge of inferior organic carbon removal (Foglia et al., 2020; Guo et al., 2016; Li et al., 2020; Lin et al., 2013; Muñoz Sierra et al., 2019). The combination of membrane technology and anaerobic treatment allows for the decoupling of HRT from SRT, which helps lower overall costs while continuing to provide adequate treatment with shorter HRTs (Ariunbaatar et al., 2021; Foglia et al., 2020; Ribera-Pi et al., 2020; van den Berg et al., 2020). anMBRs modeled in this study were sized according to their HRT. The low-strength wastewater (i.e., graywater) could be successfully treated using anMBR technology (Gouveia et al., 2015; Martin Garcia et al., 2013; Shin et al., 2014; Wang et al., 2018b, 2018a). It must to be noted, that as anMBRs achieve a high solids separation, the clogging of the pores is not expected to be major concern (Membrana, Wuppertal, Germany); microporous contactors designed for low flow rates (instead than non-porous membranes) appear to be the best approaches for higher methane recovery yields.

7.8.1 Reactor volume and membrane area

In the scenarios where a anMBR is incorporated, the anaerobic reactor volume is calculated from its hydraulic residence time assuming a frequently used value for the treatment of wastewater of 8h (Ariunbaatar et al., 2021; Foglia et al., 2020; Gouveia et al., 2015; Ribera-Pi et al., 2020; Shin et al., 2014; Shoener et al., 2016; Wang et al., 2018a, 2018b) using Eq. 21. The parameters in the equation are the reactor's volume $anMBR_{volume}$ [m³], the hydraulic retention time HRT [hours], and the flow rate [m³/h].

The membrane area is found following the same methodology as for the MBR. The obtained volumes and membrane areas for the variation of the vacuum scenario are shown in Table S7-16.

$$anMBR_{volume} = HRT * Flow\ rate$$

1837
Eq. 21
1838

1840

1841 *Table S7-16: Volumes of anMBR reactors (V2).*

UASB reactor	Units	LR	ST	MR	MHR	HR
Volume	m³	0.45	0.45	2.26	4.52	11.3
Membrane area	m²	56.5	56.5	282.5	565.0	1412.5

1842 *7.8.2 Biogas production*

1843 Biogas production is calculated assuming the production of 0.125 L CH₄ per kg of COD removed
 1844 (Ariunbaatar et al., 2021), and a methane content of 78%. The same calculations described in the UASB
 1845 section are performed to convert the L of CH₄ in STP to m³ of biogas obtained per day at 25°C.

1846 Energy consumption in the anMBR system is considered to be 0.49 kWh/m³ (Pretel et al., 2014). The net
 1847 biogas volume obtained is also calculated according to the procedure described in the UASB section. All
 1848 anMBRs for all scenarios where they are involved prove energy sufficient.

1849 *7.8.3 Sludge production*

1850 Sludge production in anMBRs is calculated from the COD content of the influent of the system, assuming
 1851 0.035 kg MLVSS/kg COD removed (Lin et al., 2011).

1852

1853

1854 7.8.4 CAPEX and OPEX

1855 The capital expenses related to the anMBR are estimated based on an inventory of components as done
 1856 with the MBR. The costs are calculated for each scenario based on flowrates and pollutant concentrations
 1857 for each building and scenario.

1858 Bioreactor costs are adapted from *Lin et al., 2011* and *Verrecht et al., 2010* considering the tanks in this
 1859 study are small-scale, thus a base of 1000 \$ is added to the original price of 236.38\$/m³ (Fletcher et al.,
 1860 2007). Membrane and air diffuser costs are taken from *Lin et al., 2011* and *Verrecht et al., 2010* as 50 \$/m².
 1861 Valves, pumps, and tanks prices are provided by suppliers (see MBR section). The price of the membrane
 1862 screen is taken from Fletcher et al., 2007.

1863 *Table S7-17: Breakdown of included elements in the anMBR obtained from supplier data collection (example for MHR*
 1864 *buildings, V2).*

MHR MBR (\$)	\$		\$
Bioreactor	2,068.43	Membranes	565
Gas diffusers	15	Valves	62.50
Gas blowers	160	Tanks	
Pumps		<i>Raw water and equalization tank</i>	1,863
<i>Pump for sludge recycling</i>	220	<i>Treated water tank</i>	1,842
<i>Permeate pump</i>	1100	<i>Cleaning chemicals tank</i>	108.09
<i>Chemical addition pumps</i>	356	<i>Sludge tank</i>	282
<i>Sludge purge pump</i>	220	MT membrane screen (0.5 mm)	1000
TOTAL (\$)	9,862.84		

1865 The OPEX are calculated assuming a cost of 0.06\$/m³ (Lema and Martinez, 2017; Pretel et al., 2014). The
 1866 total CAPEX and annual OPEX are shown in Table S7-18 for the scenario with vacuum toilets.

1867 *Table S7-18: CAPEX and OPEX of the anMBRs for all building types (V2).*

	CAPEX (\$)	OPEX (\$/yr)
LR	5856.16	29.70
ST	5856.16	29.70
MR	7863.12	148.48
MHR	9862.84	296.96
HR	14150.99	742.41

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8 Nitrogen Removal

8.1 Nitrogen removal: oxygen limited autotrophic nitrification/denitrification (OLAND) process.

The removal of nitrogen was assumed to take place in a single stage OLAND process, suitable for wastewater with high loads of organic matter in decentralized, small-scale treatment systems (Larsen et al., 2013; Lv et al., 2011; Nhu Hien et al., 2017; Windey et al., 2005). Nitrate production during the OLAND process was assumed to be negligible. A single stage OLAND process is installed in series with the UASB reactor to perform nitrogen removal from the brown water stream. Biofilm surface and volume are sized according to the influent nitrogen load..

The Oland process removal efficiencies were assumed as 38% COD, 70% TN, 8% TP and 38% TSS (Clippeleir et al., 2011; Roefs et al., 2016). The required biofilm surface, from which the reactor volumes were obtained, was calculated from the nitrogen load in the influent flow and the nitrogen surface load as follows:

8.1.1 Biofilm surface and volume

The RBC where the OLAND reaction is conducted is sized according to the nitrogen load to be treated. Initially, the biofilm surface required is calculated through Eq. 22.

N influent is the nitrogen load in the influent (the UASB's effluent) in kg/day, while the N surface load is a design parameter.

$$BFS = \frac{N_{influent}}{N_{surface\ load}} \quad Eq. 22$$

The volumes [m³], are then obtained by:

Table S8-1: Design parameters of the Oland - RBC (Roefs et al., 2017).

OLAND - RBC		Units	Value
Surface of the carrier material		m ² /m ³	350
Nitrogen surface load	N _{surface load}	Kg N/m ² day	0.015
Biofilm surface	BFS	m ²	Specific of each building type

$$V = \frac{BFS}{Surface\ of\ carrier\ material} \quad Eq. 23$$

1893 Table S8-2: Estimated performance of the Oland - RBC

OLAND		Influent/Effluent volume total	27758.5	L/day		
Parameters		Influent conditions mg/L (BrW+YW+FW)	Removal efficiency UASB %	Influent (g/day)	Effluent conditions (g/day)	Effluent mg/L
	COD	1065.15	38.00	29566.94	18331.51	660.39
	BOD	0.00		0.00	0.00	0.00
	TN	339.64	70.00	9427.78	2828.33	101.89
	NH4-N (TAN: Total ammonia N, NH3+NH4+)	282.92		7853.34	2356.00	84.88
	TP	55.93	8.00	1552.66	1428.45	51.46
	TSS	355.31	38	9862.86	6114.97	220.29
	VSS	729.72		20255.93	3492.87	125.83
	BFS (m2)	628.52				
	Volume (m3)	1.80				
	CAPEX					
CAPEX total (€)	3,027.66					
OPEX						
OPEX total (€/yr)	5,161.71					

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8.1.2 Energy Requirements

Wett (2006) reported the specific energy demand for a DEMON® SBR without hydrocyclone was approximately 0.8 kWh/kg N removed. Specific energy demand in the range of 0.8 to 1.1 kWh/kg N removed is expected depending on system design, operating conditions, and sidestream characteristics. DEMON® Hybrid Granular and Flocculent Activated Sludge Process [DeAmmon® The DeAmmon® MBBR] process was developed by Purac/Läckeby AB (Sweden) in collaboration with the University of Hannover and the Ruhr River Association (Ruhrverband). An optimized energy consumption rate of 2.3 kWh/kg-N-removed was reported (Christensson et al. 2011).

Table S8-3: Expected Energy Requirements for the Oland - RBC

0.8	kWh/kg-N-removed	14,879	kWh/yr		
1.8	kWh/kg-N-removed	33,478	kWh/yr		
335.28	mg/L		Avg	24,178	kWh/yr
24,798	kg N /year				
18,599	kg N removed				
75	% removal				

Table S8-4: Characteristics of the OLAND reactors

UASB reactor	Units	LR	ST	MR	MHR	HR
BFS	m ²	7.28	7.28	36.40	72.80	182.00
Volume	m ³	0.02	0.03	0.10	0.21	0.52

8.1.3 CAPEX and OPEX

CAPEX of a RBC operating with the OLAND process can be estimated as 1686\$/m³, while OPEX oscillate between 1.5-2.5 \$/kg of N treated. Since the effluent from the UASB is heated, the RBC is expected to have no energy demand and thus the OPEX have been taken as 1.5\$/kg N (Courstens et al., 2014; Lozano et al., 2007).

$$CAPEX = V * 1686$$

$$OPEX = kg \frac{N}{yr} * 1.5$$

Eq. 24 Table
S8-5:
CAPEX

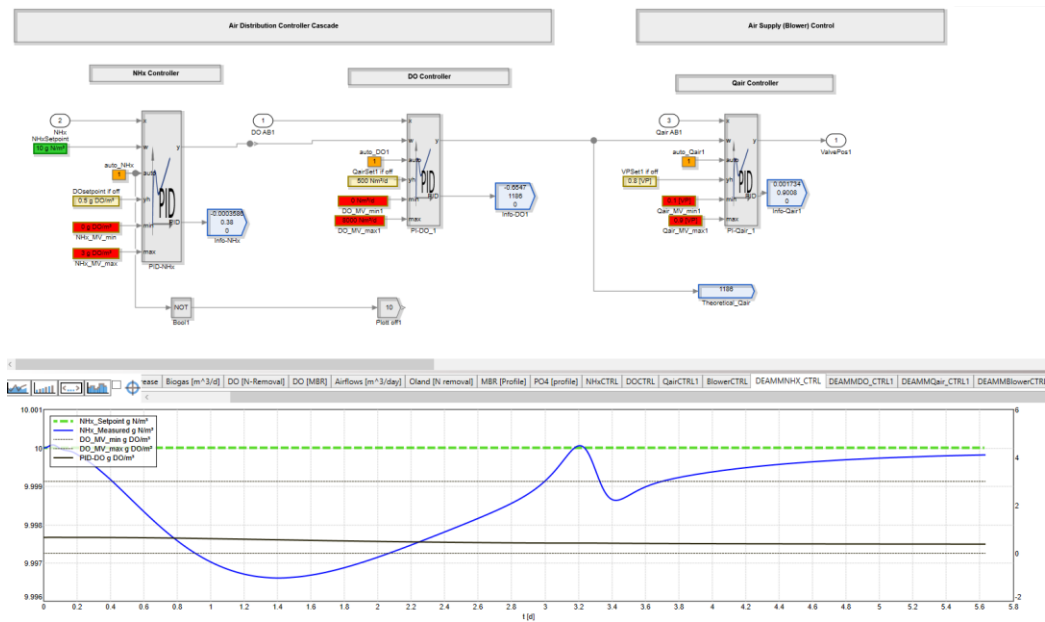
1917 and OPEX of the RBC (V1).

	CAPEX (\$)	OPEX (\$/yr)
<i>LR</i>	35.07	59.79
<i>ST</i>	35.07	59.79
<i>MR</i>	175.34	298.94
<i>MHR</i>	350.69	597.87
<i>HR</i>	876.72	1,494.68

1918

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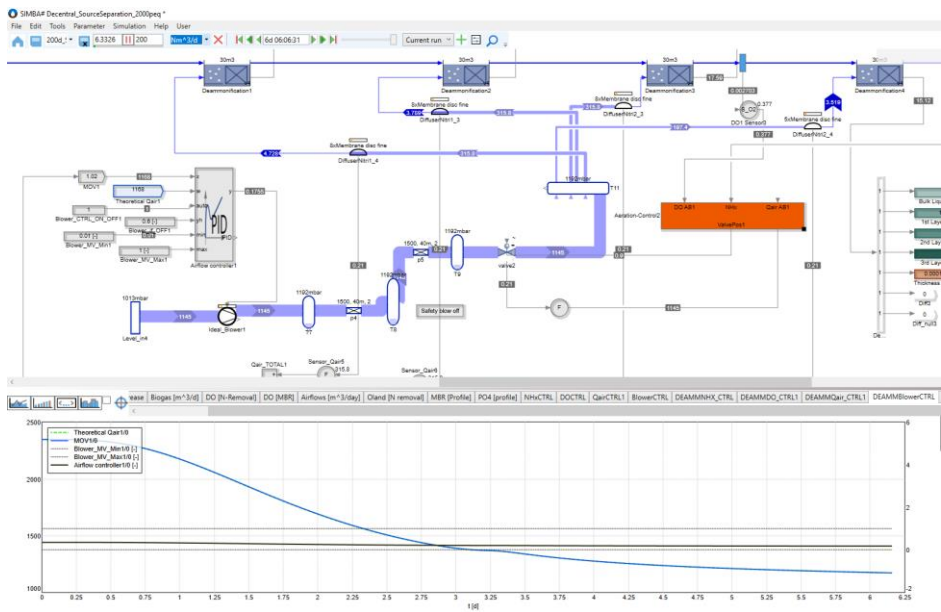
Table S8-7: Aeration control logic for the Deammonification - Oland reactor. The ABAC uses ammonia (NH4+) setpoints to guide aeration. An ammonia setpoint of 10ppm is determined, and the ABAC system continuously adjusts DO levels to maintain that ammonia concentration.



1941
1942

1943

Table S8-8: Aeration demand and blower control for the Deammonification - Oland reactor.



1944
1945

1946 Table S8-9: Parameters, design and key aspects considered in the SIMBA# model for the Deammonification - Oland
 1947 reactor.

Block Deammonification3

Block of type basmLib.asm_biofilmBlock_4, Assembly= basmLib.dll, Class= basmLib.asm_biofilmBlock_4, subtype= inCTRL_ASM

State	Bulk	B1	B2	B3	Diff: kg/d
S_VFA	0.0026625	0.002727	0.0032991	0.0035591	-0.00051723
S_F	0.66895	0.6681	0.66707	0.66638	0.0068449
S_MEOL	2.8746e-23	2.0732e-23	2.0247e-23	2.0156e-23	8.2951e-23
C_B	7.763e-09	5.6095e-09	5.4127e-09	5.3892e-09	4.3286e-09
X_B	0.040062	283.44	1117.1	2235.5	-0.0021255
S_U	139.16	139.16	139.16	139.16	-0.0050057
C_U	5.0021e-09	4.0884e-09	4.0412e-09	4.0357e-09	1.0348e-09
X_U	1.9881	13490	15066	16157	-0.10116
X_PHA	0.0002942	1.1791	0.36326	0.10301	-8.8408e-06
X_E	2.2141	14932	12182	10729	-0.11197
X_OHO	0.26896	1804.4	802.57	443.92	-0.013531
X_MEOLO	2.1386e-08	0.00013656	4.6081e-05	2.0141e-05	-1.0241e-09
X_PAO	0.082483	488.71	90.387	21.366	-0.0036647
X_AOO	0.70558	4756	1080.8	246.01	-0.035665
X_NOO	3.0981e-06	0.019724	0.0045581	0.0011897	-1.479e-07
S_NHx	78.191	77.915	77.887	77.879	3.5749
S_NO2	0.048316	0.033102	0.010311	0.0039413	0.16774
S_NO3	0.19745	0.19781	0.19547	0.19418	-0.0045844
S_N2	206.04	206.35	206.4	206.42	-3.7533
S_N_F	0.30491	0.3052	0.30579	0.30611	-0.0023098
X_N_B	0.0028043	19.841	78.2	156.49	-0.00014878
S_N_U	1.3916	1.3916	1.3916	1.3916	-5.0057e-05
X_N_U	0.13228	898.35	1023.5	1106.9	-0.0067366
S_PO4	37.745	37.747	37.747	37.747	-0.020559
X_PP_LO	0.026241	155.63	26.322	5.7961	-0.001167
X_PP_HI	0.0068343	40.435	7.3387	1.7122	-0.00030321
S_P_F	0.0098987	0.0098873	0.010052	0.010146	9.1551e-05
X_P_B	0.00088135	6.2356	24.577	49.182	-4.676e-05
S_P_U	1.3916	1.3916	1.3916	1.3916	-5.0057e-05
X_P_U	0.012367	83.835	91.531	97.198	-0.00062867
S_O2	0.37602	0.014052	0.0030482	0.0017259	5.8639
X_IG	3.712	9437.9	9440.4	9441.6	-8.7738
X_MeOH	7.8023e-06	0.05299	0.061246	0.066631	-3.9737e-07
X_MeP	0.000496	3.3706	3.8958	4.2384	-2.5276e-05
S_ALK	13.123	13.104	13.104	13.104	0.24493
X_DIG	1.9684e-05	0.08685	0.0041518	0.00020924	-6.5123e-07
S_Ca	109.27	109.27	109.27	109.27	-0.00056315
S_Mg	199.98	199.98	199.98	199.98	-0.0038341
S_K	100.91	100.91	100.91	100.91	-0.0041697
X_CaPO4	0.036138	242.55	200.71	183.06	-0.0018189
X_MgNH4PO4	0.0084269	56.734	51.572	49.9	-0.00042544
X_MgHPO4	0.0029317	19.886	22.007	23.51	-0.00014912
X_MgCO3	0.031522	211.58	175.3	160.06	-0.0015866
X_CaCO3	0.011842	79.629	69.804	66.097	-0.00059713
X_ANAMM OX	11.968	81474	85848	86727	-0.61096
TSS	17.579	1.0349e+05	1.02e+05	1.02e+05	
L_TSS kg	0.45857	41.883	41.282	41.282	
vero m/d	0	1.4564e-05	3.9259e-09	1.8111e-09	

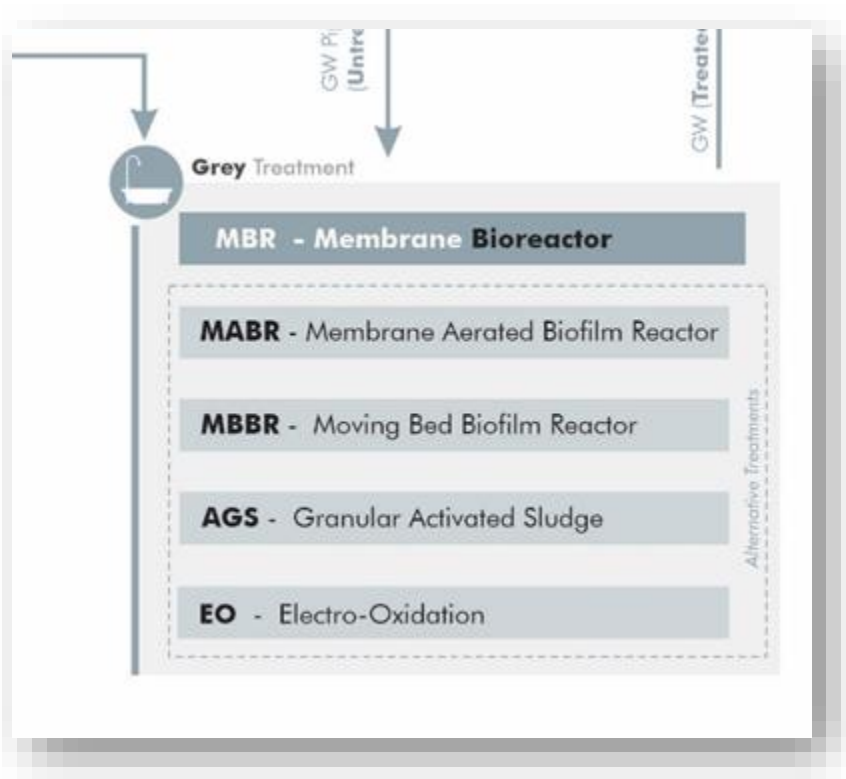
1949 Table S8-10: Parameters, design and key aspects considered in the SIMBA# model for the Deammonificatio - Oland
 1950 reactor.

Biofilm base surface area per reactor (A)	7500 m ²	
Biofilm extra surface area for diffusion per reactor (Aextra)	0 m ²	
Biofilm base surface area per volume of reactor (A/Vreactor)	250 m ² /m ³	
Total biofilm base surface per reactor volume ((A+Aextra)/Vreactor)	250 m ² /m ³	
Total solids concentration in biofilm (TSbf)	102000 g/m ³	
Volume of biofilm (Vbiof)	1.214 m ³	
Actual biofilm thickness (R)	0.182 mm	
Biofilm mass	124.438 kg	
Suspended mass	0.458 kg	
Total suspended solids concentration	17.58 g/m ³	
Total solids concentration (suspended and attached, (Mass/Liquide Volume))	4574.97 g/m ³	
Total solids mass per total biofilm surface area	16.65 g/m ²	
Total solids SRT	235.82 d	
Solids attachment rate	8.79 g/m ² /d	
Solids detachment rate (last biofilm layer)	1.51 g/m ² /d	
Reactor media fill fraction	8 %	
Total liquid volume	27.3 m ³	
Bulk liquid volume	26.09 m ³	
Volume displaced by media	2.7 m ³	

Parameter	Value	Unit
Model type (Model)	inCTRL_ASM	
Reactor volume (V)	30 m ³	
Depth of tank (h)	2 m	
Fraction of inert (carrier media) reactor volume (0..1) (fVI)	0.18*0.5=0.09 -	
Biofilm base surface area per reactor volume (fA/V)	500*0.5=250 m ² /m ³	
Expected biofilm thickness at equilibrium, A*Rref=Vbf0 (Rref)	0.00055 m	
Thickness of water layer (only if constant water volume) (RWL)	0.005 m	
Liquid diffusion boundary layer thickness (Rd)	0.0001 m	
Additional area in outer biofilm layer as fraction of base surface, Aextra=fAextra*A (fAextra)	0 -	
Fraction of biofilm volume that is water (0..1) (epsL)	0.9 -	
Density of particulate fraction of biofilm (rho)	1020000 g/m ³	
Number of biofilm layers (nlay)	3 -	
Diffusion coefficient for soluble matter (if set to 0 in ASM) (D)	0.0000864=8.64 m ² /d E-05	
Diffusion coefficient for particulate matter (if set to 0 in ASM) (Dx)	1e-10=1E-10 m ² /d	
Ratio of Diffusion in biofilm to diffusion in pure water (0-1) (fD)	1 -	
Attachment velocity of flocs to biofilm (vAtt)	0.5 m/d	
Erosion velocity (vEro)	0.001 m/d	
Artificial erosion/att. velocity for TSS balancing (vEroArt)	0.005 m/d	
Erosion velocity exponent vero=vero0 * (R/Rref)^veroEx * uero (vEroEx)	2	
Reactor type (brt)	ReactorVolumefixed	
Aeration thru carrier (instead of bulk) (aerationInnerLayer)	False	
Show reactor volume (showvol)	True	
Calculation method for extra biofilm area (methodA)	ExtraEqual	
Create additional output for x (xOutput)	False	

9 Grey Water

Different technologies meet the criteria to be feasible alternatives to treat the grey water stream. The MBR was selected to represent this study as the main technology for grey water balanced various factors like maturity, cost information availability, case studies, and reliability. MBR offered the most detailed cost data, unavailable for other options yet. This enabled a more robust techno-economic analysis. However, various technologies were modelled and assessed.



9.1 Grey Water Treatment Overview

After accounting for volumetric losses, treated BrW exhibits significantly reduced contaminant levels. Specifically, COD, TN, TP, and TSS concentrations are only 11%, 24%, 21%, and 19% of initial influent values, with BOD reduced to a negligible level. This low volume of processed BrW allows for blending with the GW flow with only minimal changes to GW composition. We observe only slight increases in TN, TSS, and VSS loads. This blended stream feeds the subsequent GW treatment line.

1969 *9.1.1.1 GW Line: MBR for Robust Removal*
1970 A side-stream Membrane Bioreactor (MBR), combining an aerated reactor with a crossflow, multitube,
1971 hollow-fiber membrane loop, serves as the GW treatment core. Aerobic treatment coupled with membrane
1972 filtration is known for excellent environmental performance in small- to medium-scale systems. It provides
1973 high pollutant removal, producing an effluent at near-potable quality. Additionally, MBRs have a smaller
1974 footprint, reduced sludge production (compared to conventional biological treatments), can remove
1975 microorganisms effectively, and their modular design is ideal for decentralized layouts (Cashman et al.,
1976 2018; Cecconet et al., 2019; Kobayashi et al., 2020).

1977 *9.1.1.2 Aerobic Membrane Bioreactors Advantages & Considerations*
1978 Since the MBR is positioned close to the reuse point, its wider removal abilities are key. MBRs outperform
1979 alternatives in eliminating active compounds, microcontaminants, androgenic activity, surfactants, and
1980 emerging contaminants in general. This is due to the membrane filtration and diverse microbial community
1981 (Cecconet et al., 2019). Our design operates with an HRT of 3 days and a volume of 108 m³. These
1982 operational parameters and efficiencies have been validated via SIMBA# modeling.

1983 *9.1.1.3 Trade-offs and Further Treatment*
1984 While MBR treatment ensures effective pollutant removal and flexibility, it raises operational costs
1985 substantially (potentially 30-40% of total operational costs for decentralized setups) (Garrido-Baserba et
1986 al., 2022). Additional disinfection is often needed, especially for reuse, due to possible post-membrane
1987 pathogen regrowth or migration (Cecconet et al., 2019). Membrane maintenance is also required to
1988 address fouling. To ensure compliance with nutrient and microbial regulations, we include RO filtration and
1989 UV disinfection downstream of the MBR.

1990 *9.1.1.4 RO, UV, and Decentralization*
1991 RO primarily targets enhanced phosphorus removal. Membrane technology is vital for decentralized setups
1992 due to its reliability and risk minimization when treating water for reuse (Fane, 2005). Finally, combining RO
1993 with vacuum UV (VUV) disinfection aims for thorough pathogen removal meeting reuse standards (Hube
1994 and Wu, 2021). While less significant, potential COD, TN, TAN, and nitrate removal by VUV is accounted
1995 for in the study (Amanollahi et al., 2021; Piras et al., 2022). This avoids the use of chlorine or ozone for
1996 disinfection.

1997 *9.1.1.5 Configuration of the MBRs*
1998 An HRT of 16.2h and a reactor volume of 164 m³ are calculated. Even if the incorporation of an MBR in the
1999 treatment layout substantially increases operational costs, the inclusion of an aerobic stage ensures
2000 adequate effluent quality. Difficulty of the proposed treatment train to meet phosphorus concentration
2001 guidelines for wastewater reuse is solved by the incorporation of a final stage composed of a flat sheet RO
2002 membrane and a UV filter which also helps damper pathogen risks.

2003 A flat sheet reverse osmosis (RO) membrane (DuPont de Nemours, Inc., Delaware, USA) was assumed
 2004 as a means of meeting current guidelines for phosphorus concentrations in wastewater reuse. The selected
 2005 membrane offered the highest removal efficiency for pollutants (including NH₄-N & P) relative to similar
 2006 models (Van Voorthuizen et al., 2005). The use of the RO membrane improved the final water quality and
 2007 provided another barrier against pathogen exposure in showers, baths, or incidental contact with recycled
 2008 water.

2009 The MBRs were assumed to use a rejection side-stream configuration and included a combination of
 2010 biological treatment in an aeration tank and ultrafiltration in a crossflow, multi-tube membrane loop (e.g.,
 2011 polyethersulphone membranes; Berghoff GmbH, Eningen, Germany) prior to RO. The hydraulic residence
 2012 time in the reactors was assumed to be 15.8 h for scenario V1 and 40 h for scenario C1. The volume of the
 2013 system was calculated using Eq. 57 in the Supplementary material (Fletcher et al., 2007; Wen et al., 1999;
 2014 Xing et al., 2001).

2015

2016 9.2 Design and Costs

2017 9.2.1 Reactor volume and membrane area

2018 The MBR in this study uses a side-stream configuration being composed of a biologic treatment tank and
 2019 a multi-tube membrane loop for crossflow flux. This installation is considered the most adequate for low-
 2020 flow treatment in apartment buildings. The bioreactor and the membranes are sized individually. Two sizing
 2021 procedures are followed for the former, giving similar results. Final reactor volumes are obtained by Eq. 26,
 2022 designed specifically for the sizing of MBR systems (Fletcher et al., 2007; Wen et al., 1999; Xing et al.,
 2023 2001), where V is the reactor volume [m³], Q the influent flow in m³, Θ_x the sludge age [days], X the sludge
 2024 concentration in the aeration tank [mg/l], k_e the substrate degradation rate constant [days⁻¹], C_i the COD
 2025 concentration in the influent and C_e the cod concentration in the effluent [mg/l]. Kinetic parameters and
 2026 average removal efficiencies were obtained from literature for MBR systems (Liu et al., 2005; Lo et al.,
 2027 2015; Wen et al., 1999; Xing et al., 2003). However, the volumes obtained from the sizing of average
 2028 biologic reactors (Eq. 27 and Eq. 28) are compared and used as reference.

$$V = \frac{QY\theta_x(C_i - C_e)}{X(1 + k_e\theta_x) - Y(C_i - C_{sup})}$$

$$HRT = \frac{(BOD_i - BOD_e)}{k_e X * BOD_e}$$

$$V = HRT * Q$$

2029

Eq. 26

2030

2031

2032

Eq. 27

2033

2034

Eq. 28

2035

2036 Design parameters are obtained from literature (Liu et al., 2005; Lo et al., 2015; Wen et al., 1999; Xing et
 2037 al., 2003) and are displayed..

2038

2039

2040 *Table S9-1: Design parameters of the MBR (Garrido-Baserba, 2022).*

MBR		Units	Value
MLSS (X) for	Sludge concentration in aeration	mg/L	13,000.00
MT sMBR	tank		
Θ_x	Sludge age	days	30.00
Y	Cellular yield	mg VSS/mg COD	0.56
K_d (30°C)	Biomass decay constant	days ⁻¹	0.08
K_e (30°C)	Substrate degradation rate constant	days ⁻¹	2.60E-03
HRT	Hydraulic residence time	days	0.66

2047

2048 The volumes obtained through both procedures are shown in

$$Sludge\ production = \frac{VX}{\theta_x}$$

2049
Eq. 29
2050

2051

2052

2053 *Table S9-2:Estimated performance for the MBR.*

2054

	INFLUENT CONDITIONS MG/L (BRW+YW+FW)	INFLUENT CONDITIONS MG/L (GW)	INFLUENT CONDITIONS MG/L (TOTAL)	REMOVAL EFFICIENCY MBR %	INFLUENT (G/DAY)	EFFLUENT CONDITIONS (G/DAY)	EFFLUENT MG/L	QUALITY STANDARDS FOR GW REUSE (MG/L)
COD	660.39	472.00	493.45	97.00	120283.5 1	3608.51	14.80	
BOD	0.00	175.00	155.07	95.80	37800.00	1587.60	6.51	10
TN	86.82	8.00	16.98	73.00	4137.90	1117.23	4.58	10
NH4-N (TAN: TOTAL AMMONIA N, NH3+NH4+)	69.80	3.00	10.61	94	2585.57	155.13	0.64	
N-NO3	0.00	6.00	5.32	39.00	1296.00	790.56	3.24	
TP	18.11	5.00	6.49	80	1582.81	316.56	1.30	0.05
TSS	220.29	175.00	180.16	99	43914.97	439.15	1.80	5
VSS	125.83	64.00	71.04	99	17316.87	173.17	0.71	

2055

2056

2057 *Table S9-3: Design parameters of the MBR (city Block scenario)*
 2058

MBR	UNITS		
MLSS (X) FOR MT SMBR	Sludge concentration in aeration tank	mg/L	13,000.00
θX	Sludge age	days	30.00
Y	Cellular yield	mg VSS/mg COD	0.56
KD (30°C)	Biomass decay constant	days-1	0.08
KE (30°C)	Substrate degradation rate constant	days-1	0.00
Q	Flow	m3/day	243.76
HRT	Hydraulic residence time	days	0.67
HRT		hours	16.20
V	Volume	m3	164.50
	<i>Volume</i>	<i>m3</i>	<i>137.20</i>
	Sludge production	g/day	71,282.25

2059

2060 Table S9-4. Sludge production is also calculated by:

$$Sludge\ production = \frac{VX}{\theta_x}$$

2061

Eq. 29

2062

2063

2064

2065 *Table S9-2:Estimated performance for the MBR.*

2066

	INFLUENT CONDITIONS MG/L (BRW+YW+FW)	INFLUENT CONDITIONS MG/L (GW)	INFLUENT CONDITIONS MG/L (TOTAL)	REMOVAL EFFICIENCY MBR %	INFLUENT (G/DAY)	EFFLUENT CONDITIONS (G/DAY)	EFFLUENT MG/L	QUALITY STANDARDS FOR GW REUSE (MG/L)
COD	660.39	472.00	493.45	97.00	120283.5 1	3608.51	14.80	
BOD	0.00	175.00	155.07	95.80	37800.00	1587.60	6.51	10
TN	86.82	8.00	16.98	73.00	4137.90	1117.23	4.58	10
NH4-N (TAN: TOTAL AMMONIA N, NH3+NH4+)	69.80	3.00	10.61	94	2585.57	155.13	0.64	
N-NO3	0.00	6.00	5.32	39.00	1296.00	790.56	3.24	
TP	18.11	5.00	6.49	80	1582.81	316.56	1.30	0.05
TSS	220.29	175.00	180.16	99	43914.97	439.15	1.80	5
VSS	125.83	64.00	71.04	99	17316.87	173.17	0.71	

2067

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Table S9-3: Design parameters of the MBR (city Block scenario)

MBR		UNITS	
MLSS (X) FOR MT SMBR	Sludge concentration in aeration tank	mg/L	13,000.00
ΘX	Sludge age	days	30.00
Y	Cellular yield	mg VSS/mg COD	0.56
KD (30°C)	Biomass decay constant	days-1	0.08
KE (30°C)	Substrate degradation rate constant	days-1	0.00
Q	Flow	m ³ /day	243.76
HRT	Hydraulic residence time	days	0.67
HRT		hours	16.20
V	Volume	m ³	164.50
	Volume	m ³	137.20
	Sludge production	g/day	71,282.25

Table S9-4: Volumes and sludge production for the MBRs in all building types (Garrido-Baserba, 2022).

Building type	Volume (Eq. 26; m ³)	Volume (Eq. 27; Eq. 28; m ³)	Sludge production (P _x ; g/day)
LR	0.89	0.80	385.69
ST	0.89	0.80	385.69
MR	4.45	3.98	1928.43
MHR	8.90	7.97	3856.86
HR	22.25	19.92	9642.14

The required membrane area is calculated with Eq. 30, where A_m is expressed in [m²], Q₀ is the flow rate [l/h], and J_Q is the clean water flux [LMH]. The obtained values are displayed in Table S9-5.

$$A_m = \frac{Q_0}{J_Q}$$

Table S9-5: Membrane area values obtained (V1).

anMBR	Units	LR	ST	MR	MHR	HR
Membrane area	m²	1.12	1.12	5.62	11.25	28.12

9.2.2 CAPEX and OPEX

The CAPEX and OPEX of the MBR are calculated using published correlations for costs of sidestream MBRs using multitube membranes as in the present study (Fletcher et al., 2007; Lo et al., 2015). Since OPEX cost trends follow an adjusted relationship with treated flow but CAPEX can have higher variations depending on the specific installation, the obtained CAPEX values are complemented by the collection of supplier information and prices. Since the cited literature was published in 2015, prices are updated to 2019 prices using the all-items HICP annual average index (Eurostat). An example for the MHR building of the elements that are included in the prices of the MBRs is shown.

Table S9-6: Breakdown of included elements in the MBR obtained from supplier data collection (example for MHR buildings, Garrido-Baserba, 2022;. V1).

MHR MBR (\$)	\$		\$
Bioreactor	5,143.13	Membranes	1,687.38
Air diffusers biologic treatment	24.00	Valves	62.5
Pumps		Tanks	
<i>Cross flow pump for MT sMBR</i>	400	<i>Raw water and equalization tank</i>	1,863
<i>Pump for sludge recycling</i>	220	<i>Treated water tank</i>	1,842
<i>Permeate pump</i>	1100	<i>Cleaning chemicals tank</i>	108.09
<i>Chemical addition pumps</i>	356	<i>Sludge tank</i>	1,146.97
<i>Sludge purge pump</i>	220	MT membrane screen (0.5 mm)	1000
TOTAL (\$)	15,173		

Total OPEX and final CAPEX obtained through both costing methods are presented for comparison. CAPEX differences between both methods for the lower buildings are due to pumps and the membrane screen being oversized since no information on smaller units was available. Since these prices do not represent the best fit for the LR and ST apartment types, the costs obtained through literature have been used as final CAPEX. However, the closeness of costs for the MR, MHR, and HR buildings is relevant since both cost assessment methodologies are totally independent from each other and they still yield similar results.

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2107 *Table S9-7: Breakdown of included elements in the MBR obtained from supplier data collection (City Block*
2108 *Scenario: 2000 p.eq).*

METHOD 1:					
Correlation					
Total CAPEX (USD 2015)	127,860.02		Per capita CAPEX (USD/PE)	63.93	
Total CAPEX (€ 2015)	155,926.86				
Total CAPEX (€ 2021)	169,679.61				

GDP chain linked volumes 2010 = 100 (EU 27)		All-items HICP annual average index 2015 = 100 (EU 27)	
2015	104.98	2015.00	100.00
2021	113.47	2019.00	108.82
% inflation	8.09	% inflation	8.82

Influent	243.76	m3/d	Sludge (UASB+MBR)	52.54	t/yr
	10,156.60	l/h		0.14	m3/day

METHOD 2:					
Supplier data					
	V (m3)	€		m3	€
Bioreactor	164.50	86,538.70	Membranes	203.13	30,469.81
Air diffusers			Valves (bef & after pumps)		62.50
biologic treatment		24.00	Tanks	m3	
Pumps			Cleaning chemicals		
Cross flow pump for MT sMBR		2,600.00	tank		730.00
Pump for sludge recycling		1,400.00	43,591.84	Gal reactor	
Permeate pump		2,600.00	Sludge tank (MBR+UASB)	4.46	700.00
Chemical addition pumps (17 GPD)		1,000.00			
Sludge purge pump		1,400.00			
MT membrane screen (0.5 mm)		1,000.00			

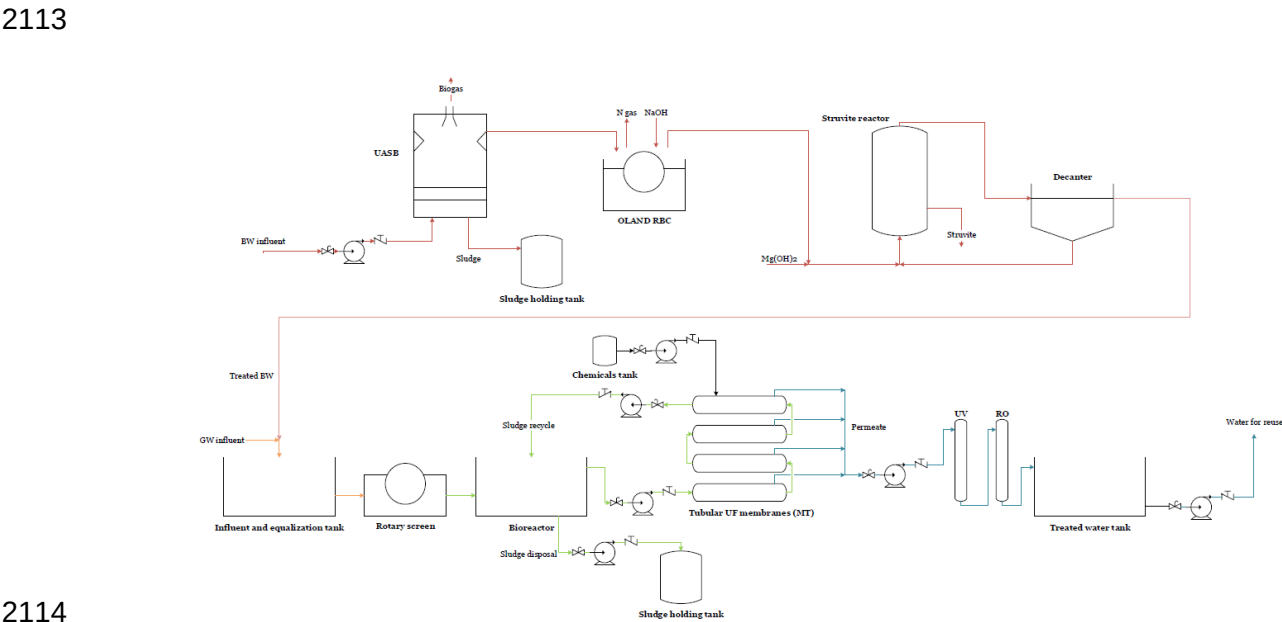
Days sludge tank	31
*monthly sludge disposal	

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2112 Fig. 9-7: BW and GW lines configuration



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2117 Table S9-8: CAPEX and OPEX of the MBRs in 2019 prices (V1).

	CAPEX correlation (\$)	CAPEX supplier data (\$)	OPEX (\$/yr)
LR	1763.88	6585.64	409.45
ST	1763.88	6585.64	409.45
MR	7177.47	10680.20	1788.72
MHR	13136.20	15173.07	3354.75
HR	29206.09	26740.17	7650.97

9.3 MBR – Modelling

The corresponding aeration system for the grey water flow and the biofilm-based nitrogen removal sub-system is used in the CTRL-ASM biokinetic model developed by the Institut für Automation und Kommunikation¹⁴⁷⁹⁶. To construct the layout of the aeration system, we included blowers, pipes, fittings, valves, and diffusers mechanistic models for each actuator. The piping system was modelled using the Darcy–Weisbach equation, with the friction factor calculated using the Swamee & Jain (1976) equation. The pressure rise across blowers and pressure drops across valves and diffusers were calculated using polynomial functions based on airflow rate, which were calibrated using manufacturer data. Aeration control was operated as ammonia-based aeration control with optimal SRT control¹⁴⁸⁹⁷ and accounted for by means of continuous feedback using proportional-integral or proportional-integral-derivative (PID) control algorithms. To model the behaviour of the automatic valves, a control algorithm was implemented that fixes the valve position of the lane with the highest oxygen requirement, thereby allowing the other valve to vary to adjust the required airflow.

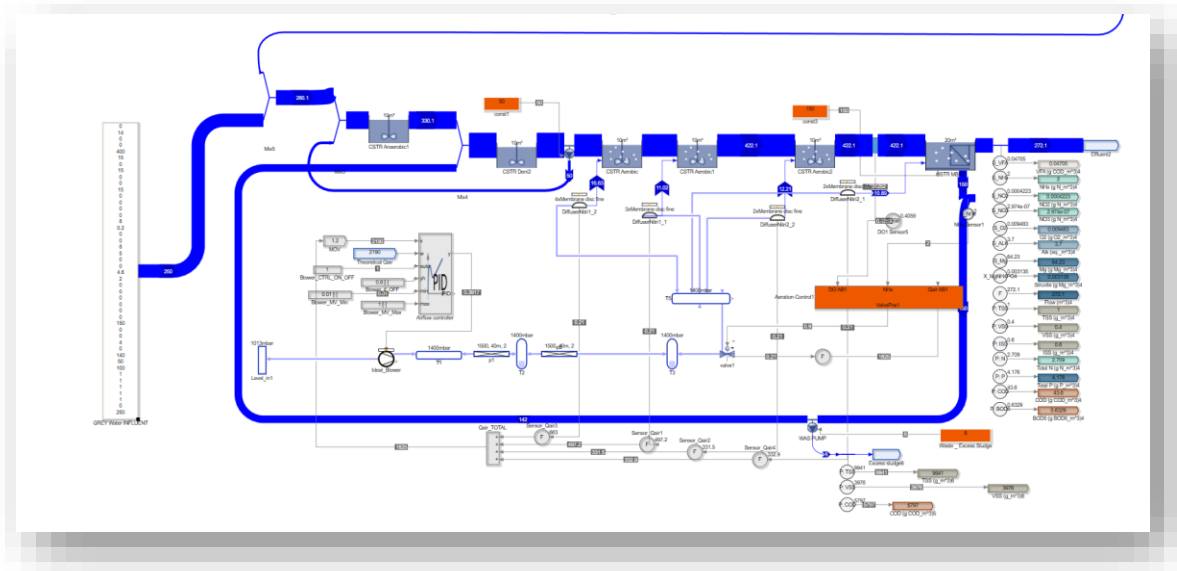
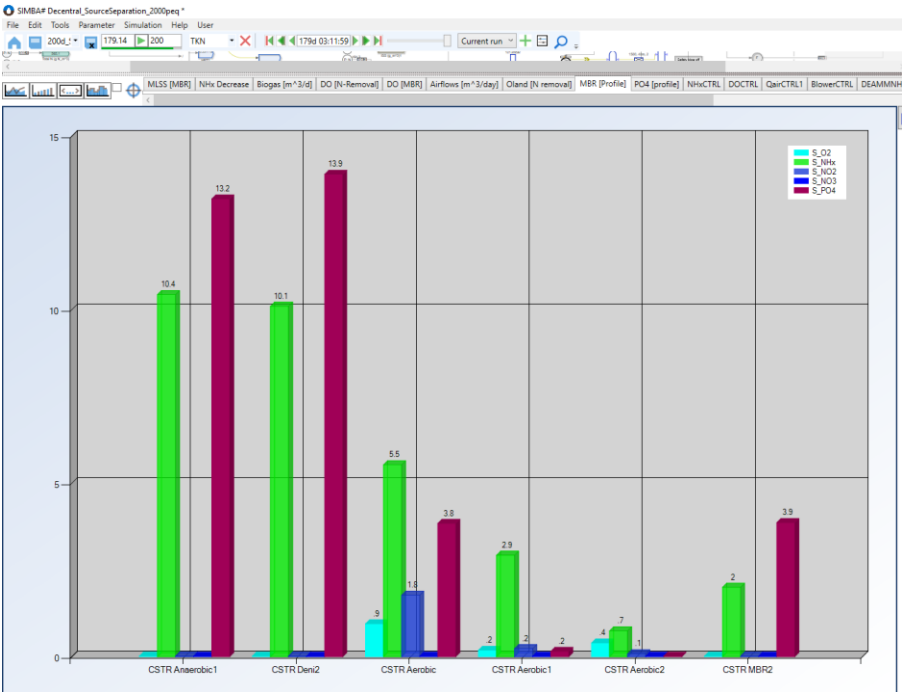


Table S9-9: MBR model within the decentralized source separation model.

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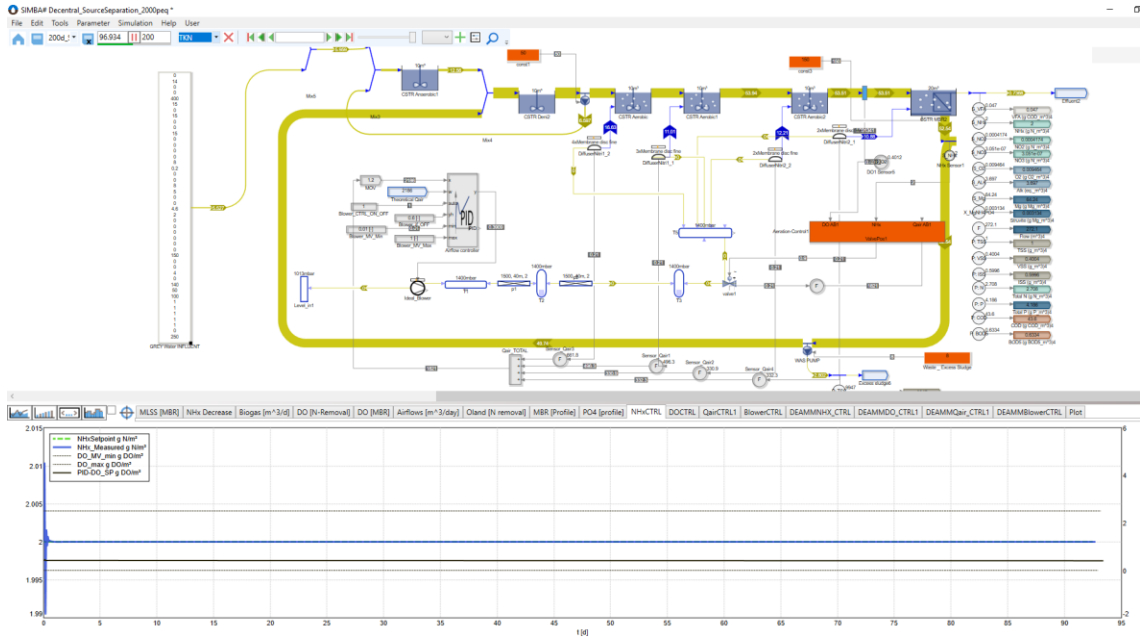


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Table S9-10: Nutrient removal and transformation along the MBR tanks in the grey water module.

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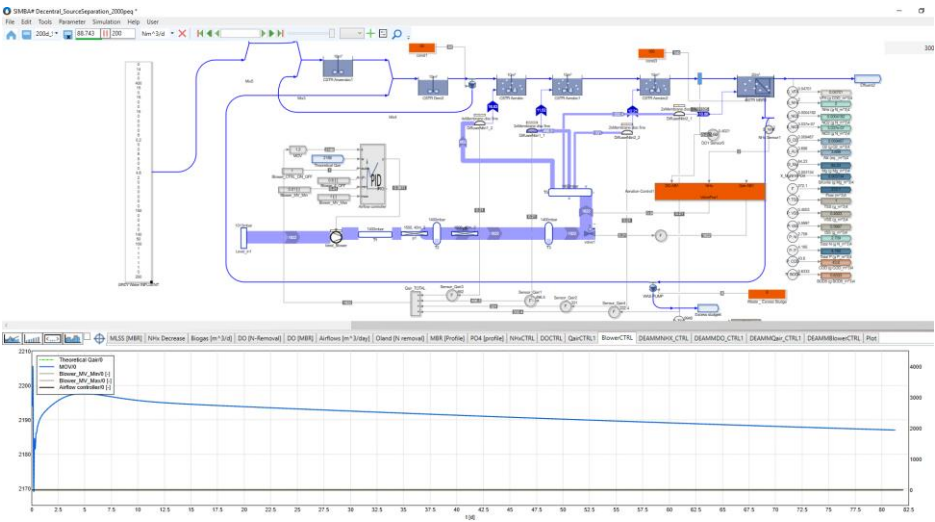
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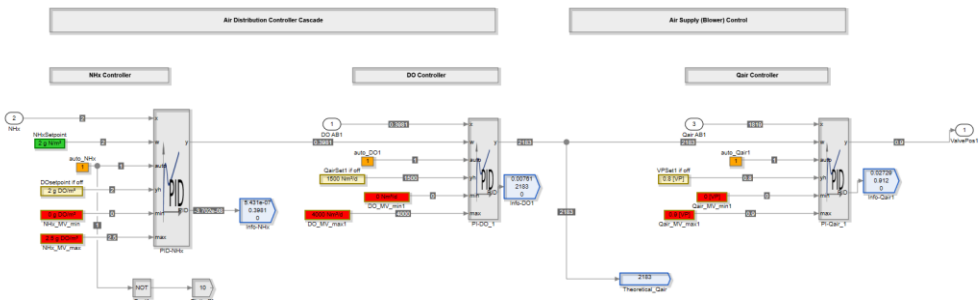
Table S9-11: MBR with an ABAC Approach: The ABAC uses ammonia (NH4+) setpoints to guide aeration. An ammonia setpoint of 2ppm is determined, and the ABAC system continuously adjusts DO levels to maintain that ammonia concentration.

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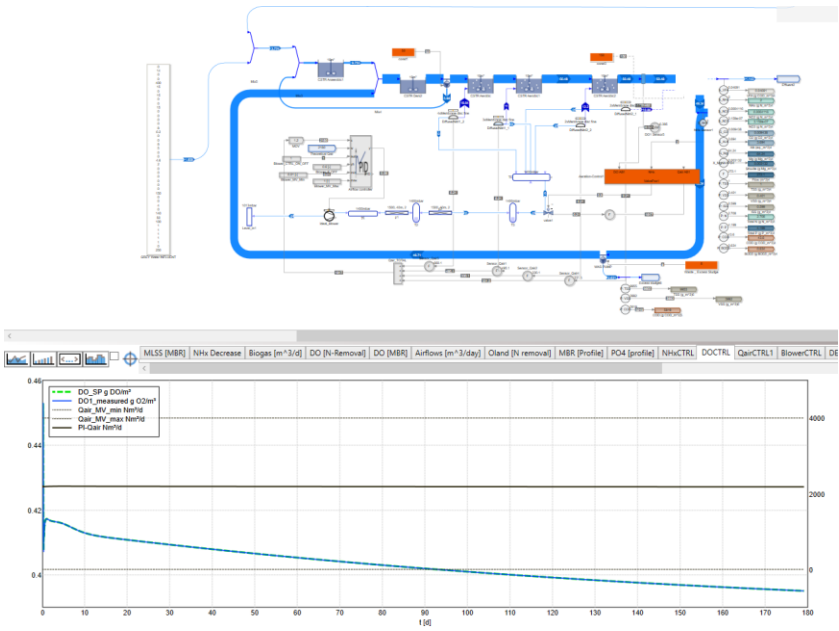
2152 Table S9-12: Energy demand and aeration control logic for MBR.



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2158 Table S9-13: Parameters, design and key aspects considered in the SIMBA# model for the MBR reactor

Block CSTR MBR2

Block of type basmLib.asm_cstrBlock_mbr, Assembly= basmLib.dll, Class= basmLib.asm_cstrBlock_mbr, subtype= inCTRL_ASM

Cont. state	ValueUnit	Description
S_VFA	0.04891 g COD/m ³	VFAs
S_F	0.4889 g COD/m ³	Fermentable substrate
S_MEOL	1.714e-133 g COD/m ³	Methanol
C_B	1.885e-16 g COD/m ³	Colloidal biodegradable substrate
X_B	671.3 g COD/m ³	Slowly biodegradable substrate
S_U	42.49 g COD/m ³	Soluble unbiodegradable organics
C_U	1.029e-18 g COD/m ³	Colloidal unbiodegradable organics
X_U	478.3 g COD/m ³	Particulate unbiodegradable organics
X_PHA	66.25 g COD/m ³	Stored PHA
X_E	620.2 g COD/m ³	Endogenous decay products
X_OHO	3162 g COD/m ³	Ordinary heterotrophs
X_MEOL	1.165e-08 g COD/m ³	Anoxic methanol utilizers
X_PAO	689 g COD/m ³	Phosphorus accumulating organisms
X_AOO	30.73 g COD/m ³	Aerobic ammonia oxidizers
X_NOO	3.384e-06 g COD/m ³	Nitrite oxidizing organisms
S_NHx	2 g N/m ³	Total ammonia
S_NO2	0.0004116 g N/m ³	Nitrite
S_NO3	3.159e-07 g N/m ³	Nitrate
S_N2	60.33 g N/m ³	Dissolved Nitrogen
S_N_F	0.3813 g N/m ³	Soluble biodegradable organic N (from S_F)
X_N_B	26.64 g N/m ³	Particulate biodegradable organic N
S_N_U	0.291 g N/m ³	Soluble unbiodegradable organic N
X_N_U	0.6148 g N/m ³	Particulate unbiodegradable organic N
S_PO4	3.866 g P/m ³	Orthophosphate
X_PP_LO	154.7 g P/m ³	Releasable stored polyphosphate
X_PP_HI	46.9 g P/m ³	Non-releasable stored polyphosphate
S_P_F	0.009271 g P/m ³	Soluble biodegradable organic P (from S_F)
X_P_B	6.982 g P/m ³	Particulate biodegradable organic P
S_P_U	0.291 g P/m ³	Soluble unbiodegradable organic P content
X_P_U	0.0562 g P/m ³	Particulate unbiodegradable organic P content
S_O2	0.009438 g O2/m ³	Dissolved oxygen
X_IG	4685 g TSS/m ³	Inorganic suspended solids
X_MeOH	0.0003041 g Me/m ³	Metal hydroxide compounds
X_MeP	0.002055 g Me/m ³	Metal phosphate compounds
S_ALK	3.694 eq/m ³	Alkalinity
X_DIG	4.469e-07 g COD/m ³	Fermentative and Methanogenic Biomass from Digester
S_Ca	135.1 gCa/m ³	Calcium ions
S_Mg	64.24 gMg/m ³	Magnesium ions
S_K	98.59 gK/m ³	Potassium ions
X_CaPO4	31.29 gCaPO4/m ³	Calcium phosphate
X_MgNH4PO4	31.18 gMgNH4PO4/m ³	Struvite
X_MgHPO4	31.16 gMgHPO4/m ³	Newberyite
X_MgCO3	31.27 gMgCO3/m ³	Magnesite
X_CaCO3	31.19 gCaCO3/m ³	Calcite
X_ANAMMOX	59.79 gCOD/m ³	Anammox bacteria
V	20 m ³	Volume
theta	35 °C	temperature damped

Parameter	ValueUnit
Model type (Model)	inCTRL_ASM
Reactor volume (Vol)	20 m ³
Height of tank (h)	4 m
With hydraulic (isvar)	True
Show reactor volume (showvol)	True
Show advanced results (advancedInfo)	False
Calculate OUR as discrete state (calculateOUR)	False
Animate aeration (animateAeration)	True
Calculation type of TSSEff (TSSEffType)	TSSEffConstant -
Variable (var) to calculate TSSEff (TSSEff=var) (varTSSEff)	1
Create input for variable VAR (showInput)	False
Zero crossing (zeroCrossing)	False
Hydraulic factor (Khyd)	200000 m/d

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9.4 Grey Water Alternatives

Five sub-models were developed to evaluate and optimize greywater treatment alternatives). The MBR selection as the main technology for grey water balanced various factors like maturity, cost information availability, case studies, and reliability. MBR offered the most detailed cost data, unavailable for other options yet. This enabled a more robust techno-economic analysis.

The surge in interest towards greywater treatment for a more sustainable urban water cycle has fueled a significant increase in relevant publications (Ceconet et al., 2019; WU et al., 2019, Vuppaladadiyam et al., 2019). These publications not only present comprehensive overviews of greywater characteristics, challenges, and opportunities for decentralized wastewater management, but also offer valuable reviews of available treatment technologies (Van de Walle et al., 2023; Ren et al., 2020; Shaikh et al., 2019). Building upon this existing literature, our study identified and selected the most commonly used and proven alternatives within each of the main treatment categories (Table S1). These categories fall into two broad groups: biological and physico-chemical. The biological group further branches into two subcategories:

- **Biofilm technologies:** This subcategory includes technologies where biofilms grow on aerated membranes (e.g., MABR) – **Model C-**, or freely (e.g., AGS) – **Model B-**, or on (or partially) moving carriers (e.g., MBBR – **Model D-**, IFAS).
- **Membrane bioreactors (MBRs) – Model A -** : These utilize membranes for filtration.

Finally, physico-chemical methods (e.g., filtration, sorption, electro-oxidation) offer significant potential, especially when combined with other approaches (e.g., HRAS-electro-oxidation).

Within this study's framework, we developed distinct models to enable a detailed assessment of the advantages and disadvantages of each main type of potential greywater treatment alternative. This study modeled five main alternatives. Below we are providing brief descriptions of these technologies along with existing case studies for greywater applications. Table S9-16 summarizes the results obtained from simulations representing these five technologies. Upon request, we can share the detailed simulation reports.

The MBR was selected to engage a broader audience and ensure reliability, thus, we opted to showcase a technology with readily available cost data, even though it wasn't our preferred choice. MABR, while mentioned as an alternative, we presented MBR technology (acknowledged as not our favorite) to illustrate overall costs using well-known and established options. However, AMBR was always a contender, but its relative novelty introduces challenges, especially with some significant cost uncertainty in some MABR equipment although we had some excellent real-based models using innovative aeration control strategies (i.e., ABNC).

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2199 While Granular AS and MBRs may benefit from some so-called "low DO strategies" that allow them to
2200 operate at lower dissolved oxygen (DO) levels than traditional DO setpoints, they indeed don't strictly fall
2201 under the definition of "low DO strategies." That term could better refer to processes like Membrane Aerated
2202 Biofilm Reactors (MABR) due to their lower oxygen requirements. On top of that, some of our investigations
2203 have examined exciting enhancing strategies in MABRs, as it has been demonstrated that MABR biofilms,
2204 for instance, can be operated by specific low oxygen strategies, the so-called "Ammonia Based Nitrification
2205 Control (ABNC)", which under dynamic load conditions offers advantages in handling peak loads and opens
2206 possibilities for process control optimization in hybrid systems involving both biofilm and suspended growth
2207 nitrification.
2208
2209 MABR boasts the highest oxygen transfer efficiency among evaluated greywater treatment candidates,
2210 achieving standard aeration efficiencies of up to 14 kg O₂/kWh. This starkly contrasts with active sludge,
2211 whose coarse-bubble range varies between 0.6 to 1.5 kg O₂/kWh and 3.6 to 4.8 kg O₂/kWh for typical fine-
2212 bubble systems. As cited, the high MLSS in MBR systems (often exceeding double that of conventional
2213 activated sludge) limits their aeration efficiency indicators, typically falling between 2 and 2.8 kg O₂/kWh
2214 (Baquero-Rodríguez, G. A., et al. 2018; Henkel et al. 2009). However, the authors emphasize that choosing
2215 the optimal greywater treatment technology, especially for reliable cost estimates (as the case of this
2216 techno-economic assessment), demands the consideration of other factors beyond oxygen transfer
2217 efficiency. Aspects like water quality, desired reuse standards, available resources, space requirements,
2218 expertise required, etc. need to be considered and integrated into this type of analysis. Interestingly, we
2219 strongly think that an eventual implementation of this concept will require combining different methods, as
2220 very often yields the most promising results for efficient and sustainable greywater treatment.
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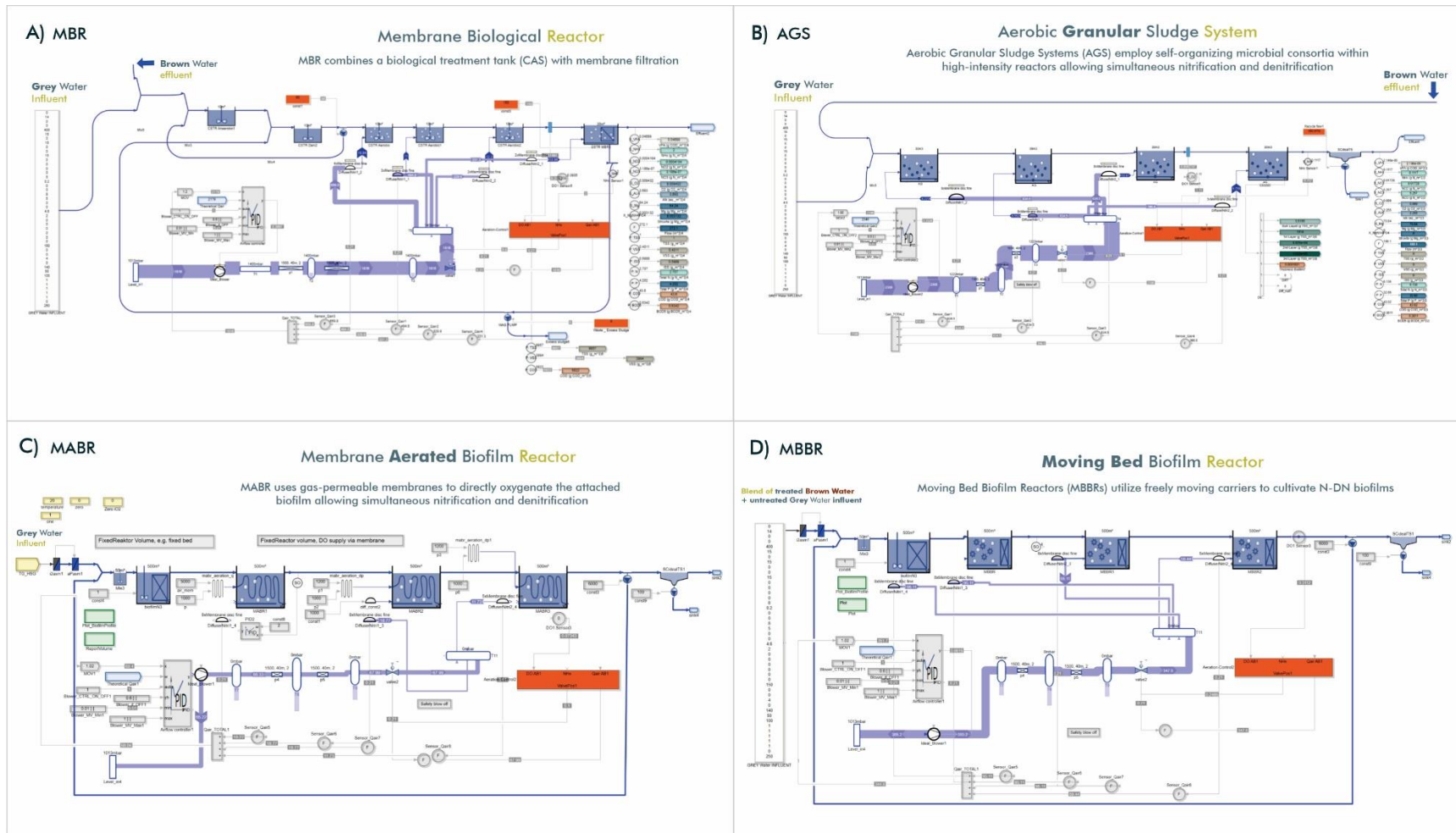
2235 Table S9-14: Model blocks & case studies for greywater treatment technologies: Membrane Bioreactors (MBRs),
 2236 Moving Bed Biofilm Reactors (MBBRs), Membrane-Aerated Biofilm Reactors (MABR/MBfRs), Aerobic Granular Sludge
 2237 (AGS), and Physicochemical Methods.

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Model block depiction (modeling software SIMBA#)	A brief definition of the rationale	Selected case studies (applied to greywater treatment)
 MBR (A)	MBRs fuse activated sludge and membrane filtration to treat greywater. Microporous membranes remove solids, delivering high-quality effluent. Increased sludge concentration boosts organic breakdown and nutrient removal. Aerobic or anaerobic options exist, but surfactant sensitivity in AnMBRs needs careful management. Membrane fouling needs attention, and operational costs can be higher. MBRs offer high efficiency and flexibility for tailored greywater treatment and have been the most studied technology for this type of stream.	<i>Ittisupornrat & Theep., 2023.</i> <i>Fikri, et al., 2023</i> <i>Palmarin & Young, 2019.</i> <i>Fountoulakis, et al. 2016</i> <i>Bani-Melhem, 2015</i> <i>Atanasova, et al. 2017</i> <i>Santasmasas, et al. 2013</i> <i>Merz, et al., 2007</i>
 MBBR (D)	Moving-bed biofilm reactors (MBBRs) effectively treat greywater using free-floating carriers colonized by microorganisms. Rotating Biological Contactors (RBCs) and Moving Bed Bioreactors (MBBRs) are popular examples. These technologies provide high flexibility and efficient pollutant removal, achieving over 90% COD reduction in some cases. These are arguably the most studied technologies after MBR for greywater applications.	<i>Abdelkader, 2021</i> <i>Ongena, et al., 2023</i> <i>Masmoudi Jabri, et al. 2019</i> <i>George, et al. 2019</i> <i>Jabornig & Favero, 2013</i> <i>Chripim, et al., 2017</i> <i>Saidi, et al. 2017</i>
 MABR /MBfRs (C)	Membrane-aerated biofilm reactors (MABR), also called membrane Biofilm Reactors (MBfRs), combine biofilm technology with a membrane unit and allow biofilm formation by supplying a gaseous substrate through a porous membrane. This technology has been shown in the literature to be able to remove organic and inorganic contaminants, such as surfactants and nitrogen, in greywater. The main characteristics include Counter-diffusion, Nitrification occurs in the inner layers; Denitrification occurs in the outer layers; performance drops as biofilm becomes too thick; biofilm management is important.	<i>Zhou, et al., 2020 (a)</i> <i>Zhou, et al., 2020 (b)</i> <i>Hooshyari, et al., 2022</i> <i>Khalil & Liu, 2021</i> <i>Christenson, et al., 2018</i> <i>Martin & Nerenberg, 2012.</i>
 AGS (B)	Aerobic granular sludge (AGS) has shown promise for greywater treatment. However, there is less available literature, as it is a relatively new technology. AGS requires precise control to induce and maintain stable granule formation and a more complex biological process compared to the attached films in MBRs or free-floating carriers in MBBRs.	<i>Wang, et al., 2018</i> <i>Hamza, et al., 2022</i> <i>Thwaites, 2018</i> <i>Katukiza, 2014</i>
Physico-chemical	Physicochemical methods for decentralized greywater treatment include membranes, sorption, ion exchange, and electro-oxidation, offering unique advantages and challenges. Activated carbon and zeolites are effective adsorbents for removing organic pollutants and nutrients like ammonium. Electro-oxidation is a novel approach to greywater treatment by utilizing electro-oxidation (EO) for nitrogen removal instead of conventional biological nitrification. This eliminates aeration needs and sludge production associated with nitrification, potentially reducing energy consumption and footprint. While eliminating aeration is beneficial, EO itself requires energy input. A proposed EO-HRAS combination for greywater treatment presents a promising solution for addressing the challenges of traditional methods.	<i>Haddad, et al., 2022</i> <i>Cecconet, et al., 2021</i> <i>Butkovskyi, et al., 2018</i> <i>Cardoso & Bodnar, 2022.</i> <i>Pidou, 2008</i> <i>Sharaf & Liu 2021</i>

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2242 Table S9-15: Screen captures of the simulations carried out for four (out of five) of the main alternatives for treating gray water. All four alternatives were modeled
 2243 on a 300-day simulation in a dynamic state. The model ran from default initial conditions at a constant loading rate until a steady state was reached. Diurnal variations
 2244 were simulated in dynamic conditions after the steady state was obtained. Most of the models were scaled up to avoid scale-dependent parameters to ensure a
 2245 precise representation of mass transfer, interfacial phenomena, mixing characteristics, and residence times.

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Table S9-16: Summary of the simulations considering the main alternatives for the gray water treatment stream [p.eq. 2,000; Grey water influent characteristics; 300 days at dynamic conditions, 25C air temperature; results recalculated from scaled-up models]

Technology	Reactor Volume ³ (m ³)	Volume of Clarifiers/Buffer Tanks ³ (m ³)	Total Volume ³ (m ³)	Media Required ² (m ³)	Effluent Nitrogen (mgN/L)	Standard Aeration Efficiency (kg O ₂ /kWh)	Air Required ³ (Nm ³ /d)
MBBR ¹	43.8	32	75.8	10,950	NH ₄ -N = 0.74 NO ₃ -N = 9.9	2 -3.5 kg O ₂ /kWh	2,0740 ⁴
MABR ²	43.8	40	83.8	3,840	NH ₄ -N = 0.72 NO ₃ -N = 5	14 kg O ₂ /kWh	835.7
AGS ³	126	40	166	---	NH ₄ -N = 0.83 NO ₃ -N = 8.6	2 - 3.0 kg O ₂ /kWh	1,454.8
MBR ⁵	43.8	4.8	49	602.5 ⁵	NH ₄ -N = 0.11 NO ₃ -N = 8.3	1.8 - 2.8 kg O ₂ /kWh	2,525.2
Electro Oxidation ⁶	19	---	22	---	NH ₄ -N = <0.5 NO ₃ -N = <2	---	---

¹Design taken from Weiss et al. (2005).

MBBR with recycling, which could be considered a type of IFAS (Integrated fixed film activated sludge), could closely match the air requirements of the AGS system.

²used the same tank volumes as for MBBR. Membrane area calculated based on TKN surface loading rate of about 2.5 gN/m²-d

³Tank volume based on volumetric loading of 1.5 m³/m³-d based on Pronk et al. (2015). The model showed that volume could be reduced to 5,000 m³.

⁴Based on coarse bubble aeration and minimum airflow of 6 m³/h/m² for carrier suspension.

⁵Includes air for aeration tanks (39,990+20,390 Nm³/d) and membrane tank (65,880 Nm³/d). Membrane tank aeration is 183 Nm³/h per cassette. 15 cassettes are required based on peak flux through membranes of 33 L/m²/h membrane area of 2,077 m² per cassette and a peaking factor of 2.5. Membrane tank sized of 240 m³ based on 15 cassettes x 16 m³ needed per cassette. MBR case does not need a primary clarifier.

⁶Based on an adapted design concept aimed to grey water from Haddad, et al 2022 and Qiao et al., 2021.

References:

MBR Aeration Efficiency

- Henkel, J., Lemac, M., Wagner, M., & Cornel, P. (2009). Oxygen transfer in membrane bioreactors treating synthetic greywater. *Water Research*, 43(6), 1711-1719.
- Baquero-Rodríguez, G. A., Lara-Borrero, J. A., Nolasco, D., & Rosso, D. (2018). A Critical Review of the Factors Affecting Modeling Oxygen Transfer by Fine-Pore Diffusers in Activated Sludge: Baquero-Rodríguez et al. *Water Environment Research*, 90(5), 431-441.

Selected Grey water Reviews:

- D. Cecconet, A. Callegari, P. Hlavínek, A.G. Capodaglio. Membrane bioreactors for sustainable, fit-for-purpose greywater treatment: a critical review. *Clean Technol. Environ. Policy*, 21 (4) (2019), pp. 745-762
- B. Wu. Membrane-based technology in greywater reclamation: a review. *Sci. Total Environ.*, 656 (2019), pp. 184-200.
- A.K. Vuppaladadiyam, N. Merayo, P. Prinsen, R. Luque, A. Blanco, M. Zhao. A review on greywater reuse: quality, risks, barriers and global scenarios. *Rev. Environ. Sci. Biotechnol.*, 18 (1) (2019), pp. 77-99

- Van de Walle, A., Kim, M., Alam, M. K., Wang, X., Wu, D., Dash, S. R., ... & Kim, J. (2023). Greywater reuse as a key enabler for improving urban wastewater management. *Environmental Science and Ecotechnology*, 100277.
- Ren, X., Zhang, Y., & Chen, H. (2020). Graywater treatment technologies and reuse of reclaimed water for toilet flushing. *Environmental Science and Pollution Research*, 27, 34653-34663.
- Shaikh, I. N., Ahammed, M. M., & Krishnan, M. S. (2019). Graywater treatment and reuse. In *Sustainable water and wastewater processing* (pp. 19-54). Elsevier.
- Kobayashi, Y., Ashbolt, N. J., Davies, E. G., & Liu, Y. (2020). Life cycle assessment of decentralized greywater treatment systems with reuse at different scales in cold regions. *Environment international*, 134, 105215.

MBR (grey water-focused case studies)

- Ittisupornrat, S., & Theepharaksapan, S. (2023). Greywater treatment performance of a pilot-scale membrane bioreactor and characteristics of bacterial biofilm signatures in permeate effluent. *Journal of Water Process Engineering*, 55, 104098.
- Fikri, E., Zulkarnain, O. F., Azizah, R., Latif, M. T., & Firmansyah, Y. W. (2023). The Application of Membrane Bioreactor for Greywater Treatment. *Journal of Ecological Engineering*, 24(6).
- Palmarin, M. J., & Young, S. (2019). Comparison of the treatment performance of a hybrid and conventional membrane bioreactor for greywater reclamation. *Journal of Water Process Engineering*, 28, 54-59.
- Fountoulakis, M. S., Markakis, N., Petousi, I., & Manios, T. (2016). Single house on-site grey water treatment using a submerged membrane bioreactor for toilet flushing. *Science of the total environment*, 551, 706-711.
- Bani-Melhem, K., Al-Qodah, Z., Al-Shannag, M., Qasaimeh, A., Qtaishat, M. R., & Alkasrawi, M. (2015). On the performance of real grey water treatment using a submerged membrane bioreactor system. *Journal of Membrane Science*, 476, 40-49.
- Atanasova, N., Dalmau, M., Comas, J., Poch, M., Rodriguez-Roda, I., & Buttiglieri, G. (2017). Optimized MBR for greywater reuse systems in hotel facilities. *Journal of environmental management*, 193, 503-511.
- Santasmasas, C., Rovira, M., Clarens, F., & Valderrama, C. (2013). Grey water reclamation by decentralized MBR prototype. *Resources, conservation and recycling*, 72, 102-107.
- Merz, C., Scheumann, R., El Hamouri, B., & Kraume, M. (2007). Membrane bioreactor technology for the treatment of greywater from a sports and leisure club. *Desalination*, 215(1-3), 37-43.

MBBR (grey water-focused case studies)

- Abdelkader, A. M. (2021). Comparative study between membrane bioreactor MBR and rotating biological contactors RBC for greywater treatment. *Int. J. Environ. Sustain Dev*, 12(4).
- Ongena, S., Van de Walle, A., Mosquera-Romero, S., Driesen, N., Gutierrez, L., & Rabaey, K. (2023). Comparison of MBR and MBBR followed by UV or electrochemical disinfection for decentralized greywater treatment. *Water Research*, 235, 119818.
- Masmoudi Jabri, K., Fiedler, T., Saidi, A., Nolde, E., Ogurek, M., Geissen, S. U., & Bousselmi, L. (2019). Steady-state modeling of the biodegradation performance of a multistage moving bed biofilm reactor (MBBR) used for on-site greywater treatment. *Environmental Science and Pollution Research*, 26, 19047-19062.
- George, A., Ancy, C. J., KR, A. R., Nair, J. P., & Nadayil, J. (2019). Characterisation of Grey Water and Treatment using Moving Bed Biofilm Reactor (Mbbbr).
- Jaborinig, S., & Favero, E. (2013). Single household greywater treatment with a moving bed biofilm membrane reactor (MBBMR). *Journal of membrane science*, 446, 277-285.
- Chrispim, M. C., & Nolasco, M. A. (2017). Greywater treatment using a moving bed biofilm reactor at a university campus in Brazil. *Journal of cleaner production*, 142, 290-296.
- Saidi, A., Masmoudi, K., Nolde, E., El Amrani, B., & Amraoui, F. (2017). Organic matter degradation in a greywater recycling system using a multistage moving bed biofilm reactor (MBBR). *Water Science and Technology*, 76(12), 3328-3339.

MABR/MBfR (grey water-focused case studies)

- Zhou, Y., Li, R., Guo, B., Zhang, L., Zou, X., Xia, S., & Liu, Y. (2020). Greywater treatment using an oxygen-based membrane biofilm reactor: Formation of dynamic multifunctional biofilm for organics and nitrogen removal. *Chemical Engineering Journal*, 386, 123989.
- Zhou, Y., Guo, B., Li, R., Zhang, L., Xia, S., & Liu, Y. (2020). Treatment of grey water (GW) with high linear alkylbenzene sulfonates (LAS) content and carbon/nitrogen (C/N) ratio in an oxygen-based membrane biofilm reactor (O2-MBfR). *Chemosphere*, 258, 127363.
- Hooshyari, G., Jackson, W., Gray, E., Song, L., Bose, A., & Callahan, M. (2022). Demonstration of a Full Size Integrated Greywater Recycling System Combining Biological Pretreatment with Reverse Osmosis. 51st International Conference on Environmental Systems.
- Khalil, M., & Liu, Y. (2021). Greywater biodegradability and biological treatment technologies: A critical review. *International Biodeterioration & Biodegradation*, 161, 105211.

- Christenson, D., Sevanthi, R., Morse, A., & Jackson, A. (2018). Assessment of membrane-aerated biological reactors (MABRs) for integration into space-based water recycling system architectures. *Gravitational and Space Research*, 6(2), 12-27.
- Martin, K. J., & Nerenberg, R. (2012). The membrane biofilm reactor (MBfR) for water and wastewater treatment: principles, applications, and recent developments. *Bioresource technology*, 122, 83-94.

AGS (grey water-focused case studies)

- Wang, L., Liang, W., Chen, W., Zhang, W., Mo, J., Liang, K., ... & Jiang, F. (2018). Integrated aerobic granular sludge and membrane process for enabling municipal wastewater treatment and reuse water production. *Chemical Engineering Journal*, 337, 300-311.
- Hamza, R., Rabii, A., Ezzahraoui, F. Z., Morgan, G., & Iorhemen, O. T. (2022). A review of the state of development of aerobic granular sludge technology over the last 20 years: Full-scale applications and resource recovery. *Case Studies in Chemical and Environmental Engineering*, 5, 100173.
- Thwaites, B. J., Short, M. D., Stuetz, R. M., Reeve, P. J., Gaitan, J. P. A., Dinesh, N., & Van Den Akker, B. (2018). Comparing the performance of aerobic granular sludge versus conventional activated sludge for microbial log removal and effluent quality: implications for water reuse. *Water research*, 145, 442-452.
- Katukiza, A. Y., Ronteltap, M., Niwagaba, C. B., Kansime, F., & Lens, P. N. L. (2014). Grey water treatment in urban slums by a filtration system: Optimisation of the filtration medium. *Journal of environmental management*, 146, 131-141.

Physico-chemical (grey water-focused case studies)

- Qiao, J., & Xiong, Y. (2021). Electrochemical oxidation technology: A review of its application in high-efficiency treatment of wastewater containing persistent organic pollutants. *Journal of Water Process Engineering*, 44, 102308.
- Mathieu Haddad, M., Mailler, M., Mazeghrane, S., Roche, C. (2022). Wastewater treatment method with maximization of biogas production comprising an electro-oxidation step. Patent.
- Cecconet, D., Bolognesi, S., Piacentini, L., Callegari, A., & Capodaglio, A. G. (2021). Bioelectrochemical greywater treatment for non-potable reuse and energy recovery. *Water*, 13(3), 295.
- Butkovskiy, A., Jeremiasse, A. W., Hernandez Leal, L., van der Zande, T., Rijnaarts, H., & Zeeman, G. (2014). Electrochemical conversion of micropollutants in gray water. *Environmental science & technology*, 48(3), 1893-1901.
- Cardoso, C. C., & Bodnar, I. (2022). Modelling treated laundry greywater reuse for irrigation using an affordable treatment method and seed germination test. *Sustainability*, 14(3), 1314.
- Pidou, M., Avery, L., Stephenson, T., Jeffrey, P., Parsons, S. A., Liu, S., ... & Jefferson, B. (2008). Chemical solutions for greywater recycling. *Chemosphere*, 71(1), 147-155.
- Sharaf, A., & Liu, Y. (2021). Mechanisms and kinetics of greywater treatment using biologically active granular activated carbon. *Chemosphere*, 263, 128113.

2401 9.5 Grey Water Line – LCA

2402

2403 9.5.1 Grey Water Line – Construction

2404

2405 9.5.1.1 *MBR System Design and Considerations*

2406

2407 Modular Design: The MBR is housed within an ISO container constructed of stainless
2408 steel. This eliminates the need for extensive construction work and simplifies the
2409 assembly process.

2410 Reactor and Membrane: The MBR tank follows the Sigmadaf SMBR reactor model,
2411 incorporating aerobic and membrane chambers along with the necessary components
2412 (air diffusers, membrane screen, valves). The 31 m² UF membrane, crucial for filtration,
2413 is composed of PVDF – the standard material for wastewater MBR modules.

2414 PVDF Production: While PVDF isn't included in the ecoinvent database, there are readily
2415 available datasets within the activity list from Yadav et al. (2021) that enable modeling
2416 its production. Keep in mind, the factory-based membrane production would utilize
2417 medium-voltage electricity, while the operational phase within residential buildings needs
2418 low voltage.

2419 Sizing and Lifespan: Reactor volume is determined using HRT, which depends on factors
2420 such as BOD concentrations, substrate degradation rate constants, and sludge
2421 concentration derived from literature (Liu et al., 2005; Lo et al., 2015). SIMBA# is used
2422 for volume verification. Membrane area sizing relies on a clean water flux of 50 Lh⁻¹m⁻²
2423 and influent flow rate. Components have varying lifespans: membranes (15 years), tanks
2424 (30 years), pumps (18 years).

2425 Power: Three pumps (cross-flow, recirculation, chemical dosing) contribute to a total
2426 power of 3.3 kW and a membrane pressure of 1.5 bar.

2427

2428 9.5.1.2 *RO and UV Treatment*

2429 RO Modeling: The ecoinvent dataset "market for seawater reverse osmosis module" is
2430 used as a foundation for modeling the RO unit. Though based on the Dow chemical
2431 SW30XLE-440i seawater desalination module, the dataset aligns well with the system's
2432 use of the Dow chemical XLE-2540 module (designed for brackish water and wastewater
2433 treatment). Both modules share similar fiberglass shell construction and polyamide thin-
2434 film composite membranes. The membrane surface area is adjusted to match the GW
2435 line flow requirements.

2436 UV: Modeling ultraviolet radiation treatment relies on determining the necessary number
2437 of lamps.

2438 Lifespan: Both RO and UV units have an expected lifespan of 5 years (Herman et al.,
2439 2017).

2440

2441 Table S9-17:: Inventory details for the construction of the treatments and processes included in the
 2442 GW line. Tables in the construction inventory refer to the total amount of materials of components
 2443 needed to build the decentralized system for the water treatment for the reference population of
 2444 300 people.

2445

Element	Amount	Unit	Material	Life span (years)	Ecoinvent dataset	
MBR, tank	1,150.00	kg	Stainless steel	30	market for steel, chromium steel 18/8	GLO
MBR, UF membrane	7.08	kg	PVDF	15		
MBR, PDVF (hydrogen)	0.92	kg	Hydrogen	-	market for hydrogen, gaseous	GLO
MBR, PDVF (electricity)	722.16	kWh	-	-	market group for electricity, medium voltage	RER
MBR, PDVF (hydrogen chloride emissions to air)	3.61	kg	Hydrogen chloride	-	Hydrochloric acid, emissions to air	-
MBR, PDVF (hydrogen emissions to air)	0.59	kg	Hydrogen	-	Hydrogen, emissions to air	-
MBR, PDVF (waste heat emissions to air)	169.92	MJ	-	-	Heat, waste, emissions to air	-
MBR, PVDF (hydrogen chloride emissions to water)	3.54	kg	Hydrogen chloride	-	Hydrochloric acid, emissions to water	-
MBR, UF membrane cassette	52.92	kg	Stainless steel	30	market for steel, chromium steel 18/8	GLO
MBR, cross flow, recirculation, and chemical addition pumping	0.15	unit	-	18	market for water pump, 22kW	GLO
RO unit for GW	2.60	m ²	-	5	market for seawater reverse osmosis module	GLO
UV unit for GW	1.00	unit	-	5	market for ultraviolet lamp, for water disinfection	GLO

2446

2447

2448 9.5.2 Grey Water Line – Operation

2449 The grey water treatment process has specific electricity demands for each stage:

- 2450 ▪ Membrane Bioreactor (MBR):
- 2451 ▪ Aerobic Module: 0.5 kWh*m-3
- 2452 ▪ Anoxic and Anaerobic Chambers (plus pumping): 0.159 kWh*m-3
- 2453 ▪ Reverse Osmosis (RO): 0.6 kWh per cubic meter of permeate
- 2454 ▪ Ultraviolet (UV): 0.1 kWh*m-3

2456 Chemical Usage and Emissions

- 2457 ▪ Sodium Hypochlorite: 11 mg/L is used to maintain membrane permeability within the
- 2458 MBR system.
- 2459 ▪ Emissions from MBR: This process includes the following emissions into the air:
- 2460 ▪ Carbon dioxide (CO₂): Equivalent to 50% of influent COD in mass.
- 2461 ▪ Nitrous Oxide (N₂O): Accounts for 0.9% of total influent nitrogen.
- 2462 ▪ Non-methane volatile organic compounds (NMVOCs): Estimated at 0.46 g*m³

2463 The RO process generates approximately 1800 m³*yr⁻¹ of reject water. While not suitable for
 2464 direct reuse or drinking, this water remains microorganism-free and potentially viable for
 2465 applications like cleaning or plant watering.

2466 *Table S9-18:: Inventory details for the annual operation of the grey water line (FU: water treatment for 300*
 2467 *people during a year).*

Element	Amount	Unit	Ecoinvent dataset	
MBR, aerobic chamber, electricity	6,716.60	kWh	market group for electricity, low voltage	RER
MBR, additional, electricity	2,135.88	kWh	market group for electricity, low voltage	RER
MBR, NaClO	147.77	kg	sodium hypochlorite, without water, in 15% solution state	RER
MBR, CO ₂ emissions to air	166.85	kg	Carbon dioxide, fossil, emissions to air	-
MBR, N ₂ O emissions to air	2.26	kg	Dinitrogen monoxide, emissions to air	-
MBR, NMVOC emissions to air	20.60	kg	NMVOC, non-methane volatile organic compounds, emissions to air	-
RO, electricity	6,700.20	kWh	market group for electricity, low voltage	RER
UV, electricity	1,116.70	kWh	market group for electricity, low voltage	RER

2468

2469

10 Phosphorus Recovery

Small-scale phosphorus recovery in the form of struvite, which would be accompanied by ammoniacal nitrogen removal, was assumed to take place in a crystallizer followed by a decanter (Ali, 2005; Kataki et al., 2016; Shaddel et al., 2020). Removal efficiencies, design calculations, energy demand, and the mass of added $\text{Mg}(\text{OH})_2(\text{s})$ needed to maintain supersaturation at a pH of 8 were calculated to obtain the effluent concentrations and operational costs. Phosphorus recovery through struvite recovery is likely to become more important to sustainability in the water sector; however, this approach still presents operational challenges, even in large facilities. Its implementation may only take place as operators gain more experience and pilot-scale treatment systems demonstrate reliable system performance. However, even if the struvite recovery only addresses the prevention of capacity loss due to detrimental struvite precipitation inside reactors and piping, significant infrastructural sustainability goals would still be achieved.

10.1 Struvite Reactor – Design and Costs

Assuming a hydraulic retention time of 3.5h (Tarragó et al., 2016) and using Stokes' law to determine reactor volumes and terminal particle diameter size, the operating flow for each building was obtained. The decanter was sized to separate and recirculate particles half the size of those not previously separated in the crystallizer to enhance secondary nucleation and has retention time of 1 h. P-removal and $\text{NH}_4\text{-N}$ -removal were calculated from the influent concentration assuming a phosphate removal efficiency of 90%, as reported by Siciliano et al. (2020).

The steps taken to assess the performance of the struvite reactor and decanter are described in this section, taking as an example the MHR building.

10.1.1 Final ammonia, TN and TP concentrations

To calculate the amount of nutrients in the influent which will be eliminated, the limiting reactant (either NH_4^+ or PO_4^{3-}) must be determined. To do so, influent concentrations are used:

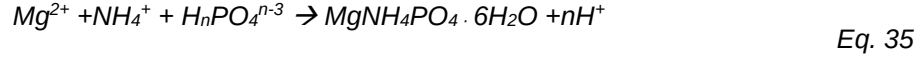
$$0.539 \frac{\text{m}^3}{\text{day}} * 269.45 \frac{\text{g N} - \text{NH}_4^+}{\text{m}^3} = 145.23 \frac{\text{g N} - \text{NH}_4^+}{\text{day}} \quad \text{Eq. 31}$$

$$145.2 \frac{\text{g N} - \text{NH}_4^+}{\text{day}} * \frac{1 \text{ mole N} - \text{NH}_4^+}{14 \text{ g N} - \text{NH}_4^+} * \frac{1 \text{ mole NH}_4^+}{1 \text{ mole N} - \text{NH}_4^+} = 10.37 \frac{\text{moles NH}_4^+}{\text{day}} \quad \text{Eq. 32}$$

$$0.539 \frac{\text{m}^3}{\text{day}} * 162.43 \frac{\text{g TP}}{\text{m}^3} * 0.72 = 63.03 \frac{\text{g TP}}{\text{day}} \quad \text{Eq. 33}$$

$$63 \frac{\text{g P} - \text{PO}_4^{3-}}{\text{day}} * \frac{1 \text{ mole P} - \text{PO}_4^{3-}}{30.97 \text{ g P} - \text{PO}_4^{3-}} * \frac{1 \text{ mole PO}_4^{3-}}{1 \text{ mole P} - \text{PO}_4^{3-}} = 2.04 \frac{\text{moles PO}_4^{3-}}{\text{day}} \quad \text{Eq. 34}$$

2497 As seen for the MHR building, phosphate is the chemical entity which has the less moles, and
 2498 which will therefore determine the extent of the reaction (shown in Eq. 35).



2499 From the reacted phosphate moles, the ammonia eliminated is calculated, enabling to find the
 2500 final ammonia concentration. A 1.5 $Mg^{2+}:PO_4^{3-}$ molar ratio as used gives a conversion of 90% of
 2501 phosphate is considered (de Graaff et al., 2010; Siciliano et al., 2020). The influent and effluent
 2502 of the reactor are approximated to be equal since the reacted struvite, added base and
 2503 recirculated solids represent only a small fraction of the influent (S. Puig, personal communication,
 2504 2017).

$$2.04 \frac{\text{moles } PO_4^{3-}}{\text{day}} * 0.9 = 1.836 \frac{\text{moles } PO_4^{3-} \text{ reacted}}{\text{day}} = \frac{\text{moles } NH_4^+ \text{ reacted}}{\text{day}} \quad \text{Eq. 36}$$

$$\begin{aligned} 10.37 \frac{\text{moles } NH_4^+}{\text{day}} - 1.836 \frac{\text{moles } NH_4^+ \text{ reacted}}{\text{day}} &= 8.53 \frac{\text{moles } NH_4^+}{\text{day}} \\ &= 119.5 \frac{g \text{ N} - NH_4^+}{\text{day}} \end{aligned} \quad \text{Eq. 37}$$

2505

$$\text{Final N} - NH_4^+ \text{ concentration} = \frac{119.5 \frac{g \text{ N} - NH_4^+}{\text{day}}}{0.539 \frac{m^3}{\text{day}}} = 221.7 \frac{g \text{ N} - NH_4^+}{m^3} \quad \text{Eq. 38}$$

2506 The N concentration in the effluent can also be calculated by subtracting the reacted N in
 2507 ammoniacal form, if the N concentration in the influent is known (in this case, 759.75 g TN/m³).

$$607.79 \frac{g \text{ TN}}{m^3} - \left(269.45 \frac{g \text{ N} - NH_4^+}{m^3} - 221.7 \frac{g \text{ N} - NH_4^+}{m^3} \right) = 560 \frac{g \text{ TN}}{m^3} \quad \text{Eq. 39}$$

2508 The phosphorus concentration in the effluent is obtained knowing that initially 72% of the TP is in
 2509 the form of phosphate:

$$2.04 \frac{\text{initial moles } PO_4^{3-}}{\text{day}} - 1.836 \frac{\text{moles } PO_4^{3-} \text{ reacted}}{\text{day}} = 0.20 \frac{\text{moles } PO_4^{3-} \text{ final}}{\text{day}} \quad \text{Eq. 40}$$

$$0.20 \frac{\text{moles } PO_4^{3-}}{\text{day}} * \frac{1 \text{ mole P} - PO_4^{3-}}{1 \text{ mole } PO_4^{3-}} * \frac{30.97 \text{ g P} - PO_4^{3-}}{1 \text{ mole } PO_4^{3-}} = 6.19 \frac{g \text{ P} - PO_4^{3-}}{\text{day}} \quad \text{Eq. 41}$$

$$\frac{6.19 \frac{g \text{ P} - PO_4^{3-}}{\text{day}}}{0.539 \frac{m^3}{\text{day}}} = 11.5 \frac{g \text{ P} - PO_4^{3-}}{m^3} \quad \text{Eq. 42}$$

$$162.42 \frac{g \text{ TP}}{m^3} - \left(162.42 \frac{g \text{ TP}}{m^3} * 0.72 - 11.5 \frac{g \text{ P} - PO_4^{3-}}{m^3} \right) = 57 \frac{g \text{ TP}}{m^3} \quad \text{Eq. 43}$$

2510 10.1.2 Struvite production

2511 The reacted phosphate moles are also used to calculate the production of struvite (Eq. 35):

$$2.04 \frac{\text{moles } PO_4^{3-}}{\text{day}} * 0.9 * \frac{1 \text{ mole struvite}}{1 \text{ mole } PO_4^{3-}} = 1.836 \frac{\text{moles struvite}}{\text{day}} \quad \text{Eq. 44}$$

$$1.836 \frac{\text{moles struvite}}{\text{day}} * \frac{245.4 \text{ g struvite}}{1 \text{ mol struvite}} * \frac{1 \text{ kg}}{1000 \text{ g}} * \frac{365 \text{ days}}{\text{yr}} = 164 \frac{\text{kg struvite}}{\text{yr}} \quad \text{Eq. 45}$$

2512 10.1.3 Mg(OH)₂ consumption

2513 Using the aforementioned molar ratio between magnesium hydroxide and phosphate, the
2514 required base per year is calculated:

$$2.04 \frac{\text{moles } PO_4^{3-}}{\text{day}} * \frac{1.5 \text{ moles } Mg(OH)_2}{1 \text{ mole } PO_4^{3-}} * \frac{58.32 \text{ g } Mg(OH)_2}{1 \text{ mole } Mg(OH)_2} * \frac{1 \text{ kg}}{1000 \text{ g}} * \frac{365 \text{ days}}{\text{yr}} \\ = 64.99 \frac{\text{kg } Mg(OH)_2}{\text{yr}} \quad \text{Eq. 46}$$

2515 10.1.4 Electricity demand

2516 Finally, the electricity demand is calculated as it will be necessary to obtain the struvite reactor's
2517 OPEX. Struvite reactors have an energy consumption of around 2.2 kWh per each kilogram of
2518 recovered phosphorus (Ostara Nutrient Recovery Technologies Inc., Vancouver, Canada).

$$1.84 \frac{\text{moles struvite}}{\text{day}} * \frac{1 \text{ mole TP}}{1 \text{ mole } PO_4^{3-}} * \frac{30.97 \text{ g TP}}{1 \text{ mole TP}} * \frac{1 \text{ kg}}{1000 \text{ g}} * \frac{365 \text{ days}}{1 \text{ yr}} \\ = 20.45 \frac{\text{kg TP recovered}}{\text{yr}} \quad \text{Eq. 47}$$

$$20.45 \frac{\text{kg TP recovered}}{\text{yr}} * \frac{2.2 \text{ kWh}}{\text{kg}} = 45 \frac{\text{kWh}}{\text{yr}} \quad \text{Eq. 48}$$

2519 10.1.5 Reactor volume

2520 Assuming a reactor volume of 3.5 hours, which is sufficient for the obtention of struvite (Tarragó
2521 et al., 2016), the required volumes can be calculated with each building's influent flow [m³/day] to
2522 the equipment by:

$$V = \text{Influent flow} * 3.5 \text{ h} * \frac{1 \text{ day}}{24 \text{ h}} \quad \text{Eq. 49}$$

2523 The dimensions of the reactor can be obtained if a ratio between its diameter and height is set.
2524 In this study, a 1:4 correlation is taken to match with average struvite reactor models. Solving the
2525 system posed by Eq. 50 and Eq. 51 yields the diameter and height of the reactor:

$$V = \pi * \frac{D^2}{4} * h \quad \text{Eq. 50}$$

$$h = 4 * D \quad \text{Eq. 51}$$

2526 By calculating the section area of the reactor, the ascensional velocity of the fluid is found, which
 2527 allows to apply Stokes' law and calculate the terminal diameter [m] of the struvite particles using
 2528 Eq. 52 and Eq. 53. **Error! Reference source not found.** shows the characteristics of the influent
 2529 needed for the application of Stokes' law.

$$v = \frac{Q}{A} \quad \text{Eq. 52}$$

$$d_p = \left(\frac{v * 18 * \mu}{g * (\rho_s - \rho_l)} \right)^{\frac{1}{2}} \quad \text{Eq. 53}$$

2530

2531 *Table S10-1:: Parameters for the application of Stokes' law in the struvite reactor.*

Struvite reactor		Units	Value
Solid density	ρ_s	kg/m ³	1700
Liquid density	ρ_l	kg/m ³	995.65
Gravity	g	m*s ²	9.81
Viscosity	μ	kg*m ⁻¹ *s ⁻¹	7.978E-4

2532 *10.1.6 Decanter volume*

2533 The decanter volume is also obtained through Stokes' law. It is sized to separate and recirculate
 2534 particles half the size of those not eliminated in the reactor:

$$u_T = \frac{1}{18} * \frac{\left(\frac{d_p}{2}\right)^2 * g * (\rho_s - \rho_l)}{\mu} \quad \text{Eq. 54}$$

2535 By fixing a retention time of 1h (S. Puig, personal communication, 2017), the dimensions of the
 2536 decanter can be determined by Eq. 55, where h is the hight [m], v is the velocity [m/s] and t is the
 2537 retention time [s] Considering the retention time equal to the settling velocity, Eq. 56 gives the
 2538 volume of the decanter in m³ when knowing the influent flow [m³/day]. The diameter [m] can be
 2539 found through Eq. 57. The final values obtained for each building type can be found:

$$h = v * t \quad \text{Eq. 55}$$

$$V = \text{Influent flow} * 1h * \frac{1 \text{ day}}{24 h} \quad \text{Eq. 56}$$

$$V = \pi * \frac{D^2}{4} * h \quad \text{Eq. 57}$$

2540

2541 Table S10-2: Characteristics of the struvite reactors and decanters (V1).

	LR	ST	MR	MHR	HR
<i>moles NH₄⁺/day</i>	1.04	1.04	5.19	10.37	25.94
<i>moles (PO₄)₃-/day</i>	0.20	0.20	1.02	2.04	5.09
<i>g N-NH₄⁺/m³ effluent</i>	221.88	221.88	221.88	221.88	221.88
<i>g TN /m³ effluent</i>	560.21	560.21	560.21	560.21	560.21
<i>moles (PO₄)₃- reacted/day</i>	0.02	0.02	0.10	0.20	0.51
<i>g P-PO₄³⁻/m³ effluent</i>	11.69	11.69	11.69	11.69	11.69
<i>g TP/m³ effluent</i>	57.17	57.17	57.17	57.17	57.17
<i>Struvite production (kg/yr)</i>	16.41	16.41	82.04	164.08	410.19
<i>Mg(OH)₂ consumption (kg/yr)</i>	6.50	6.50	32.49	64.99	162.47
<i>Electricity demand (kWh/yr)</i>	4.56	4.56	22.78	45.55	113.89
<i>Reactor volume (m³)</i>	7.86E-03	7.86E-03	3.93E-02	7.86E-02	1.97E-01
<i>Reactor diameter (m)</i>	1.35E-01	1.35E-01	2.32E-01	2.92E-01	3.97E-01
<i>Reactor height (m)</i>	5.40E-01	5.40E-01	9.28E-01	1.17E+00	1.59E+00
<i>v (m/s)</i>	4.36E-05	4.36E-05	7.38E-05	9.32E-05	1.26E-04
<i>d_p (m)</i>	9.41E-06	9.41E-06	1.22E-05	1.38E-05	1.60E-05
<i>u_t (m/s)</i>	1.09E-05	1.09E-05	1.84E-05	2.33E-05	3.15E-05
<i>Decanter volume (m³)</i>	2.25E-03	2.25E-03	1.12E-02	2.25E-02	5.61E-02
<i>Decanter height (m)</i>	3.92E-02	3.92E-02	6.63E-02	8.37E-02	1.13E-01
<i>Decanter diameter (m)</i>	2.70E-01	2.70E-01	4.64E-01	5.84E-01	7.94E-01

2542 10.1.1 CAPEX and OPEX

2543 The CAPEX of the struvite reactor and the decanter can be divided in two groups, including
2544 equipment costs and construction costs.

2545 The former is usually found around 0.76\$/L of reactor, while the latter can be estimated at around
2546 0.53\$/L of reactor (Etter et al., 2011). Total CAPEX are those of 1.295 \$/L tank for both the reactor
2547 and the struvite decanter (Eq. 58).

2548 OPEX, on the other hand, depend on the consumption of magnesium hydroxide [kg] and
2549 electricity demand of the installation [kWh], as seen in Eq. 59. Total costs are shown in **Error!**
2550 **Reference source not found..**

$$CAPEX = (V_{reactor} + V_{decanter}) * 1.295 \quad \text{Eq. 58}$$

$$OPEX = 0.2525 * \text{required Mg(OH)}_2 + 0.13 * \text{electricity demand} \quad \text{Eq. 59}$$

2551 Table S10-3:: CAPEX and OPEX of the struvite reactors and decanters for all building types (V1).

CAPEX Reactor	CAPEX Decanter	CAPEX Total (\$)	OPEX Total (\$/yr)
---------------	----------------	------------------	--------------------

LR	10.18	2.91	13.09	2.23
ST	10.18	2.91	13.09	2.23
MR	50.90	14.54	65.44	11.17
MHR	101.79	29.08	130.88	22.33
HR	254.48	72.71	327.19	55.83

Table S10-4: Information regarding the final struvite reactors and decanters for the city block scenario

Struvite Production	Influent conditions mg/L (BrW+YW+FW)	Influent/Effluent volume total
	Influent mg/L	Effluent mg/L
COD	660.39	660.39
BOD	0.00	0.00
TN	101.89	86.82
NH₄-N (TAN: Total ammonia N, NH₃+NH₄⁺)	84.88	69.80
TP	51.46	18.11
TSS	220.29	220.29
VSS	125.83	125.83
Parameters		
moles NH₄⁺/day	168.29	
moles (PO₄)₃⁻/day	33.21	
g N-NH₄⁺/m³ effluent	69.80	
g TN /m³ effluent	86.82	
moles (PO₄)₃⁻ reacted/day	3.32	
g P-PO₄₃⁻/m³ effluent	3.71	
g TP/m³ effluent	18.11	
Struvite production (kg/yr)	2677.11	
Mg(OH)₂ consumption (kg/yr)	1060.37	safety factor (*2.5)
Electricity demand (kWh/yr)	743	1,858

Table S10-5:: Information regarding the final struvite reactors and decanters for the city block scenario

Reactor volume (m³)	4.05
D	1.09
h	4.35
A	0.93
v	3.45E-04
dp	2.65E-05
ut	8.62E-05
Decanter volume (m³)	1.16
h	0.31
D	2.18

CAPEX	
CAPEX reactor (€)	5,242.31
CAPEX decanter (€)	1,497.80
CAPEX total (€)	6,740.11
OPEX	
OPEX total (€/yr)	443.83
Benefits	
0.36	€/kg struv
974.47	€/yr

2559

2560

11 Yellow Water

The Yellow Water (YW) treatment is focused on Nutrient Recovery. The YW line is specifically designed to maximize nutrient recovery from urine. A key concern is urea hydrolysis, which can potentially cause odours, phosphorus loss (due to precipitation), and ammonia loss (through evaporation) (Chen et al., 2017). To address this, we employ controlled hydrolysis via an electrochemical cell coupled with a crystallizer (De Paepe et al., 2020a). First, we assumed that the urea in the urine will be allowed to hydrolyze, resulting in the production of ammonia and bicarbonate. As a result of the pH increase associated with this process, the precipitation of struvite and other minerals (e.g., Mg, Ca, K, and Na salts; Maurer et al., 2006) occurs, increasing the risk of clogging pipes and equipment. Odor nuisance, ammonia loss through volatilization are other challenges associated with urea hydrolysis (Christiaens et al., 2017; De Paepe et al., 2020; De Paepe et al., 2020b Maurer et al., 2006; Rossi et al., 2009). To avoid the need to add chemicals (i.e., caustics, acids) to inhibit microbial activity and thus prevent urea hydrolysis, an electrochemical cell similar to the unit proposed by De Paepe et al. (2020) was included. This provides controlled hydrolysis within the system, stabilizing the urine without requiring chemical additives. We expect the following outcomes:

- **Efficient Nitrogen Conversion:** Total Nitrogen (TN) is effectively converted to Total Ammonium Nitrogen (TAN) with only about 3% loss expected.
- **COD Removal:** Significant reduction of organic matter (COD) for a cleaner effluent.
- **Nutrient Recovery:** We anticipate recovering 30% of phosphate, leading to an overall 22% recovery rate of Total Phosphorus (TP).

Precipitation of around 30% of phosphates mainly as calcium phosphate is expected in the cell, while the resulting stream is directed to a MABR for nitrification. After stabilization, the effluent undergoes complete nitrification in a Membrane Aerated Biofilm Reactor (MABR). This produces a nitrite concentrate (0.15L per L of urine) with minimal COD content. The design relies on urine being collected separately. Holding containers are distributed strategically to ensure proper collection (van Vliet et al., 2010). Combining the electrochemical cell and MABR provides a compact, low-chemical approach ideal for extreme decentralization. Its adaptability makes it attractive for challenging scenarios, even space applications (De Paepe et al., 2020a; Zhan et al., 2022). The recovered concentrate from the urine treatment train is used in the vertical farm in conjunction with the rest of harvested fertilizers. Urine holding containers are distributed among the buildings to ensure proper collection (van Vliet et al., 2010).

2595 **11.1 MABR**

2596 For the scenario involving urine source-separation, an MABR is included to achieve the
2597 nitrification of urine.

2598 **11.1.1 Liquid fertilizer recovery**

2599 The liquid fertilizer volume obtained is calculated expecting 15% of the initial collected volume of
2600 urine is recovered in the concentrate (De Paepe et al., 2018). The price of fertilizer recovered
2601 from urine is around 10.5 \$/L according to *Chipako and Randall, 2020*.

2602 **11.1.2 CAPEX and OPEX**

2603 CAPEX are obtained from literature data and assumed to be 732 \$/m³d (Casey et al., 2008).
2604 OPEX are calculated from small-scale MABR observed annual power demand values (3.4
2605 kWh/PE) assuming an average electricity cost of 0.13\$/kWh (Gritti, 2019).

2606 *Table S11-1.: CAPEX and OPEX for the MABR employed for the nitrification of urine (US\$).*

	CAPEX (\$)	OPEX (\$/yr)
LR	9	5
ST	9	5
MR	46	27
MHR	92	53
HR	231	133

2607 **11.2 Uridis cell**

2608 The stabilization of urine in the scenario where it is source-separated is carried out in an
2609 electrochemical cell coupled with a crystallizer (Uridis cell, Hydrohm).

2610 The cell allows to increase the pH of urine due to the release of hydroxyl ions in the cathode of
2611 the cell, which causes the precipitation of salts (collected in a consecutive crystallizer), and hence
2612 the scaling potential of the flow is reduced (URIDIS technology, www.hydrohm.com). Phosphates
2613 in urine precipitate with calcium and magnesium, allowing for the recovery of the nutrient.
2614 Furthermore, water in the anode is acidified creating a potential cleaning and sanitizing flow for
2615 the toilets, membranes, and electrodes. Thus, pathogen presence and unpleasant odor can be
2616 avoided. The treated urine is collected and sent to the next stage of treatment. The authors
2617 propose the use of MABR to carry out the nitrification of ammoniacal nitrogen yielding a liquid
2618 solution which can be valorized as fertilizer (De Paepe, 2020; De Paepe et al., 2020a).

2619

11.2.1 Phosphorus recovery

30% of phosphates in urine were expected to be recovered in the form of mainly calcium phosphate precipitates (De Paepe et al., 2020), which are sold at a price of 0.3 \$/kg (Etter et al., 2011). An example on how to calculate the total mass of calcium phosphate recovered in the HR building for the USS scenario is shown in Eq. 60 and Eq. 61.

$$1.7575 \frac{\text{moles } PO_4^{3-}}{\text{day}} * 0.9 * \frac{1 \text{ mole } Ca_3(PO_4)_2}{2 \text{ mole } PO_4^{3-}} = 0.791 \frac{\text{moles } Ca_3(PO_4)_2}{\text{day}} \quad \text{Eq. 60}$$

$$0.791 \frac{\text{moles } Ca_3(PO_4)_2}{\text{day}} * \frac{310,18 \text{ g } Ca_3(PO_4)_2}{1 \text{ mol } Ca_3(PO_4)_2} * \frac{1 \text{ kg}}{1000 \text{ g}} * \frac{365 \text{ days}}{\text{yr}} = 89.54 \frac{\text{kg struvite}}{\text{yr}} \quad \text{Eq. 61}$$

11.2.2 CAPEX and OPEX

CAPEX ARE estimated at 150 \$/PE while OPEX ARE calculated from an annual energy consumption of 13 kWh/PE (Personal communication, K. Rabaey).

Table S11-2: CAPEX and OPEX for the electrochemical (Uridis) cell (USS).

	CAPEX (\$)	OPEX (\$/yr)
LR	1800	20
ST	1800	20
MR	9000	101
MHR	18000	203
HR	45000	507

Table S11-3: Design parameters of the Urine-Diverting system.

Urine containers (final waste)		
Number of containers per building according to Vliet		
TYPE 9	2.00	containers/building
Cost of urine storage 1 m3	1,500.00	€
Number of containers total	16.00	m3
CAPEX (€)	24,000.00	
OTR	10	gO2m2/d
Packing density	500	m2/m3
Oxygen demand	26.31	kg/day
Membrane required	2.63	m2/m3
Volume of MABR tank	5.26E-03	m3

$SA_{mem} = \frac{O_{2,Dem} \times 1000}{OTR}$	$O_{2,Dem} = Q_{ww} \times \frac{(C_{COD,in} + C_{N-NH_4,in} \times 4.6)}{1000}$	
Nº wc/hh	1.00	
Nº wc/total	833.33	
Urine diverting toilets		
Vliet et al.	450.00	€/wc
Laufen save!	1,200.00	€/wc
CAPEX (€)	375,000.00	
Volume of cell	7	l
Number of cells	833.33	
Volume of total cells	5,833.33	l
	5.83	m3

2631

2632

2633 11.2.3 Yellow Water Piping

2634 *Table S11-4: Design parameters of the Urine-Diverting sewer.*

YW sewer	
Hab	2,000.00
Hab/building	250.00
Number eq household	104.17
A (floor surface per storey)	670.00
ρ	0.16
f2	1.44
Pipeline m	158.51
Number of storeys	11.19
CAPEX (€)	91,751.44
OPEX (€/yr)	215.57
mm diameter, HDPE pipe	32.00
€/m	72.36
€/m*yr	0.17
PE/house	2.40
€/PE CAPEX	33.00
€/PE*yr OPEX	1.13

2635

2636

Table S11-5: Capital expenses [CapEx] breakdown of costs for decentralized wastewater treatment alternative. The yellow-shaded area highlights the treatment CapEx costs related to the yellow water piping.

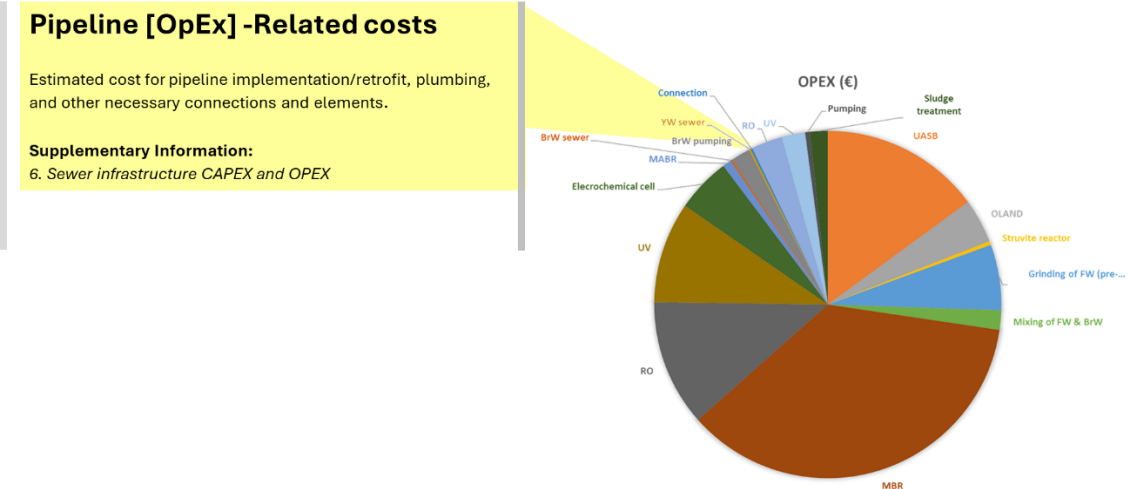
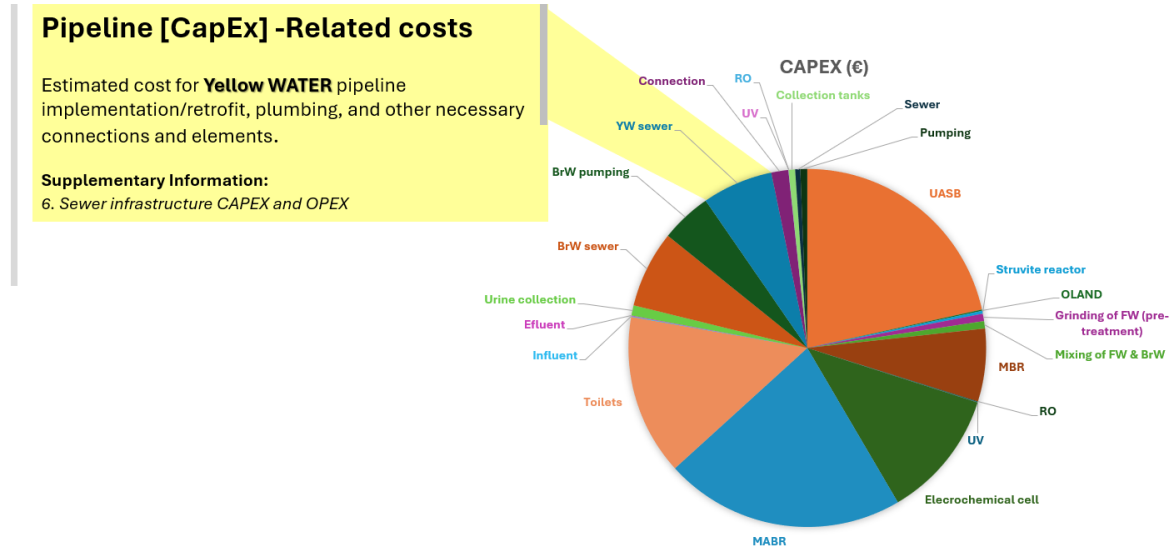


Table S11-6: Operational expenses [OpEx] breakdown of costs for decentralized wastewater treatment alternative. The yellow-shaded area highlights the treatment OpEx costs related to the yellow water piping.

11.3 Yellow Water Line – LCA

11.3.1 Yellow Water – LCA: Construction

The construction of the electrochemical cell is guided by the study of De Paepe et al. (2020). Here's a breakdown of the materials used:

- Capacity: Designed for one toilet per household, the EC has a total volume of 1.3 m3 with a 7 L cell per toilet.
- Cell Body: Made of polymethyl methacrylate (PMMA) with a wall thickness of 3 mm.
- Ion Exchange Membrane: Polystyrene-based with a thickness of 0.45 mm, in line with typical commercial models.
- Electrodes:
 - Anode: Graphite
 - Cathode: Stainless steel
- Anolyte/Catholyte Vessels: Constructed of glass with an expected lifespan of 30 years.
- Lifespan: The majority of the EC components are designed to last 10 years without replacement.

Table S11-7: Inventory details for the construction of the treatments and processes included in the YW line. Tables in the construction inventory refer to the total amount of materials of components needed to build the decentralized system for the water treatment for the reference population of 300 people.

Element	Amount	Unit	Material	Life span (years)	Ecoinvent dataset	
EC cell, body	24.98	kg	Polymethyl methacrylate	10	market for polymethyl methacrylate, beads	GLO
EC cell, ion exchange membrane	0.03	kg	Polystyrene	10	market for polystyrene, general purpose	GLO
EC cell, anode	1.26	kg	Graphite	10	market for graphite	GLO
EC cell, cathode	0.00	kg	Stainless steel	10	market for steel, chromium steel 18/8	GLO
EC, anolyte	0.37	kg	Glass	30	market for flat glass, uncoated	RER
EC cell, catholyte	0.51	kg	Glass	30	market for flat glass, uncoated	RER
EC, urine tank	175.00	kg	Fibreglass	30	glass fibre reinforced plastic, polyester resin, hand lay-up	GLO
EC, water tank	150.00	kg	PVC	30	market for polyvinylchloride, suspension polymerised	GLO
MABR, membrane	89.20	kg	Silicone rubber	10	market for silicone product	RER
MABR, module housing	13.64	kg	PVC	10	market for polyvinylchloride, suspension polymerised	GLO
MABR, recirculation modules	6.57	kg	Glass	30	market for flat glass, uncoated	RER
MABR, recirculation pump	0.38	unit	-	18	market for pump, 40W	GLO

11.3.1 Yellow Water – LCA: Operation

The electricity requirements of the EC cell and the MABR are 13.5 kWh*PE-1*yr-1 and 3.88 kWh*PE-1*yr-1, respectively (Hydrohm, Ghent, Belgium; Gritti, 2019; Zhai et al., 2023).

Hydrogen gas and carbon dioxide are produced in the EC, and a small percentage of nitrogen is lost through denitrification. Hydrogen generates current calculated through Eq. 10, where CE is the coulombic efficiency, which takes an average value of 0.37 (De Paepe et al., 2020), Q is the flowrate [L/d], and Current generated is expressed in amperes. As observed, the amount of produced electricity can be neglected.

$$Current_{generated} = CE * (COD_{in} - COD_{out}) * Q * \frac{4 \frac{mol e^-}{mol O_2} * 96.485 \frac{C}{mol e^-}}{32 \frac{g O_2}{mol O_2} * \frac{(24 * 60 * 60)s}{d}} \quad Eq. 10$$

Low nitrogen loss takes place in the MABR. N₂O emissions are estimated using a 0.005% emission factor with respect to influent nitrogen load (Kinh et al., 2017). CO₂ emissions are calculated considering 0.6 kg CO₂*m-3 from an influent load of 2000 mg COD/L and operation with mixed bacteria (Tawfik et al., 2010; Zhang et al., 2022). NaOH addition is required to maintain pH in the MABR to compensate for ammonia loss and enable full nitrification. Assuming a requirement of 1 mol of OH⁻ per mol of nitrogen (De Paepe et al., 2021), the amount of a 0.5 M NaOH solution needed is calculated. pH control is also needed during the collection of urine, to increase from pH 8 to 11 and avoid nitrogen loss in the collection tank (De Paepe et al., 2020).

Table S11-8: Inventory details for the annual operation of the grey water line (FU: water treatment for 300 people during a year).

Element	Amount	Unit	Ecoinvent dataset	
EC, electricity	4050.00	kWh	market group for electricity, low voltage	RER
EC, produced electricity	0.95	kWh	market group for electricity, low voltage	RER
EC, CO ₂ emissions to air	1.37	kg	Carbon dioxide, fossil, emissions to air	-
MABR, electricity	1,164.00	kWh	market group for electricity, low voltage	RER
EC, CO ₂ emissions to air	3.35	kg	Carbon dioxide, fossil, emissions to air	-
MABR, N ₂ O emissions to air	0.05	kg	Dinitrogen monoxide, emissions to air	-
MABR, NaOH	2,804	kg	sodium hydroxide, without water, in 50% solution state	GLO
Urine collection, NaOH	4.59	kg	sodium hydroxide, without water, in 50% solution state	GLO

2689 **12 Rain harvesting**

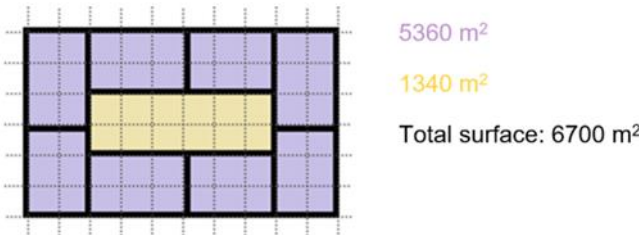
2690 **12.1 Rainwater collection area**

2691 The rainwater collection and treatment system mirror a portion of the reuse layout for high-quality
2692 results. It includes the following components:

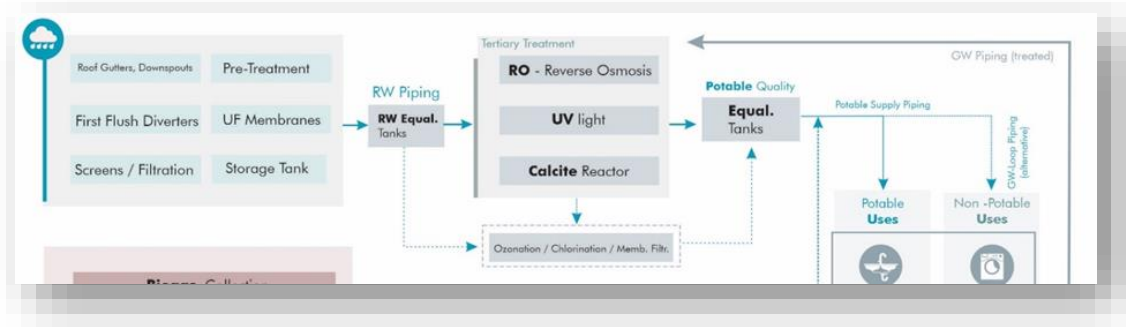
- 2693 ▪ **UF (Ultrafiltration):** Provides an initial barrier against pollutants.
- 2694 ▪ **RO (Reverse Osmosis):** Removes over 90% of a wide range of contaminants,
2695 ensuring water quality.
- 2696 ▪ **UV Disinfection:** Eliminates pathogens for safety.
- 2697 ▪ **Remineralization:** A calcite bed contactor adjusts mineral content for taste and
2698 consistency with traditional drinking water (Garfí et al., 2016; Mohamed Ghali et al.,
2699 2017).

2700 The combination of RO and UV is widely used in potable reuse schemes, representing a proven
2701 and reliable treatment approach (Jeffrey et al., 2022). To accommodate the treatment process,
2702 the system includes 15m³ collection and potable water holding tanks (lined with PVC and FPP).
2703 While we could optimize tank sizing based on local rainfall, we've standardized this component
2704 across scenarios for a fairer comparison in our impact assessment. Since the tanks' contribution
2705 to the overall impact is likely minor, this simplification has minimal effect on the study's findings.
2706 This study considers the scale of a city block of eight high-rise buildings, with 670 sq. meter roof
2707 surface per one building, each with 12 stories. The city block has a total surface area of 6700 sq.
2708 meters. This study assumes that 80% of the area could be available for the collection of water.

- 2709 ▪ N° of buildings: 8;
- 2710 ▪ Area per building: 670 sq meter;
- 2711 ▪ Area inside: 1,340 sq meter;
- 2712 ▪ Total surface area 6,700 sq meter:



2714 Rainwater treatment employed a combination of pre-filters, such as downspout diverters and first
2715 flush filters (RainHarvestSystems.LLC, 2021), in-tank filtration, RO followed by UV treatment
2716 combination. The rainwater disinfection and treatment systems were selected from among the
2717 smallest models available.

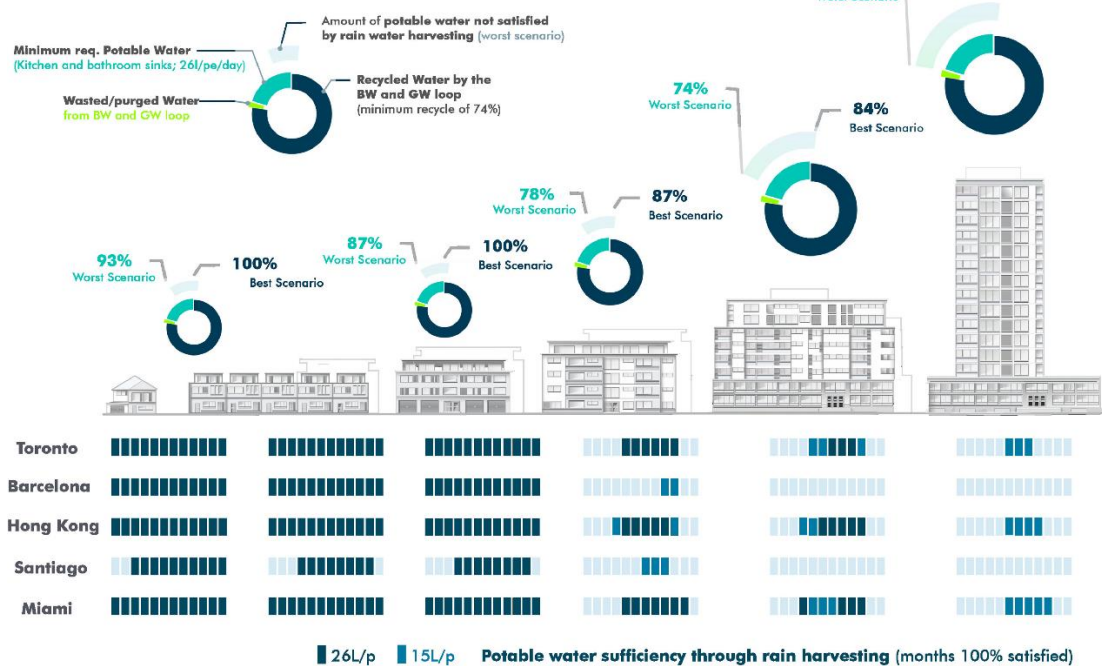


2718

2719 12.1.1 Rain harvesting potential.

2720 To estimate the supply of rainwater (m³/month), average monthly rainfall (mm) data was extracted
 2721 from Climate Data Org (2021). The authors acknowledge that rainfall regimes and overall extreme
 2722 variability are being impacted by climate change (IPCC, 2022, IPCC, 2021; Slater et al., 2021;
 2723 UNEP, 2021) and that estimates based on historic averages or return periods might be inaccurate
 2724 in the coming decades. To assess the potential of rainwater systems to complement the existing
 2725 access to a centralized water supply, it would be more appropriate to consider a particularly dry
 2726 period (e.g., the driest year in a 20- or 50-year period). Nevertheless, according to the latest IPCC
 2727 report, this approach could be very short-lived as extreme variability is expected to change
 2728 drastically in the upcoming decades (IPCC, 2022). Future studies on rainwater capture capacity
 2729 should include these most recent forecasts. Furthermore, other options for storing precipitation
 2730 generated by shorter, more intense storms (e.g., managed aquifer recharge) should be
 2731 considered.. For this analysis, five cities were selected to cover a variety of climates according to
 2732 the Köppen-Geiger climate classification, which considers temperature and precipitation patterns:
 2733 i) Miami (North America), which exhibits an equatorial climate; ii) Santiago de Chile (South
 2734 America), which was representative of an arid climate; iii) Barcelona (Europe), which has
 2735 Mediterranean climate with a dry summer; iv) Hong Kong (Asia), which is a warm climate with dry
 2736 winters; and v) Toronto (North America) which is a representative temperate climate zone.
 2737 Precipitation patterns (i.e., average monthly values) are included for each case study in the SI
 2738 section

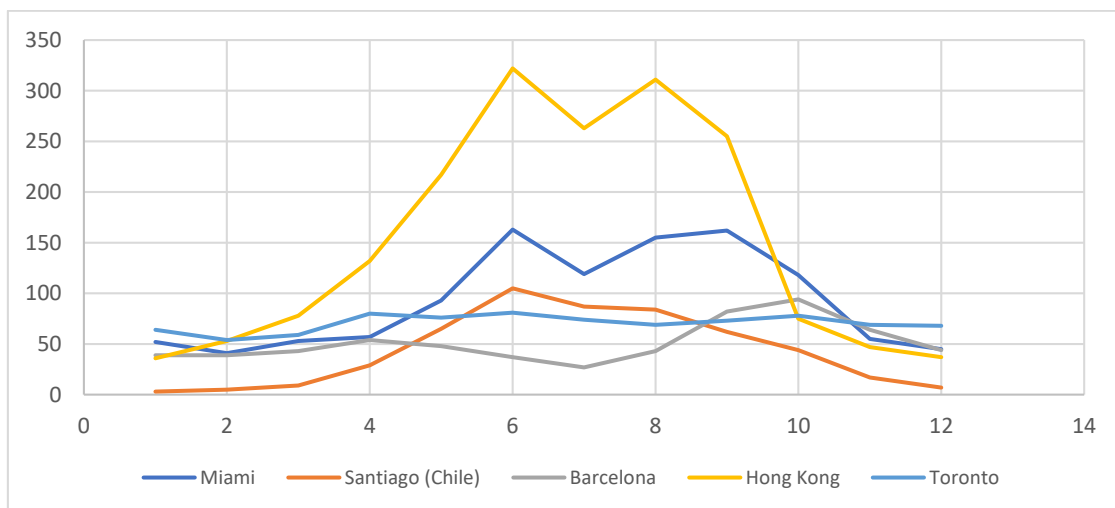
Percentage reduction in water consumption (%)



2739

2740

2741 Rainfall values were multiplied by the roof surface of each dwelling type (m²), and a correction
 2742 factor for roof losses of 0.9 was included. Drinking water demands and rainwater accumulations
 2743 were estimated for each type of building and location. Rainwater accumulated in the storage tanks
 2744 was carried over to between months.



2745

2746 *Table S12-1: Monthly rainfall (Climate Data Org) (mm). Detailed analysis for each city depending on the*
 2747 *different rain patterns in the various climatic regions,*

2748

2749

12.2 Rainwater Line - LCA

12.2.1 Rainwater Line – LCA: Construction

The rainwater treatment system begins with a PDVF Out-in UF membrane module with a stainless-steel cassette, which is a scalable and compact technology from Dow Chemical that does not require construction work for installation. The RO and UV units of the RW line are sized based on the monthly demand of potable water, considering that it is only distributed for 28 days. This ensures that the system can cover demand peaks during periods of sufficient rainfall.

Remineralization is carried out in a calcite bed with a residence time of 8 minutes. The contactor is made of fiberglass and has a total volume of 92 L, with a bed volume of 40 L. The lifespan of the fiberglass shell is 30 years, while the liner needs to be replaced every 15 years.

Finally, the treated rainwater is stored in two steel tanks, each with a volume of 15 m³. The rainwater tank has a PVC liner, while the potable water tank has an FPP liner. Both liners have a thickness of 0.15 mm and need to be replaced every 15 years.

Table S12-2: Table summarizing the key components of the rainwater treatment system. Tables in the construction inventory refer to the total amount of materials of components needed to build the decentralized system for the water treatment for the reference population of 300 people (Barnosell, 2023).

Component	Material	Size	Lifespan
PDVF Out-in UF membrane module	Stainless steel	Scalable, compact	N/A
RO and UV units	N/A	Sized based on monthly demand (28 days distribution)	N/A
Remineralization contactor	Fiberglass	1 m height, 0.34 m diameter, 92 L total volume, 40 L bed volume	30 years (shell), 15 years (liner)
Rainwater tank	Steel	15 m ³	Liner: 15 years
Potable water tank	Steel	15 m ³	Liner: 15 years

Table S12-3: Inventory details for the construction of the treatments and processes included in the RW line. Tables in the construction inventory refer to the total amount of materials of components needed to build the decentralized system for the water treatment for the reference population of 300 people (Barnosell, 2023).

Element	Amount	Unit	Material	Life span (years)	Ecoinvent dataset	
UF membrane	1.87	kg	PVDF	15		
UF, PDVF (hydrogen)	0.22	kg	Hydrogen	-	market for hydrogen, gaseous	GLO
UF, PDVF (electricity)	170.63	kWh	-	-	market group for electricity, medium voltage	RER
UF, PDVF (hydrogen chloride emissions to air)	0.85	kg	Hydrogen chloride	-	Hydrochloric acid, emissions to air	-
UF, PDVF (hydrogen emissions to air)	0.14	kg	Hydrogen	-	Hydrogen, emissions to air	-
UF, PDVFP (heat emissions to air)	40.15	MJ	-	-	Heat, waste, emissions to air	-
UF, PDVF (hydrogen chloride emissions to water)	0.84	kg	Hydrogen chloride	-	Hydrochloric acid, emissions to water	-
UF membrane cassette	12.50	kg	Stainless steel	30	market for steel, chromium steel 18/8	GLO
RO unit for RW	0.88	m ²	-	5	market for seawater reverse osmosis module	GLO
UV unit for RW	1.00	unit	-	5	market for ultraviolet lamp, for water disinfection	GLO
Calcite bed, tank	0.25	kg	Fibreglass	30	glass fibre reinforced plastic, polyester resin, hand lay-up	GLO
RW holding tank	356.04	kg	Steel	30	market for steel, low-alloyed	GLO
RW holding tank, liner	6.07	kg	PVC	15	market for PVC, suspension polymerised	GLO
Potable water holding tank	356.04	kg	Steel	30	market for steel, low-alloyed	GLO
Potable water holding tank, liner	4.15	kg	FPP	15	market for polypropylene, granulate	GLO

12.2.1 Rainwater Line – LCA: Operation

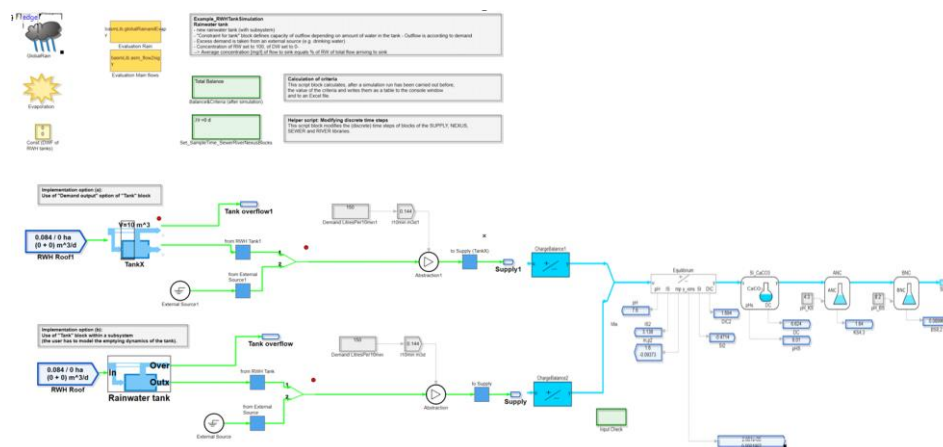
The energy demand in the rainwater line comes from the UF membrane (0.065 kWh*m-3), the RO unit (0.6 kWh*m-3), and the UV module (0.1 kWh*m-3) (Al Hawari et al., 2020; Giammar et al., 2022; Glover et al., 2022; Tow et al., 2021). Additionally, the addition of 0.12 kg CaCO3 per cubic metre for remineralization is required (Garfí et al., 2016).

Table S12-4: Inventory details for the annual operation of the grey water line (FU: water treatment for 300 people during a year). (Barnosell, 2023).

Element	Amount	Unit	Ecoinvent dataset	
UF, electricity	Specific for each scenario	kWh	market group for electricity, low voltage	RER
RO, electricity		kWh	market group for electricity, low voltage	RER
UV, electricity		kWh	market group for electricity, low voltage	RER
CaCO ₃ , remineralization		kg	market for calcium carbonate, precipitated	RER

12.3 Rainwater Harvesting – Modelling

The rainwater treatment module, also created in SIMBA#, estimates the collection and storage of rainwater and calculates the water quality parameters. The model simulates the redirection of harvested flows into designated rain tanks, accounting for different rain patterns in various climatic regions. The harvested water is stored for later use and goes through pre-filters, in-tank filtration, reverse osmosis (RO), and a tailored UV treatment combination. The model supports the analysis of the mixing of two different potable water sources, centralized supply and treated roof-harvested water. It enables the control of drinking water quality, speciation and the calculation of parameters such as buffering capacities, ionic strength, alkalinity, hardness, and calcite saturation. The space requirements for this module are estimated at 20-40 m³, primarily due to storage tanks, which can vary based on storage goals or capabilities, along with equalization tanks (30 m³), while the required equipment occupies less than 2-3 m³.



12.4 Rainwater line - LCA

The energy demand in the rainwater line comes from the UF membrane (0.065 kWh*m-3), the RO unit (0.6 kWh*m-3), and the UV module (0.1 kWh*m-3) (Al Hawari et al., 2020; Giammar et al., 2022; Glover et al., 2022; Tow et al., 2021). Additionally, the addition of 0.12 kg CaCO3 per cubic metre for remineralization is required (Garfí et al., 2016). The rainwater line is sized for each of the site-specific scenarios (see Scenarios).

Table S12-5: Inventory details for the annual operation of the grey water line (FU: water treatment for 300 people during a year).

Element	Amount	Unit	Ecoinvent dataset
UF, electricity	Specific for each scenario	kWh	market group for electricity, low voltage
RO, electricity		kWh	market group for electricity, low voltage
UV, electricity		kWh	market group for electricity, low voltage
CaCO ₃ , remineralization		kg	market for calcium carbonate, precipitated

12.5 Droughts and Rain harvesting

Rainwater harvesting is used as one of the two potable water sources. The other source is the existing centralized supply. At times when rainwater is not enough, potable water is obtained from the existing supply. The decentralized system can provide more than 85% of the water demand (without considering the water for drinking). As indicated, the total potable demand could be satisfied if a direct potable reuse scheme was approved and all the water could be recycled, satisfying >95% of the potable water demand. Therefore, in cases where there is not enough rain, the decentralized will likely have the means to provide water to its residents. In contrast, the centralized water supply may struggle to find another source of water if reservoirs run dry and

groundwater is dwindling. Therefore, while the connection to a centralized system is not fully required, that connection is not expected to have a significant impact in metropolitan areas with an already existing infrastructure where tapping into the already existing centralized potable supply is easily available. It is important to note that no changes in the piping of the building are expected, as only the connection to the source of the potable water would change, which means that at ground level can be a connection to the centralized network of potable water or a connection to the purification systems treating rainwater (or grey water to potable reuse in drought scenarios). Both of these connections will likely be placed at ground level (close to the basement, service, or parking areas). In the case of new residential development far from metropolitan areas, we do expect some additional costs in bringing the centralized piping to those areas, and it will widely depend on distance, terrain, materials, and characteristics of the existing, and closest centralized system. For those scenarios, the presented alternative or a version completely tailored to those characteristics could be proposed and save these additional costs derived from a connection to a centralized source that may not be as reliable as the DSS itself.

12.6 Design flow of potable water

The design flow of potable water for 2000 residents is a conservative value of 50 cubic meters per hour. Assuming a moderate value of 250 l/d per resident. A safety factor of 2.5 is incorporated into our design flow calculations. This buffer ensures that even during peak demand periods, we meet the residents' essential needs.

The potable water design flow, and the corresponding multi-stage RO system, is based on established per capita consumption standards for residential populations. We have referenced regional benchmarks and adjusted estimates to account for water-efficient fixtures and potential conservation measures encouraged within our community. The multi-stage RO system was selected for its advanced water purification capabilities (see Figure 1), ensuring potable water quality meets or exceeds all relevant standards.

Table S12-6: Design configuration for RO and some of the design parameters of the rainwater treatment process flow.

RW						
RO						
*sizing according to demand, not rainfall (constant between countries; climate change; others)						
Influent	58.7	m3/d		CAPEX		
	2444.9	l/h				
	2.4	m3/h		€/membrane		173.6
	0.0	m3/min		CAPEX (equipment)		347.2
XLE-2521	1.4	m3/h				
Number of parallel membran	1.7	2.0		OPEX		
Parameters				€/m3		0.2
				OPEX €/day		10.0
Dimensions				OPEX €/yr		3641.0
Lenght (m)	0.5					
Diameter (m)	0.1					
Volume (m^3)	0.0					
Energy requirment	10923.0	kWh/yr				
Influent	46.9	m3/d		CAPEX		
	1956.0	l/h				
	2.0	m3/h		€/membrane		345.5
	0.0	m3/min		CAPEX (equipment)		276.4
11 GPM UV-SPH-11	0.0	m3/min				
Number of parallel membran	0.8	0.8		OPEX		
Parameters				€/m3		0.2
				OPEX €/day		7.5
Dimensions				OPEX €/yr		2741.5
Diameter (m)	0.1					
Lenght (m)	0.9					
Volume (m^3)	0.0					
Energy requirment	1884.8	kWh/yr				
Collection tanks						
	m3	m3 tank	Tank	Liner	CAPEX (€)	
Treated water	410.8	422.9	5195.0	2344.0	7539.0	
Collected water	410.8	422.9	5195.0	2344.0	7539.0	
*25% of demand (according to rainfall)						
Rain water Piping						
Pumping+FILTER						
	€/m3	Total				
CAPEX (€)	304.1	16114.7				
OPEX (€/yr)	10.4	553.3				
Hab	2000.0		32.0	mm diameter, HDPE pipe		
Hab/building	250.0		72.4	€/m		
Number eq household	104.2		0.2	€/m*yr		
A (floor surface per storey)	670.0		2.4	PE/house		
p	0.2		30.0	m2/PE		
f2	1.4					
Pipeline m	158.5					
Number of storeys	11.2					
Cost filter	425.0					
CAPEX (€)	11893.9					
OPEX (€/yr)	26.9	*Gutter and downpipes already installed (Domènech				
		**Calculated for all 8 buildings (joint collection: evacuation in 1 building)				

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2864 We've accounted for pre-treatment, membrane selection, energy optimization, and brine
2865 management within the RO design. Sufficient water storage tanks are included to account for
2866 fluctuations in rainwater availability. Sizing depends on projected demand, rainfall patterns, and

2867 the desired length of backup supply during dry periods. Our system features a robust rainwater
2868 collection scheme that optimizes capture from rooftops and suitable ground surfaces. Detailed
2869 meteorological data informs our rainfall catchment estimations, helping size the system
2870 appropriately.

2871 Our design process carefully considers a robust storage solution for rainwater. The storage tank's
2872 size is directly influenced by the following:

- 2873 ▪ **Design Flow:** The calculated potable water design flow for our community (discussed in
2874 a previous response).
- 2875 ▪ **Rainfall Variability:** Meticulous analysis of local rainfall patterns to understand periods
2876 when rainwater availability drops. (discussed in comment#9, #11, 11 and many others).
- 2877 ▪ **Buffer Time:** The desired length of time the stored water should cover potable needs in
2878 the absence of fresh rainfall.
- 2879 ▪ **System Flexibility:** Our design aims for a modular, scalable approach. This means the
2880 storage system could consist of multiple tanks or the potential for future expansion to
2881 adapt to evolving needs or climate uncertainty.

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13 Potable Water Treatment.

13.1 RO treatment for collected rainwater.

Even if rainwater is one of the lowest TDS water sources and should only really require particulate removal (MF) and disinfection, the overall picture is more complex. To ensure the safety and suitability of rainwater for drinking, especially for long-term consumption, RO is widely recognized as the most effective treatment option by leading authorities and specialized vendors. Studies of various entities, including the Centers for Disease Control and Prevention (CDC), the New South Wales government, and the University of Arizona, consistently highlight RO's superior ability to remove a broad spectrum of contaminants like bacteria, viruses, heavy metals, and even "forever chemicals" like PFAS, compared to other alternatives. While its higher initial cost and energy consumption are factors to consider, RO's consistent delivery of safe, high-quality drinking water, free from harmful contaminants, plus a potential upholding of public confidence in rainwater harvesting, could outweigh these concerns for many potable applications.

While we acknowledge that many scenarios could use simpler and more cost-effective technological configurations (e.g., pre-filtration, ultrafiltration, and UV are the easiest to implement), RO has been proven to be the safest and most effective under different types of scenarios where rainwater quality is of concern (Alim et al., 2020; Lee et al., 2017; Liu et al., 2021; Wang, 2014). This is particularly important as rainwater quality can vary significantly depending on factors like the local environment, roofing materials, birds, and collection methods (Gwenzi et al., 2015; Gikas & Tsihrintzis, 2012). Studies have shown that even seemingly clean rainwater can harbor contaminants exceeding recommended drinking water standards (Angrill et al., 2017; Lee et al., 2012). Therefore, while simpler and potentially cheaper options are available, guaranteeing the safety and potability of harvested rainwater often necessitates robust treatment methods like RO. This selection also relates to the previously discussed rationale behind choosing MBR for greywater treatment during the economic assessment. Though less cost-competitive compared to some alternatives, MBR represents a mature concept and reliable delivery, leading to a realistic analysis factoring in both cost and performance. Similarly, incorporating RO in rainwater treatment prioritizes two key objectives:

- Meeting the strictest drinking water standards in any scenario, regardless of local factors or potential contamination.
- Providing a comprehensive techno-economic assessment that considers non-ideal conditions and potential risks.

Therefore, while rainwater exhibits desirable qualities like low hardness and turbidity, and often meets WHO standards for nitrate and nitrite concentrations (Liu et al., 2021; Lee et al., 2017), its composition can be significantly altered throughout its journey from cloud to collection (Gwenzi et al., 2015). Roof, pipe, and tank materials can leach contaminants like lead, copper, arsenic, and

VOCs (Kim et al., 2023). Bird/rodent/insect excrement can introduce pathogens like bacteria and viruses, along with nutrients like nitrogen and phosphorus (Villagómez-Márquez et al., 2023). Surface runoff can further contribute heavy metals, PAHs, pesticides, and herbicides (Liu et al., 2021). Even organic matter and "forever chemicals" like PFAS have been found in rainwater, highlighting the diverse range of potential contaminants (Berthou et al., 2023; Kim et al., 2023, Villagómez-Márquez et al., 2023). This necessitates sophisticated treatment like reverse osmosis (RO) to guarantee rainwater's safety and suitability for consumption. While RO demands higher upfront investment and ongoing maintenance, its consistent delivery of safe, high-quality drinking water often outweighs these considerations, making it the preferred choice for many potable applications.

The MBR-RO-UV combination of technologies has been proved to eliminate bacteria and viruses (Friedler and Gilboa, 2010; Ghernaot et al., 2019; Tang et al., 2018). Close physical distances between treatment and equipment, as the proximity of feed to treated water tanks, could offer a chance for microbial transport (e.g., aerosols, cross-connections, etc.) (Bhattacharjee and Datta, 2019). The UV disinfection unit poses a barrier to the physical movement of bacteria and enhances microbial quality to ensure the resultant effluent represents no health risks. Periodical quality tests would be scheduled to avoid the growth of bacteria resistant to UV treatment, bacterial hopping, and regrowth. If elevated concentrations of viruses are detected in the recycled water, the UV fluence could be increased (Pullerits et al., 2020).

References:

Selected Entities:

US [CDC.gov].

- https://www.cdc.gov/healthywater/drinking/home-water-treatment/household_water_treatment.html
- [://efaidnbmnnnibpcajpcglclefindmkaj/https://www.cdc.gov/healthywater/pdf/drinking/Household_Water_Treatment.pdf](https://www.cdc.gov/healthywater/pdf/drinking/Household_Water_Treatment.pdf)

Australia (NSW Government)

- [://efaidnbmnnnibpcajpcglclefindmkaj/https://www.health.nsw.gov.au/environment/water/Documents/rainwater-treatment-guide.pdf](https://www.health.nsw.gov.au/environment/water/Documents/rainwater-treatment-guide.pdf)

University of Arizona

- [://efaidnbmnnnibpcajpcglclefindmkaj/https://extension.arizona.edu/sites/extension.arizona.edu/files/pubs/az1863-2021.pdf](https://extension.arizona.edu/sites/extension.arizona.edu/files/pubs/az1863-2021.pdf)

Rainwater Quality:

2962 ▪ Alim, M. A., Rahman, A., Tao, Z., Samali, B., Khan, M. M., & Shirin, S. (2020). Suitability
2963 of roof harvested rainwater for potential potable water production: A scoping review.
2964 Journal of cleaner production, 248, 119226.

2965 ▪ Angrill, S., Petit-Boix, A., Morales-Pinzón, T., Josa, A., Rieradevall, J., & Gabarrell, X.
2966 (2017). Urban rainwater runoff quantity and quality—A potential endogenous resource in
2967 cities?. Journal of Environmental Management, 189, 14-21.

2968 ▪ Gwenzi, W., Dunjana, N., Pisa, C., Tauro, T., & Nyamadzawo, G. (2015). Water quality
2969 and public health risks associated with roof rainwater harvesting systems for potable
2970 supply: Review and perspectives. Sustainability of Water Quality and Ecology, 6, 107-
2971 118.

2972 ▪ Lee, M., Kim, M., Kim, Y., & Han, M. (2017). Consideration of rainwater quality
2973 parameters for drinking purposes: A case study in rural Vietnam. Journal of environmental
2974 management, 200, 400-406.

2975 ▪ Gikas, G. D., & Tsihrintzis, V. A. (2012). Assessment of water quality of first-flush roof
2976 runoff and harvested rainwater. Journal of Hydrology, 466, 115-126.

2977 **Rainwater Technologies:**

2978 ▪ Liu, X., Ren, Z., Ngo, H. H., He, X., Desmond, P., & Ding, A. (2021). Membrane
2979 technology for rainwater treatment and reuse: A mini review. Water Cycle, 2, 51-63.

2980 ▪ Wang, W., Zhang, Y., Esparra-Alvarado, M., Wang, X., Yang, H., & Xie, Y. (2014). Effects
2981 of pH and temperature on forward osmosis membrane flux using rainwater as the makeup
2982 for cooling water dilution. Desalination, 351, 70-76.

2983 ▪ Lee, J. Y., Bak, G., & Han, M. (2012). Quality of roof-harvested rainwater—comparison of
2984 different roofing materials. Environmental pollution, 162, 422-429.

2985 **Rainwater PFAS:**

2986 ▪ Kim, Y., Pike, K. A., Gray, R., Sprankle, J. W., Faust, J. A., & Edmiston, P. L. (2023).
2987 Non-targeted identification and semi-quantitation of emerging per-and polyfluoroalkyl
2988 substances (PFAS) in US rainwater. Environmental Science: Processes & Impacts.

2989 ▪ Berthou, M., Gérard, V., Pélingre, M., Bagard, A., Batteux, T. L., & Losfeld, G. Is it raining
2990 PFAS in France? An analysis of 52 PFAS at nanogram per liter levels in French
2991 rainwaters during autumn season. Journal of Environmental Quality.

2992 ▪ Villagómez-Márquez, N., Abrell, L., Foley, T., & Ramírez-Andreotta, M. D. (2023).
2993 Organic micropollutants measured in roof-harvested rainwater from rural and urban
2994 environmental justice communities in Arizona. Science of The Total Environment, 876,
2995 162662.

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2998

2999 **13.2 RO Design.**

3000 The potable water design flow, and the corresponding multi-stage RO system, is based on
3001 established per capita consumption standards for residential We have referenced regional
3002 benchmarks and adjusted estimates to account for water-efficient fixtures and potential
3003 conservation measures encouraged within our community. The multi-stage RO system was
3004 selected for its advanced water purification capabilities, ensuring potable water quality meets or
3005 exceeds all relevant standards.

3006

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3008

3009 *Table S13-1: Design configuration for RO and some of the design parameters of the rainwater treatment*
3010 *process flow.*

RW						
*sizing according to demand, not rainfall (constant between countries; climate change; others)						
RO						
Influent	58.7	m ³ /d		CAPEX		
	2444.9	l/h				
	2.4	m ³ /h		€/membrane		173.6
	0.0	m ³ /min		CAPEX (equipment)		347.2
XLE-2521	1.4	m ³ /h				
Number of parallel membran	1.7	2.0		OPEX		
Parameters				€/m ³		0.2
				OPEX €/day		10.0
Dimensions				OPEX €/yr		3641.0
Lenght (m)	0.5					
Diameter (m)	0.1					
Volume (m ³)	0.0					
Energy requirment	10923.0	kWh/yr				
Influent	46.9	m ³ /d		CAPEX		
	1956.0	l/h				
	2.0	m ³ /h		€/membrane		345.5
	0.0	m ³ /min		CAPEX (equipment)		276.4
11 GPM UV-SPH-11	0.0	m ³ /min				
Number of parallel membran	0.8	0.8		OPEX		
Parameters				€/m ³		0.2
				OPEX €/day		7.5
Dimensions				OPEX €/yr		2741.5
Diameter (m)	0.1					
Lenght (m)	0.9					
Volume (m ³)	0.0					
Energy requirment	1884.8	kWh/yr				
Collection tanks						
	m ³	m ³ tank	Tank	Liner	CAPEX (€)	
Treated water	410.8	422.9	5195.0	2344.0	7539.0	
Collected water	410.8	422.9	5195.0	2344.0	7539.0	
*25% of demand (according to rainfall)						
Rain water Piping						
Pumping+FILTER						
	€/m ³	Total				
CAPEX (€)	304.1	16114.7				
OPEX (€/yr)	10.4	553.3				
Hab	2000.0		32.0	mm diameter, HDPE pipe		
Hab/building	250.0		72.4	€/m		
Number eq household	104.2		0.2	€/m*yr		
A (floor surface per storey)	670.0		2.4	PE/house		
p	0.2		30.0	m ² /PE		
f2	1.4					
Pipeline m	158.5					
Number of storeys	11.2					
Cost filter	425.0					
CAPEX (€)	11893.9					
OPEX (€/yr)	26.9	*Gutter and downpipes already installed (Domènech				
		**Calculated for all 8 buildings (joint collection: evacuation in 1 building)				

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13.2.1 Models and sizes

The chosen model of reverse osmosis membranes is selected because of its removal efficiency (Van Voorthuizen et al., 2005). The smallest available size is picked for both the treatment of GW and RW in all building types, except for the HR building in scenarios C1, C2, and USS, where the next available size is picked to match the operating flowrate requirements. Table S13-2 shows size and model information of the selected models.

Table S13-2: RO model and sizes for GW and BW.

Model	Length (m)	Diameter (m)	Volume (m ³)
XLE-2521	0.533	0.061	0.002
XLE-4021	0.533	0.099	0.004

13.2.2 CAPEX and OPEX

CAPEX ARE obtained from supplier data (Dow FilmTec.), while OPEX ARE estimated per m³ of treated wastewater (0.17 \$/m³) (Almar Water Solutions Ltd.). Table S13-3 shows the final costs of the RO system for GW and RW treatment.

Table S13-3: CAPEX and OPEX of the RO (V1).

	CAPEX supplier data (\$)	OPEX GW (\$/yr)	OPEX RW (\$/yr)
LR	173.59	81.92	8.24
ST	173.59	81.92	8.24
MR	173.59	409.59	41.22
MHR	173.59	819.19	82.44
HR	173.59	2047.96	206.09

13.3 UV

13.3.1 Models and sizes

UV filters for use in wastewater treatment (Applied Membranes Inc., Vista, CA) are fitted for each building type. The most adequate size is selected according to operational flux as shown in Table S13-4 (e.g., for scenario V1). All scenarios result in the same combination of UV filters. For RW, the smallest available model is selected for all building types.

Table S13-4: UV model and sizes for GW (Applied Membranes Inc., Vista, CA.) (V1).

	Model	Length (m)	Diameter (m)	Volume (m ³)
LR	2 GPM UV-SPH-2	0.064	0.262	0.001
ST	2 GPM UV-SPH-2	0.064	0.262	0.001
MR	2 GPM UV-SPH-2	0.064	0.262	0.001

MHR	3 GPM UV-SPH-3	0.064	0.363	0.001
HR	11 GPM UV-SPH-11	0.064	0.894	0.003

13.3.2 CAPEX and OPEX

The same procedure as for the RO membranes was followed assuming an estimative cost of 0.16 \$/m³ (Mazuki et al., 2020).

Table S13-5: CAPEX and OPEX of the UV filters (V1).

	CAPEX supplier data GW (\$)	CAPEX supplier data RW (\$)	OPEX GW (\$/yr)	OPEX RW (\$/yr)
LR	167.41	167.41	77.10	7.76
ST	167.41	167.41	77.10	7.76
MR	167.41	167.41	385.50	38.79
MHR	176.87	167.41	771.00	77.59
HR	345.47	167.41	1927.50	193.97

More SAFETY considerations:

The MBR-RO-UV combination of technologies has been proved to eliminate bacteria and viruses (Friedler and Gilboa, 2010; Ghernaot et al., 2019; Tang et al., 2018). Close physical distances between treatment and equipment, as the proximity of feed to treated water tanks, could offer a chance for microbial transport (e.g., aerosols, cross-connections, etc.) (Bhattacharjee and Datta, 2019). The UV disinfection unit poses a barrier to the physical movement of bacteria and enhances microbial quality to ensure the resultant effluent represents no health risks. Periodical quality tests would be scheduled to avoid the growth of bacteria resistant to UV treatment, bacterial hopping, and regrowth. If elevated concentrations of viruses are detected in the recycled water, the UV fluence could be increased (Pullerits et al., 2020).

13.4 Rainwater Line - LCA

13.4.1 Rainwater Line – LCA: Construction

The rainwater treatment system begins with a PDVF Out-in UF membrane module with a stainless-steel cassette, which is a scalable and compact technology from Dow Chemical that does not require construction work for installation. The RO and UV units of the RW line are sized based on the monthly demand of potable water, considering that it is only distributed for 28 days. This ensures that the system can cover demand peaks during periods of sufficient rainfall.

Remineralization is carried out in a calcite bed with a residence time of 8 minutes. The contactor is made of fiberglass and has a total volume of 92 L, with a bed volume of 40 L. The lifespan of the fiberglass shell is 30 years, while the liner needs to be replaced every 15 years.

Finally, the treated rainwater is stored in two steel tanks, each with a volume of 15 m³. The rainwater tank has a PVC liner, while the potable water tank has an FPP liner. Both liners have a thickness of 0.15 mm and need to be replaced every 15 years.

Table S13-6: Table summarizing the key components of the rainwater treatment system

Component	Material	Size	Lifespan
PDVF Out-in UF membrane module	Stainless steel	Scalable, compact	N/A
RO and UV units	N/A	Sized based on monthly demand (28 days distribution)	N/A
Remineralization contactor	Fiberglass	1 m height, 0.34 m diameter, 92 L total volume, 40 L bed volume	30 years (shell), 15 years (liner)
Rainwater tank	Steel	15 m ³	Liner: 15 years
Potable water tank	Steel	15 m ³	Liner: 15 years

Table S13-7: Inventory details for the construction of the treatments and processes included in the RW line. Tables in the construction inventory refer to the total amount of materials of components needed to build the decentralized system for the water treatment for the reference population of 300 people (Barnosell, 2023).

Element	Amount	Unit	Material	Life span (years)	Ecoinvent dataset	
UF membrane	1.87	kg	PVDF	15		
UF, PDVF (hydrogen)	0.22	kg	Hydrogen	-	market for hydrogen, gaseous	GLO
UF, PDVF (electricity)	170.63	kWh	-	-	market group for electricity, medium voltage	RER
UF, PDVF (hydrogen chloride emissions to air)	0.85	kg	Hydrogen chloride	-	Hydrochloric acid, emissions to air	-
UF, PDVF (hydrogen emissions to air)	0.14	kg	Hydrogen	-	Hydrogen, emissions to air	-
UF, PDVFP (heat emissions to air)	40.15	MJ	-	-	Heat, waste, emissions to air	-
UF, PDVF (hydrogen chloride emissions to water)	0.84	kg	Hydrogen chloride	-	Hydrochloric acid, emissions to water	-
UF membrane cassette	12.50	kg	Stainless steel	30	market for steel, chromium steel 18/8	GLO
RO unit for RW	0.88	m ²	-	5	market for seawater reverse osmosis module	GLO
UV unit for RW	1.00	unit	-	5	market for ultraviolet lamp, for water disinfection	GLO
Calcite bed, tank	0.25	kg	Fibreglass	30	glass fibre reinforced plastic, polyester resin, hand lay-up	GLO
RW holding tank	356.04	kg	Steel	30	market for steel, low-alloyed	GLO
RW holding tank, liner	6.07	kg	PVC	15	market for PVC, suspension polymerised	GLO
Potable water holding tank	356.04	kg	Steel	30	market for steel, low-alloyed	GLO
Potable water holding tank, liner	4.15	kg	FPP	15	market for polypropylene, granulate	GLO

13.4.2 Rainwater Line – LCA: Operation

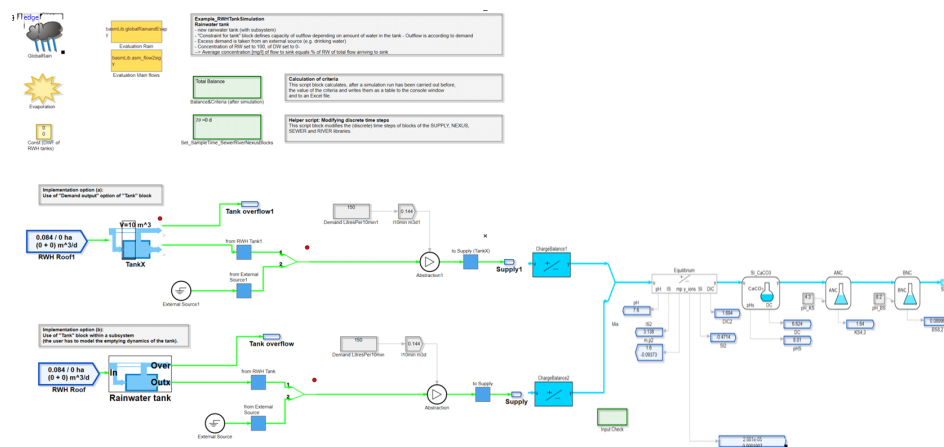
The energy demand in the rainwater line comes from the UF membrane (0.065 kWh*m-3), the RO unit (0.6 kWh*m-3), and the UV module (0.1 kWh*m-3) (Al Hawari et al., 2020; Giammar et al., 2022; Glover et al., 2022; Tow et al., 2021). Additionally, the addition of 0.12 kg CaCO₃ per cubic metre for remineralization is required (Garfí et al., 2016).

Table S13-8: Inventory details for the annual operation of the grey water line (FU: water treatment for 300 people during a year). (Barnosell, 2023).

Element	Amount	Unit	Ecoinvent dataset	
UF, electricity	Specific for each scenario	kWh	market group for electricity, low voltage	RER
RO, electricity		kWh	market group for electricity, low voltage	RER
UV, electricity		kWh	market group for electricity, low voltage	RER
CaCO ₃ , remineralization		kg	market for calcium carbonate, precipitated	RER

13.5 Rainwater Harvesting – Modelling

The rainwater treatment module, also created in SIMBA#, estimates the collection and storage of rainwater and calculates the water quality parameters. The model simulates the redirection of harvested flows into designated rain tanks, accounting for different rain patterns in various climatic regions. The harvested water is stored for later use and goes through pre-filters, in-tank filtration, reverse osmosis (RO), and a tailored UV treatment combination. The model supports the analysis of the mixing of two different potable water sources, centralized supply and treated roof-harvested water. It enables the control of drinking water quality, speciation and the calculation of parameters such as buffering capacities, ionic strength, alkalinity, hardness, and calcite saturation. The space requirements for this module are estimated at 20-40 m³, primarily due to storage tanks, which can vary based on storage goals or capabilities, along with equalization tanks (30 m³), while the required equipment occupies less than 2-3 m³.



13.6 Rainwater line - LCA

The energy demand in the rainwater line comes from the UF membrane (0.065 kWh*m-3), the RO unit (0.6 kWh*m-3), and the UV module (0.1 kWh*m-3) (Al Hawari et al., 2020; Giammar et al., 2022; Glover et al., 2022; Tow et al., 2021). Additionally, the addition of 0.12 kg CaCO3 per cubic metre for remineralization is required (Garfí et al., 2016). The rainwater line is sized for each of the site-specific scenarios (see Scenarios).

Table S13-9: Inventory details for the annual operation of the grey water line (FU: water treatment for 300 people during a year).

Element	Amount	Unit	Ecoinvent dataset
UF, electricity	Specific for each scenario	kWh	market group for electricity, low voltage
RO, electricity		kWh	market group for electricity, low voltage
UV, electricity		kWh	market group for electricity, low voltage
CaCO ₃ , remineralization		kg	market for calcium carbonate, precipitated

14 Storage tanks

Additional equipment necessary for the processing of water are influent and effluent equalisation tanks, and diverse holding tanks for urine, sludge, process products, and chemicals required for cleaning and operation. Equalisation units are steel tanks of 30 m³ with a PVC liner and 25 m³ with a FPP liner for the GW+BrW influent and total effluent, respectively, sized according to Manderso (2018). BrW and OFMSW are mixed and homogenized during pre-treatment in a 3 m³ stainless steel tank. The urine treatment line requires a 2 m³ urine and a 5 m³ treated water holding tank, made of fibreglass and PVC, respectively. Finally, PVC chemical and sludge holding tanks of 10 L and 750 L for monthly chemical recharge and sludge disposal are included.

Tanks used to store recycled water or potable water were assumed to be composed of FPP (flexible polypropylene) liners, whereas tanks used for storage of black, grey, brown water or sewage were assumed to use PVC (polyvinyl chloride) liners. Smaller tanks were assumed for rainwater collection (since smaller volumes are required) and larger steel tanks with the indicated liners were employed for grey and black water management (Enduramaxx Ltd, Lincolnshire, United Kingdom; Power Plastics Ltd, North Yorkshire, United Kingdom). A rotary screen was included in the design before the bioreactor to reduce membrane fouling and clogging.

Table S14-1: Inventory details for the construction of the equalisation tanks. Tables in the construction inventory refer to the total amount of materials of components needed to build the decentralized system for the water treatment for the reference population of 300 people.

Element	Amount	Unit	Material	Life span (years)	Ecoinvent dataset	
Influent equalisation tank	712.07	kg	Steel	30	market for steel, low-alloyed	GLO
Influent equalisation tank, liner	12.14	kg	PVC	15	market for polyvinylchloride, suspension polymerised	GLO
Effluent equalisation tank	593.39	kg	Steel	30	market for steel, low-alloyed	GLO
Effluent equalisation tank, liner	6.92	kg	FPP	15	market for polypropylene, granulate	GLO

14.1 Tank sizing

Tank sizes have been chosen as explained in the main paper assuming one- or two-weeks storage of wastewater. Volumes and prices vary according to each treatment line configuration. Both the rainwater collection and the potable water holding tanks were sized to store a month's potable water demand. A 2.0 safety factor was applied to 210 m³, which corresponds to 420 m³. Table S14-4 shows the volumes and CAPEX of RW tanks for all building types

Table S14-2: Storage capacity (m³) and CAPEX (\$) of a week's wastewater production (principal scenario, V1).

	Raw water and equalization tank	CAPEX (\$)	Treated water tank	CAPEX (\$)	Sludge tank	CAPEX (\$)
LR	4.72	626	9.45	783	0.21	103
ST	4.72	626	9.45	783	0.21	103
MR	23.62	1180	47.25	1381	1.04	713
MH	47.25	1863	94.49	1842	2.08	1147
R						
HR	118.12	2393	236.23	3125	5.19	2155

Table S14-3: Storage capacity (m³) of two weeks' wastewater production (additional scenario, V1).

	Raw water and equalization tank	CAPEX (\$)	Treated water tank	CAPEX (\$)	Sludge tank	CAPEX (\$)
LR	30	1580	30	1580	0.9	448
ST	30	1580	30	1580	0.9	448
MR	160	3934	160	3934	4	713
MH	300	6793	300	6793	7	1147
R						
HR	800	19679	800	19679	18	2164

Both the rainwater collection and the potable water holding tanks were sized to store a month's potable water demand. Table S14-4 shows the volumes and CAPEX of RW tanks for all building types.

Table S14-4: Volumes and costs of rainwater tanks (V1).

	Volume (m ³)	Collection tank CAPEX (\$)	Treated water tank CAPEX (\$)
LR	3.73	717.39	745.53
ST	3.72	717.39	745.53
MR	18.60	1180.00	1296.00

MHR	37.20	1805.00	1898.00
HR	93.00	3340.00	3377.00

3155 14.2 Space Requirements [equalisation and storage tanks]

3156 *Table S14-5: Space requirements for the different equalisation and storage tanks.*

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Space Requirements		m ³
Food Waste	Mixing Tank	20
	Conditioning Tank	23
	Storage	40
Brown W	Sludge Tank	5
Grey W	Influent Equalization	50
	Effluent Equalization	100
Yellow W	Urine Tank	16
Total		254
Vertical Farming	Operations	50
Rainwater	Average Storage	400
	High Storage	400
Total		1094

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Table S14-6: Space requirements for the different units and processes.

Space requirements	
Volumes	m³
UASB	16.07
OLAND	1.80
Struvite reactor	4.05
MBR	164.50
Sludge tank (MBR & UASB)	4.46
Chemicals tank	0.50
RO	0.01
UV	0.01
Equalization of influent	50
Equalization of effluent	100
Urine tank	16.00
MABR	0.01
Electrochemical cell	*Placed in toilets, not basement
RO RW	3.12E-03
UV RW	2.27E-03
TOTAL SPACE	266.90
Space available	m²
Area of building	5,360.00
Area of inside	1,340.00
Total area	6,700.00
Height of basement	3
*Assuming treatments are under inside space	
Volume available	4020
% occupied	6.64

15 Sewer & Piping

The need to separate BrW, GW, and YW and capture RW creates the necessity for additional piping in the building. The already existing sewer network is considered to be suitable for the transport of GW and re-circulation of potable water after treatment. The impacts of extra piping for BrW, YW, and RW are included in the study.

High density polyethylene (HDPE) pipes of standardized diameters of 32 mm and 75 mm are used for the collection of both YW and RW, and BrW, respectively. The length of piping necessary is calculated based on the dimensions of the described building on the Urban Water Infrastructure Model (UWIM) methodology by Maurer et al. (2013). The UWIM model uses housing density [ρ , dwellings $\cdot$ m⁻²] and dimensions (A [m²] and dimensionless model parameter f_2 based on the ratio between length and width of A) to give the meters of private water (L_s [m]) distribution pipeline that adjust to the target settlement through Eq. 1 (Maurer et al., 2010). The housing shape factor (which takes values between 0.2 and 5) is taken as 1.44 (Maurer et al., 2013, 2010). The design equations include a model parameter (f_2) which representing a housing shape factor and must be estimated for each scenario (Maurer et al., 2013).

$$L_{s,private} = 0.5 * A * \sqrt{f_2 * \rho} \quad \text{Eq. 2}$$

f_2 is a model parameter representing the form factor of a housing plot [no units]. Private sewers are thus defined as the pipelines from each house until the first Y-joint that makes connection the water main sewer infrastructure. For this study, f_2 was estimated based on an adaptation of the sensitivity analysis for the determination of f_2 carried out by Maurer et al. (2013) using the sewer lengths obtained for an average European residential area as a reference to minimize the relative error (RL)² through Eq. 1 (Roefs et al., 2016). The described calculations lead to a value of f_2 of 1.44, which agreed with standard values (1 – 2) for f_2 and was consistent with typical proportions of buildings (Blumensaat et al., 2012; Maurer et al., 2010). To facilitate the comparison of costs, the studied buildings were all assumed to have a length: width ratio of 1.44, except for the low-rise housing type which was composed of five consecutive terraced houses with a shaping factor of 2.29 each to better fit the dwelling type.

$$R_L = \log \left(1 - \frac{L_{s,data} - L_{s,sewer}}{L_{s,data}} \right)$$

As described by Maurer et al. (2013), the UWIM model is sensitive to f_2 and may yield different sewer lengths depending on the value of this parameter. Furthermore, the model was applied to buildings instead of settlements. Therefore, the results using this methodology serve as estimates. In concordance with previous research (Adams et al., 1972; Maurer et al., 2010), the length of pipe per capita decreases as density increases.

15.1 Comparison centralized vs decentralized

The methodology used in this study was also used to calculate the piping costs and compare the decentralized system versus the centralized. These calculations belong to a previous paper: Garrido-Baserba, et al, 2018. “The economics of wastewater treatment decentralization: a techno-economic evaluation” in *Environmental science & technology*, 52(15), pp.8965-8976, but we add them here to facilitate the comparison between the main two paradigms.

The methodology was used for comparative and standardization purposes between the sewer distribution of a new development either in centralized or decentralized fashion. Both systems were compared using the methodology from Roefs et al. (2016). Each development consisted in a series of districts servicing 1200 PE. Each district was distributed in neighborhoods of 50 households representing a total of 120 PE. Each neighborhood has a surface area of 2.5 ha.

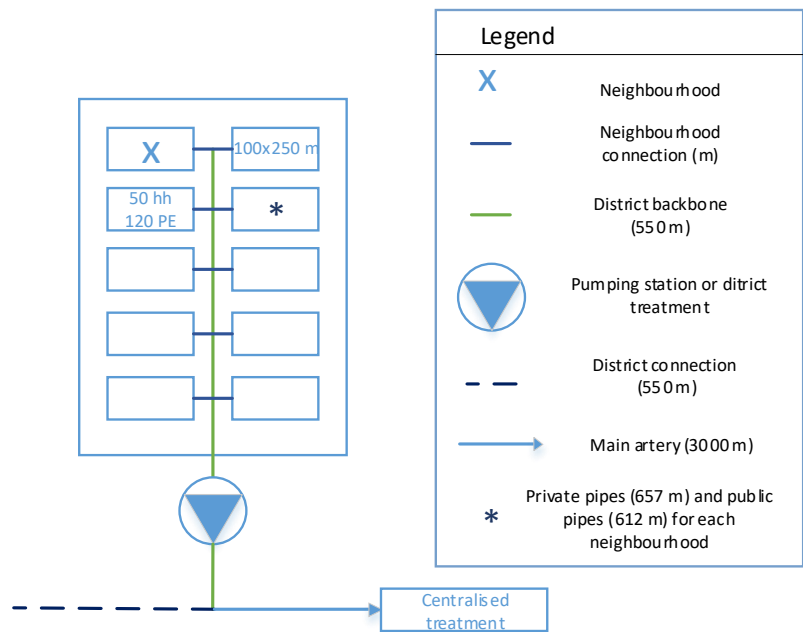


Table S15-1: District configuration. Adapted from Roefs et al. (2016)

In both the conventional and hybrid alternatives, districts were connected to a collection system that connected district to district and to the central WWTP. A backbone pipe was used as connection between neighborhoods within the district. At the neighborhood level, both private and public sewers were taken into account. Private sewers were defined as the sewers from the house to the first Y-joint that makes connection with the water main (Maurer et al., 2013; Roefs et al., 2016). A detailed description of sewer infrastructure is shown in supplemental information.

Centralized sewer infrastructure was based on the deployment of the common canalization, where the collected wastewater from households is diverted and treated at the centralized facility

Source-separated alternatives doubled the canalization requirements at the household level (i.e., BW and GW). As for hybrid alternatives, vacuumed BW was treated at district level, whereas GW was treated in a centralized system. Treated BW effluent may end up failing to meet discharge requirements. Thus, for safety reasons, and assuming no flexibility in future legislation, the BW effluent joined the GW stream after the corresponding BW treatment. Once both streams were merged, the resulting combined stream was treated in a centralized system. The decentralized alternative arranges for the treatment of both streams at the district level.

The length and diameter of the pipes as well as the pumping system were adapted from the methodology presented by Maurer et al. (2013) and Vreeburg (2007), and further adapted and applied by Roefs et al. (2016). Sewer cost calculations were also retrieved from the aforementioned studies. Similarly to Roefs et al. (2016), all sewers were separated and rainwater drainage was not taken into account.

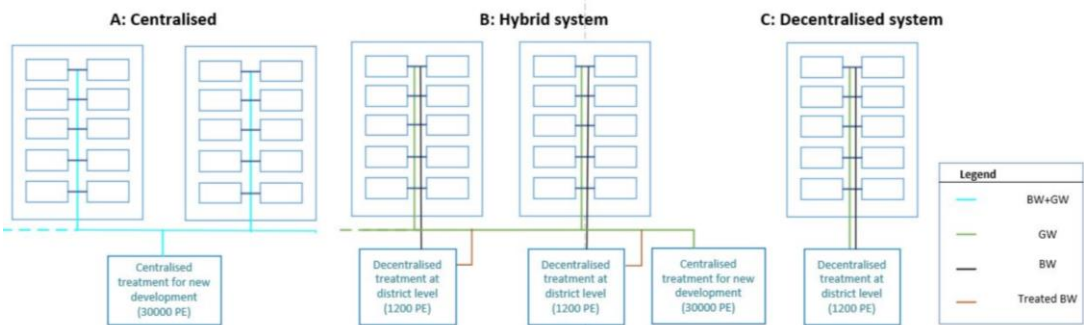
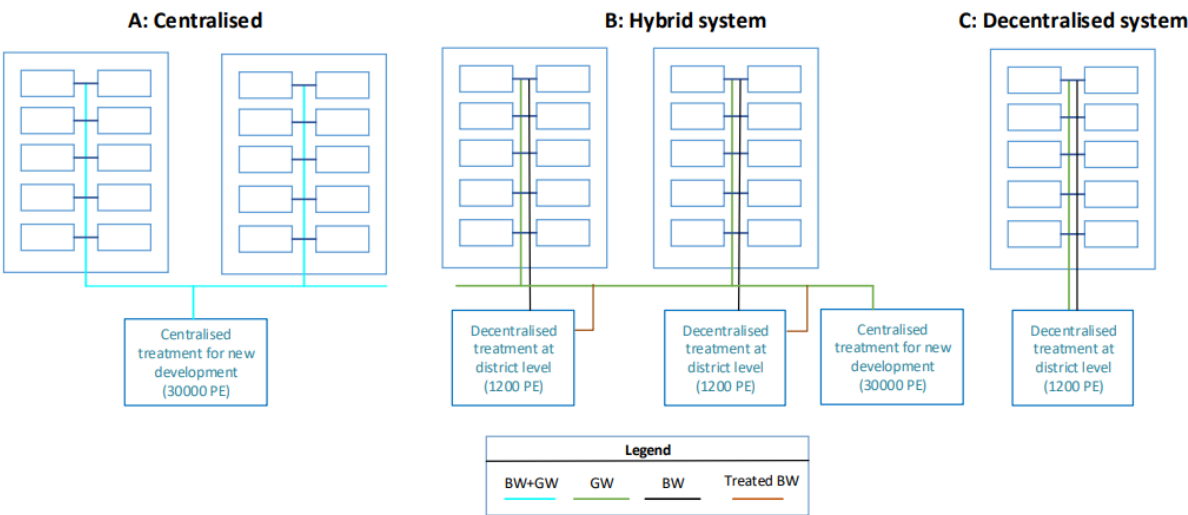


Table S15-2: Layout and labels of the district and the neighborhood for the three approaches: centralized, hybrid and decentralized.

Dimensions and costs of sewer system

CAPEX for the sewage system was obtained through empirical equations used by Roefs et al. (2016).

$$\text{Gravity: CAPEX Gravity Sewer} \left(\frac{\text{€}}{\text{m}} \right) = 130 \cdot 1.3^{\frac{\text{diameter}-300}{120}} \quad (\text{S12})$$

$$\text{Pressure: CAPEX Pressure Sewer}^{70-110 \text{ mm}} \left(\frac{\text{€}}{\text{m}} \right) = \text{diameter (mm)} \cdot 0.51 \cdot 1.1 \quad (\text{S13})$$

$$\text{CAPEX Pressure Sewer}^{150-400 \text{ mm}} \left(\frac{\text{€}}{\text{m}} \right) = \text{diameter (mm)} \cdot 0.61 \cdot 1.1 \quad (\text{S14})$$

$$\text{Vacuum: CAPEX Vacuum Sewer} \left(\frac{\text{€}}{\text{m}} \right) = \text{diameter (mm)} \cdot 0.59 \cdot 0.7 \cdot 1.1 \quad (\text{S15})$$

OPEX for sewage system was obtained directly from Roefs et al. (2016) and it can be found in table S11. CAPEX and OPEX for the corresponding pumping system were also taken from the aforementioned study. In table S11, CAPEX and OPEX for each alternative are shown. CAPEX and OPEX for the sewer infrastructure are calculated depending on the pipeline type. For the scenarios using vacuum toilets, BW is evacuated using HDPE pipes operating at vacuum ($\phi = 70$ mm), while RW and GW are transported with gravity pipes made of unreinforced concrete ($\phi = 110$ mm). Both BW and GW are collected using unreinforced concrete, gravity sewers of diameters of 70 and 110 mm, respectively, in the cases using conventional toilets. For the separation of urine, GW is evacuated using the same pipeline as in the other cases while brown and yellow water are collected separately by gravity sewers of 70 and 32 mm, respectively.

Sewer CAPEX are obtained using Eq. 62 and Eq. 63 while OPEX are equivalent to 1 \$/m*yr for vacuum pipelines and to 0.17 \$/m*yr for gravity sewers (Roefs et al., 2017).

$$\text{CAPEX Vacuum} = \phi \text{ (mm)} * 0.59 * 0.7 * 1.1 \quad \text{Eq. 62}$$

$$\text{CAPEX Gravity} = 130 * 1.3^{\frac{\phi(\text{mm})-300}{120}} \quad \text{Eq. 63}$$

Pipeline lengths and costs are calculated for all scenarios (e.g., **Error! Reference source not found.** displays all sewer-related data for the V1 scenario).

Table S15-3: Sewer information for the main type of buildings.

Building type	LR	ST	MR	MHR	HR
Equivalent households	5.00	5.00	25.00	50.00	125.00
A	400.00	270.00	350.00	510.00	670.00
ρ	0.01	0.02	0.07	0.10	0.19
f2	2.29	1.44	1.44	1.44	1.44
Pipeline length, BW and BW (m)	33.84	22.03	56.09	95.75	173.53
CAPEX BW (\$)	1076.08	700.64	1783.75	3045.09	5518.53
OPEX BW (\$/year)	33.84	22.03	56.09	95.75	173.53
CAPEX GW (\$)	859.01	2903.59	1890.56	4813.12	8216.62
OPEX GW (\$/year)	1.70	5.75	3.75	9.54	16.28

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Table S15-4:: Pipes dimensions and costs for each configuration. Adapted of Roefs et al. (2016). . These calculations belong to a previous paper: Garrido-Baserba, et al, 2018. "The economics of wastewater treatment decentralization: a techno-economic evaluation" in Environmental science & technology, 52(15), pp.8965-8976

	Description	Wastewater typology	Pipe typology	Material	Length/unit ¹ (m)	Total length (m)	Diameter (mm)	CAPEX (€/m)	CAPEX (€)	OPEX (€/m/year)	OPEX (€/year)
Centralized	District Backbone	GW+BW	Gravity	Unreinforced concrete	550	13,750	200	104.4	1,436,459	0.17	2,337
	Neighbourhood connection	GW+BW	Gravity	Unreinforced concrete	25	3,125	200	104.4	326,467	0.17	531
	District connection	GW+BW	Pressure	HDPE	550	12,250	250	167.7	2,054,937	1.00	12,250
	Public sewer	GW+BW	Gravity	Unreinforced concrete	612	153,000	200	104.4	15,983,871	0.17	26,010
	Private sewer	GW+BW	Gravity	Unreinforced concrete	657	164,250	110	85.8	14,094,134	0.17	27,922
	Main column	GW+BW	Pressure	HDPE	3,000	3,000	400	268.4	805,200	1.00	3,000
	Pumping system								1,328,200		46,350
	TOTAL COSTS								36,029,268		118,400
Hybrid	District Backbone	BW	Vacuum	HDPE	550	13,750	70	31.8	437,264	1.00	13,750
	Neighbourhood connection	BW	Vacuum	HDPE	25	3,125	70	31.8	99,378	1.00	3,125
	Public sewer	BW	Vacuum	HDPE	612	153,000	70	31.8	4,865,553	1.00	153,000
	Private sewer	BW	Vacuum	HDPE	657	164,250	70	31.8	5,223,314	1.00	164,250
	BW supernatant sewer	Treated BW	Gravity	Unreinforced concrete	10	250	70	78.6	19,656	0.17	43
	District Backbone	GW	Gravity	Unreinforced concrete	550	13,750	200	104.4	1,436,459	0.17	2,338
	Neighbourhood connection	GW	Gravity	Unreinforced concrete	25	3,125	200	104.4	326,468	0.17	531

	District connection	GW+BW	Pressure	HDPE	550	12,250	200	134.2	1,643,950	1.00	12,250
	Public sewer	GW	Gravity	Unreinforced concrete	612	153,000	200	104.4	15,983,872	0.17	26,010
	Private sewer	GW	Gravity	Unreinforced concrete	657	164,250	110	85.8	14,094,135	0.17	27,923
	Main column	GW+BW	Pressure	HDPE	3,000	3,000	350	234.8	704,550	1.00	3,000
	Pumping system								2,335,125		61,950
	TOTAL COSTS								47,169,724		468,169
Decentralized	District Backbone	BW	Vacum	HDPE	550	13,750	70	31.8	437,263	1.00	13,750
	Neighbourhood connection	BW	Vacum	HDPE	25	3,125	70	31.8	99,378	1.00	3,125
	Public sewer	BW	Vacum	HDPE	612	153,000	70	31.8	4,865,553	1.00	153,000
	Private sewer	BW	Vacum	HDPE	657	164,250	70	31.8	5,223,314	1.00	164,250
	District Backbone	GW	Gravity	Unreinforced concrete	550	13,750	200	104.4	1,436,459	0.17	2,337
	Neighbourhood connection	GW	Gravity	Unreinforced concrete	25	3,125	200	104.4	326,467	0.17	531
	Public sewer	GW	Gravity	Unreinforced concrete	612	153,000	200	104.4	15,983,871	0.17	26,010
	Private sewer	GW	Gravity	Unreinforced concrete	657	164,250	110	85.8	14,094,134	0.17	27,922
	Pumping system								1,350,000		28,125
	TOTAL COSTS								43,816,443		419,051

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3277 Table S15-5: Sewer information for the city block scenario.

Sewers	
*GW sewer is considered to already be in buildings in avg and lower bound scenarios	**Assuming High-Rise type buildings
BrW sewer	
Hab	2,000.00
Hab/building	250.00
Number eq household	104.17
A (floor surface per storey)	670.00
ρ	0.16
f2	1.44
Pipeline m	158.51
Number of storeys	11.19
CAPEX (€)	99,699.95
OPEX (€/yr)	215.57
BrW pumping	
Total CAPEX (€)	66,000.00
Total OPEX (€/yr)	2,260.00
mm diameter, HDPE pipe	70.00
€/m	78.62
€/m*yr	0.17
PE/house	2.40
m2/PE	30.00
m2/HH	72
€/PE CAPEX	33.00
€/PE*yr OPEX	1.13
YW sewer	
Hab	2,000.00
Hab/building	250.00
Number eq household	104.17
A (floor surface per storey)	670.00
ρ	0.16
f2	1.44
Pipeline m	158.51
Number of storeys	11.19
CAPEX (€)	91,751.44
OPEX (€/yr)	215.57
mm diameter, HDPE pipe	32.00
€/m	72.36
€/m*yr	0.17
PE/house	2.40
€/PE CAPEX	33.00
€/PE*yr OPEX	1.13

15.2 Sewer infrastructure CAPEX and OPEX

The cost of the pipeline that needs to be deployed in order to provide the assessed buildings with wastewater collection services can be fully avoided in the present study. Thus, the saving benefits stemming from the use of a completely decentralized treatment system are calculated by considering both the construction and maintenance costs of the connector to water main and also the public charges allocated to the inhabitants of each block.

Table S15-6: Infrastructure charges for all assessed buildings.

	LR	ST	MR	MHR	HR	City Block
Inhabitants	12	12	60	120	300	2000
Infrastructure charges						
Water consumption (m ³ /month)	45.8	45.8	228.8	457.6	1143.9	6163
Infrastructure charges (\$/month)	12.9	12.9	64.3	128.6	321.4	754.2
Infrastructure charges (\$/30 yr)	2371.8	2371.8	11859.0	23718.0	59295.1	280532
Connection to water main						
Installation CAPEX (\$)	1262.8	1262.8	1262.8	1262.8	1262.8	3862.8
Installation OPEX (\$/30yr)	2725.3	2725.3	2725.3	2725.3	2725.3	2725.3
Total costs						
Total CAPEX (\$)	1262.8	1262.8	1262.8	1262.8	1262.8	3862.8
Total OPEX (\$/30yr)	5097.1	5097.1	14584.3	26443.3	62020.4	62020.4

15.3 Pipeline and pumping materials - LCA

HDPE pipes for the collection and re-circulation of water are modelled from the market for polyethylene pipe, corrugated, DN 75 dataset in ecoinvent. BrW pipes of DN 75 directly use the base inventory provided by ecoinvent while for the DN 32 piping, the amount of plastic material is edited correspondingly to the change in diameter, while transport is maintained. The lengths of the parallel YW and BrW sewers are that of 184 m, while 368 m of piping are required for the collection and re-circulation of RW to households.

Power, hydraulic, and pressure capacity of pumps for the circulation of BrW and return of treated GW and RW to households is calculated and modelled in the Activity Browser using the market for water pump, 22kW (GLO) dataset as a baseline in ecoinvent. To ensure the building's requirements are covered, three pumps with a total nominal power of 6.6 kW is proposed. A lifespan of 18 years is considered for all pumps (Herman et al., 2017).

Table S15-7: Inventory details for the construction and materials needed for the sewer system and pumping equipment. Tables in the construction inventory refer to the total amount of materials of components needed to build the decentralized system for the water treatment for the reference population of 300 people..

Element	Amount	Unit	Material	Lifespan (years)	Ecoinvent dataset	
BrW pipe	183.71	m	HDPE	70	market for polyethylene pipe, corrugated, DN 75	GLO
YW pipe	183.71	m	HDPE	70	model for DN 32 based on market for polyethylene pipe, corrugated, DN 75	GLO
RW pipe	367.42	m	HDPE	70	model for DN 32 based on market for polyethylene pipe, corrugated, DN 75	GLO
Pumping of BrW, YW, and RW	0.3	unit	-	18	market for water pump, 22kW	GLO

15.4 Tube-in-tube approach (Brown and Yellow Water)

The study has considered (and modeled) existing and commercially available innovative concepts of pipes that allow the separation of the different wastewater streams within the existing infrastructure. Conventional domestic drainage systems are built as flushed one-pipe-system for all partial flows of domestic wastewater. Recently a few companies have offered alternatives to split the drained streams without affecting the structural fabric of existing buildings, in particular, the line inventory. Taking advantage of no substantial changes in the overall flow in the produced wastewater (only a potential reduction in flow if water-efficient or vacuum toilets were to be implemented). New pipelines could be installed inside the existing ones following a tube-in-tube approach (or replaced with pipelines with such characteristics). A tube-in-tube approach or the so-called double inliner system would be feasible for retrofitting source separation systems into existing pipes without extensive constructive intervention. (Hamburg Cycle 2012, STOWA, 2019, EVaSens, 20140

Similarly, some available literature reviews and projects have illustrated comprehensively the civil engineering aspects of separate collection and transport of black water concepts with minimal structural changes inside existing buildings. Whereas some are merely theoretical concepts, others have already been shown to be practically feasible.

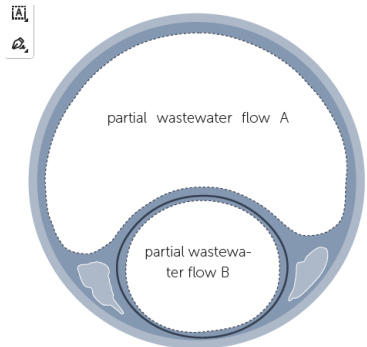


Figure 2: Cross-section of the double inliner



Figure 3: Moulding for the connection of the vacuum toilet

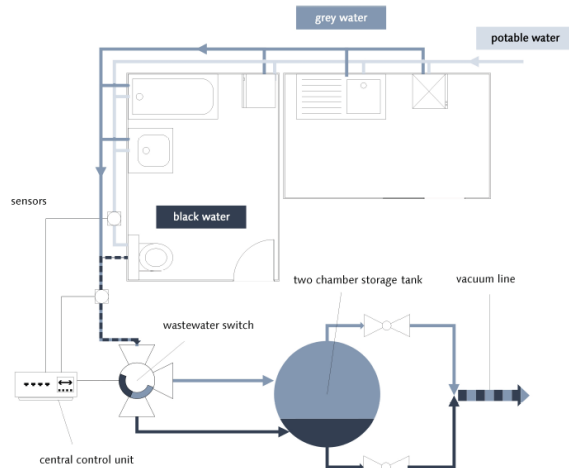


Figure 4: The idea behind the AWAS-System

Table S15-8. Concepts of double piping integration by Hamburg Water Cycle® (2019). The concepts are based on their exclusive system allowing spatial separation [EVaSENS], which is tube-in-tube reconstruction.

FIGURE 19 SCHEMATIC DRAWING OF THE PIPE WITHIN PIPE CONCEPT

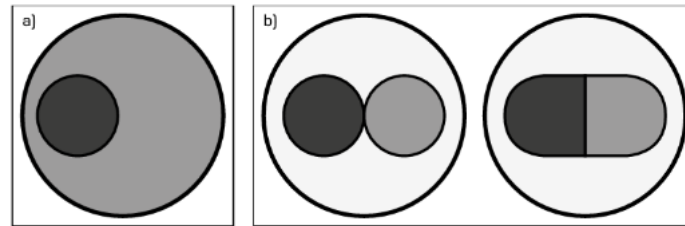


Table S15-9. STOWA illustrates scenarios of small-diameter flexible pipe into the existing drainage network with the advantage of a complete and comprehensive physical separation of black and grey water already at the level of every single sanitary appliance (Harder, 2012)

15.5 Considerations for the Piping Drinking Water Demand

The proposed decentralized water reuse system is designed to achieve high recovery rates, potentially reclaiming and purifying over 90-95% of wastewater to a quality suitable for potable use. This is supported by the findings of Englehardt et al. (2013) and Mattos et al. (2023), who demonstrated the effectiveness of a similar treatment train in removing contaminants and producing potable water from domestic wastewater. In an ideal scenario, this reclaimed water would meet all household needs, including drinking water.

However, recognizing that public acceptance of drinking reclaimed water can be a barrier, we explored a scenario where 15% of the total water demand, corresponding to drinking and cooking needs, is met through alternative sources like rainwater harvesting or connection to the centralized grid. This 15% figure is based on typical household water use patterns and aims to address potential concerns regarding the direct consumption of reclaimed water.

It's important to emphasize that the separation of this 15% is primarily driven by social perception rather than technical limitations. The system, equipped with advanced treatment technologies like reverse osmosis (RO), is capable of producing reclaimed water that meets or exceeds drinking water standards for the entire household. This is consistent with the findings of Mattos et al. (2023), who demonstrated the ability of a household greywater reuse system to produce high-quality water suitable for potable reuse, even under challenging conditions.

In the 15% scenario, a form of dual piping might be necessary to ensure that the designated drinking water sources are kept separate from the reclaimed water used for other purposes. However, this is not the preferred or most efficient option. We advocate for educating the public about the safety and quality of reclaimed water, aiming to eliminate the need for dual piping and maximize the efficiency and sustainability of the decentralized system. While a dual piping system is technically feasible to ensure a separate supply of drinking water, it is not economically ideal due to the redundancy of treating all water to drinking quality standards. The overall cost increase of implementing dual piping is estimated to be approximately 5.6%, which, while not substantial, highlights the importance of educating users and promoting the acceptance of reclaimed water to avoid unnecessary expenses.

3370 In the most practical scenario, rainwater or water from the centralized grid would be used to
3371 augment the reclaimed water supply, ensuring a continuous and reliable source of high-quality
3372 water for all household needs. This approach minimizes infrastructure requirements and
3373 maximizes the benefits of the decentralized system, aligning with the overarching goal of
3374 promoting sustainable and efficient water management practices.

- 3375 • **Rationale for the 15% Allocation:** The system is designed to reclaim and purify over
3376 90-95% of wastewater to drinking water quality. The remaining 15% is allocated to
3377 drinking and cooking needs, addressing potential public concerns about direct potable
3378 reuse. This 15% can be sourced from rainwater harvesting, connection to the
3379 centralized grid, or the system itself if public acceptance allows.
- 3380 • **Dual Piping Considerations:** While the system can produce drinking water quality for
3381 all uses, a dual piping scenario is considered to accommodate potential public
3382 reluctance towards consuming reclaimed water. This scenario would involve separate
3383 piping for the 15% drinking water demand, sourced from rainwater or the centralized
3384 grid. While a dual piping system is technically feasible to ensure a separate supply of
3385 drinking water, it is not economically ideal due to the redundancy of treating all water to
3386 drinking quality standards. The overall cost increase of implementing dual piping is
3387 estimated to be approximately 5.6%, which, while not substantial, highlights the
3388 importance of educating users and promoting the acceptance of reclaimed water to
3389 avoid unnecessary expenses.
- 3390 • **Dual Piping Implementation:** In the unlikely event of dual piping implementation, a
3391 simplified system would be employed, potentially using a dedicated line for drinking
3392 water to critical fixtures like kitchen and bathroom sinks. The most practical scenario,
3393 however, involves using rainwater or centralized water to augment the reclaimed water
3394 supply, eliminating the need for extensive dual piping.

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16 Pumping

Pumping is required for the correct collection of BrW and avoidance of pipeline clogging, as well as for the return of treated water to households, both for GW and RW. Sizing of pumps considers a maximum height of 36 m, the flow rates of each type of water, and a water pump efficiency of 70%. In the case of RW, flow rate is sized according to demand. The proposed pumps could deliver adequate water pressure of 50 to 70 psi to showers, sinks, and other house appliances.

Pumping costs for GW and RW are calculated assuming per capita CAPEX of 33 \$ and OPEX of 1.13 \$/yr as adapted from Roefs et al. (2017). Calculations taking operational flow as a base are also done taking CAPEX of 304 \$/m³ and 10.5 \$/yr*m³ to compare the results. Both methods yield the same final costs. The highest possible rainwater flow per day is assumed as a worst-case scenario for the sizing of rainwater pumps while the average GW flow is taken as wastewater is assumed constant.

For the V1 and V2 scenarios (Garrido-Baserb, 2022) where vacuum pumping is required for BW, vacuum pump catalogues are consulted to obtain the most cost-effective fit for every building type considering pump capacities and prices. A vacuum on demand system is compared to a constant vacuum system, which is found more adequate for all building types. Terraced houses are thus designed to have a common vacuum system. **Error! Reference source not found.** shows the compared costs of the CVS and VOD installations.

Table S16-1: Black water pumping CAPEX for the V1 and V2 scenarios.

Constant Vacuum System (CVS)			Vacuum on demand system (VOD)		
1 Vacuum generator			1 Vacuum generator (vacuum tank + pump)		
\$/unit	Capacity (toilets)	TOTAL COST	\$/unit	Capacity (toilets)	TOTAL COST
4890.40	15.00		1713.60	1.00	
Units needed			Units needed		
LR	1.00	4890.40	5.00		8568
ST	1.00	4890.40	5.00		8568
MR	1.67	8150.67	25.00		42840
MHR	3.33	16301.33	50.00		85680
HR	8.33	40753.33	125.00		214200
City Block	60	285116.43	875		14999400

OPEX for the BW line are calculated through the collection of data on OPEX for vacuum toilet installations. Costs regarding the pumping system are selected and electricity is found to be the principal source of operational costs.

Additionally, oil filters and gaskets for vacuum pumps need to be changed every 1000 operational hours and 5 years, respectively.

However, these costs are omitted since they can be considered negligible in front of the costs of electricity (oil filters have a price of around 18 \$/unit while gaskets cost 32 \$/unit). The average electricity consumption of vacuum pumps is that of 19.68 kWh/PE* yr (Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, 2016). **Error! Reference source not found.** shows the final OPEX for all building types for the V1 and V2 scenarios.

Table S16-2: Black water pumping OPEX for the V1 and V2 scenarios.

	PE	kWh/yr	OPEX (\$/yr)
LR	12.00	236.16	30.70
ST	12.00	236.16	30.70
MR	60.00	1180.80	153.50
MHR	120.00	2361.60	307.01
HR	300.00	5904.00	767.52
City Block	2000.00	45380.00	8,640.89

16.1 Pipeline and pumping - LCA

The impacts of the piping infrastructure during the operation phase originate from the pumping stations. Operation of pumps is based on a study by de Souza et al. (2021), who model the energy consumption of water pumping systems of multi-family buildings of the same characteristics as the one in this thesis. The ecoinvent database provides a dataset for the operation of electric water pumps which includes not only the electricity consumption but also the use of lubricating oil and the waste oil generated.

Table S16-3: Inventory details for the annual operation of pipeline and pumps (FU: water treatment for 300 people during a year).

Element	Amount	Unit	Ecoinvent dataset
Main pumping	17,280	MJ	market for water pump operation, electric
			GLO

17 Installation & Production

17.1 Installation (LCA)

As equipment is installed inside buildings which are already existent, all impacts related to drilling, land extraction and occupation, transport of removed land, and other associated processes are not part of the impacts of the installation of the decentralized system. The installation of the larger reactor (i.e., MBR) as an ISO container helps facilitate the installation, and even enable an easier expansion of the system if needed later.

Regarding pipeline, most studies assessing the installation phase refer to trenching (Du Fei et al., 2013; Hajibabaei et al., 2018; Xiong et al., 2020). However, as the additional pipelines installed in the building run from the dwellings to the basement, no trenches are required. According to cost-calculating software developed by CYPE (Alicante, Spain), the indoor installation of PE pipes of DN 32 in walls does not require machinery, but values for waste produced are given per metre of installed pipeline. This data is taken as part of the installation inventory, and proportionally incremented for the DN 70 pipes. Waste related to tanks, valves, filters, and pumps is also taken from CYPE software.

Hours of work are not considered as part of the inventory, however, the commuting of workers to the building from an assumed distance of 15 km is included for all days necessary for the installation of all the equipment, considering 8 hours of work per day. Hours of work for pipeline installation are obtained from company data (CYPE, Alicante, Spain), while treatment units are divided between bioreactors, taking a full day of installation, membranes, taking two to three hours, UV treatment taking two hours, tanks taking two hours, and additional treatment taking two to three hours (incl. remineralization treatment, pumping, and electrochemical treatment) (Hutchinson, 2004; Woodard, 2019). An additional four days of work are assumed to complete the accommodation of the system and its auxiliary components (e.g., connection of pipes to utilities in households). Four workers per car are assumed for the calculation of the total required commutes. Taking these considerations into account, the installation could be completed in a week (with four specialists working simultaneously), resulting in twelve commutes by car. Some exchanges might be missing as no additional information could be found for the further developing of the installation inventory. However, work hours are expected to have the highest weight, while other exchanges are complimentary.

Table S17-1: Inventory details for the installation of pipeline and equipment. Tables in the construction inventory refer to the total amount of materials of components needed to build the decentralized system for the water treatment for the reference population of 300 people.

Element	Amount	Unit	Ecoinvent dataset	
DN 32 pipe installation	4.00	kg	market group for waste polyethylene	GLO
DN 70 pipe installation	2.81	kg	market group for waste polyethylene	GLO
Stopcock, pumps, filter, and valves installation	4.07	kg	market group for waste paperboard	EU without CH
Tanks installation	15.00	kg	market group for waste paperboard	EU without CH
Commuting	210.00	km	market for transport, passenger car, large size, petrol, EURO 5	GLO

17.2 Production (LCA)

Many of the listed materials or components need further processing to be ready for installation. The considered production processed for the parts that require manufacturing or treatment are presented in Table S17-2.

Injection moulding is primarily considered for the manufacturing of plastic components as it is the most widespread process. Similarly, for plastic tank manufacturing, alternatives such as rotational moulding are not available in ecoinvent, therefore assuming injection moulding is a reliable approach. The inventory for the fabrication of hollow fibre membranes including solution and polymer preparation, hollow fibre extrusion, coagulation, rinsing, and pre-conditioning as well as module fabrication is based on Prézéus et al. (2021), as ecoinvent does not provide specific datasets and, as explained in the Boundaries section of the main document, the activity represents a significant part of the fabrication and maintenance stage for the whole system. Stainless steel and steel tanks are based on the sheet rolling process, while composite (in this case, fibreglass) tanks are hand-laid up.

3496 Table S17-2: Inventory details for the production processes considered. Tables in the construction inventory
 3497 refer to the total amount of materials of components needed to build the decentralized system for the water
 3498 treatment for the reference population of 300 people.

Element	Amount	Unit	Ecoinvent dataset	
Plastic tanks	437.65	kg	market for injection moulding	GLO
PVC sheet	36.43	kg	market for extrusion, plastic film	GLO
FPP sheet	22.15	kg	market for extrusion, plastic film	GLO
PE disks	618.00	kg	market for injection moulding	GLO
Steel components	7.00	kg	market for metal working, average for steel product manufacturing	GLO
Stainless steel tanks	1,577.54	kg	market for sheet rolling, chromium steel	GLO
Steel tanks	2,017.54	kg	market for sheet rolling, steel	
Polycarbonate components	0.21	kg	market for injection moulding	GLO
Silicone hollow fibre and cassette	268.18	m ² membrane		
Hollow fibre, tap water	46,178.58	kg	tap water production, ultrafiltration treatment	EU without CH
Hollow fibre, softened water	10,498.72	kg	market for water, completely softened	RER
Hollow fibre, epoxy resin	50.13	kg	market for epoxy resin, liquid	RER
Hollow fibre, calcium carbonate	16.89	kg	market for calcium carbonate, precipitated	RER
Hollow fibre, electricity	1,322.21	kWh	market group for electricity, medium voltage	RER
Hollow fibre, natural gas	65.52	m ³	market for natural gas, low pressure	RoW
Hollow fibre, factory	0.00	unit	market for chemical factory, organics	GLO
Hollow fibre, liquid waste	56.44	m ³	treatment of wastewater, average, wastewater treatment	EU without CH
Hollow fibre, solid waste	113.28	kg	treatment of municipal solid waste, incineration	RoW

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18 Cost Assessment

18.1 Construction costs

Construction costs for all building were calculated using architecture journals EME DOS and CONSTRUC. Since these provide Spanish prices, the values have been adjusted to EU-27 average prices using Eurostat indexes for the construction costs of new apartment buildings.

EME DOS provides 3 different costing values depending on the building's quality, while CONSTRUC only gives one average value. The final values used for LR and ST buildings have been those of EME DOS for the highest quality to avoid underestimations.

For MR, MHR, and HR buildings CONSTRUC data has been used since the type of building described in the journal is the most fitting with the buildings assessed in the study.

Table S18-1: Construction costs (where LQ: low quality; MQ: medium quality; HQ: high quality).

	LR (1 house)	LR (5 houses)	ST	MR	MHR	HR	City Block
Total m²	180	900	810	2,450	4,590	10,720	85,760
EMEDOS LQ	200,968	1,004,841	644,817	1,950,372	3,653,961	8,533,870	68,270,960
EMEDOS MQ	211,039	1,055,196	776,741	2,349,403	4,401,535	10,279,837	82,238,696
EMEDOS HQ	233,440	1,167,201	840,164	2,541,238	4,760,932	11,119,213	88,953,704
CONSTRUC	225,180	1,125,900	609,080	1,575,081	2,950,865	6,891,781	55,134,248

Table S18-2: Construction costs m² per building for different qualities 1) Simple Quality (€/m²); 2) Average Quality (€/m²), 3) High-End Quality (€/m²) .

2nd term 2022 CONSTRUC	Simple Quality (€/m ²) CAT	Average Quality (€/m ²) CAT	High-End Quality (€/m ²) CAT	
Edificios entre medianeras (costs €/m²) - 3 types				
Costs	739.8	770.14	834.71	
% plumbing	2.14	3.65	5.36	
Total to discount	2.14	3.65	5.36	
Final costs	723.97	742.03	789.97	
AVG EMEDOS	861.23		m2 per building	8,040.00
AVG CONSTRUC	751.99			

3517 Table S18-3: Construction costs m² per building for different qualities 1) Simple Quality (€/m2); 2) Average
 3518 Quality (€/m2), 3) High-End Quality (€/m2).

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Costs for city block				
EMEDOS	Simple Quality (€/m2) CAT	Average Quality (€/m2) CAT	High-End Quality (€/m2) CAT	AVG
	6,299,897.09	6,579,339.95	7,893,539.86	6,924,258.97
CONSTRUC	5,820,704.97	5,965,920.32	6,351,355.13	6,045,993.47

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3522 Table S18-4: Construction costs m² per building for different qualities 1) Simple Quality (€/m2); 2) Average
 3523 Quality (€/m2), 3) High-End Quality (€/m2).

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3rd term 2022 EMEDOS				
	Calidad sencilla (€/m2)	Calidad media (€/m2)	Calidad alta (€/m2)	m2/hh
Multi-family residential building with a basement garage	808.22	844.07	1,012.67	75.00
Solar energy [%]	0.78	0.78	0.78	0.78
Plumbing and gas [%]	4.54	4.54	4.54	4.54
% assigned to plumbing	0.50	0.50	0.50	0.50
Plumbing and gas [%]	2.27	2.27	2.27	2.27
Total to discount	3.05	3.05	3.05	3.05
	Calidad sencilla (€/m2) CAT	Calidad media (€/m2) CAT	Calidad alta (€/m2) CAT	m2/hh
Final costs	783.57	818.33	981.78	75.00

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3528 **18.2 Breakdown of costs and benefits (without monitoring costs) for all scenarios**

3529 *Table S18-5: Breakdown of costs for all buildings for the five main types of building scenario (Garrido-*
 3530 *Baserba et al, 2022). City Block scenario not included in this table (see below).*

<i>Total costs</i>	Low-rise housing		Short top building		Mid-rise building		Mid/high-rise building		High-rise building	
(\$)	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX
GW line										
Sewer	2,904	88	1,891	58	4,813	147	8,217	250	14,891	453
Pumping	394	208	394	208	1,970	1,040	3,941	2,080	9,851	5,200
MBR	1,764	6,294	1,764	6,294	7,177	27,497	13,136	51,571	29,206	117,614
RO	174	1,259	174	1,259	174	6,296	174	12,593	174	31,482
UV	167	1,185	167	1,185	167	5,926	177	11,852	345	29,630
Total treatments	2,105	8,739	2,105	8,739	7,518	39,719	13,487	76,016	29,725	178,727
TOTAL GW	5,403	9,035	4,389	9,004	14,302	40,906	25,644	78,346	54,467	184,380
BW line										
Sewer	1,076	520	701	339	1,784	862	3,045	1,472	5,519	2,668
Pumping	4,890	472	4,890	472	8,151	2,360	16,301	4,719	40,753	11,799
UASB	3,341	2,057	3,341	2,057	16,705	10,286	33,410	20,571	83,525	51,429
OLAND	35	919	35	919	175	4,595	351	9,191	877	22,977
Struvite reactor	13	34	13	34	65	172	131	343	327	858
Total treatments	3,389	3,011	3,389	3,011	16,946	15,053	33,892	30,105	84,729	75,264
TOTAL BW	9,356	4,003	8,980	3,821	26,880	18,275	53,238	36,297	131,001	89,730
Rain water										
Pumping	40	21	40	21	202	107	404	213	1,010	533
Tank	1,463		1,463		2,476		3,703		6,717	
RO	174	127	174	127	174	634	174	1,267	174	3,168
UV	167	119	167	119	167	596	177	1,193	345	2,982
Total rainwater	1,844	267	1,844	267	3,019	1,337	4,457	2,673	8,246	6,683
TOTAL	16,602	13,305	15,214	13,093	44,201	60,517	83,339	117,316	193,714	280,793

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3532 **18.3 Total costs including monitoring for the city block scenario.**

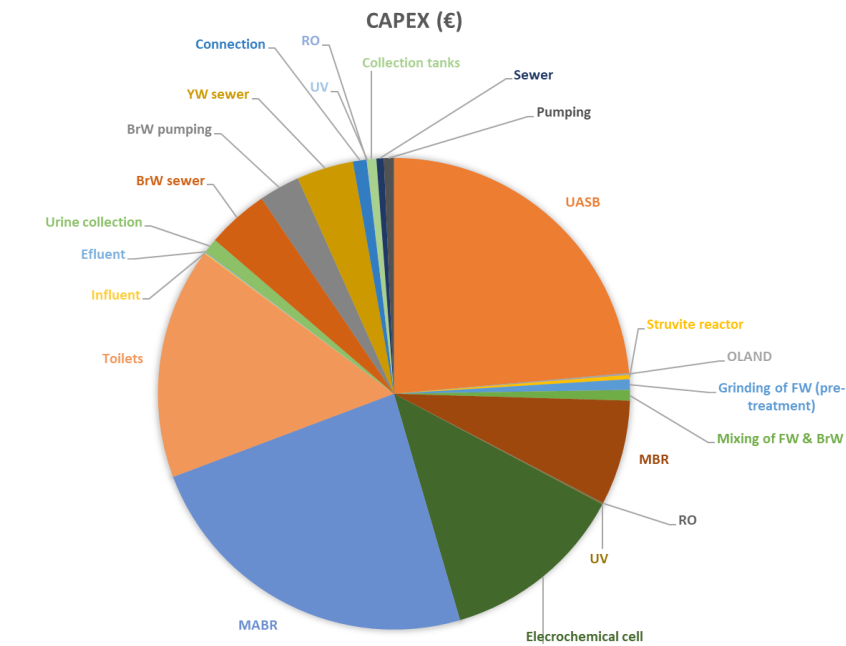
3533 *Table S18-6.Total costs for the housing development (city block) not including monitoring.*

<i>Total costs</i>			
	CAPEX (€)	OPEX (€/yr)	OPEX (€) – 30 Years
BrW+nrcYW+FW			
UASB	556,833.33	27,269.61	419,200.72
OLAND	3,027.66	5,161.71	79,348.14
Struvite reactor	6,740.11	443.83	6,822.73
Grinding of FW (pre-treatment)	17,215.63	7,678.40	118,035.87
Mixing of FW & BrW	17,116.00	2,282.77	35,091.75
Treated effluent (BR+nrcYW+FW) + GW			
MBR	169,679.61	45,368.58	697,426.31
RO	1,388.72	14,792.46	227,396.37
UV	1,174.60	11,833.97	181,917.10
YW			
Electrochemical cell	300,000.00	6,396.30	98,326.81
MABR	561,078.00	1,010.00	15,526.18
Toilets	375,000.00		
Equalisation & collection			
Influent	1,491.00		
Efluent	1,597.00		
Urine collection	24,000.00		
Sewer			
BrW sewer	99,699.95	215.57	3,313.87
BrW pumping	66,000.00	2,260.00	34,741.74
YW sewer	91,751.44	215.57	3,313.87
Connection	22,055.12		3,138.96
Rainwater			
RO	347.18	3,641.01	55,971.18
UV	276.38	2,741.46	42,143.00
Collection tanks	15,078.00		
Sewer	11,893.93	26.95	414.23
Pumping	16,114.70	553.31	8,505.73
Sludge treatment		2,054.34	31,580.21
TOTAL	2,359,558.36		2,062,214.76

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3535 Table S18-7: Total capital costs (CapEx) not including monitoring for the city block scenario.

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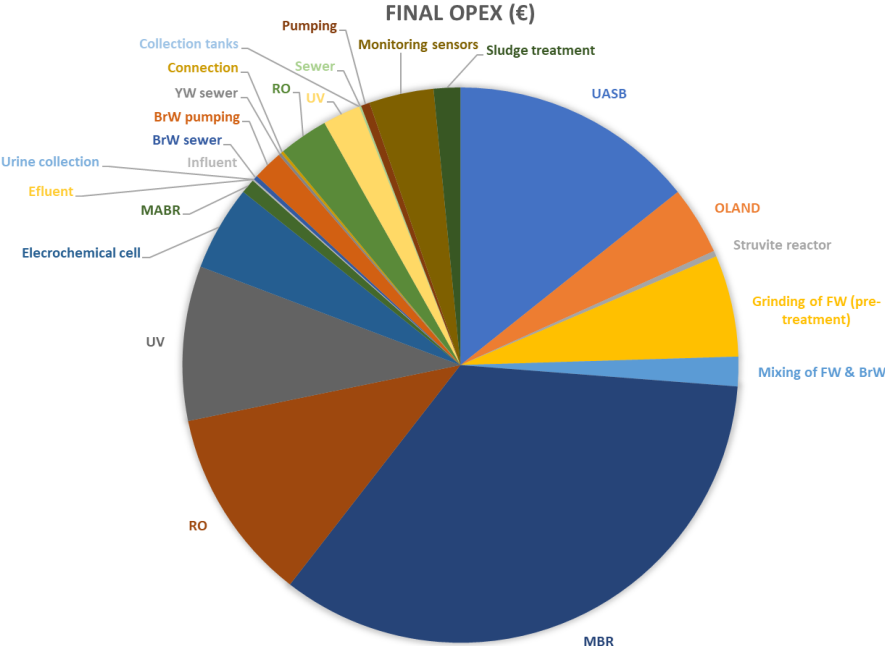


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3539 Table S18-8: Total operational costs (OpEx) not including monitoring for the city block scenario.

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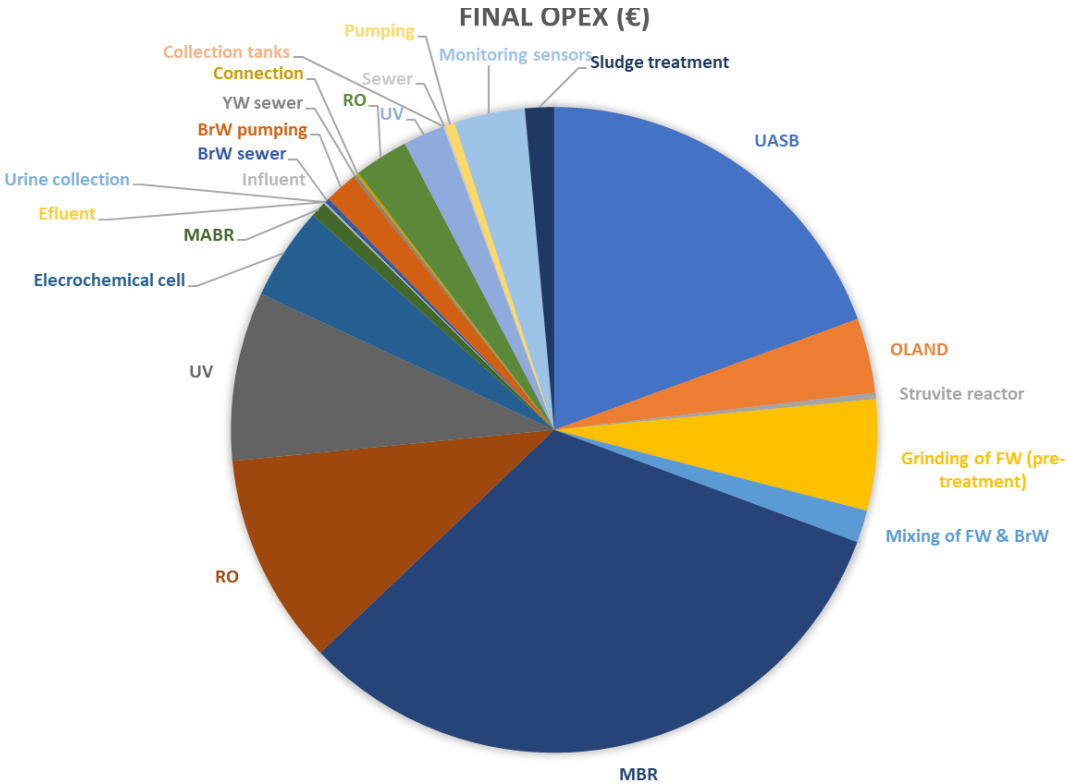
3543 Table S18-9: Total costs for the housing development (city block) including monitoring.

Total costs			
	CAPEX (€)	OPEX (€/yr)	OPEX (€)
BrW+nrcYW+FW			
UASB	556,833.33	27,269.61	419,200.72
OLAND	3,027.66	5,161.71	79,348.14
Struvite reactor	6,740.11	443.83	6,822.73
Grinding of FW (pre-treatment)	17,215.63	7,678.40	118,035.87
Mixing of FW & BrW	17,116.00	2,282.77	35,091.75
Treated effluent (BR+nrcYW+FW) + GW			
MBR	169,679.61	45,368.58	697,426.31
RO	1,388.72	14,792.46	227,396.37
UV	1,174.60	11,833.97	181,917.10
Yellow Water			
Electrochemical cell	300,000.00	6,396.30	98,326.81
MABR	561,078.00	1,010.00	15,526.18
Toilets	375,000.00		
Equalisation & collection			
Influent	1,491.00		
Effluent	1,597.00		
Urine collection	24,000.00		
Sewer			
BrW sewer	99,699.95	215.57	3,313.87
BrW pumping	66,000.00	2,260.00	34,741.74
YW sewer	91,751.44	215.57	3,313.87
Connection	22,055.12		3,138.96
Rain Water			
RO	347.18	3,641.01	55,971.18
UV	276.38	2,741.46	42,143.00
Collection tanks	15,078.00		
Sewer	11,893.93	26.95	414.23
Pumping	16,114.70	553.31	8,505.73
Monitoring sensors			
Sludge treatment		2,054.34	31,580.21
TOTAL	2,359,558.36		2,062,214.76
**Biogas already accounted for in energy demand of UASB			
Benefits	€/yr	€	
Struvite; from struvite reactor	974.47	14,979.97	
YW; P from MEC	192.35	2,956.92	
YW; liquid fertilizer from MABR	1,207,237.50	18,558,199.35	
TOTAL	1,208,404.32	18,576,136.24	

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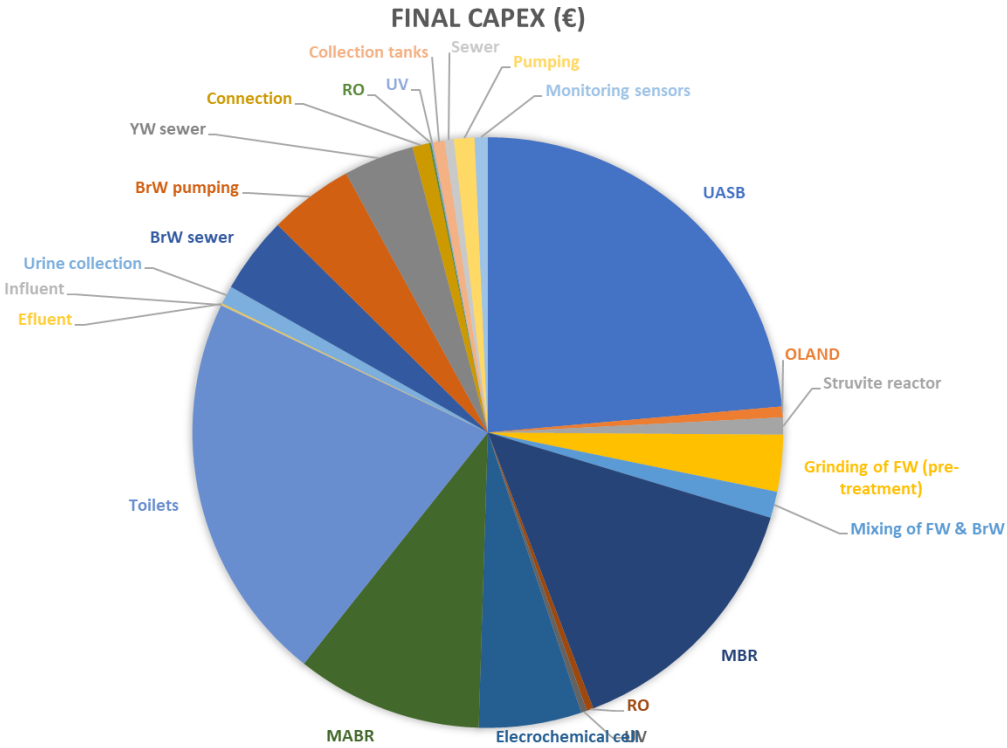
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3546 Table S18-10: Total operational costs (OpEx) including monitoring for all scenarios (\$).



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3548 Table S18-11: Total Capital costs (CapEx) including monitoring for all scenarios (\$).



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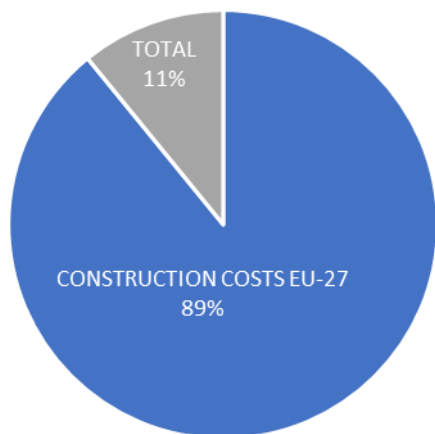
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18.4 Total costs of synergetic strategies

Table S18-12: Total Capital costs (CapEx) and Operational costs (OpEx) including the synergetic strategies.

	Building costs		CAPEX			CAPEX + OPEX
	CONSTRUCTION COSTS EU-27	CAPEX [\$ /30y]	%	OPEX [\$ /30y]	CapEx + OpEx	%
D-SS	65,075,251	2,377,421	3.26	2,043,168	4,420,589	6.05
	CONSTRUCTION COSTS EU-27	Rainwater				
RW	65,075,251	58,571	0.08	116,565	175,136	0.24
	CONSTRUCTION COSTS EU-27	Vertica Farming				
VF	65,075,251	2,468,709	3.38	3,097,675	5,566,384	7.62
	CONSTRUCTION COSTS EU-27	Solar Energy				
PV	65,075,251	3,043,618	4.17	268,440	3,312,058	4.54
	CONSTRUCTION COSTS EU-27	TOTAL (NO Paybacks)				
Total (No Payback)	65,075,251	7,948,320	10.88	5,525,847	13,474,168	18.45
	CONSTRUCTION COSTS EU-27	TOTAL (With Paybacks)				
Total (Payback)	65,075,251	-324,435	-0.50	1,381,462	1,718,733	2.57

Table S18-13: Total initial costs (CapEx) when including the synergetic strategies.



■ CONSTRUCTION COSTS EU-27 ■ TOTAL

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Table S18-14: Total Capital costs depending on location for when including the different payback mechanisms.

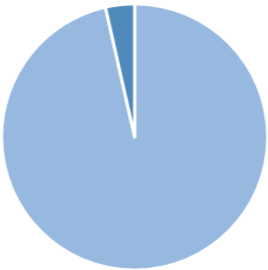
		Benefits after payback				
	D-SS CAPEX	VF	PV	RW	CAPEX [30 years]	%
Barcelona	2,377,421	1,100,319	857,890	28,426	390,787	16.4
Amsterdam	2,377,421	1,100,319	-1,371,543	159,672	2,488,974	104.7
Chile (Santiago)	2,377,421	1,100,319	300,532	-21,945	998,515	42.0
Hong Kong	2,377,421	1,100,319	857,890	479,573	-60,360	-2.5
Seoul	2,377,421	1,100,319	3,087,323	-14,896	-1,795,325	-75.5
Toronto	2,377,421	1,100,319	-256,827	195,250	1,338,680	56.3
Miami	2,377,421	1,100,319	6,710,153	199,267	-5,632,317	-236.9
AVG	2,377,421	1,100,319	1,455,060	146,478	-324,435	-14

							Wo Benefits	W Benefits
	D-SS CapEx	D-SS OpEx	Total [CapEx +OpEx]	Benefits [30y]	Cost - Benefits [30y]	%		
							\$/m3	\$/m3
Barcelona	2,377,421	2,043,168	4,420,589	1,986,635	2,433,955	45	1.62	0.89
Amsterdam	2,377,421	2,043,168	4,420,589	-111,553	4,532,142	-3	1.62	1.66
Chile (Santiago)	2,377,421	2,043,168	4,420,589	1,378,906	3,041,683	31	1.62	1.12
Hong Kong	2,377,421	2,043,168	4,420,589	2,437,782	1,982,807	55	1.62	0.73
Seoul	2,377,421	2,043,168	4,420,589	4,172,747	247,843	94	1.62	0.09
Toronto	2,377,421	2,043,168	4,420,589	1,038,742	3,381,847	23	1.62	1.24
Miami	2,377,421	2,043,168	4,420,589	8,009,739	-3,589,150	181	1.62	-1.32
AVG	2,377,421	2,043,168	4,420,589	2,701,857	1,718,733	61	1.62	0.63

VF					PV			
		Wo Benefits		W Benefits			Wo Benefits	W Benefits
	COST	NET	\$/m3	\$/m3	COST	NET	\$/m3	\$/m3
Barcelona	3,097,675	- 1,100,319	1.14	-0.40	3,276,424	-857,890	1.20	-0.31
Amsterdam	3,097,675	- 1,100,319	1.14	-0.40	3,143,392	1,371,543	1.15	0.50
Chile (Santiago)	3,097,675	- 1,100,319	1.14	-0.40	3,243,166	-300,532	1.19	-0.11
Hong Kong	3,097,675	- 1,100,319	1.14	-0.40	3,276,424	-857,890	1.20	-0.31
Seoul	3,097,675	- 1,100,319	1.14	-0.40	3,409,457	3,087,323	1.25	-1.13
Toronto	3,097,675	- 1,100,319	1.14	-0.40	3,209,908	256,827	1.18	0.09
Miami	3,097,675	- 1,100,319	1.14	-0.40	3,625,634	6,710,153	1.33	-2.46
AVG	3,097,675	- 1,100,319	1.14	-0.40	3,312,058	1,455,060	1.21	-0.53

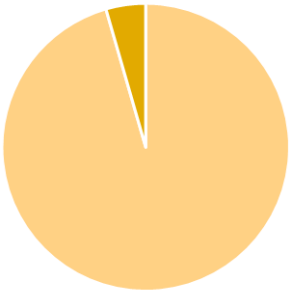
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3564 Table S18-15: Total initial costs (CapEx) for the decentralized source separation.



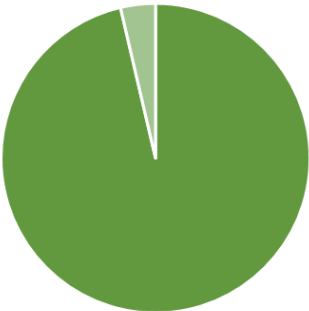
3565 CONSTRUCTION COSTS EU-27 CAPEX [\$ / 30y]

3566 Table S18-16: Total initial costs (CapEx) for the photovoltaic installation.



3567 CONSTRUCTION COSTS EU-27 SOLAR ENERGY CAPEX

3568 Table S18-17: Total initial costs (CapEx) for the vertical farming.



3569 CONSTRUCTION COSTS EU-27 VF CAPEX

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18.5 Water Economics: Evaluating Centralized and Decentralized Costs (Section 18 High-level Summary)

Therefore, the difference between the main water costs (i.e., treatment, potabilization, and sewer) and the billed water costs in different cities not only illustrates the complexity of water economics, but also that when excluding regional disparities and recognizing societal services as resilience or recycling, the costs between the centralized and decentralized approaches are comparable. The conventional centralized system has an approximate cost of $1.2 \pm 0.5 \$/\text{m}^3$ without considering any recycling capability and taking advantage of an already-built infrastructure and the economies of scale (SS). Even if the D-SS can lower the overall operational costs (due to higher recovery efficiencies) when compared to the conventional approach, the need to adapt the infrastructure (i.e., NoMix toilets, brown-yellow lines, remote monitoring and control, etc.) still results in higher overall costs $1.8 \pm 0.3 \$/\text{m}^3$. Nevertheless, as the D-SS approach enables the recycling of 85-95% of the water, a more realistic comparison with the centralized paradigm should also consider the cost of either direct or indirect potable reuse to account for such resilience-enhancing capability. Centralized potable reuse strategies also vary significantly in cost and type, but the most common and benchmarked alternatives are in the range of $1.2\text{-}2 \$/\text{m}^3$ (Keller et al., 2021). The addition of potable reuse would significantly increase the overall cost of water ($2 \pm 0.5 \$/\text{m}^3$), but it would allow a more comprehensive comparison with the D-SS approach given they would provide the same societal service (i.e., drinking-quality water without tapping on traditional supply sources). Using this comparison, the costs of the decentralized system would be lower than the combination of the conventional system when augmented with reuse potable strategies.

19 Model Overview (SIMBA#)

We developed a series of models based on the source-separation concept to investigate the feasibility of implementing decentralized water and wastewater treatment systems. The models were built following the recommendations of the IWA Guidelines for Using Activated Sludge Models (Rieger et al. 2012a) and using the advanced modelling platform SIMBA# [v4.2]. All the models were designed with the energy-producing anaerobic co-digestion process as the main treatment with the influent flows derived from a source separation approach (i.e., organic waste and brown, yellow, and grey water) instead of using the energy-intense conventional aeration-based treatment (i.e., activated sludge), which do not follow a source separation approach. The developed models for the mainstream process were built on an adapted biokinetic model based on ADM1 (Anaerobic Digestion Model) of the International Water Association. The adapted models were specifically built to allow the solving of multiple substrates (i.e., food, agricultural, and industrial wastes), including brown and black water streams (i.e., toilet-captured flows), and it was modified to consider pH changes in the internal pH value calculation by using a specific algebraic equation solver.

The corresponding aeration system for the grey water flow (i.e., showers, faucets flows, garage, garden) and the biofilm-based nitrogen removal sub-system used the inCTRL-ASM biokinetic model developed by the Institut für Automation und Kommunikation (ifak 2017). To construct the layout of the aeration system, we included blowers, pipes, fittings, valves, and diffusers mechanistic models for each actuator. The piping system was modelled using the Darcy–Weisbach equation, with the friction factor calculated using the Swamee & Jain (1976) equation. The pressure rise across blowers and pressure drops across valves and diffusers are calculated using polynomial functions based on airflow rate, which have been calibrated using manufacturer data. More information on the aeration system models can be found in Schraa et al. (2015). Aeration control was accounted for by means of continuous feedback using proportional-integral or proportional-integral-derivative (PID) control algorithms. To model the behavior of the automatic valves, a control algorithm was implemented that fixes the valve position of the lane with the highest oxygen requirement and allows the other valve to vary to adjust the required airflow.

The sub-system for the nitrogen removal of the effluent generated in the anaerobic co-digestion mainstream process was modeled with an in-house inCTRL-ASM biofilm-based biokinetic model, which includes two-step nitrification and the growth of anammox bacteria (AMX), in addition to hydrolysis, adsorption, fermentation, and the growth of ordinary heterotrophic organisms (OHO), phosphorus accumulating organisms (PAO), and methylophs. The anammox biokinetic sub-model was based on the model of Koch et al. (2000), and the value of the half-saturation coefficient for oxygen was determined based on data reported by Strous et al. (1997).

Simulation results were cross-checked with an Excel-based model exclusively built for this project. The Excel-based model was used to calculate in steady-state conditions the size, cost,

performance, and main technical details of all necessary equipment units and correlate, through engineering-based equations, all collected knowledge from literature, manufacturers, and specialized software (e.g., Capdetworks, etc.). The simulation results were further cross-checked with complementary software specialized in source separation modelling [Sampson; Zinati, 2021] and software to provide detailed mass and energy flow analysis [e!Sankey; Barnosell, 2023] (SS).

19.1 The SIMBA modules

The source separation-based model is applied to one of the urban development scenarios (city block). The D-SS scenario was simulated using the modeling software SIMBA#, which was augmented with manufacturing specifications and available technical literature. The separation-based model comprises five main modules: the Anaerobic Digestion Module, the Nitrogen Recovery Module, the Co-Digestion Module, the Greywater Module, and the Rainwater Harvesting Module.

- The Anaerobic Digestion Module
- The Nitrogen Recovery Module
- The Co-Digestion Module
- The Greywater Module
- The Rainwater Harvesting Module.

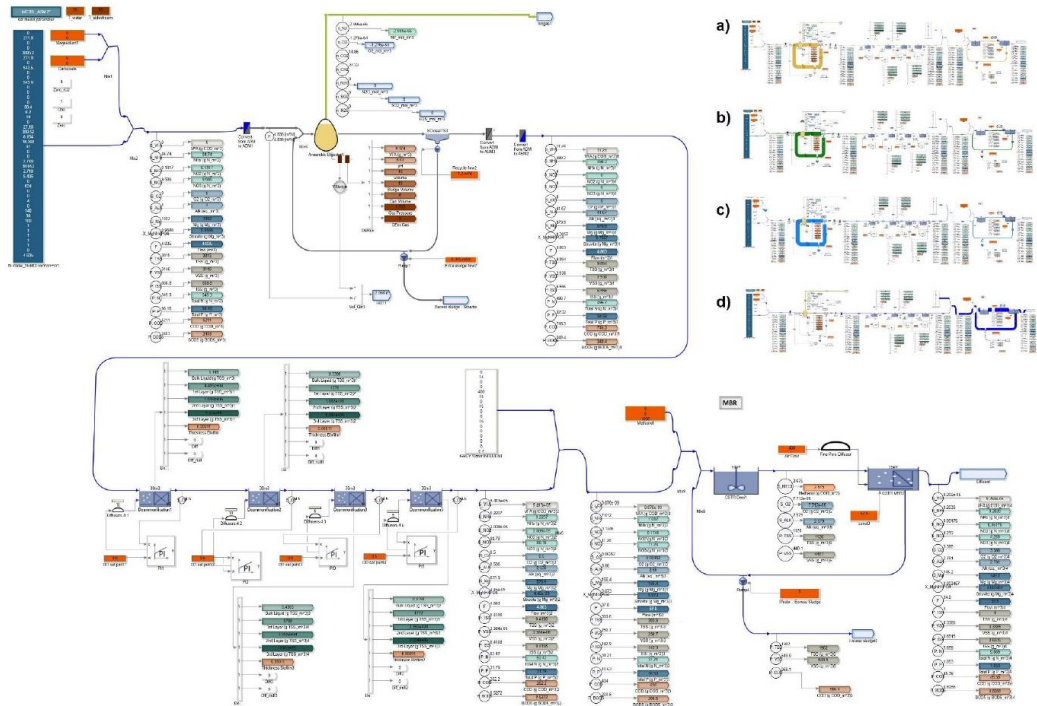


Table S19-1. SIMBA# simulation showcasing the Sankey diagrams for the flow movement of a) chemical oxygen demand; b) total nitrogen; c) total phosphorus; and d) volume.

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3663 **19.2 The Anaerobic Digestion Module**

3664 The Anaerobic Digestion (AD) module consists of an up-flow anaerobic sludge blanket reactor
3665 (UASB) with simultaneous struvite precipitation, treating approximately 10% of the system's flow,
3666 which includes brown water and organic waste. This module was constructed using an adapted
3667 biokinetic model based on ADM1 (Anaerobic Digestion Model). The UASB is designed with a
3668 hydraulic retention time (HRT) of 7.15 days and a solids retention time (SRT) of 30 days. It
3669 features a degassing membrane contactor and a reactor for gas and liquid separation. The total
3670 space requirements for this module are approximately 40 m³, encompassing the UASB (20 m³),
3671 struvite precipitation (4 m³), digestate tanks (5 m³), microturbines (3 m³), chemical dosing (1 m³),
3672 and monitoring equipment (2 m³). The produced biogas is used for energy production, contributing
3673 to approximately 60% of the energy requirements. The module also yields struvite precipitate
3674 (18% P recovery and 3% N recovery) and digestate (60% P recovery and 15% N recovery).

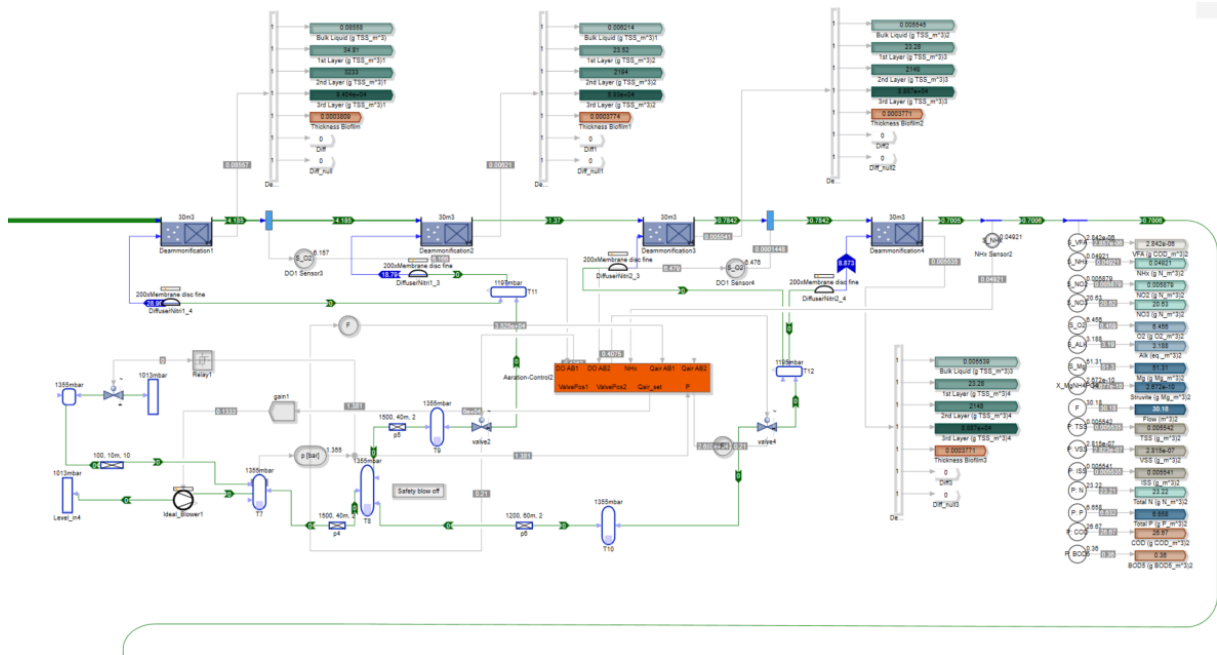
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19.3 The Nitrogen Recovery Module

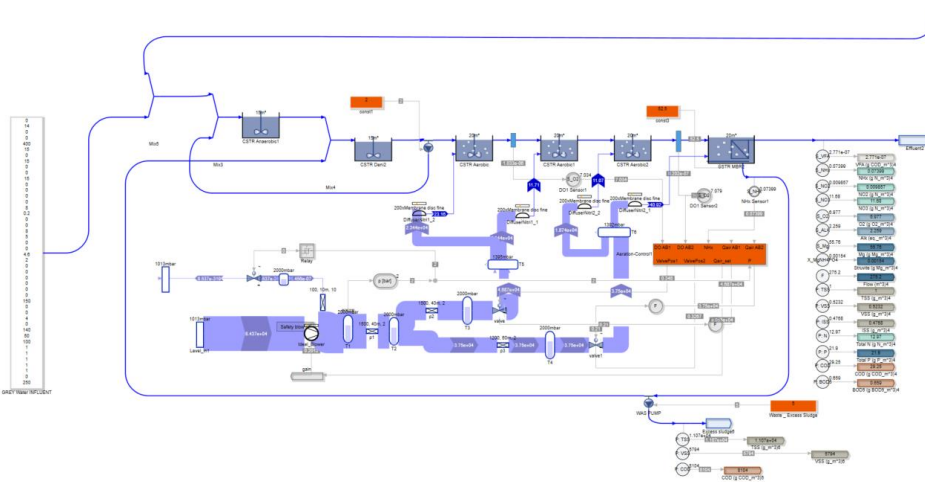
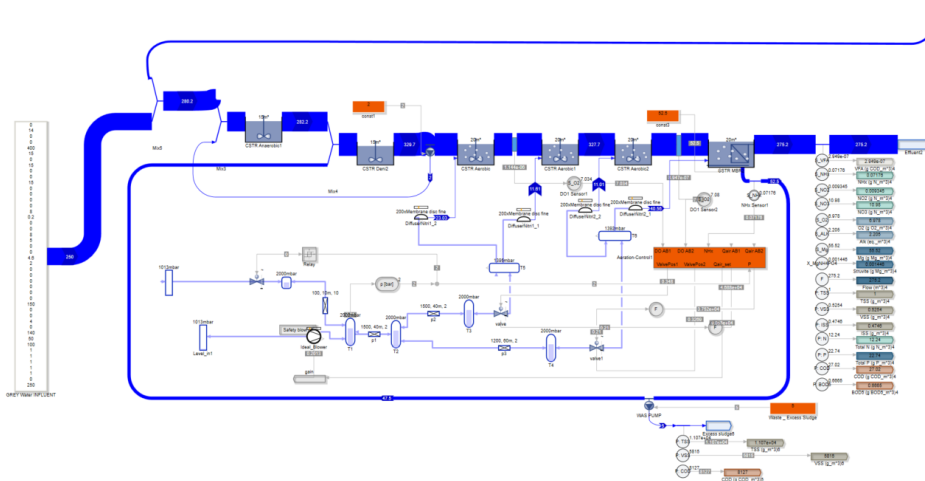
The nitrogen removal module, responsible for treating effluent from anaerobic co-digestion, is modeled using a single-stage OLAND process, suitable for decentralized, small-scale treatment systems with high organic matter loads. The main goal of the process is to reduce the nitrogen concentration, which is reduced by approximately 65-70%. The Oland model is constructed with an in-house inCTRL-ASM biofilm-based biokinetic model, incorporating two-step nitrification and the growth of anammox bacteria (AMX), as well as other processes like hydrolysis, adsorption, fermentation, and the growth of various organisms. To avoid algebraic issues due to the small size of the decentralized unit, the nitrogen removal module utilizes four scaled-up reactors instead of a single reactor. This module requires approximately 5 m³ of space, including a monitoring station and equipment. The aeration system for the nitrogen module is integrated with the Grey Water Module's aeration system.



19.5 The Greywater Module

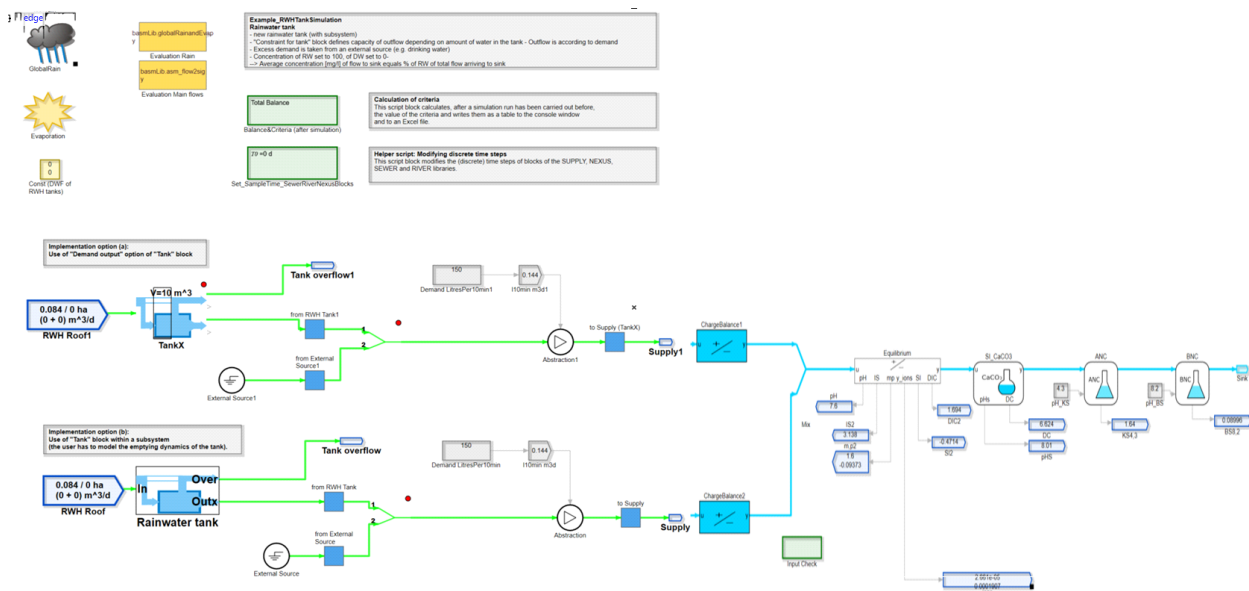
The greywater module aims to treat greywater flows (e.g., showers, faucets, garage, garden, etc.) to potable quality water, even when non-potable uses are considered. While greywater flows make up to 85% of the system's flow, their concentrations of COD, N, and P are only 15%, 2%, and 7%, respectively. To treat this low-strength stream, two main scenarios are considered: the use of a membrane bioreactor (MBR) or the Nereda Process (granular-based technology). Both processes are modeled using an inCTRL-ASM biokinetic model under the SIMBA# platform.

For the granular-based Nereda scenario, a variable volume biofilm model is employed. This model allows for the modeling of granular sequential bioreactors (GSBRs) without the need for a separate variable volume tank and a recycle stream. The model predicts biofilm thickness, allows for non-uniform biofilm geometries, and models the impact of mixing intensity on the biofilm detachment rate. The Nereda model combines existing biofilm and sequencing batch reactor (SBR) models within the SIMBA# platform. In the case of the MBR scenario, the space requirements are approximately 200 m³, which includes the main MBR system and related equipment (150 m³), equalization tanks (30 m³), and purification-related treatment (10 m³).



19.6 The Rainwater Harvesting Module

The rainwater treatment module, also created in SIMBA#, estimates the collection and storage of rainwater and calculates the water quality parameters. The model simulates the redirection of harvested flows into designated rain tanks, accounting for different rain patterns in various climatic regions. The harvested water is stored for later use and goes through pre-filters, in-tank filtration, reverse osmosis (RO), and a tailored UV treatment combination. The model supports the analysis of the mixing of two different potable water sources, centralized supply and treated roof-harvested water. It enables the control of drinking water quality, speciation and the calculation of parameters such as buffering capacities, ionic strength, alkalinity, hardness, and calcite saturation. The space requirements for this module are estimated at 20-40 m³, primarily due to storage tanks, which can vary based on storage goals or capabilities, along with equalization tanks (30 m³), while the required equipment occupies less than 2-3 m³.



19.7 Material flow analysis and SIMBA# models

Complementary MFA figures showcasing the movement of the components in water and flow volumes through the system individually. Sankey diagrams obtained from the simulation program are added to showcase conformity with the flows calculated through MFA in a visual manner.

Figure S1 focuses on organics, which are the main component of BrW and are mostly eliminated in the UASB reactor, where biogas production can be observed both in the MFA and SIMBA# Sankey diagrams. The additional COD input originating from GW production is tackled in the MBR.

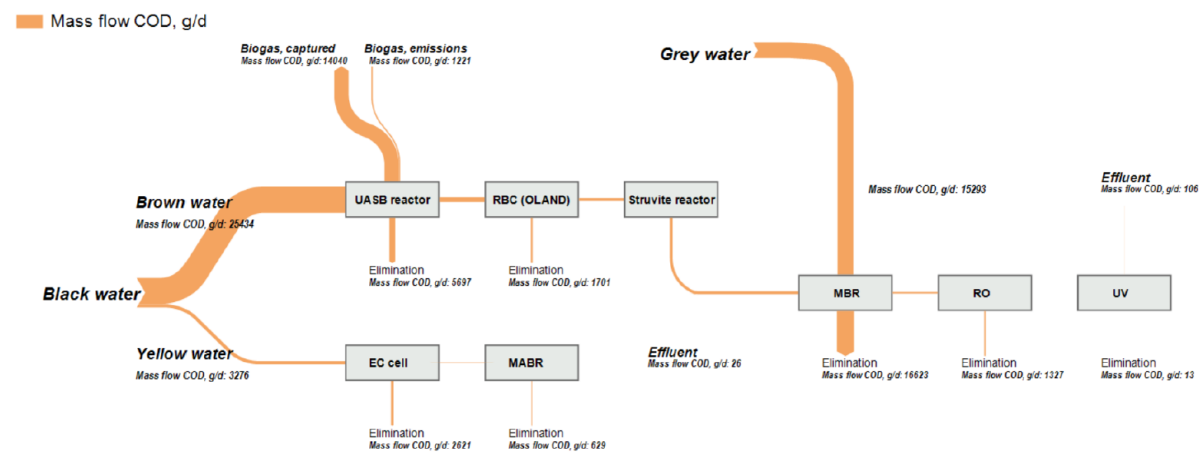


Figure S1: MFA of the decentralized system showcasing total chemical oxygen demand (COD) in g/d, for the reference population of 300 people.

Figure S2 helps assess the efficiency of nitrogen recovery achieved in the system. The main nitrogen source is BW, including the highest presence in YW and a significant amount of pollutants in BrW. GW has a low nutrient content, but its representation helps identify losses and put in evidence how the anammox process helps eliminate almost 24% of input nitrogen, while up to 61% is recovered mostly in the MABR.

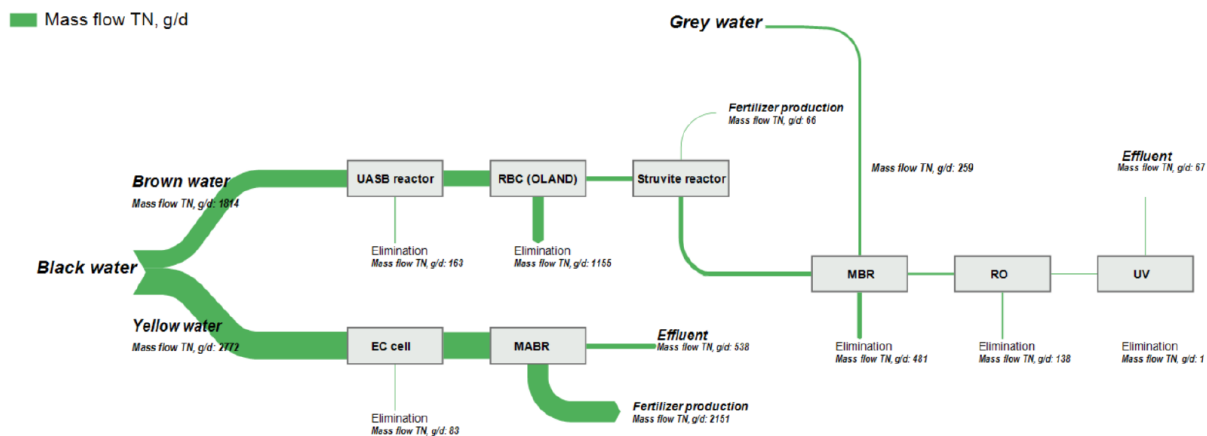


Figure S2: MFA of the decentralized system showcasing total nitrogen (TN) in g/d, for the reference population of 300 people.

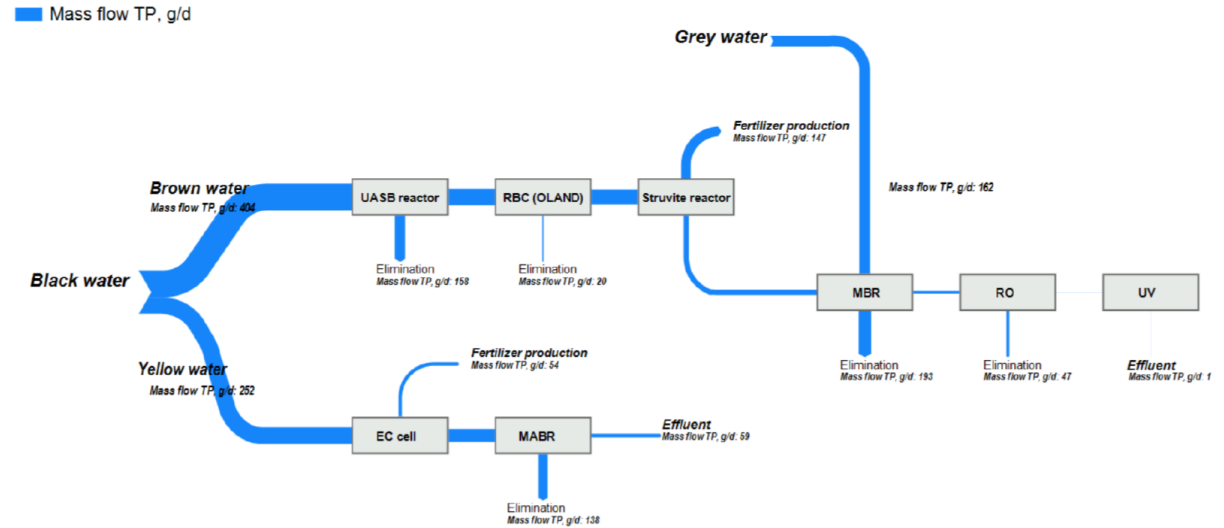


Figure S3: MFA of the decentralized system showcasing total phosphorus (TP) in g/d, for the reference population of 300 people.

Material Flow Analysis for extreme decentralization

Nutrient balance

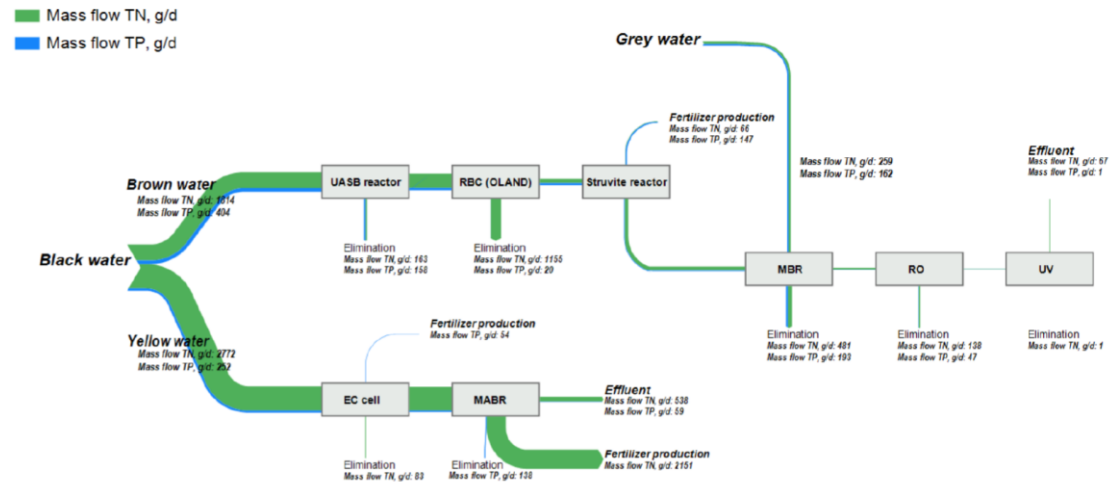


Figure S4: MFA of the decentralized system showcasing mass flows of total nitrogen (TN) and total phosphorus (TP) in g/d, for the reference population of 300 people.

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Material Flow Analysis for extreme decentralization

Nutrient and COD balance (with sludge line represented)

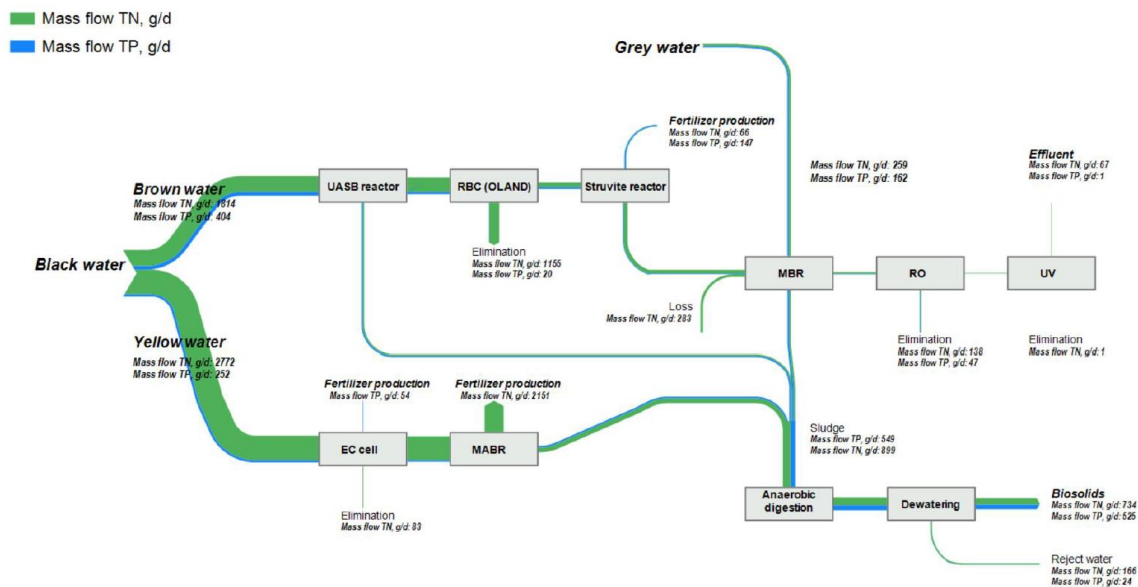


Figure S5: MFA of the decentralized system showcasing mass flows for total nitrogen (TN) and total phosphorus (TP) in g/d also showcasing the sludge treatment line, for the reference population of 300 people.

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Material Flow Analysis for conventional treatment

Nutrient balance

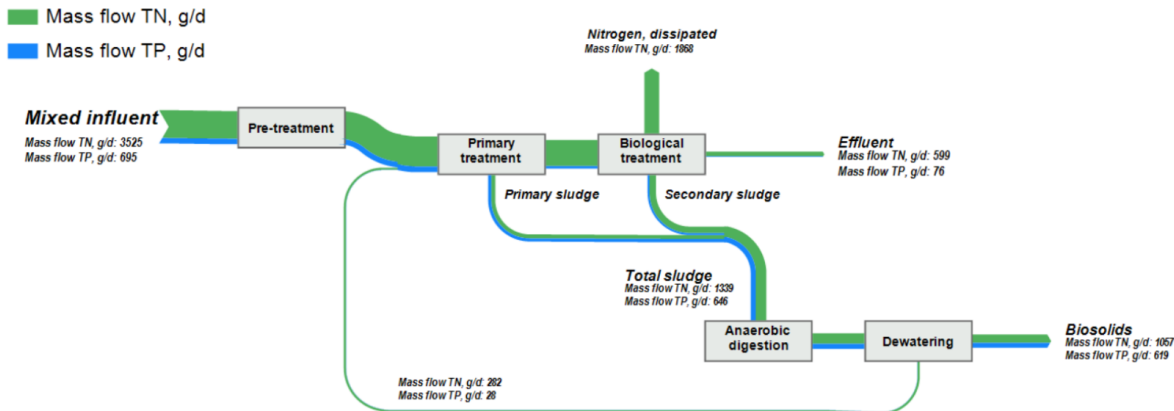
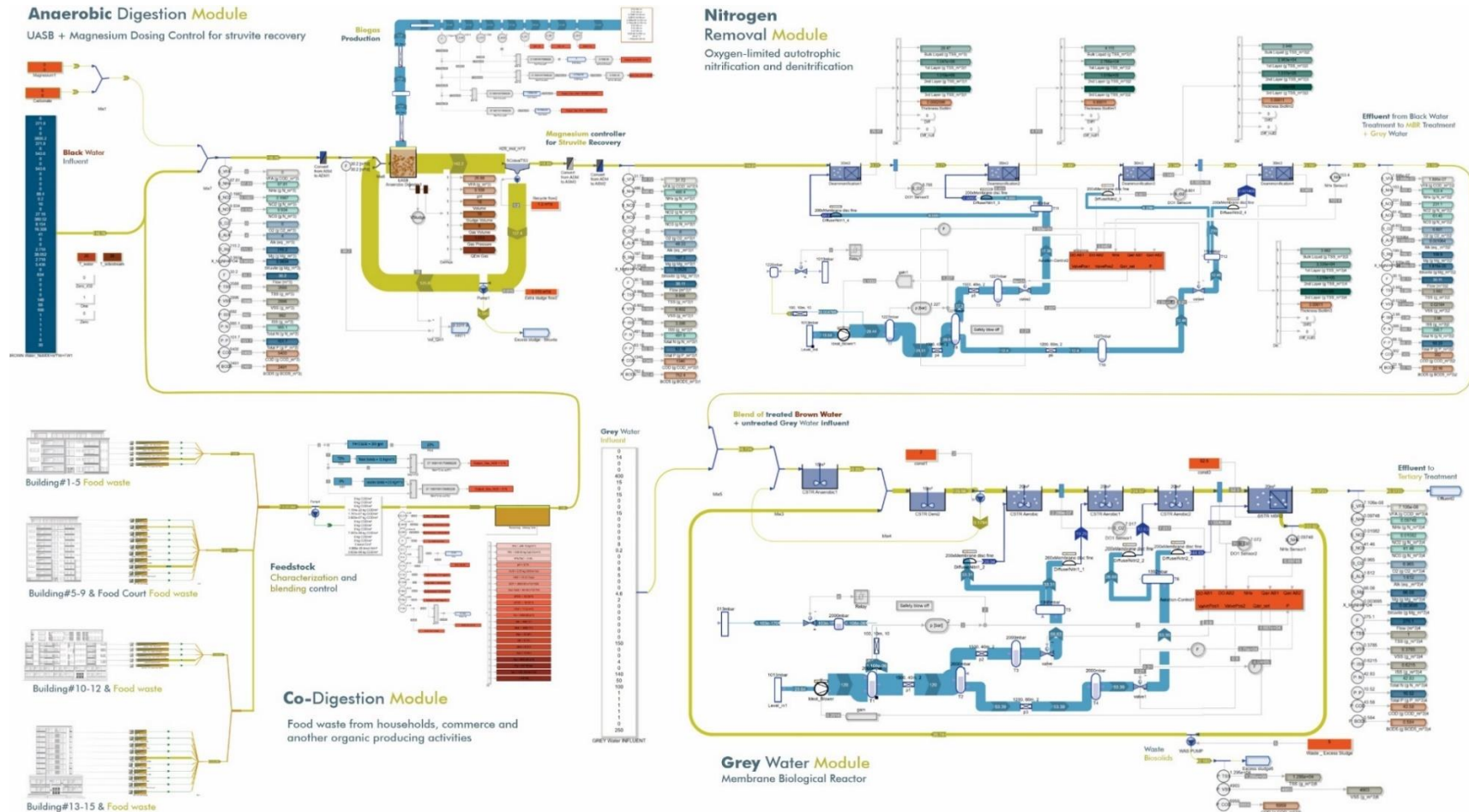


Figure S6: MFA of the conventional system showcasing mass flows for total nitrogen (TN) and total phosphorus (TP) in g/d, for the reference population of 300 people.

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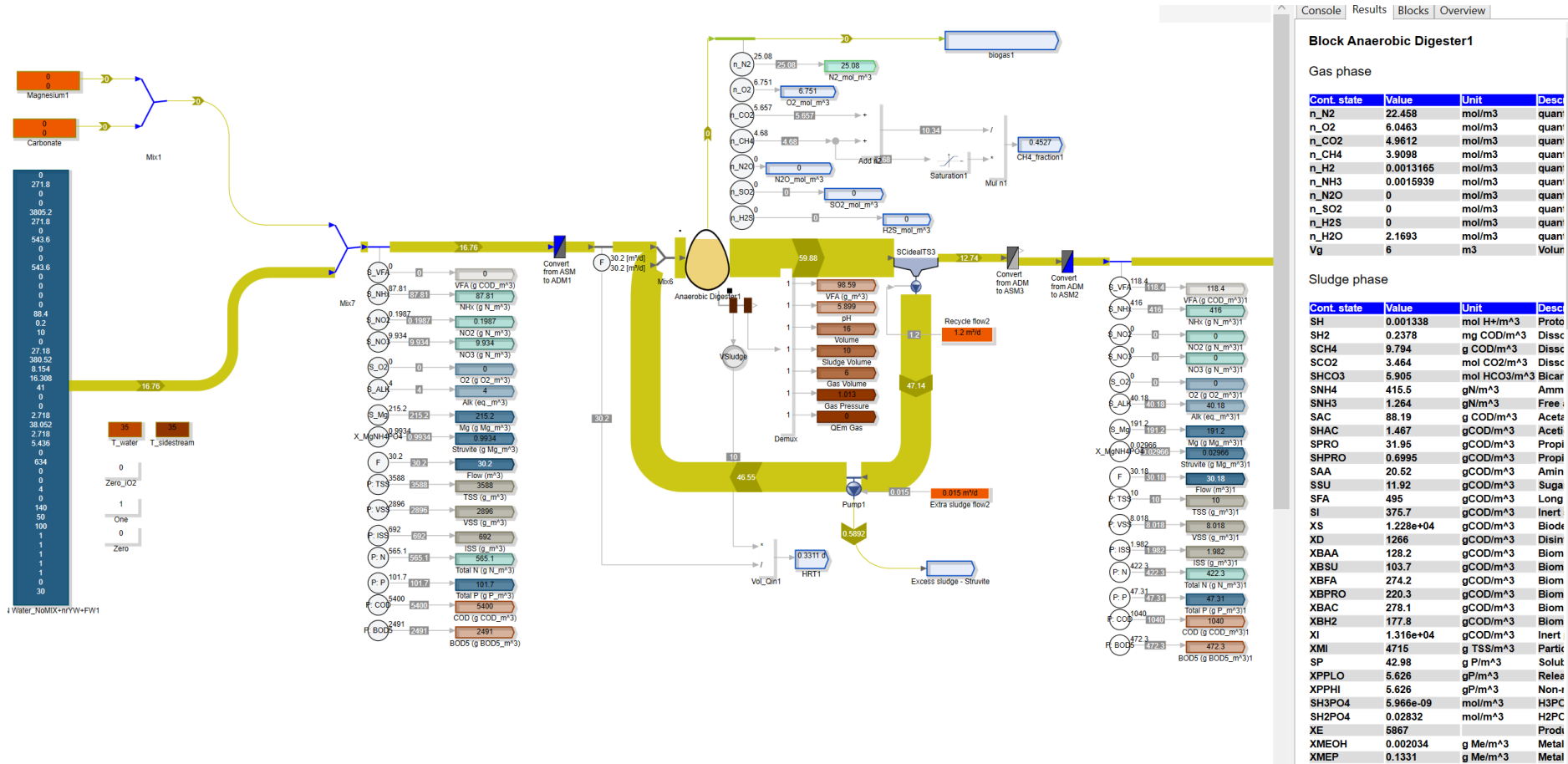
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3790 Table S19-2. The source separation-based model in an urban cluster [city block] was obtained by the modeling software SIMBA#. The visual represents a Sankey
 3791 diagram of TKN mass flow, g N/day (green), and the biogas and air flows, m3/day (light blue). The model includes three main types of controllers: a) Chemical
 3792 dosing of magnesium for struvite recovery; b) Aeration controllers for both Oland and MBR/Nereda oxygen requirements; c) co-digestion module for the
 3793 appropriate blending of feedstocks properties (i.e... organics from households, commerce, restaurants, etc.).

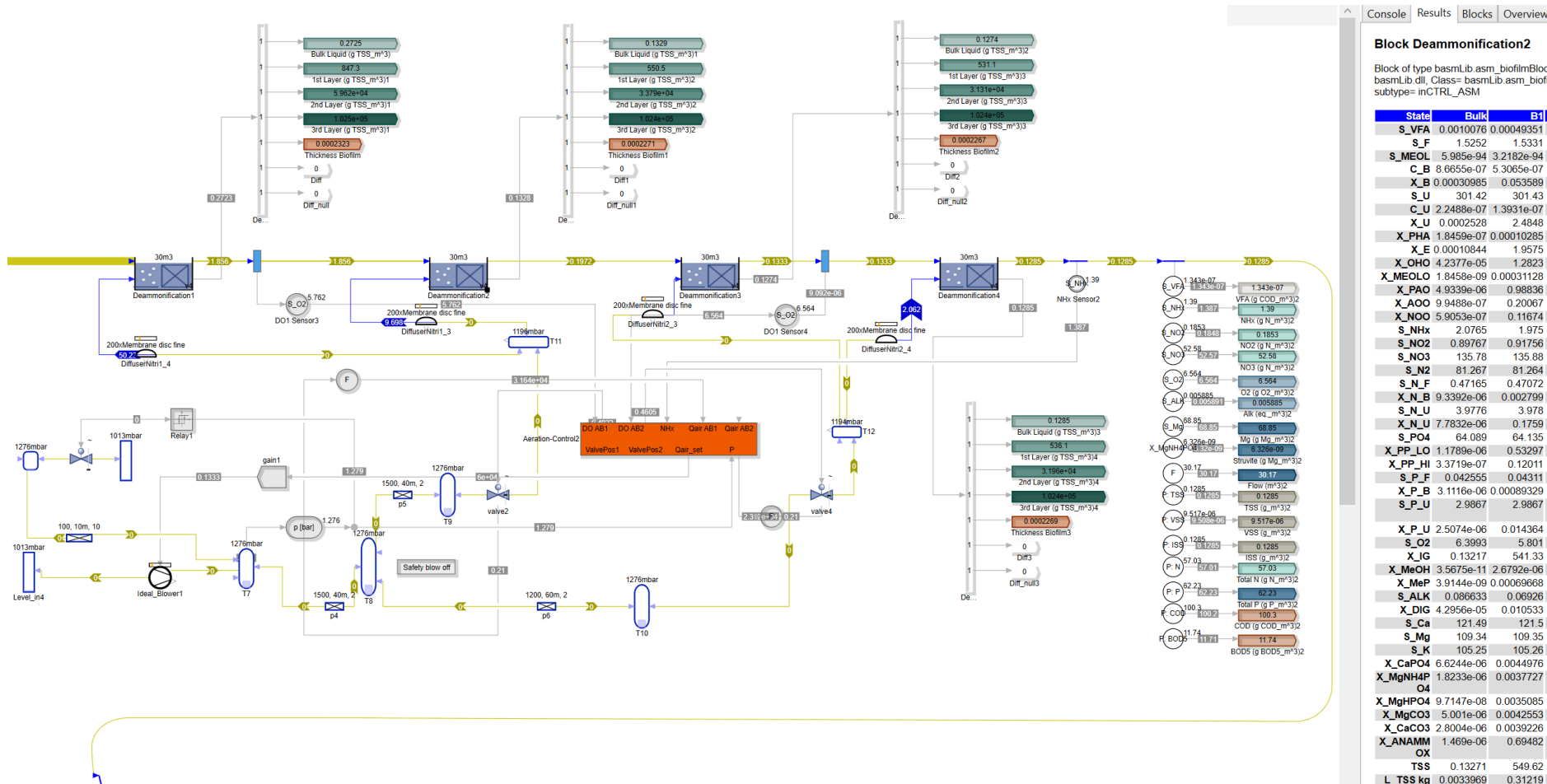


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Table S19-3. The visual represents a Sankey diagram of TKN mass flow, g N/day (green), of the main anaerobic co-digestion treatment receiving brown water and urban-derived feedstocks (i.e... organics from households, commerce, restaurants, and the anaerobic digester includes the chemical dosing of magnesium for struvite recovery;

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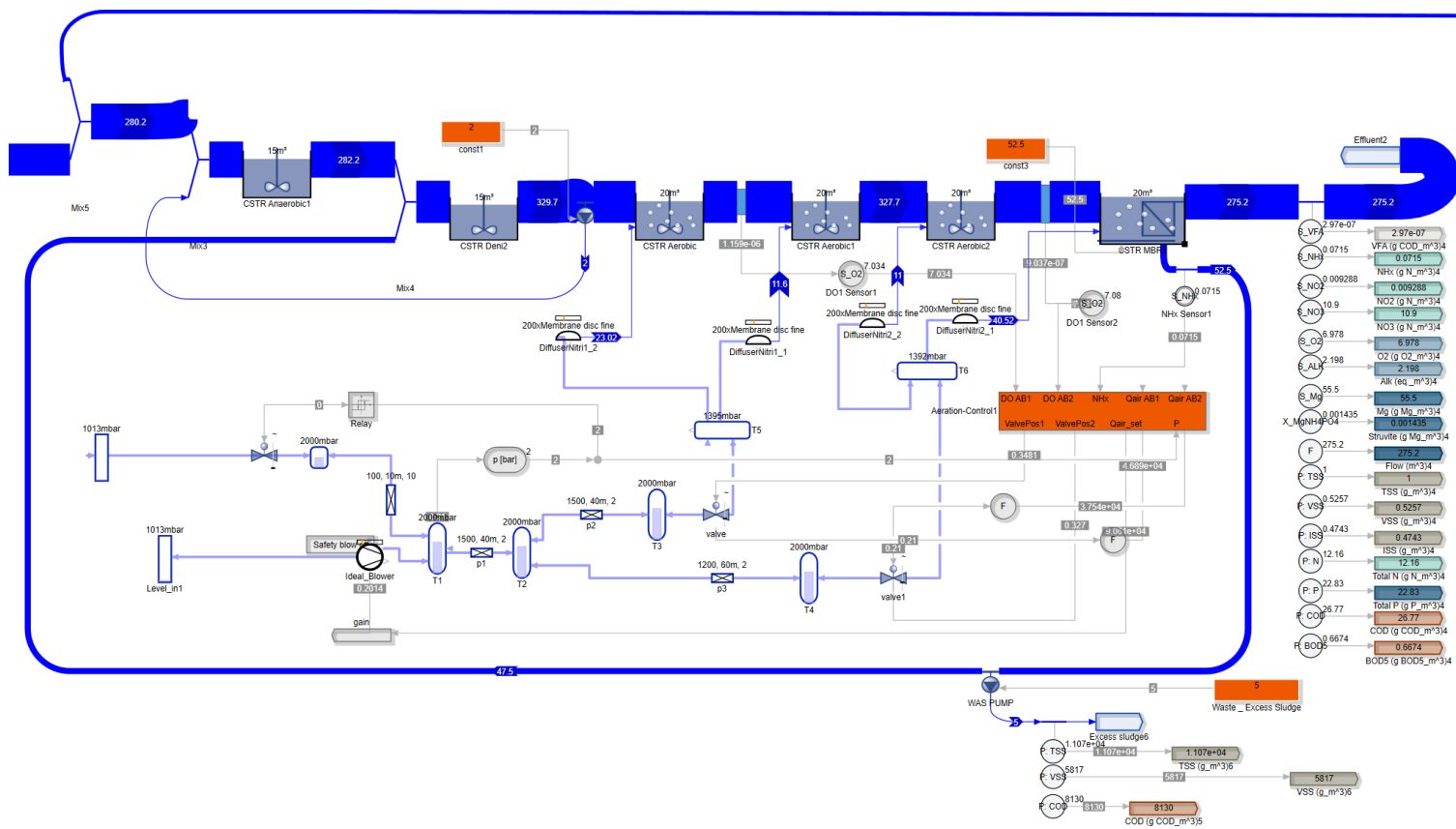


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Table S19-4. The sub-system for the nitrogen removal of the effluent generated in the anaerobic co-digestion mainstream process was modeled with an in-house inCTRL-ASM biofilm-based biokinetic model. The biofilm-based model predicts the biofilm thickness without being constrained by a maximum thickness, allows non-uniform biofilm geometries, and models the impact of mixing intensity on the biofilm detachment rate. The model combines the existing biofilm and sequencing batch reactor (SBR) models in SIMBA# (see ifak, 2017 for details). The model also allows the area and the surface of the biofilm media to facilitate the modeling of membrane-aerated biofilm reactors (MABRs).



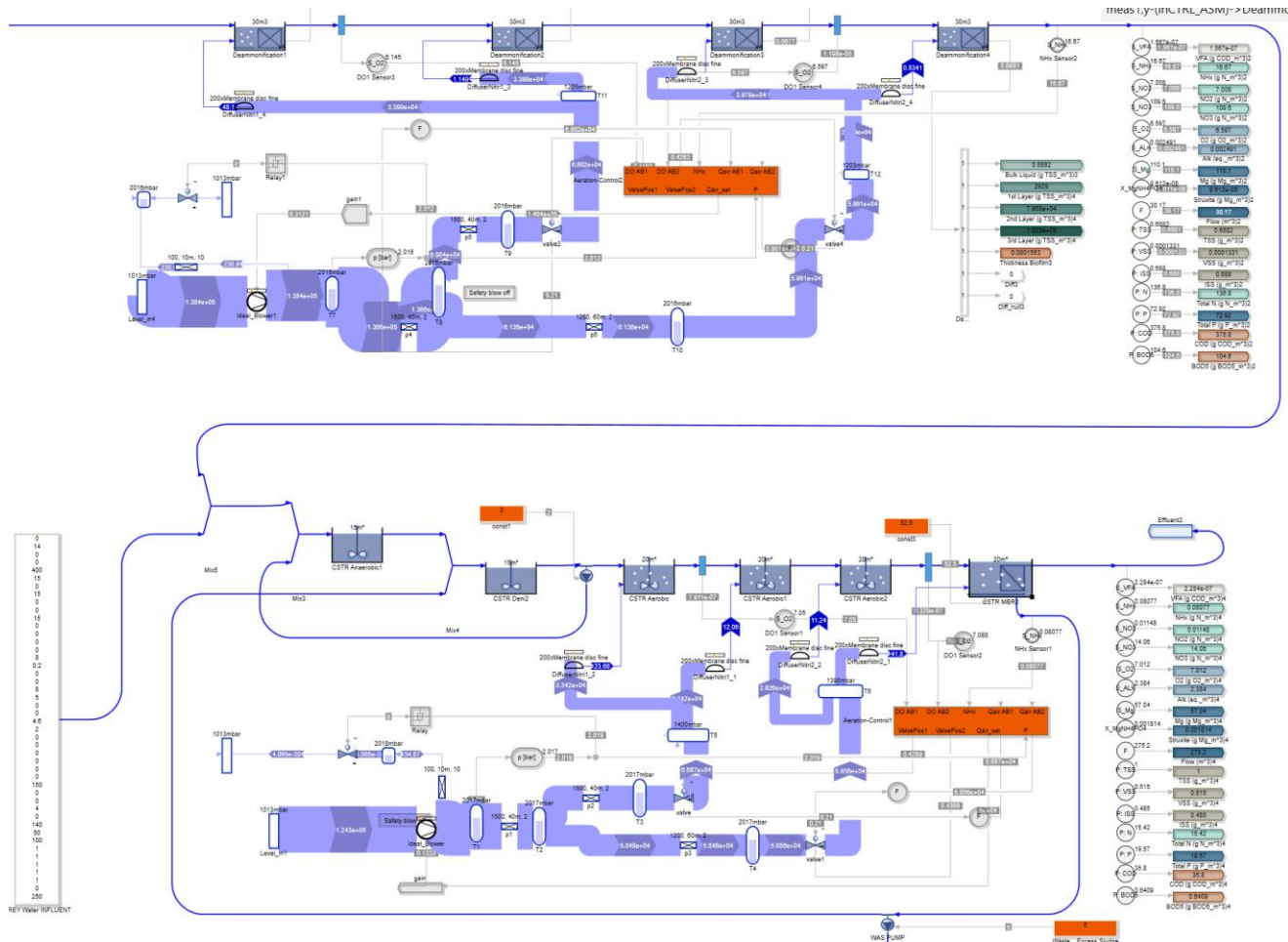
subtype= inCTRL_ASM

Cont. state	Value	Unit	Desc
S_VFA	2.971e-07	g COD/m ³	VFAs
S_F	0.639	g COD/m ³	Ferm
S_MEOL	1.844e-12	g COD/m ³	Meth
C_B	5.729e-16	g COD/m ³	Collo
X_B	119.3	g COD/m ³	Slow
S_U	25.4	g COD/m ³	Solut
C_U	8.165e-16	g COD/m ³	Collo
X_U	1970	g COD/m ³	Partic
X_PHA	0.0001993	g COD/m ³	Store
X_E	1631	g COD/m ³	Endo
X_OHO	3115	g COD/m ³	Ordin
X_MEOL	0.2148	g COD/m ³	Anox
X_PAO	593	g COD/m ³	Phos
X_AOO	110.8	g COD/m ³	Aerol
X_NOO	61.96	g COD/m ³	Nitrite
S_NHx	0.0715	g N/m ³	Total
S_NO2	0.009287	g N/m ³	Nitrite
S_NO3	10.9	g N/m ³	Nitrat
S_N2	10.5	g N/m ³	Dissc
S_N_F	0.8413	g N/m ³	Solut (S_F)
X_N_B	6.685	g N/m ³	Partic
S_N_U	0.2872	g N/m ³	Solut
X_N_U	126.4	g N/m ³	Partic
S_PO4	22.64	g P/m ³	Ortho
X_PP_LO	339.2	g P/m ³	Relax
X_PP_HI	72	g P/m ³	Non-i
S_P_F	0.02591	g P/m ³	Solut (S_F)
X_P_B	1.987	g P/m ³	Partic
S_P_U	0.1154	g P/m ³	Solut
X_P_U	10.11	g P/m ³	Partic
S_O2	6.978	g O2/m ³	Dissc
X_IG	3266	g TSS/m ³	Inorg
X_MeOH	0.01311	g Me/m ³	Metal
X_MeP	0.4924	g Me/m ³	Metal
S_ALK	2.198	eq/m ³	Alkali
X_DIG	1.662	g COD/m ³	Ferm Biom
S_Ca	140.3	g Ca/m ³	Calci
S_Mg	55.5	g Mg/m ³	Magr
S_K	103	g K/m ³	Potas
X_CaPO4	15.87	g CaPO4/m ³	Calci
X_MgNH4PO4	15.87	g MgNH4PO4/m ³	Struv
X_MgHPO4	15.87	g MgHPO4/m ³	Newt
X_MgCO3	15.87	g MgCO3/m ³	Magr
X_CaCO3	15.87	g CaCO3/m ³	Calci
X_ANAMMOX	501.6	g COD/m ³	Anam
V	20	m ³	Volun
theta	35	°C	temp

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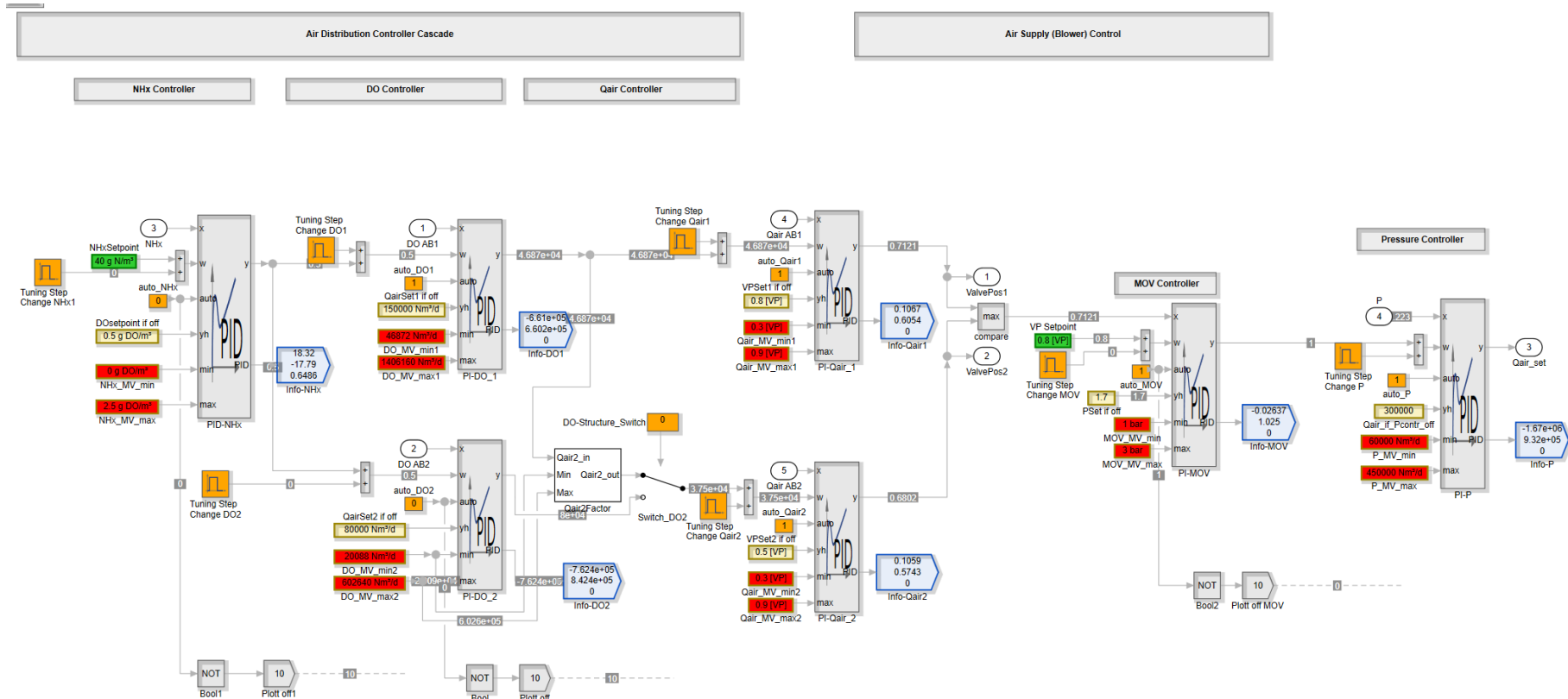
3805 Table S19-5. Membrane bioreactor in SIMBA#, which includes aeration controllers for both Oland and MBR oxygen requirements.

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3808 Table S19-6. Membrane bioreactor in SIMBA#, which includes aeration controllers for both Oland and MBR oxygen requirements. To construct the layout of the
 3809 aeration system, we included blowers, pipes, fittings, valves, and diffusers mechanistic models for each actuator. The piping system was modelled using the
 3810 Darcy–Weisbach equation, with the friction factor calculated using the Swamee & Jain (1976) equation. The pressure rise across blowers and pressure drops
 3811 across valves and diffusers are calculated using polynomial functions based on airflow rate, which have been calibrated using manufacturer data. More
 3812 information on the aeration system models can be found in Schraa et al. (2015).



3817

3818 *Table S19-8. Aeration controllers for both Oland and MBR oxygen requirements. More information on the aeration system models can be found in Schraa et al.*
 3819 *(2015). Aeration control was accounted for by means of continuous feedback using proportional-integral or proportional-integral-derivative (PID) control*
 3820 *algorithms. To model the behavior of the automatic valves, a control algorithm was implemented that fixes the valve position of the lane with the highest oxygen*
 3821 *requirement and allows the other valve to vary to adjust the required airflow.*

3822

Parameter block GREY Water INFLUENT		
Parameter		
Model or signal type inCTRL_ASM		
VFAs S_VFA	0	g COD/m ³
Fermentable substrate S_F	14	g COD/m ³
Methanol S_MEOL	0	g COD/m ³
Colloidal biodegradable substrate C_B	0	g COD/m ³
Slowly biodegradable substrate X_B	400	g COD/m ³
Soluble unbiodegradable organics S_U	15	g COD/m ³
Colloidal unbiodegradable organics C_U	0	g COD/m ³
Particulate unbiodegradable organics X_U	15	g COD/m ³
Stored PHA X_PHA	0	g COD/m ³
Endogenous decay products X_E	0	g COD/m ³
Ordinary heterotrophs X_OHO	15	g COD/m ³
Anoxic methanol utilizers X_MEOL	0	g COD/m ³
Phosphorus accumulating organisms X_PAO	0	g COD/m ³
Aerobic ammonia oxidizers X_AOO	0	g COD/m ³
Nitrite oxidizing organisms X_NOO	0	g COD/m ³
Total ammonia S_NHx	8	g N/m ³
Nitrite S_NO2	0.2	g N/m ³
Nitrate S_NO3	0	g N/m ³
Dissolved Nitrogen S_N2	0	g N/m ³
Soluble biodegradable organic N (from S_F) S_N_F	8	g N/m ³
Particulate biodegradable organic N X_N_B	5	g N/m ³
Soluble unbiodegradable organic N S_N_U	0	g N/m ³
Particulate unbiodegradable organic N X_N_U	0	g N/m ³
Orthophosphate S_PO4	4.6	g P/m ³
Releasable stored polyphosphate X_PP_LO	2	g P/m ³
Non-releasable stored polyphosphate X_PP_HI	0	g P/m ³
Soluble biodegradable organic P (from S_F) S_P_F	0	g P/m ³
Particulate biodegradable organic P X_P_B	0	g P/m ³
Soluble unbiodegradable organic P content S_P_U	0	g P/m ³
Particulate unbiodegradable organic P content X_P_U	0	g P/m ³
Dissolved oxygen S_O2	0	g O2/m ³
Inorganic suspended solids X_IG	150	g TSS/m ³
Metal hydroxide compounds X_MeOH	0	g Me/m ³
Metal phosphate compounds X_MeP	0	g Me/m ³
Alkalinity S_alk	4	eq/m ³
Fermentative and Methanogenic Biomass from Digester X_DIG	0	g COD/m ³
Calcium ions S_Ca	140	gCa/m ³
Magnesium ions S_Mg	50	gMg/m ³
Potassium ions S_K	100	gK/m ³
Calcium rhosphat X_CaPO4	1	gCaPO4/m ³
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Parameter block BROWN Water_NoMIX+nrYW+FW1		
Parameter		
Model or signal type inCTRL_ASM		
VFAs S_VFA	0	g COD/m ³
Fermentable substrate S_F	5436*0.05	g COD/m ³
Methanol S_MEOL	0	g COD/m ³
Colloidal biodegradable substrate C_B	0	g COD/m ³
Slowly biodegradable substrate X_B	5436*0.7	g COD/m ³
Soluble unbiodegradable organics S_U	5436*0.05	g COD/m ³
Colloidal unbiodegradable organics C_U	0	g COD/m ³
Particulate unbiodegradable organics X_U	5436*0.1	g COD/m ³
Stored PHA X_PHA	0	g COD/m ³
Endogenous decay products X_E	0	g COD/m ³
Ordinary heterotrophs X_OHO	5436*0.1	g COD/m ³
Anoxic methanol utilizers X_MEOL	0	g COD/m ³
Phosphorus accumulating organisms X_PAO	0	g COD/m ³
Aerobic ammonia oxidizers X_AOO	0	g COD/m ³
Nitrite oxidizing organisms X_NOO	0	g COD/m ³
Total ammonia S_NHx	88.4	g N/m ³
Nitrite S_NO2	0.2	g N/m ³
Nitrate S_NO3	10	g N/m ³
Dissolved Nitrogen S_N2	0	g N/m ³
Soluble biodegradable organic N (from S_F) S_N_F	5436*0.05*0.1	g N/m ³
Particulate biodegradable organic N X_N_B	5436*0.7*0.1	g N/m ³
Soluble unbiodegradable organic N S_N_U	5436*0.05*0.03	g N/m ³
Particulate unbiodegradable organic N X_N_U	5436*0.1*0.03	g N/m ³
Orthophosphate S_PO4	82*0.5	g P/m ³
Releasable stored polyphosphate X_PP_LO	0	g P/m ³
Non-releasable stored polyphosphate X_PP_HI	0	g P/m ³
Soluble biodegradable organic P (from S_F) S_P_F	5436*0.05*0.01	g P/m ³
Particulate biodegradable organic P X_P_B	5436*0.7*0.01	g P/m ³
Soluble unbiodegradable organic P content S_P_U	5436*0.05*0.01	g P/m ³
Particulate unbiodegradable organic P content X_P_U	5436*0.1*0.01	g P/m ³
Dissolved oxygen S_O2	0	g O2/m ³
Inorganic suspended solids X_IG	4559-3925	g TSS/m ³
Metal hydroxide compounds X_MeOH	0	g Me/m ³
Metal phosphate compounds X_MeP	0	g Me/m ³
Alkalinity S_alk	4	eq/m ³
Fermentative and Methanogenic Biomass from Digester X_DIG	0	g COD/m ³
Calcium ions S_Ca	140	gCa/m ³
Magnesium ions S_Mg	50	gMg/m ³
Potassium ions S_K	100	gK/m ³
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3824 Table S19-9. Influent fractionation and main characteristics from the brown water stream and the grey water stream.

Parameter block Deammonification2

Parameter

Model type	inCTRL_ASM	
Reactor volume	30	m ³
Depth of tank	2	m
Fraction of inert (carrier media) reactor volume (0..1)	0.18*0.5	
Biofilm base surface area per reactor volume	500*0.5	m ² /m ³
Expected biofilm thickness at equilibrium, A*Rref=Vbf0	0.00055	m
Thickness of water layer (only if constant water volume)	0.005	m
Liquid diffusion boundary layer thickness	0.0001	m
Additional area in outer biofilm layer as fraction of base surface, Aextra=fAextra*A	0	
Fraction of biofilm volume that is water (0..1)	0.9	
Density of particulate fraction of biofilm	1020000	g/m ³
Number of biofilm layers	3	
Diffusion coefficient for soluble matter (if set to 0 in ASM)	0.0000864	m ² /d
Diffusion coefficient for particulate matter (if set to 0 in ASM)	1e-10	m ² /d
Ratio of Diffusion in biofilm to diffusion in pure water (0-1)	1	
Attachment velocity of flocs to biofilm	0.5	m/d
Erosion velocity	0.001	m/d
Artificial erosion/att. velocity for TSS balancing	0.005	m/d
Erosion velocity exponent $vero=vero0 * (R/Rref)^{veroEx} * uero$	2	

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Table S19-10. A biofilm-based block definition in SIMBA#. Biofilm thickness, without being constrained by a maximum thickness, allows non-uniform biofilm geometries and models the impact of mixing intensity on the biofilm detachment rate.

3831 19.8 Detailed mass and energy flow analysis

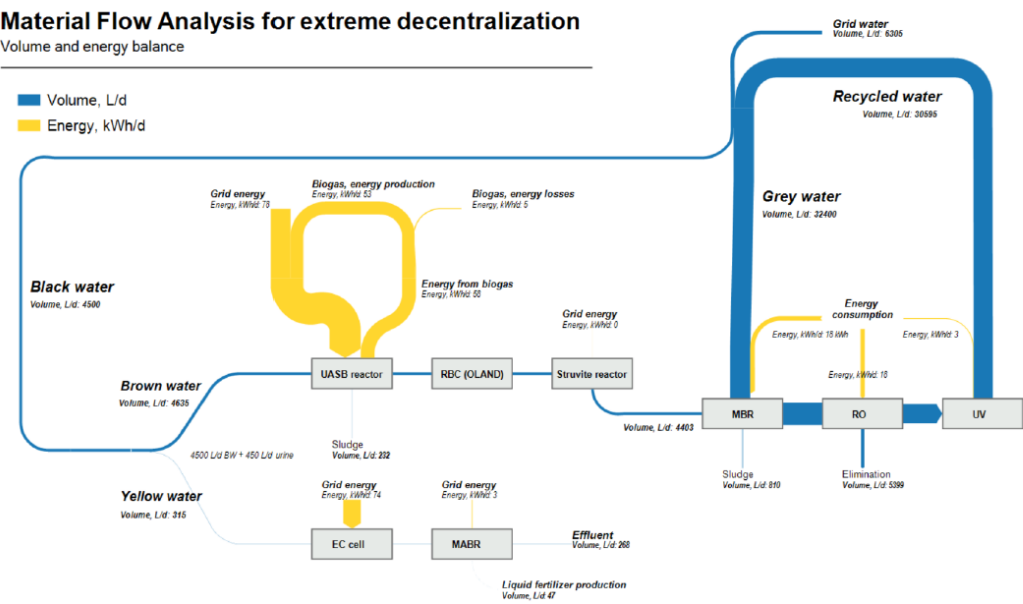


Figure 3: MFA of the decentralized system including water volume and energy.

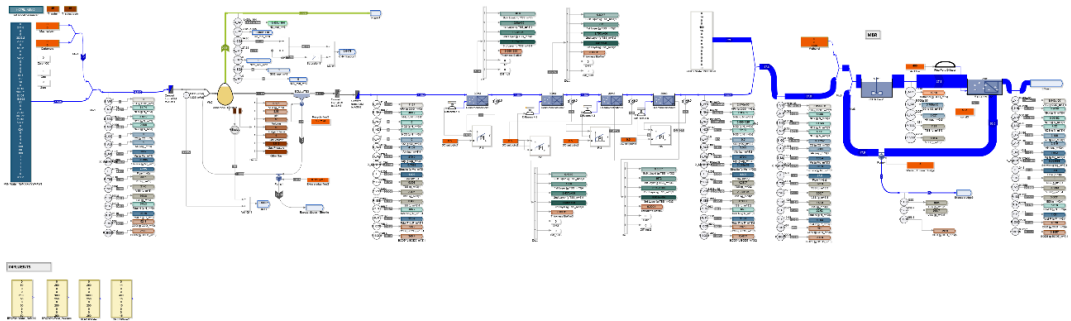


Figure 4: Sankey diagram for volume obtained from SIMBA# simulation.

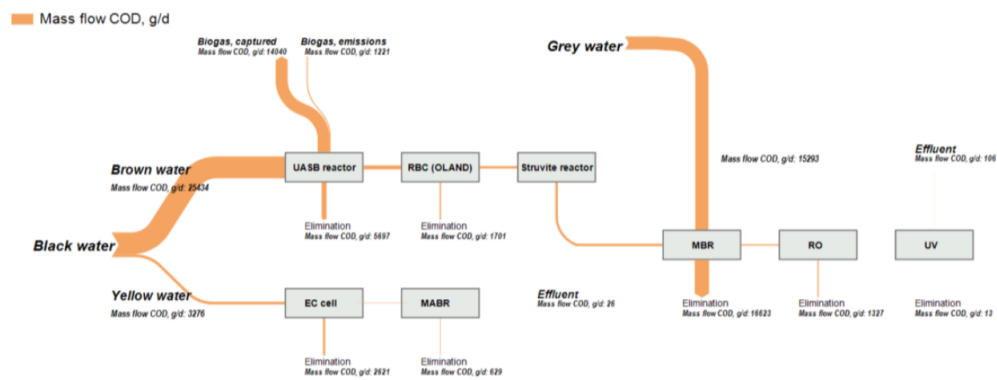
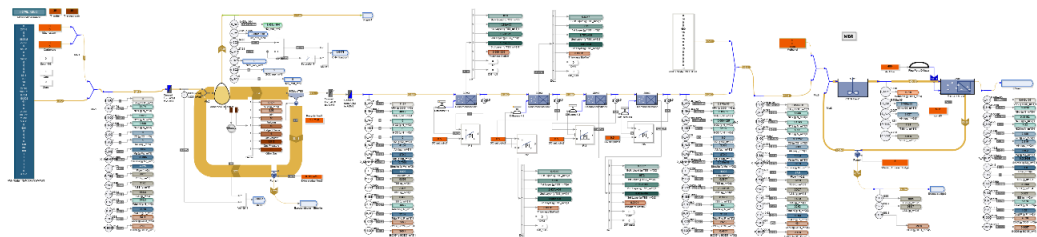


Figure 5: MFA of the decentralized system showcasing total COD in g/d.



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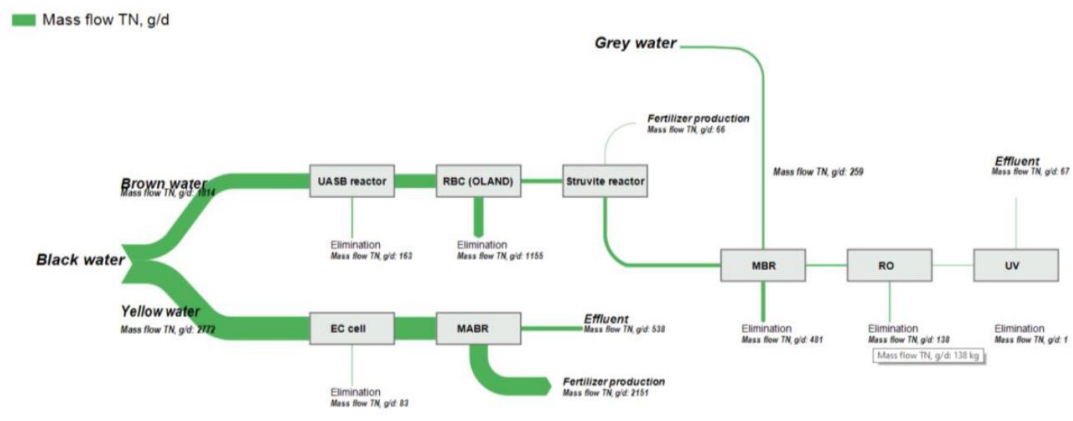
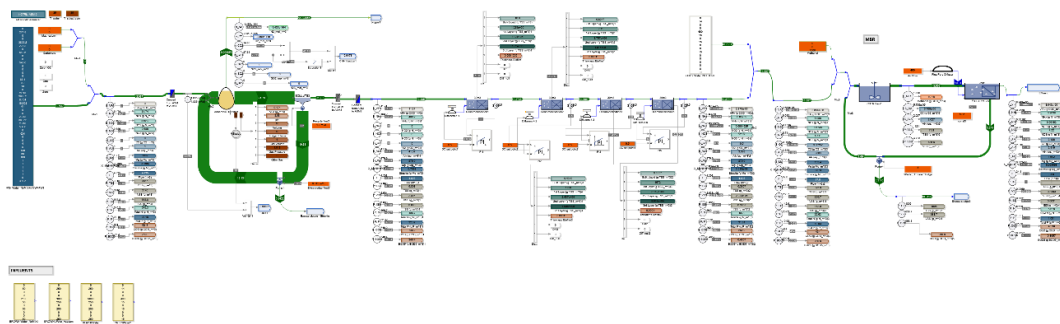
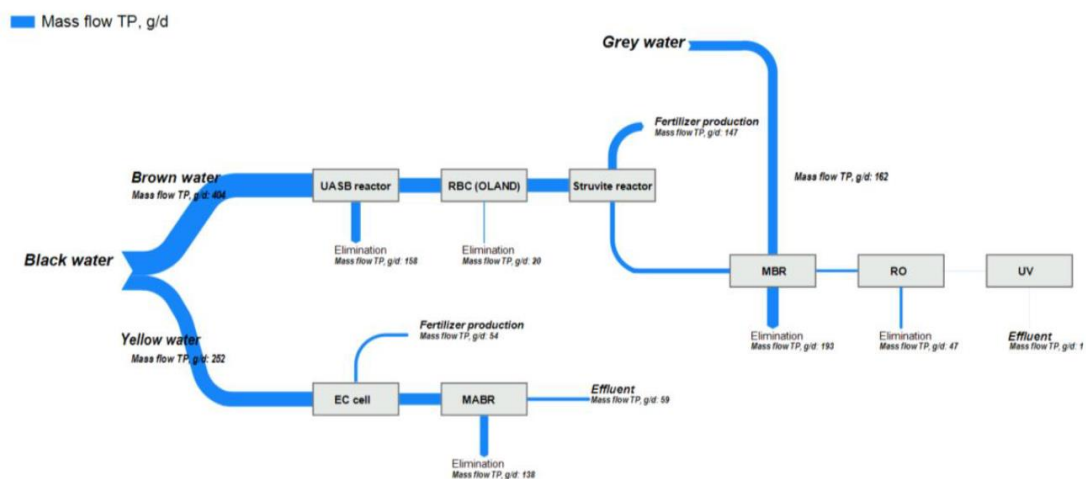


Figure 7: MFA of the decentralized system showcasing TN in g/d.



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Figure 9: MFA of the decentralized system showcasing TP in g/d.

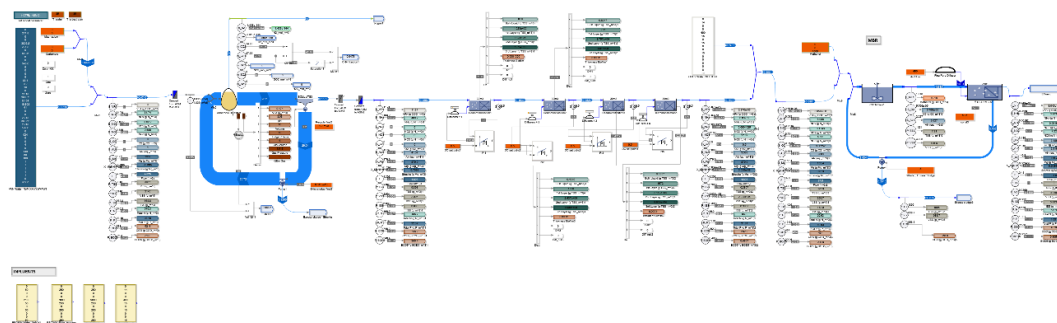
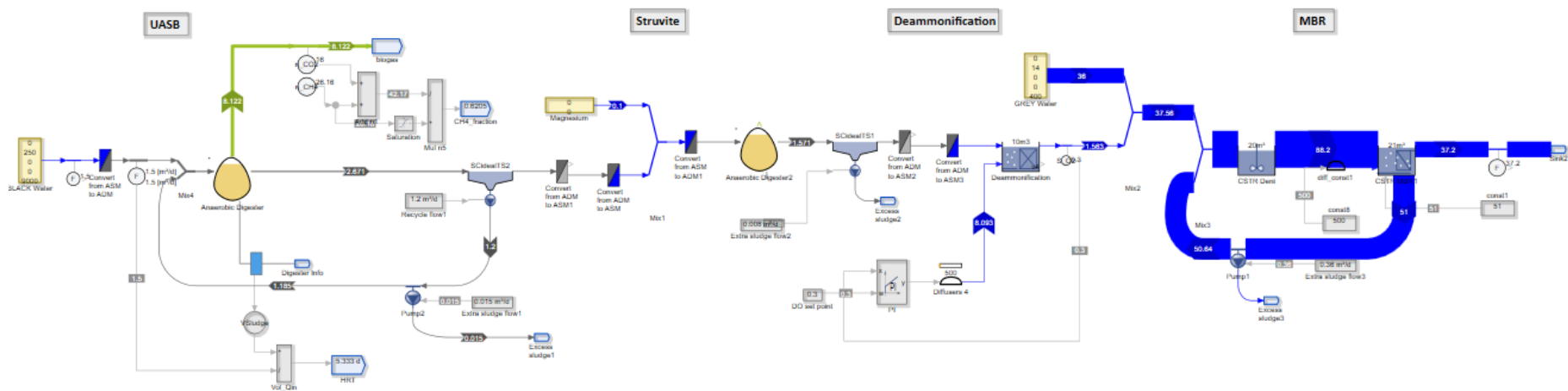


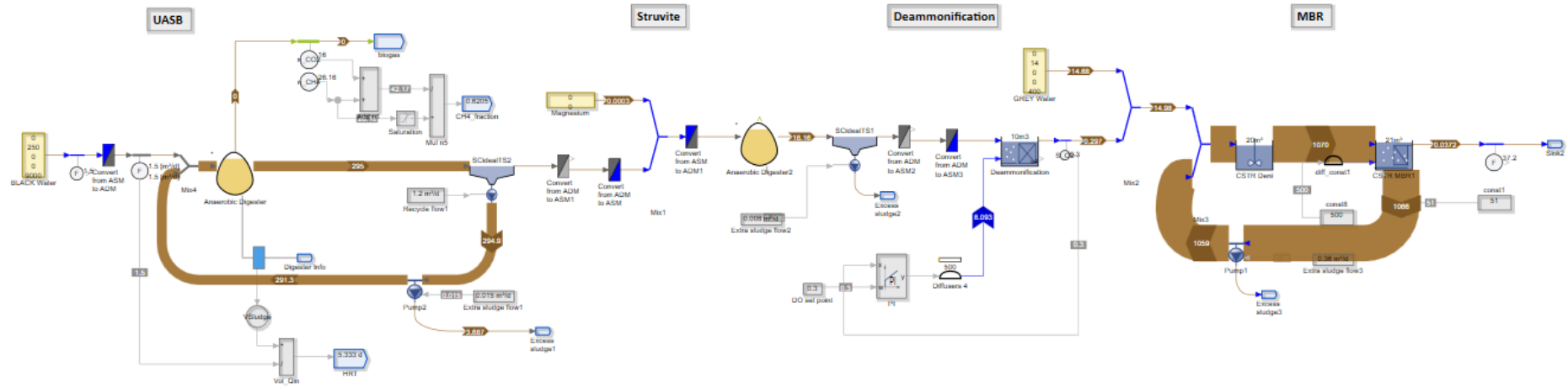
Figure 10: Sankey diagram for TP obtained from SIMBA# simulation.

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3868 Next figures shows the evolution in the water's quality and flow as it moves through the treatment plant using figures obtained from the SIMBA after a 500 days
3869 simulation. The difference in flowrate between GW and BW can be observed, with the GW line requiring much higher capacity. The evolution of the concentration
3870 of three example pollutants (those being COD, TKN, and P) in mg/L is shown. The incorporated biologic treatments (i.e., UASB and MBR) help drastically reduce
3871 the COD concentration in both GW and BW. Specifically, the MBR is the treatment with the highest removal efficiency for this pollutant and allows to reduce the
3872 COD concentration from 1070 to 5 mg/L. As for TKN. note how the deammonification stage (which consists of an RBC operating with the OLAND process) is
3873 capable of reducing form 2000 mg/L of nitrogen oxides to around 100 mg/L. Afterwards, while the UASB barely contributes to the removal of nitrogen, the MBR
3874 polishes the concentration of the treated BW and helps treat the additional input of TKN that the GW effluent supposes (panel c). Finally, it depicts the variation
3875 in TP concentration achieved in the circuit, with the MBR being again especially efficient and the struvite recovering process allowing for the production of 37-
3876 913 kg of the fertilizer (the lower end of the range being the production in LR buildings and the higher end being the struvite obtained in HR buildings).

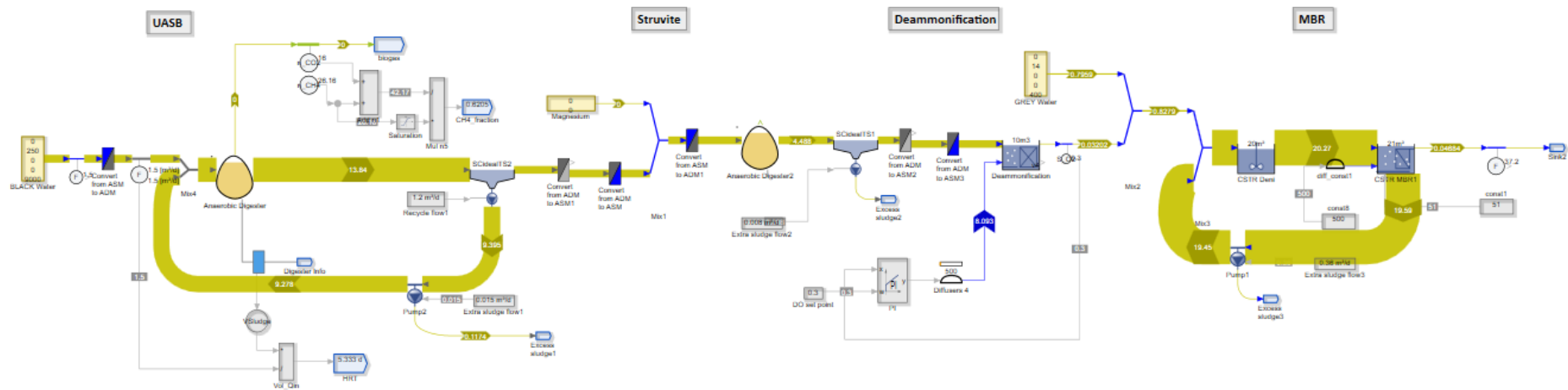


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3878 Fig. 19-1: Model of V1 layout obtained by the modelling software SIMBA#. The sanky diagram represents m3/day. Five models corresponding to the five
3879 scenarios under consideration were built and tested.



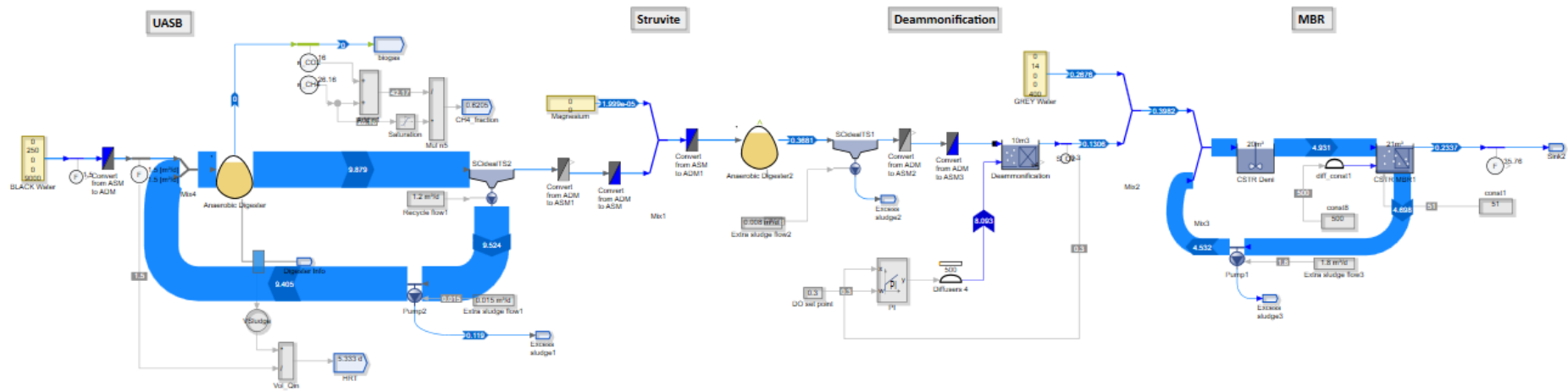
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3881 *Fig. 19-2: Model of V1 layout obtained by the modelling software SIMBA#. The sanky diagram represents COD, mg COD/L. Five models corresponding to the*
 3882 *five scenarios under consideration were built and tested.*



3883

3884 Fig. 19-3: Model of V1 layout obtained by the modelling software SIMBA#. The sanky diagram represents TKN, mg N/L. Five models corresponding to the five
 3885 scenarios under consideration were built and tested.



3886

3887 *Fig. 19-4: Model of V1 layout obtained by the modelling software SIMBA#. The sanky diagram represents phosphorus, mg P/L. Five models corresponding to*
 3888 *the five scenarios under consideration were built and tested.*

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3890 20 Effluent composition

3891 Effluent concentrations and performance were obtained based on reported removal efficiencies and
3892 confirmed by the modelled system using the software SIMBA# (ifak, 2021). The simulations were used to
3893 evaluate both the performance and feasibility of the process flow diagrams. The effluent characteristics
3894 obtained from both the modelling approach and the reported-based calculations were compared to ensure
3895 the correctness of the calculations.

3896 Removal efficiencies and influent/effluent ratios widely influence final water composition and are therefore
3897 confirmed with SIMBA#. When simulation is not possible, data is obtained from reported values. The
3898 following shows the final composition of water after leaving the treatment train, which is capable of meeting
3899 reuse standards of US EPA (EPA/600/R-12/618) and EU regulation 2020/741, and drinking water
3900 requirements by WHO (GDWQ,2022), US EPA (SDWA,1974), and EU Directive 2020/2184.

3901 *Table S20-1: Effluent composition [mg/l] of water destined for reuse. COD: chemical oxygen demand; BOD: biological*
3902 *oxygen demand, TN: total nitrogen; TAN: total ammonia nitrogen; TP: total phosphorus; TSS: total suspended solids;*
3903 *VSS: volatile suspended solids.*

	Effluent composition (mg/l)	Grey water reuse standards	Drinking water standards
COD	3.45	-	< 10 mg/l
BOD	0.18	< 10 mg/l	< 5 mg/l
TN	2.20	< 10 mg/l	-
TAN	0.03	-	< 1.5 mg/l
N-NO ₃	0.85	-	< 50 mg/l
TP	0.04	< 0.05 mg/l	-
TSS	0.0	< 10 mg/l	-
VSS	0.0	-	-

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3906 This table shows the most restrictive threshold values for each pollutant extracted from the cited legislation
3907 and standards. In the case of water reuse, those values related to urban and bathing applications are
3908 selected. Control of some pollutants is not prioritized in legislation regarding reuse or drinking water quality
3909 due to their low impact on the target applications. For example, phosphorus limits are usually not included
3910 in potable water legislation as its ingestion is not toxic for humans unless the levels of the pollutant in water
3911 are exceptionally high. However, its presence enhances microbial growth, which is strictly regulated in
3912 drinking water policies and addressed in the health and safety section. Phosphorus can also cause grave
3913 environmental problems due to eutrophication. Therefore, the limit for phosphorus for reuse applications is
3914 stringent.

3915 The following table compiles the results from previous research including different types of toilets and
 3916 treatment trains (Garrido-Baserba, et al. 2022).

3917 *Table S20-2: Composition of treated Brown water + Grey water effluent for reuse on the building scenarios (Garrido-*
 3918 *Baserba, et al. 2022).*

Effluent concentrations (mg/l)					
	V1	V2	C1	C2	UD
COD	1.33	1.91	1.46	1.46	1.94
BOD	0.72	1.39	0.76	1.07	1.14
TN	2.10	4.21	2.25	3.22	6.59
NH4-N	0.11	2.21	0.12	1.69	1.65
N-NO₃	0.78	1.27	0.59	0.97	1.17
TP	0.04	0.13	0.04	0.10	0.18
TSS	0.02	0.04	0.03	0.03	0.05
VSS	0	0.02	0.02	0.02	0.03

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21 Material Flow Analysis

This section draws upon the valuable research conducted by Irene Barnosell Roura in her master's thesis ("The environmental impacts of extreme water and wastewater decentralization: a life cycle assessment approach"), completed in collaboration with the Norwegian University of Science and Technology within the framework of this project.

21.1 Material Flow Analysis (MFA) for Resource Tracking

In the field of industrial ecology, Material Flow Analysis (MFA) is a powerful tool used to quantify and visualize the movement of materials or energy within a system (Graedel, 2019; Laner et al., 2014). Due to its emphasis on resource recycling and reuse, MFA is highly relevant for assessing the efficiency of decentralized water systems. Sankey diagrams are frequently used in MFA to clearly communicate results, and this study will adhere to this common practice by presenting findings both visually and numerically using e!Sankey software.

While MFAs can be dynamic (representing change over time), the MFAs performed in this study are static. They depict the operation of the decentralized system under normal, steady-state conditions. We acknowledge that some variations in flow could occur during system disruptions or deviations in pollutant loads.

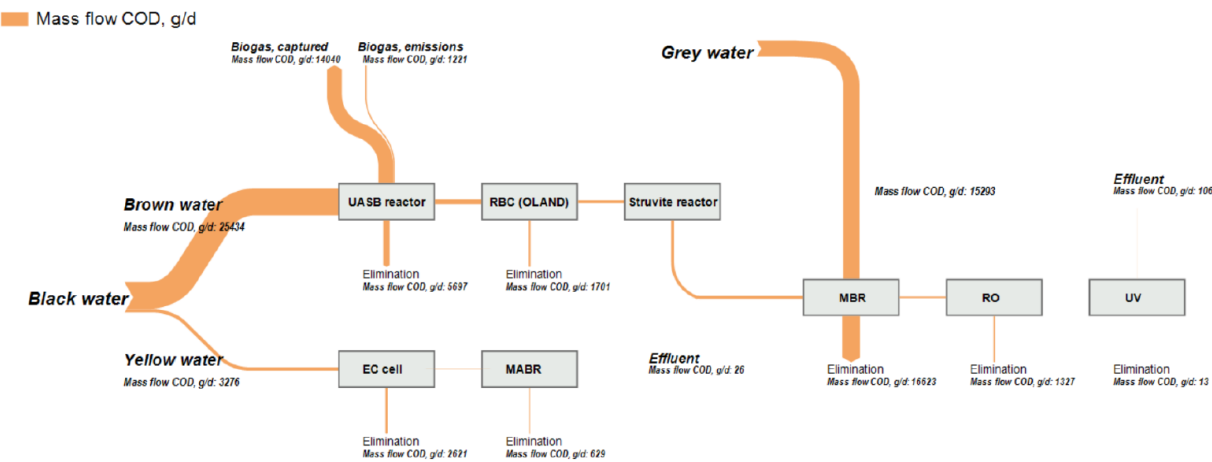
To minimize uncertainty, we draw on average values for household wastewater from western countries and combine calculations of pollutant removal, recovery, and loss with simulation results using SIMBA#. We simulate 300 days of operation to confirm steady-state results and extract component balances. Our MFA data integrates findings from both simulations and these calculations. Treatment processes represented in the simulation include UASB, OLAND, and MBR reactors. Additional calculations (struvite recovery, RO, YW treatment) are based on literature and company data. We carefully cross-check calculations and simulation outputs to ensure consistency in removal efficiencies and treatment parameters.

Our MFAs provide analyses of nutrients (TN and TP), volume, energy, and Chemical Oxygen Demand (COD) as a representation of organic matter flow. This focus aligns with the goals of the decentralized water system. To facilitate visualization, we present a joint Sankey diagram for COD, TN, and TP, as well as a separate MFA exclusively for nutrients. We also generate a water/energy diagram, as these resources are closely linked (Sanders and Webber, 2012; United States Department of Energy, 2014).

Beyond visual and numerical representations, MFA helps establish clear system boundaries, supports consistent framework definition, improves understanding of flow movement, and ensures mass balance consistency (crucial for the subsequent LCA). MFA complements LCA by providing a broader overview of the system. The results of our MFA—particularly relating to water, nutrient, and energy recycling—will directly inform our Life Cycle Assessment.

3955 Table S21-1: MFA of the decentralized system showcasing total chemical oxygen demand (COD) in g/d, for the
3956 reference population of 300 people. (Barnosell, 2022).

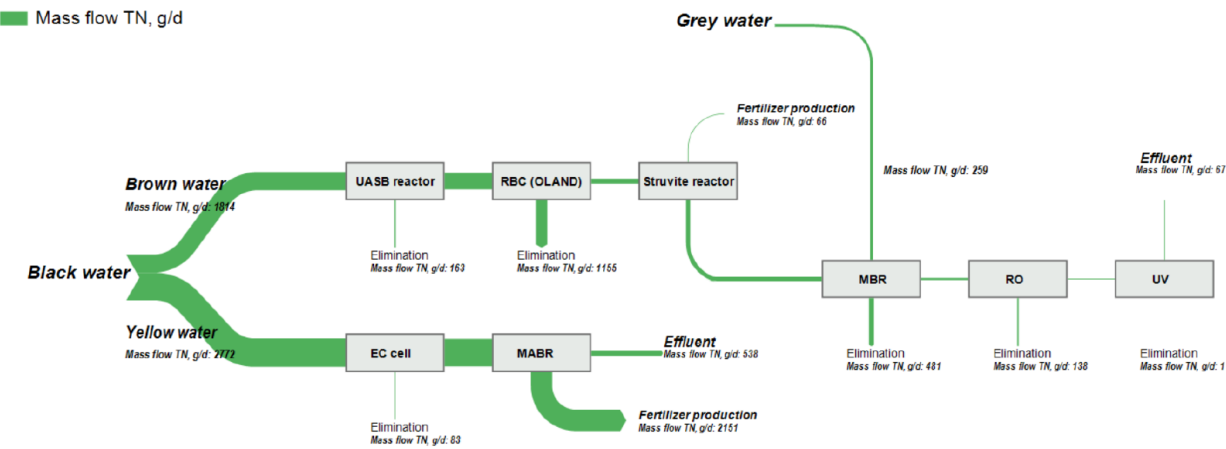
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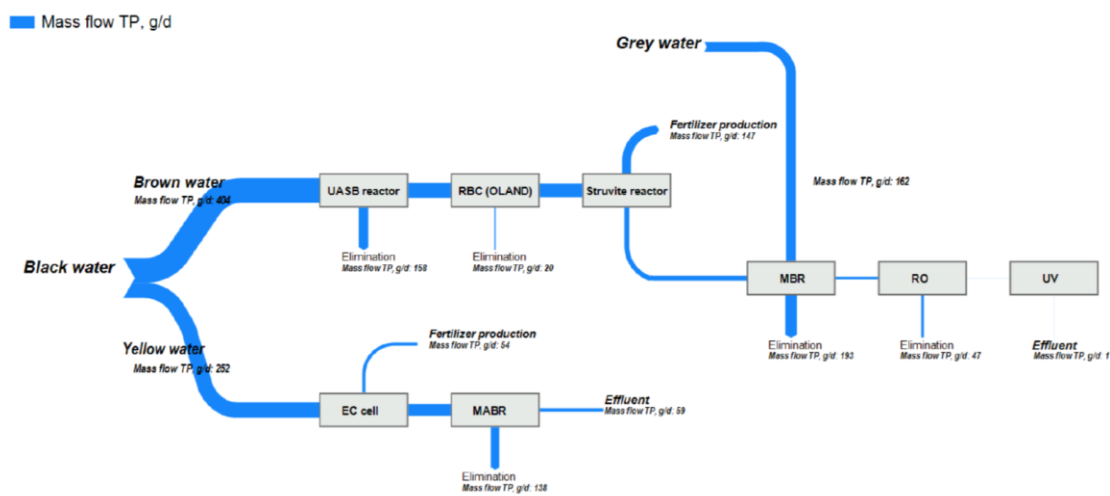
3960 Table S21-2: MFA of the decentralized system showcasing total nitrogen (TN) in g/d, for the reference population of
3961 300 people. (Garrido-Baserba, et al. 2022).



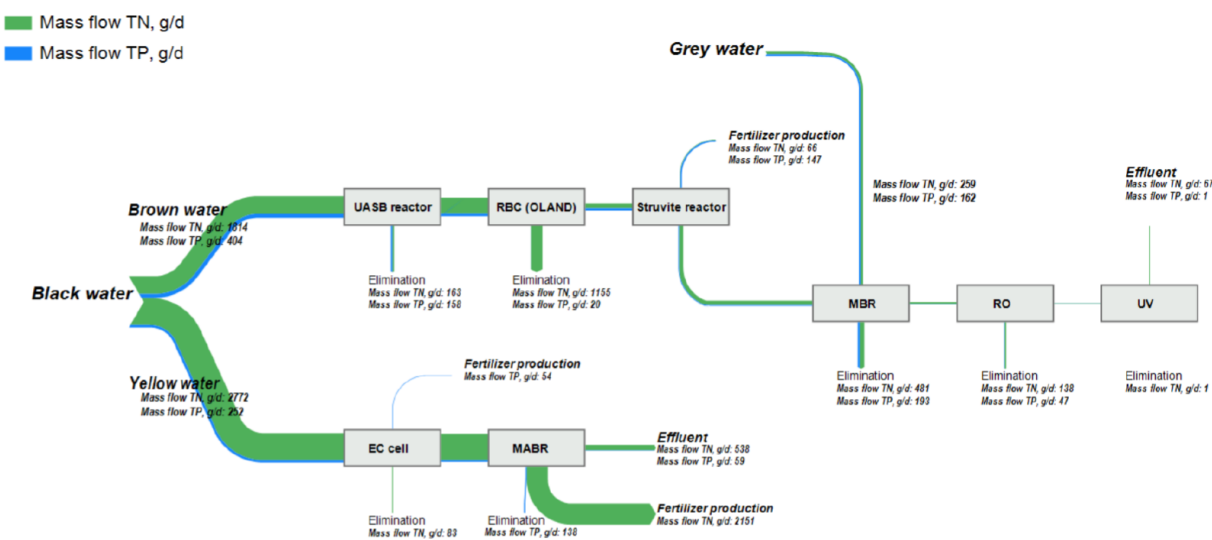
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3964 Table S21-3: MFA of the decentralized system showcasing total phosphorus (TP) in g/d, for the reference population
3965 of 300 people.

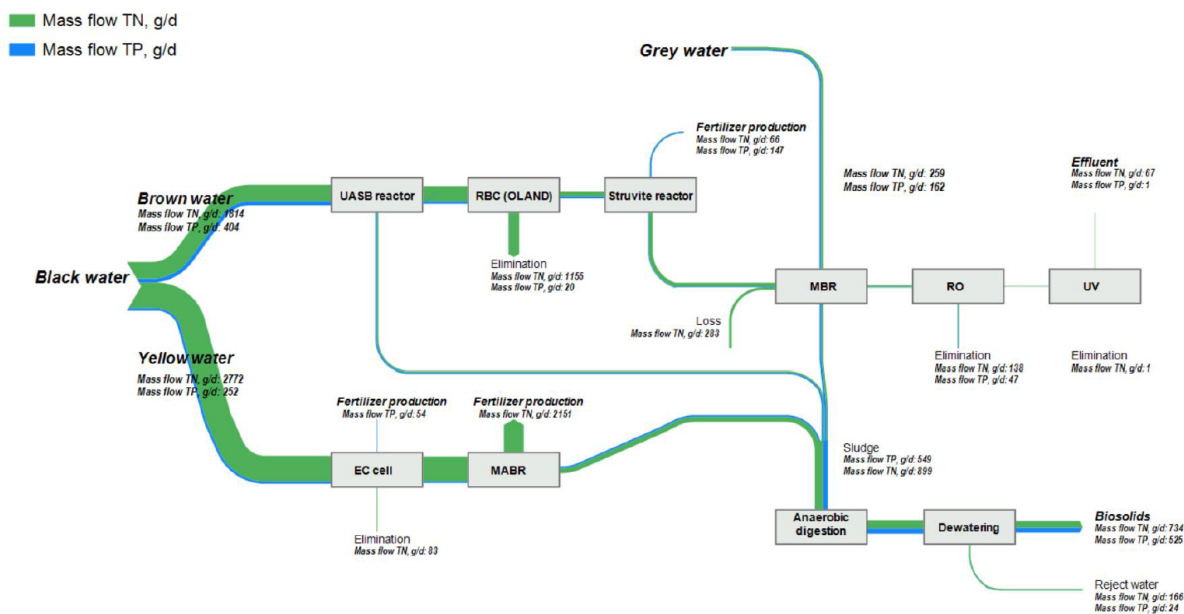


3966
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3968
3969 Table S21-4: MFA of the decentralized system showcasing mass flows of total nitrogen (TN) and total phosphorus (TP)
3970 in g/d, for the reference population of 300 people.



3976

3977 Table S21-5: MFA of the decentralized system showcasing mass flows for total nitrogen (TN) and total phosphorus (TP) in g/d also showcasing the sludge treatment line, for the reference population of 300 people.
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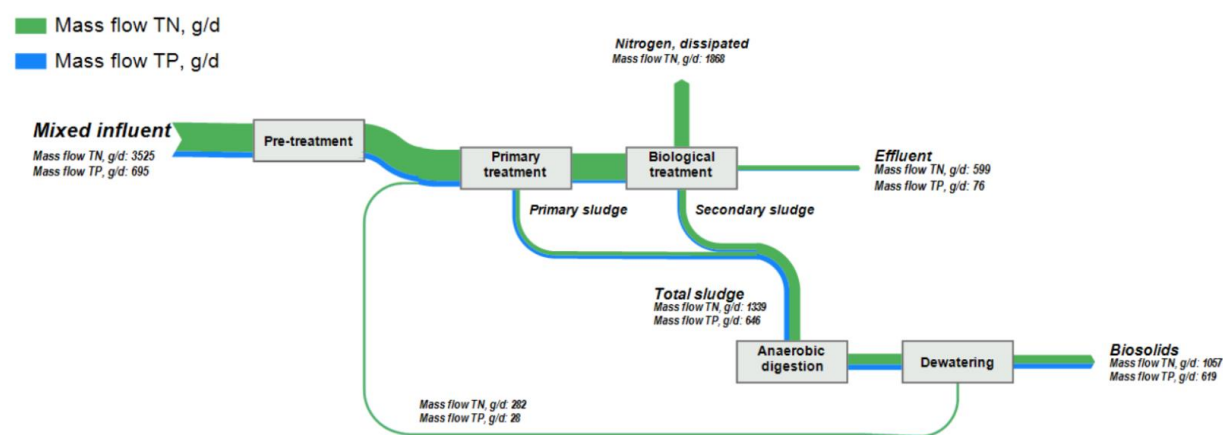


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3982 Table S21-6: MFA of the conventional system showcasing mass flows for total nitrogen (TN) and total phosphorus (TP)
3983 in g/d, for the reference population of 300 people.



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22 Life Cycle Assessment

This section draws upon the valuable research conducted by Irene Barnosell Roura in her master's thesis ("The environmental impacts of extreme water and wastewater decentralization: a life cycle assessment approach"), completed in collaboration with the Norwegian University of Science and Technology within the framework of this project.

This study examines the environmental impacts of a decentralized wastewater treatment and reuse system designed for buildings. The system recycles wastewater and treats rainwater for drinking purposes. This decentralized approach is compared to traditional centralized water management systems.

The study finds that decentralized systems offer significant environmental benefits, including:

1. **Increased resource recovery:** Potential to double nutrient and energy recovery compared to conventional systems.
2. **Reduced environmental impact:** Outperforms centralized systems in many key impact categories.
3. **Rainwater capture benefits:** Provides positive environmental outcomes, but requires site-specific analysis due to varying rainfall patterns.

Key Points:

- System operation is the main driver of environmental impact.
- Regional factors, like electricity mix, significantly influence operational impacts.
- Site-specific assessments are crucial for successful implementation.

22.1 Methodology

Life Cycle Assessment (LCA) offers a powerful way to quantify the environmental impacts of systems, processes, or products. By carefully tracking inputs and outputs, LCA identifies potential sources of environmental harm and offers insights into the magnitude and overall significance of these impacts throughout a system's lifespan.

This LCA uses an attributional approach, meaning the focus is on quantifying the impacts directly associated with the defined water treatment system. A consequential LCA, on the other hand, assesses how changes in a system's operation might alter environmental impacts.

Garrido-Baserba et al. (2022) explored the economic and technical feasibility of decentralized water systems. This collaboration work aims to build upon that foundation by focusing specifically on the environmental sustainability of extreme decentralization in urban buildings. It seeks to understand the full

environmental impact of these systems, considering the entire infrastructure needed for water management (pipelines, treatment plants, etc.).

Methodology: The study employs Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) to track resource flows, identify potential for recovery, and quantify environmental impacts.

Comparison: The decentralized system is compared to traditional centralized water management methods to evaluate its relative benefits and challenges from an environmental perspective.

Site-Specific Analysis: To understand how regional factors might affect the system's performance, the study models its implementation in different European cities. This analysis helps assess the impact of variables like electricity mix and rainfall patterns on the overall sustainability of the decentralized system.

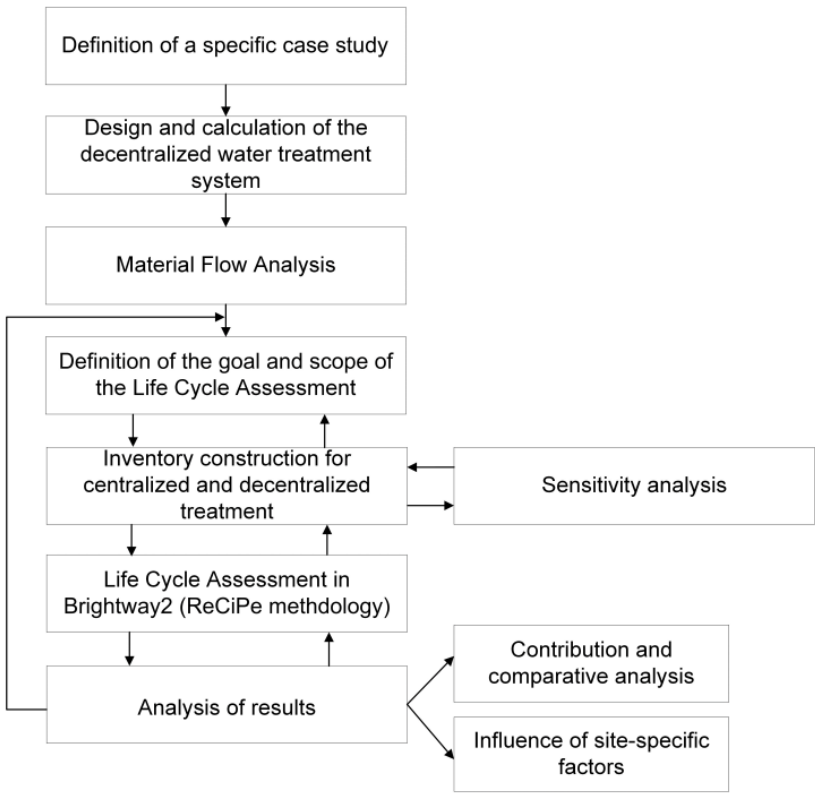


Table S22-1: Simplified methodological approach followed to assess the environmental performance of water and wastewater decentralization.

This LCA follows the established methodology in ISO 14040:2006 and ISO 14044:2006 standards, ensuring a transparent and rigorous approach. Key phases include defining the goal and scope, building the inventory, impact assessment, and interpreting results – an iterative process where choices made in each step inform and refine other steps.

22.1.1 Goal and Scope

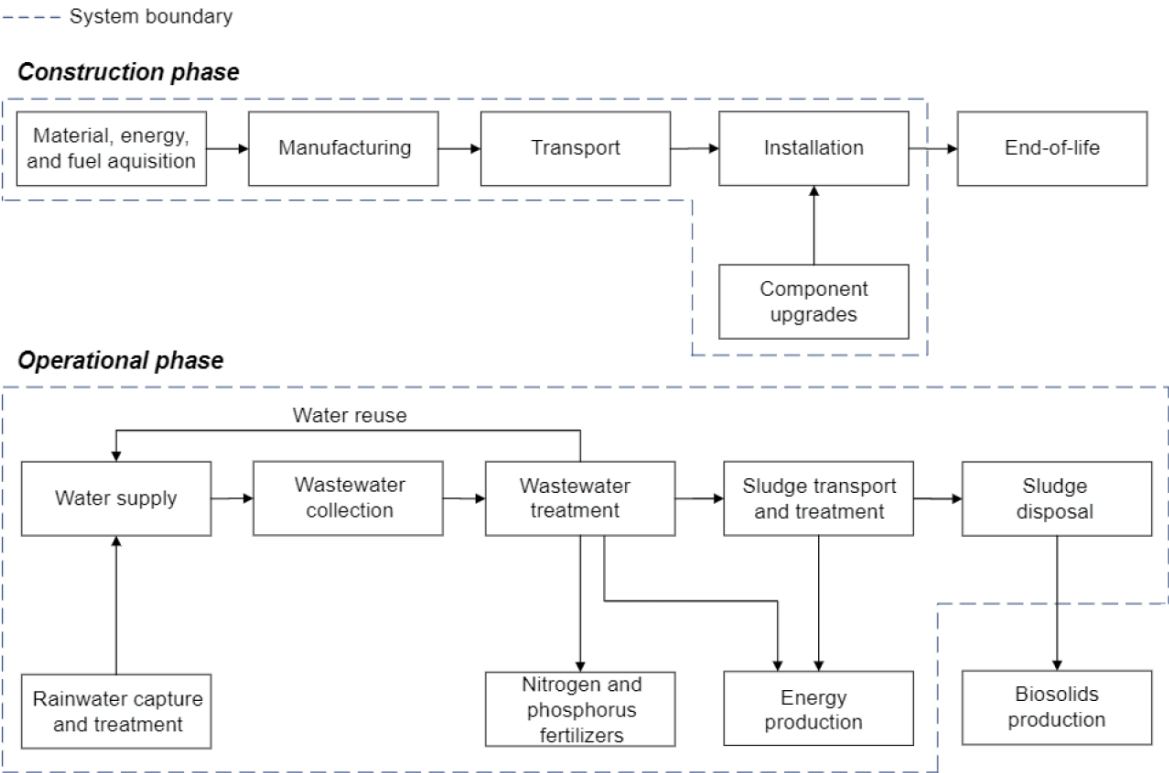
This LCA's goal is to evaluate the environmental impacts of decentralized water and wastewater management. As LCA methodology has evolved, its role extends beyond quantifying impacts to informing process design, marketing, decision-making, and even broader sustainability transitions. This study provides a standardized methodology suitable for comparative analysis, potentially aiding in early design assessments and comparisons with existing treatment technologies. The key audience includes scientists, decision-makers, technology manufacturers, and even end-users of the water systems, as all can benefit from understanding the environmental implications.

To accurately capture the full environmental profile of decentralized wastewater treatment, this LCA encompasses:

- Construction: Material acquisition, manufacturing processes, and installation of the system.
- Operation: Emissions, energy/chemical usage, resource recovery, and long-term maintenance.
- Waste Management: Including sludge processing (with biogas generation).

Data used includes up-to-date reported values, calculations, simulation results (SIMBA#), and information from the recently updated ecoinvent v3.9.1 database.

Table S22-2: Simplified view of the established boundaries, applicable to both centralized and decentralized treatment



22.1.1.1 *Scope of Assessment*

To comprehensively evaluate decentralized wastewater treatment, this study incorporates construction, operation, maintenance, waste treatment, and resource recovery within the European region (see Figure 5). We utilize current data from reported values, personal calculations, SIMBA# simulations, and the recently updated ecoinvent v3.9.1 database.

22.1.1.2 *Construction Impacts*

Decentralized systems require unique on-site infrastructure for each building, potentially leading to significant construction-related costs and impacts. We thoroughly assess material inputs, manufacturing processes, and the installation of components such as pipes, treatment equipment, and supporting elements. Details and lifespans of all materials are provided in the supplementary material.

22.1.1.3 *Operational Impacts*

Optimized processes and source separation enable decentralized systems to potentially outperform traditional treatment in terms of lower energy consumption, chemical use, and overall emissions to air, water, and land. Importantly, on-site reuse avoids effluent discharge and associated environmental impacts (Hasik et al., 2017). Exclusions include micropollutants and microbial pathogens due to current LCA methodological limitations (Corominas et al., 2020; Harder et al., 2017). Operational exchanges are detailed in the supplementary material.

22.1.1.4 *Waste Management and Resource Recovery*

The management of sludge was approached through anaerobic digestion with the production of biogas. The sludge anaerobic digester and post-treatment equipment are assumed to be installed in the building but the produced digestate would be outsourced in case of further treatment is deemed necessary. Therefore, transport to the treatment facility would be considered in such case.

22.1.1.5 *System Lifespan and Maintenance*

We assume a 30-year operational lifespan for the decentralized system, with components replaced as needed. Membrane upgrades are given particular attention due to their potential impact. In line with common LCA practice, lesser maintenance activities and end-of-life impacts are excluded due to their relatively negligible contributions (Carré et al., 2017; Corominas et al., 2020).

22.1.1.6 *Centralized Treatment Baseline*

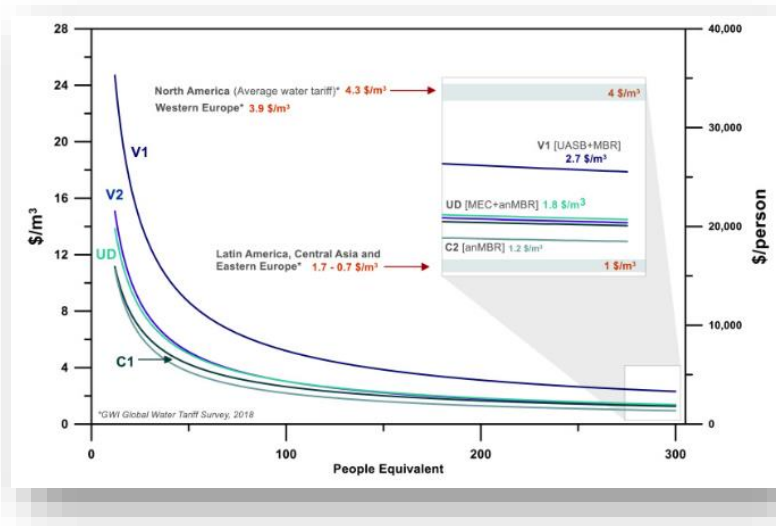
To ensure a robust comparison, centralized treatment boundaries mirror those of the decentralized system. This includes treatment plants, pipelines, pumping stations, potable water production, sludge management, and component lifespans/upgrades. Network losses are a critical factor in this assessment. Please refer to the centralized section within this supplementary information [23.3 Centralized (CAS) – LCA]

22.1.2 Functional unit

The functional unit of the study is providing potable water supply and treating wastewater for a population equivalent of 300 people over a period of one year. The total population of 300 inhabitants has total GW and BW demands of 32400 L*d⁻¹ and 4500 L*d⁻¹ and an annual wastewater production of 13,518 m³*yr⁻¹.

22.1.2.1 *From high-rise buildings to City block.*

While the main study is based around the wastewater requirements for 2,000 people equivalent a year and the data used in the LCA is based on a population of 300. As discussed, we initially conducted a techno-economic analysis for all the most common residential developments. The study showed that buildings with more 300 inhabitants demonstrate the potential economic benefits of this concept as the economies of scale are already decreasing the overall costs (Garrido-Baserba, 2022), indicating that the impact in the economies of scale between a 300 or a 2,000 people equivalent should be similar. However, to better reflect a real-world application in an urban environment, we decided to scale the findings to a more typical city block population of 2000 people. Therefore, based on these preliminary results we were able to conclude that treated water price (\$/m³) for city block of 2,000 people equivalent, should be in principle very similar to 6.7 high rise buildings (2000/300). This previous study supported the assumption that the LCA of this concept when applied to a city block shouldn't be much different that the LCA of this concept when applied to 7 buildings.



In the figure above there is a summary of the treated water price (\$/m³) and cost per person for five different alternatives of decentralized source separation (V1, V2, C1, C2, and UD) depending on the number of inhabitants (and without considering water or sewer connection savings). Therefore, based on these preliminary results we were able to conclude that treated water price (\$/m³) for city block of 2,000 people equivalent, should be in principle very similar to 6.7 high rise buildings (2000/300). A closer look at the high-

4114 rise housing Building (i.e., 300 people) shows that the water price could be potentially lower than many
4115 regional averages (i.e., North America and Western Europe). The right axis corresponds to \$/person in a
4116 30-year horizon.

4117 22.1.3 Inventory construction

4118 **Allocation Methodology:** We employ the ecoinvent "Allocation at the point of substitution" model. This
4119 means impacts of waste requiring further treatment are attributed to the main activity being studied. Since
4120 we include waste treatment and resource recovery, this rule also applies to valuable byproducts, ensuring
4121 allocation reflects how impacts are distributed throughout the system.

4122 **Transport:** "Market for" datasets in ecoinvent offer built-in average transport distances relevant to specific
4123 components. Additional transport needs (e.g., worker commuting) are added independently.

4124 **Detailed Inventory:** The supplementary material presents specific flows, quantities, and activities
4125 considered. It's organized as follows:

- 4126 • **Construction Inventory:**

- 4127 ○ Material requirements

- 4128 ○ Production processes

- 4129 ○ Installation costs

- 4130 • **Operation Inventory:** Emphasis on recovered resources (water, energy, nutrients)

4131 **Resource Recovery**

- 4132 • **Recycled/Treated Water:** Replaces tap water as quality is equivalent. Inventory accounts for
4133 extraction, treatment, and transport processes typical of tap water provision.

- 4134 • **Sludge Treatment:** Since externalized from the decentralized site, we model impacts using the
4135 ecoinvent dataset "treatment of sewage sludge by anaerobic digestion." Output flows are
4136 normalized to our functional unit.

- 4137 • **Recovered Nutrients and Energy:** Inventory includes only those derived directly from the in-
4138 building system (see Figure 4). Biogas from sludge is treated separately to avoid conflating
4139 sources.

- 4140 •

4141 **Substitution Approach**

4142 Recovered nutrients are credited based on substitution of conventional fertilizers, a common LCA practice.
 4143 We include both phosphorus and nitrogen offsets. While excluding magnesium, potassium, and calcium
 4144 could introduce some underestimation, their minor quantities suggest negligible overall impact. The
 4145 specifics of these substitution choices are as follows:

- 4146 • **Struvite:** Replaces monoammonium phosphate (NH4H2PO4) due to similar composition and
 4147 widespread use.
- 4148 • **Ca-P from Urine:** Substitutes inorganic P-based fertilizer.
- 4149 • **Liquid Urine Concentrate:** Replaces N- and P-based fertilizers.

4150 **Centralized Treatment Baseline**

4151 To ensure fair comparison, the centralized scenario's inventory mirrors that of the decentralized, as much
 4152 as possible. Four transport distances are modeled (Figure 6):

- 4153 • Potable water sourcing/distribution
- 4154 • Wastewater collection/discharge

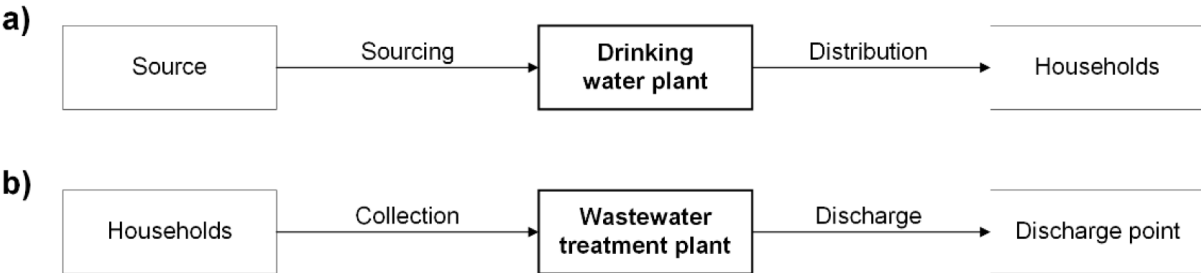
4155 Wastewater treatment itself uses pre-reported gate-to-gate impacts of conventional European WWTPs.
 4156 These were cross-checked against other available LCA studies to ensure comparability.

4157

4158 *Table S22-3: Summary of the sections of the inventory found in the supplementary material for decentralized and*
 4159 *centralized water treatment.*

	Construction	Operation
Decentralized system	Pipeline and pumping materials	Pumping
	Treatment unit materials	Treatment units
	- Brown water line	- Brown water line
	- Grey water line	- Grey water line
	- Yellow water line	- Yellow water line
	- Rainwater line	- Rainwater line
	- Additional equipment	Resource recovery
	Production processes	
	Installation	
Centralized system	Infrastructure	Pumping
	- Pipeline and pumping	Potable water production
	- Potable water production	Wastewater treatment
	- Wastewater treatment	

Table S22-4: Transport and treatment sections considered in the inventory for centralized potable water and wastewater treatment.



22.1.4 Case Description

This study uses a reference population of 300 inhabitants (as the High-Rise Building scenario), as decentralized water systems become cost-effective at this scale (Garrido-Baserba et al., 2022). Both centralized and decentralized treatment models are designed to provide water and wastewater treatment for this population over a one-year period. The scenarios for comparing centralized and decentralized treatment focus on a European setting. Data used reflects European water use, composition, building characteristics, and context. The environmental analysis prioritizes European input factors, using global inputs only when regional data is unavailable. To assess site-specific impacts, four case studies model implementation in: (i) Barcelona (Spain), (ii) Trondheim (Norway), (iii) Vienna (Austria), and (iv) Bucharest (Romania). These models consider regional differences in factors like electricity mixes, fertilizer production methods, and precipitation patterns.

Daily water demand is set at 15L per capita for blackwater (BW) and 108L per capita for greywater (GW). This assumes the use of water-efficient toilets for urine separation, as typical toilets consume 40L per flush (Rabaey et al., 2020). Average yellow water (YW) production is estimated at 1.5L per person per day with a 70% recovery ratio from urine-diverting toilets (Lienert and Larsen, 2010). Urea hydrolysis is assumed for non-collected urine and in the treatment process of source-separated YW, allowing for controlled precipitation of valuable phosphorus salts (mainly $\text{Ca}_3(\text{PO}_4)_2$). Site-specific rainfall patterns are incorporated to estimate potential potable water production from rainwater (RW) capture and treatment systems.

22.1.5 Scenarios

In addition to a general European setting (EU), we evaluate decentralized system performance in four cities chosen specifically to capture variations in climate, electricity mix, and fertilizer production technologies: Barcelona (Spain), Trondheim (Norway), Vienna (Austria), Bucharest (Romania)

Table S22-5: Summary of the main characteristics for the five scenarios.

	Europe	Barcelona	Trondheim	Vienna	Bucharest
Abbreviation	EU	ES	NO	AT	RO
Köpper climate classification	-	Csa	Dfc	Cfb	Cfa
Climate name	-	Mediterranean	Continental Subarctic	Marine West Coast	Humid Subtropical
Rainfall (mm/yr)	-	614	1123	703	699
Electricity mix (ecoinvent)	RER	ES	NO	AT	RO
Sourcing distance (km)	36.5	52.5	15	165	14.5
Wastewater collection distance (km)	10	6	4	9	11.5

Limitations and Adaptations

- **EU Scenario:** Due to rainfall variability across Europe, only wastewater reuse is included, not rainwater capture. Centralized comparison also reflects this limitation.
- **Site-Specific Scenarios:** Regional ecoinvent datasets offer realistic modeling of fertilizer production, waste management, and electricity mixes. The variations from the average EU scenario will be analyzed specifically.

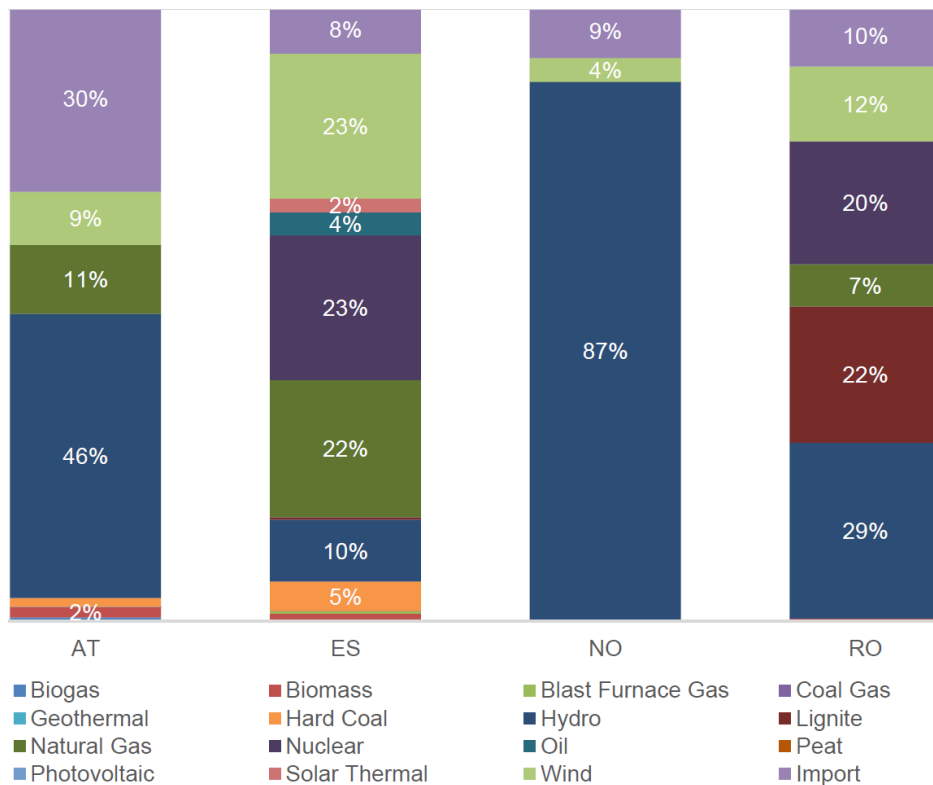
Expectations and Implications

- **Barcelona (ES):** Limited rainfall hinders potable water generation from rainwater. Its electricity mix features notable nuclear and wind components.
- **Trondheim (NO):** Ample rainfall offers good potential for rainwater capture. Norwegian electricity relies heavily on renewable hydropower, potentially providing an environmental advantage for the electricity-dependent decentralized system.
- **Vienna (AT):** Similar to Norway in hydropower use, but also imports electricity.
- **Bucharest (RO):** Most diverse electricity mix, with a higher presence of fossil-based sources.

Electricity Mix Composition (Illustrates regional variation)

Centralized Systems: For fairness, conventional scenarios are modeled in parallel, reflecting each city's water transportation, sourcing, and treatment practices.

Table S22-6: Electric mix used to model the four site-specific scenarios (Wernet et al., 2016). The abbreviations used are the ones assigned to the site-specific scenarios and refer to the cases of Vienna (AT), Barcelona (ES), Trondheim (NO), and Bucharest (RO).



For the modelling of scenarios, the datasets available for national data are used. The baseline scenario uses the RER dataset for these activities as described throughout the inventory. The baseline scenario modelled for comparison with conventional treatment provides the impacts for a general, European setting and excludes rainwater treatment. Re-calculation of installation, manufacturing, and material requirements is done to exclude equipment described in the Rainwater line section (in Decentralized system: construction inventory). Pipeline and pumping materials are also adapted to only those required for BrW and YW. Regarding operation, the Rainwater line (in Decentralized system: operation inventory) is also removed from the inventory. This scenario is compared to the centralized system described in the Conventional treatment inventory section, which does not consider the handling of any rainwater.

Table S22-7: National datasets available in ecoinvent for Spain, Norway, Austria, and Romania.

Inventory	Activity
Construction	market for waste polyethylene
	market for waste paperboard
	market for electricity, medium voltage
	treatment of municipal solid waste, incineration
Operation	market for electricity, low voltage
	market for inorganic nitrogen fertiliser, as N
	market for inorganic phosphorus fertiliser, as P ₂ O ₅

22.2 Impact assessment

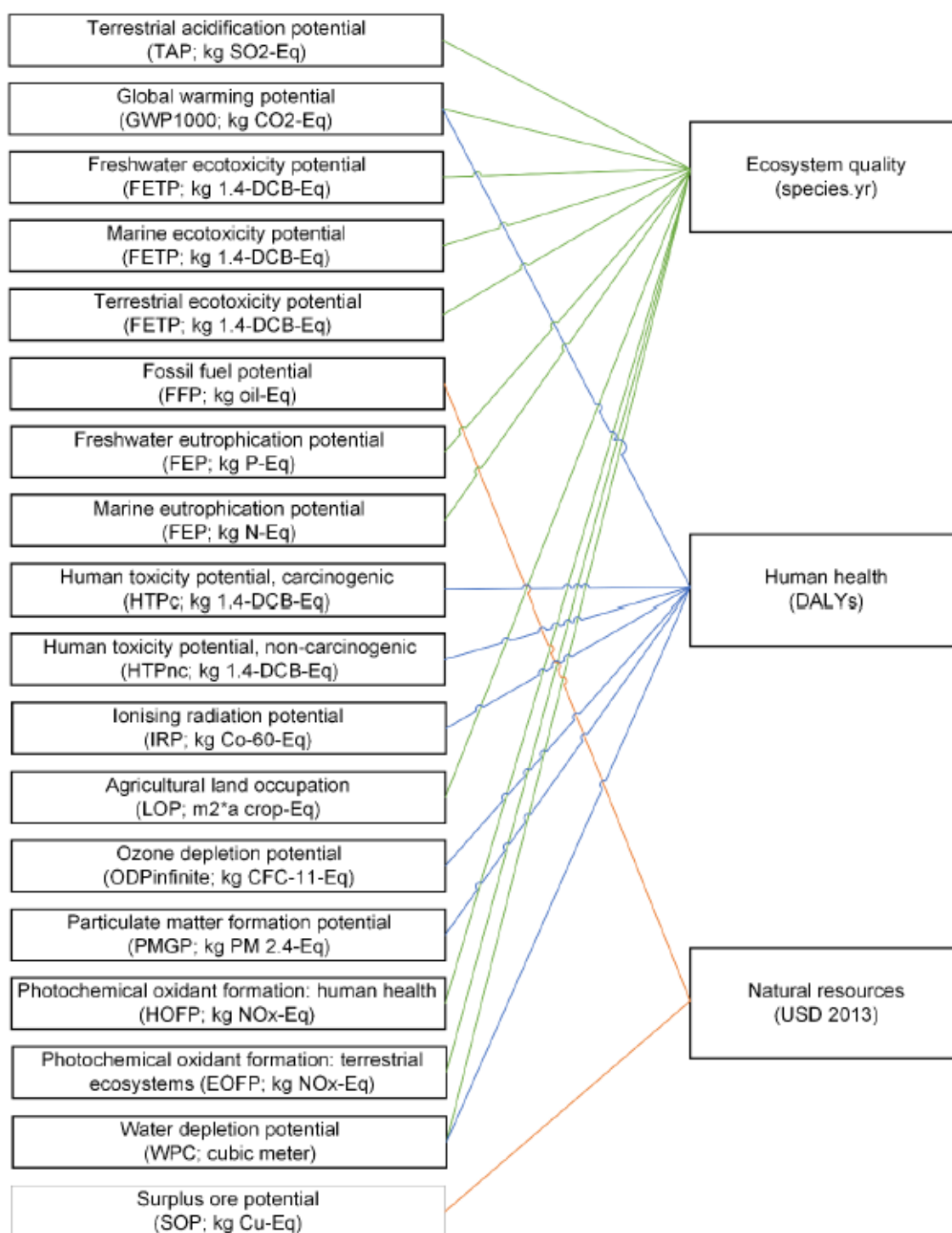
ReCiPe (H) v1.03 is employed for impact assessment. Decentralized system results cover all 18 midpoint indicators (excluding surplus ore potential due to data limitations) and the 3 endpoint categories (PRé, 2018). Note that within ReCiPe v.1.03:

- Human toxicity potential (HTP) combines both carcinogenic and non-carcinogenic impacts (HTPc and HTPnc).
- Photochemical oxidant formation potential (POFP) is presented as an average of human and ecosystem impacts (HOFP and EOFP).

In the water and wastewater domain, change, eutrophication, and ecotoxicity indicators hold particular significance. ReCiPe endpoint categories simplify result communication (Risch et al., 2014). Figure 7 (not provided, but assumed elsewhere) details ReCiPe indicators, their link to areas of protection, and corresponding units. Bold items indicate those included in this study. While we cannot quantify surplus ore potential, the "natural resources" endpoint does incorporate metal depletion.

All impacts presented in the results section reflect one year of plant operation. Construction-related impacts have been annualized to align with the 30-year lifespan of the plant.

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4255 *Table S22-8: Midpoint indicators and their relation to endpoints.*

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4259 **22.2.1 Reference flows for the construction inventory**

4260 A dataset for an activity for each of the components of the system described in the previous sections has
 4261 been created. In order to obtain the annual impacts of the construction of the plant distributed throughout
 4262 its lifespan, the reference flows in Table S22-9 are used. Construction and installation of decentralized
 4263 equipment is included while the construction of the sludge treatment facility is not as it is expected to be
 4264 the same as in the centralized treatment.

4265 *Table S22-9: Reference flows for the calculation of annualised construction impacts (FU: water treatment for 300 people*
 4266 *during a year).*

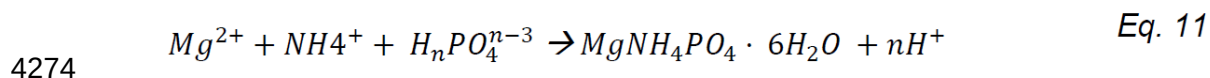
Component	Lifespan	Amount	Unit	Name of the modelled dataset
Electrochemical cells	10	0.10	unit	EC treatment urine
HPMC	7	0.14	unit	Biogas capture
Influent and effluent equalisation tanks	30	0.03	unit	Equalisation tanks
Installation of system	30	0.03	unit	Installation
MABR	10	0.10	unit	MABR unit
Main pumping equipment	18	0.06	unit	Pumping (BrW, YW, and RW)
MBR	15	0.07	unit	MBR unit
Pipeline for BrW, DN 70	70	2.62	m	Pipe (BrW)
Pipeline for YW and RW, DN 32	70	7.87	m	Pipe (YW and RW)
Pre-treatment (BrW and OFMSW)	30	0.03	unit	Pre-treatment
Production processes	30	0.03	unit	Production processes
Main holding tanks	30	0.03	unit	Rainwater line tanks
RBC	10	0.10	unit	RBC (OLAND process)
RO module for GW	5	0.20	unit	RO for GW
RO module for RW	5	0.20	unit	RO for RW
Struvite reactor and decanter	30	0.03	unit	Struvite precipitation treatment
UASB reactor	30	0.03	unit	UASB reactor
UF filtration and remineralization	15	0.07	unit	Potabilization
UV module for GW	5	0.20	unit	UV for GW
UV module for RW	5	0.20	unit	UV for RW

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4268 22.2.2 Resource recovery

4269 The recovered resources in the plant are listed in Table S22-10, and the approach to their inclusion in the
4270 LCA is summarized.

4271 The amount of produced sludge is calculated from mass balances and correctness is verified by comparison
4272 with references (Faragò et al., 2021; Glover et al., 2022; IWA, 2007). Struvite production is calculated from
4273 reacted phosphate moles, which are the limiting reactant in the struvite formation reaction (see Eq. 11).



4275 Nitrogen concentrate is calculated considering 0.15 L liquid fertilizer*L recovered urine-1 (De Paepe et al.,
4276 2018), and calcium phosphate precipitates are expected to contain 30% of influent phosphate (De Paepe
4277 et al., 2020).

4278 Monoammonium phosphate mass is standardly given as nutrient supply as kilograms of N or P2O5. From
4279 the conversion of struvite to monoammonium phosphate, 122.91 kg of P2O5 and 24.25 kg of N are
4280 obtained, which would lead to absolute masses of monoammonium phosphate of 236.37 kg and 285.25
4281 kg, respectively, as mass content in total product is that of 52% P2O5 and 8.5% N. To avoid the double-
4282 counting of fertilizer mass, 236.37 kg are counted for P2O5 as total monoammonium phosphate, and the
4283 remaining mass is considered to be nitrogen supply as monoammonium phosphate. The calculation for the
4284 replacement of Ca-P precipitates considers available P as P2O5. Finally, N and P in urine concentrate are
4285 replacements for available N and P (as P2O5) fertilizers.

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4288 *Table S22-10: Inventory details regarding recovered resources for the annual operation of the decentralized plant (FU:*
 4289 *water treatment for 300 people during a year).*

Resource and origin	Amount	Unit	Approach	Comments
Water, recycled	11,167 + Captured rainwater	m ³	Replacement for tap water	Dataset used: market for tap water (Europe without Switzerland). Total volume is dependent on site
Energy from biogas, UASB reactor	19,351.98	kWh	Discounted from the energy consumption of the reactor	No sludge treatment considered, energy only from main reactor
Sludge, UASB	1700.00	kg	Treated by anaerobic digestion to prioritize resource recovery	Dataset used: treatment of sewage sludge by anaerobic digestion (CH)
Sludge, MBR	2.600	kg	Treated by anaerobic digestion to prioritize resource recovery	Dataset used: treatment of sewage sludge by anaerobic digestion (CH)
Sludge, MABR	24.39	kg	Treated by anaerobic digestion to prioritize resource recovery	Dataset used: treatment of sewage sludge by anaerobic digestion (CH)
Struvite, precipitation reactor	425	kg	Replacement for a total of 285.25 kg of monoammonium phosphate	Dataset used: market for monoammonium phosphate (RER)
Ca-P precipitates, EC	100	kg	Replacement for a total of 32 kg of phosphorus fertilizer as P ₂ O ₅	Dataset used: market group for inorganic phosphorus fertiliser, as P ₂ O ₅ (RER)
Liquid fertilizer (as N), MABR	17.25	m ³	Replacement for a total of 707 kg of nitrogen fertilizer as N	Dataset used: market group for inorganic nitrogen fertiliser, as N (RER)
Liquid fertilizer (as P), MABR	17.25	m ³	Replacement for a total of 116 kg of phosphorus fertilizer as P ₂ O ₅	Dataset used: market group for inorganic phosphorus fertiliser, as P ₂ O ₅ (RER)

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4293 22.2.3 LCA results: total impacts

4294

4295 Total scores of impacts for the operation and construction phases are shown for all scenarios,
 4296 as well as the final total scores, the avoided impacts achieved

4297 Table S22-11: Total impacts on all ReCiPe midpoint and endpoint indicators for the European average (EU) scenario.

Scenario: EU	Operation	Construction	Total impacts	Avoided impacts	Water reuse
Terrestrial acidification potential (TAP; kg SO₂-Eq)	74,0	3,0	77,0	36,7	13,2
Global warming potential (GWP1000; kg CO₂-Eq)	29.400,0	776,0	30.176,0	8.890,0	4.010,0
Freshwater ecotoxicity potential (FETP; kg 1.4-DBC-Eq)	3.130,0	179,0	3.309,0	518,0	217,0
Marine ecotoxicity potential (METP; kg 1.4-DBC-Eq)	3.930,0	227,0	4.157,0	687,0	295,0
Terrestrial ecotoxicity potential (TETP; kg 1.4-DBC-Eq)	127.000,0	14.900,0	141.900,0	44.100,0	13.600,0
Fossil fuel potential (FFP; kg oil-Eq)	5.500,0	220,0	5.720,0	2.430,0	953,0
Freshwater eutrophication potential (FEP; kg P-Eq)	20,6	0,3	20,9	3,4	2,4

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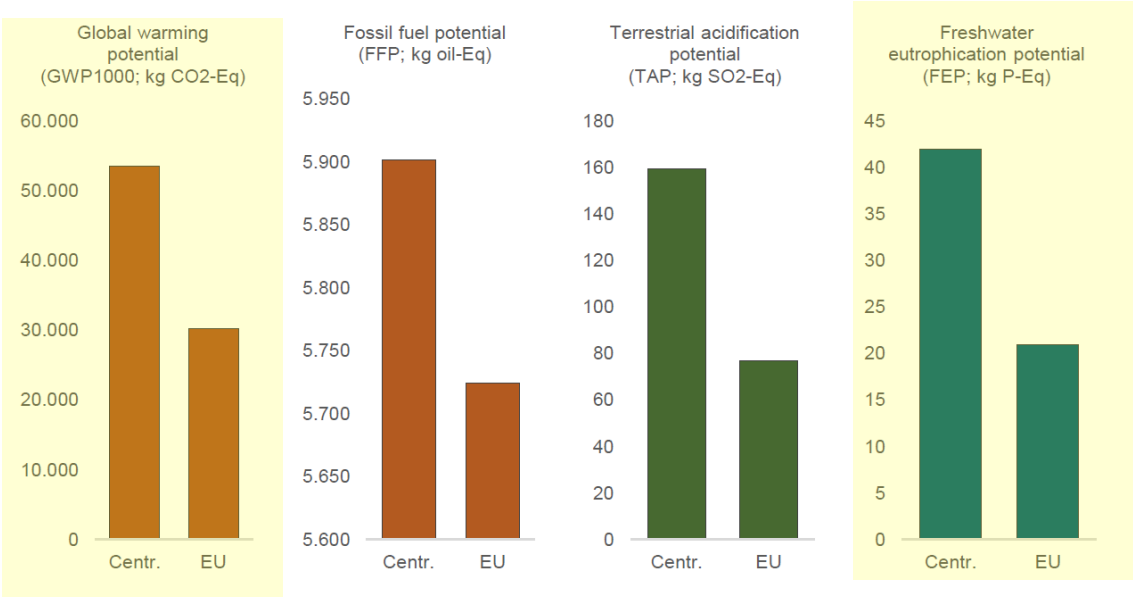
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4301 Table S22-12: Contributions of the construction and operational phases to total environmental impacts for the EU
 4302 scenario of the decentralized system.

	Abbreviation	Construction	Operation
Terrestrial acidification	TAP	3,90%	96,10%
Global warming	GWP1000	2,57%	97,43%
Freshwater ecotoxicity	FETP	5,41%	94,59%
Marine ecotoxicity	METP	5,47%	94,53%
Terrestrial ecotoxicity	TETP	10,49%	89,51%
Fossil depletion	FFP	3,85%	96,15%
Freshwater eutrophication	FEP	1,50%	98,50%
Marine eutrophication	MEP	4,73%	95,27%
Human toxicity	HTP	4,83%	95,17%
Ionising radiation	IRP	0,54%	99,46%
Agricultural land occupation	LOP	4,77%	95,23%
Ozone depletion	ODP _{infinite}	0,63%	99,37%
Particulate matter formation	PMFP	4,49%	95,51%
Photochemical oxidant formation	POFP	3,79%	96,21%
Water consumption	WCP	2,90%	97,10%
Ecosystem quality (endpoint)	-	2,94%	97,06%
Human health (endpoint)	-	6,92%	93,08%
Natural resources (endpoint)	-	9,76%	90,24%

4303
 4304
 4305 Table S22-13: Comparison of total scores for ReCiPe midpoint indicators GWP1000, FFP, TAP, and FEP for
 4306 conventional centralized treatment (centr.) and the European average scenario of the decentralized system (EU).



4309 22.2.4 Contribution and Comparative Analysis (EU Scenario)

- 4310 • **Decentralized Outperformance:** Results show the decentralized system outperforms
4311 conventional treatment in 10/15 midpoint indicators, notably including global warming potential
4312 (GWP1000), freshwater and marine eutrophication (FEP and MEP), terrestrial acidification
4313 (TAP), and others.
- 4314 • **Construction vs. Operation:** Construction's contribution to total impacts ranges from a
4315 negligible ~0.5% to a maximum of 10.5%. Ecotoxicity indicators are impacted most substantially
4316 due to steel, copper, and related material production. However, annualized construction impacts
4317 over the system's 30-year lifespan greatly minimize their relative significance.
- 4318 • **GWP1000 (Climate Change):** During both construction and operation, electricity is the key
4319 contributor to GWP1000, at roughly 30% and 75% respectively. Additional operational emission
4320 sources are the UASB, RBC, and MBR reactors. However, resource recoveries
4321 (nutrients, energy, water) mitigate impacts significantly. Construction phase activities leading to
4322 GWP include steel production, ethylene, hard coal, iron, and clinker acquisition. The
4323 decentralized system shows a 44% improvement in GWP1000 over conventional treatment.
- 4324 • **FEP (Freshwater Eutrophication):** Impacts arise from phosphorus leakages during mining
4325 (lignite, hard coal, copper). Resource recovery, especially water reuse, plays a major role in
4326 mitigation. **The decentralized system achieves a 50% FEP reduction.**
- 4327 • **Improvements: A Key Advantage** Significantly reduced pumping requirements drive energy
4328 savings for centralized treatment. Importantly, the higher energy cost of technologies like the
4329 UASB is outweighed by better removal efficiency, minimized sludge, and biogas production – all
4330 with environmental benefits. Also, decentralized systems eliminate GHG emissions (especially
4331 N₂O), reduce resource leakages, and support water reuse – furthering improvements over the
4332 conventional approach.

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22.2.5 LCA results: process contribution figures

Insight into the elementary flows and process contributions to each midpoint impact category are given. Charts are obtained using Birghtway2's Activity Browser and set to a level of detail of 0.87% of total contribution for midpoints and 2% for endpoints. The operation and annualised construction phases are shown separately to facilitate visualization, and a relative cut-off type allows to show the impacts in higher detail. For some indicators, elementary flow contributions are not included as they do not provide additional information. These include freshwater eutrophication potential, for which almost 100% of impacts are due to phosphate emissions, water consumption potential and land occupation for which elementary flows are water and land, respectively, and ionising radiation potential containing only emissions from uranium.

22.2.5.1 *Global Warming potential (FEP)*

Table S22-14: Elementary flow contributions to the GWP1000 indicator for the decentralized system, including impacts of the operational phase and the fraction of the construction phase corresponding to 1/30 years of plant lifespan.

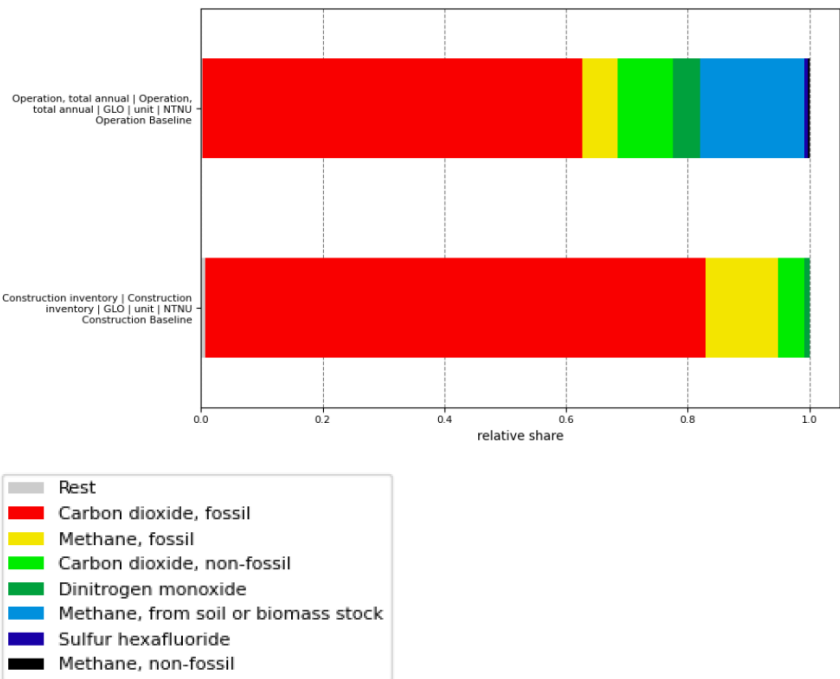
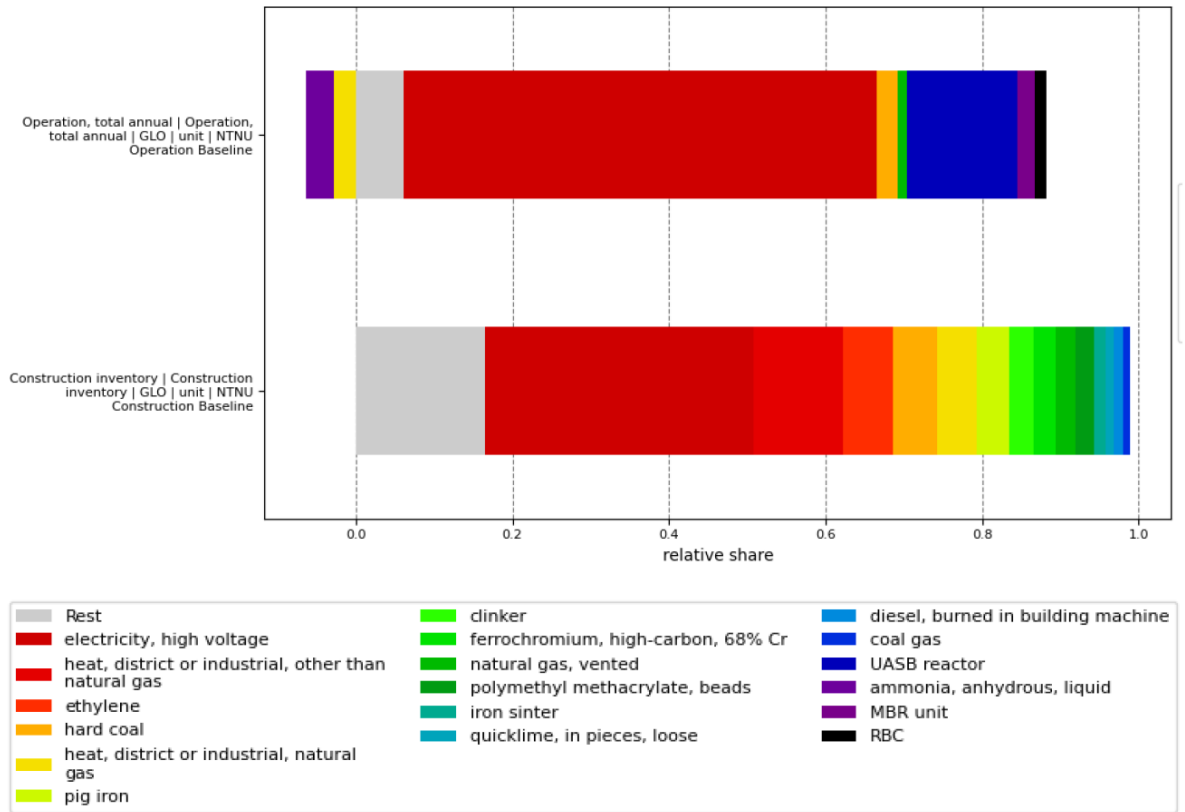
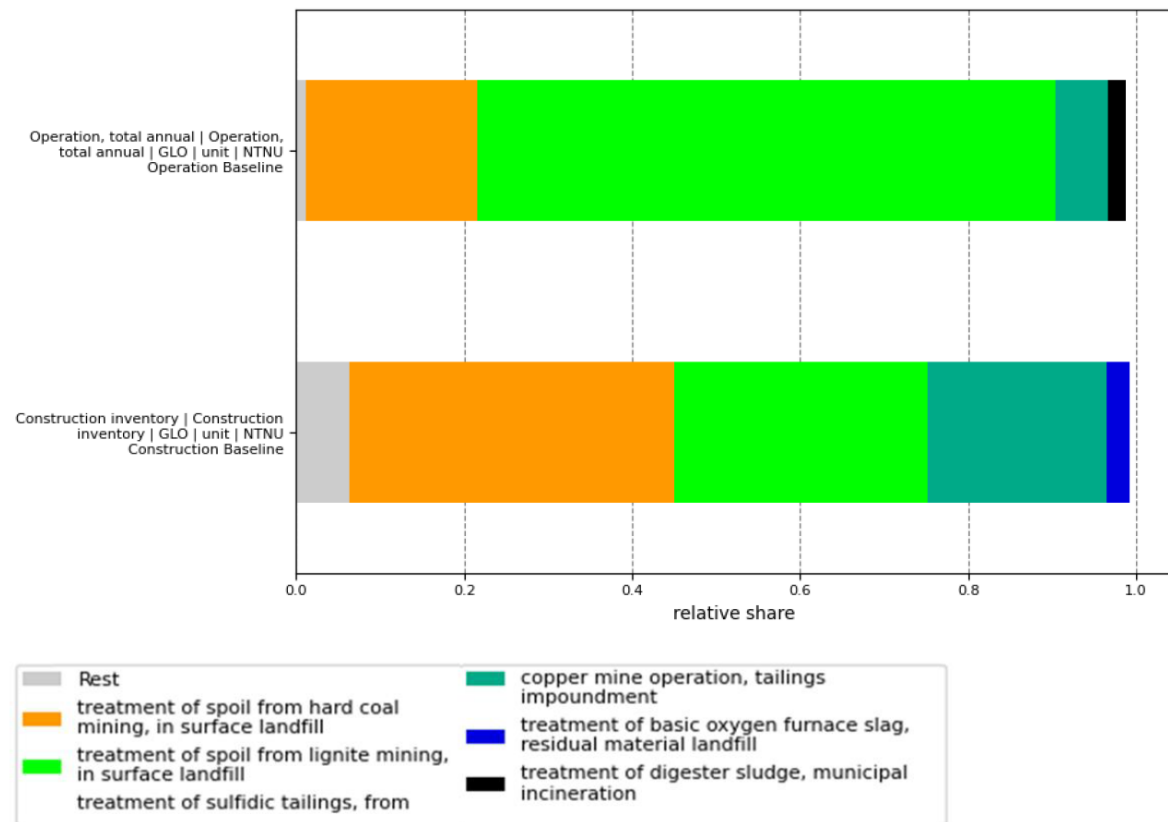


Table S22-15: Process contributions to the GWP1000 indicator for the decentralized system, including impacts of the operational phase and the fraction of the construction phase corresponding to 1/30 years of plant lifespan.



22.2.5.2 Freshwater eutrophication potential (FEP)

Table S22-16: Process contributions to the FEP indicator for the decentralized system, including impacts of the operational phase and the fraction of the construction phase corresponding to 1/30 years of plant lifespan.



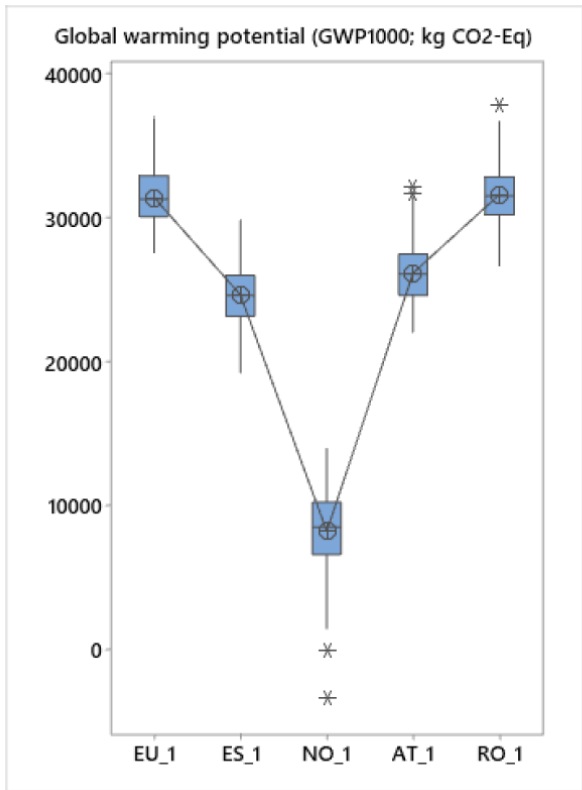
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22.2.6 Sensitivity analysis

Results for the sensitivity analysis of the inventory data from ecoinvent are presented in this section. Data is obtained in the Activity Browser and analysed in Minitab statistical software, version 19.2.

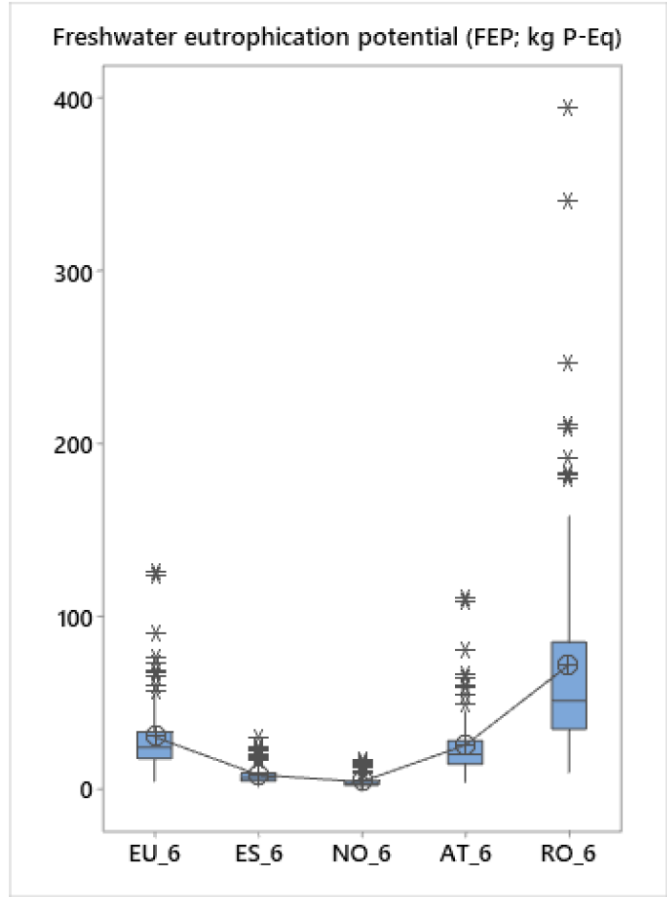
Table S22-17: Box plot and grouping information using the Games-Howell method (95% confidence) for the terrestrial acidification potential indicator. Abbreviations refer to the site-specific scenarios: Vienna (AT), Barcelona (ES), Trondheim (NO), and Bucharest (RO). Box plots illustrate the distribution of data, with the center line indicating the median, the box boundaries representing the 25th (Q1) and 75th percentiles (Q3), and the whiskers extending to the minimum and maximum values (or 1.5 times the interquartile range beyond the box, whichever is smaller).



Factor	N	Mean	Grouping
RO_1	100	31598	A
EU_1	100	31396	A
AT_1	100	26146	B
ES_1	100	24639	C
NO_1	100	8233	D

Means that do not share a letter are significantly different.

Table S22-18: Box plot and grouping information using the Games-Howell method (95% confidence) for the freshwater eutrophication potential indicator. Abbreviations refer to the site-specific scenarios: Vienna (AT), Barcelona (ES), Trondheim (NO), and Bucharest (RO). Box plots illustrate the distribution of data, with the center line indicating the median, the box boundaries representing the 25th (Q1) and 75th percentiles (Q3), and the whiskers extending to the minimum and maximum values (or 1.5 times the interquartile range beyond the box, whichever is smaller)



Factor	N	Mean	Grouping
RO_6	100	72,12	A
EU_6	100	30,35	B
AT_6	100	25,64	B
ES_6	100	8,422	C
NO_6	100	4,453	D

Means that do not share a letter are significantly different.

4408

4409 23 Centralized water treatment

4410 23.1 The Conventional Approach: Limitations and Inefficiencies

4411 Urban wastewater treatment typically encompasses multiple stages with varying technologies, driven by
4412 plant size and discharge quality requirements. While conventional plants treat effluent sufficiently for
4413 discharge into natural water bodies, the water quality falls short of potable standards. Thus, complex
4414 extraction, treatment, and extensive distribution networks are necessary for potable water provision. This
4415 centralized approach is characterized by:

- 4416 • **Extensive Infrastructure:** Significant distances exist between water treatment facilities and
4417 communities, necessitating lengthy piping networks for both wastewater collection and treated
4418 water distribution. For realism, our European average scenario assumes distances for
4419 wastewater extraction (to plant) and discharge (from plant) of 10 km and 6
4420 km, respectively. Potable water also travels an average of 36 km before treatment.
- 4421 • **Operational Challenges:** Centralized plants involve pre-treatment (removal of grit, etc.), primary
4422 treatment (physical/chemical separations), and biological treatment (primarily via aerobic
4423 sludge). Sludge stabilization is common, sometimes including energy recovery (biogas), but
4424 nutrient recovery remains marginal. Tertiary treatment and disinfection stages exist for stricter
4425 effluent requirements. Overall, this approach suffers from high energy consumption, chemical
4426 needs, waste generation, and aging infrastructure – all driving operational costs. Transport loss is
4427 an additional drawback.

4428

4429 23.1.1 Resource Recovery: Missed Opportunities in Conventional Systems

4430 The emphasis on removing nutrients (nitrogen, phosphorus) for environmental discharge, rather than
4431 recovery, represents a substantial inefficiency. These are precisely the materials most useful for fertilizer
4432 production. Despite recent research progress, resource recovery at wastewater treatment plants
4433 (WWTPs) is limited. Worldwide, few facilities integrate recovery technologies with both developed and
4434 developing nations facing this challenge. Recovery, when used, primarily targets solids from sludge
4435 dewatering for land application. Further compounding the loss, less than 40% of the initial nitrogen
4436 present in raw wastewater reaches the sludge through conventional treatment due to dissipation during
4437 biological stages.

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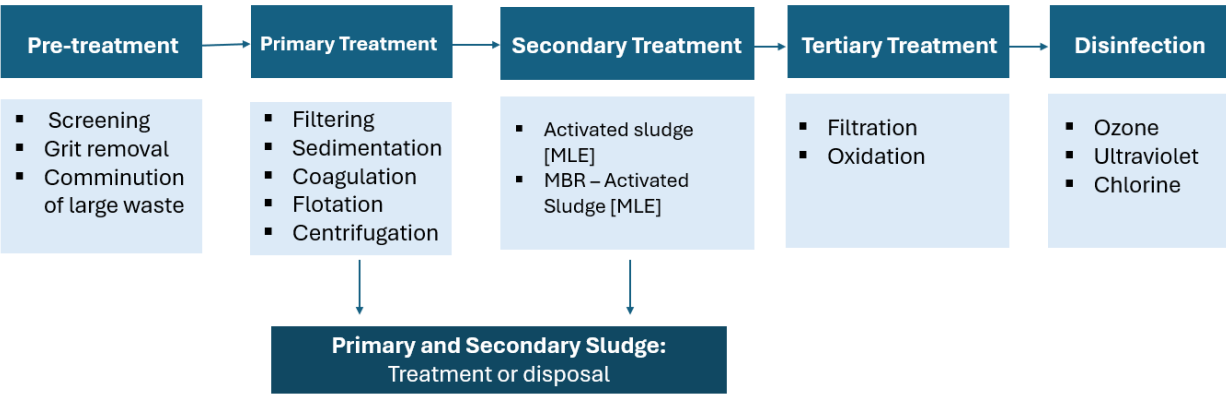
4441 23.1.2 Centralized Scenario Description

4442 23.1.2.1 *Train description*

4443

4444 The centralized scenario assumes a conventional wastewater treatment train with the following stages:

- 4445 ▪ Pre-treatment: Screening, grit removal, and comminution of large waste.
- 4446 ▪ Primary Treatment: Physical and chemical separation processes, including filtering, sedimentation, 4447 coagulation, flotation, and centrifugation, primarily targeting the elimination of suspended solids, 4448 oils, and odors.
- 4449 ▪ Secondary Treatment: Aerobic activated sludge process for biological treatment. Traditional 4450 Activated Sludge (CAS) with MLE Configuration: The Modified Ludzack-Ettinger (MLE) process 4451 serves as a cornerstone of biological nutrient removal. For both centralized-based models and the 4452 decentralized model, we ensured an identical influent (though drawn from different streams within 4453 the overall system), identical aeration setup and control parameters (ABAC, airflow/valve-opening 4454 logic, blower settings, etc.), plus matched environmental conditions.
- 4455 ▪ Sludge Treatment: Stabilization of combined primary and secondary sludges. Anaerobic digestion 4456 for biogas production and nutrient recovery is considered as a potential enhancement.
- 4457 ▪ Tertiary Treatment: Additional nutrient removal processes are employed to meet strict effluent 4458 quality standards and match the decentralized high-quality effluent. These could include filtration 4459 membranes, enhanced biological phosphorus removal, such as CEPT (Chemical Enhanced 4460 Phosphorus Treatment), using ferric chloride (FeCl₃) and aluminum sulfate (Al₂(SO₄)₃), and 4461 advanced oxidation processes (AOP).
- 4462 ▪ Final Disinfection: Ozone, ultraviolet radiation, or chlorine are used to ensure health safety.



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Table S23-1: Flowchart of conventional wastewater treatment.

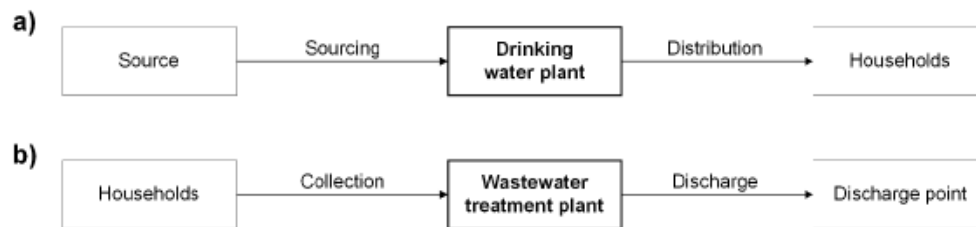


Figure 6: Transport and treatment sections considered in the inventory for centralized potable water and wastewater treatment.

To comprehensively assess a conventional treatment scenario, we employed two centralized models for robust comparison: i) Traditional Activated Sludge (CAS) with MLE Configuration: The Modified Ludzack-Ettinger (MLE) process serves as a cornerstone of biological nutrient removal. For both centralized-based models and the decentralized model, we ensured an identical influent (though drawn from different streams within the overall system), a shared co-digestion approach, identical aeration setup and control parameters (ABAC, airflow/valve-opening logic, blower settings, etc.), plus matched environmental conditions. This carefully standardized approach enables the most direct comparison for a variety of treatment performance aspects and; ii) MBR as CAS: Recognizing the inherent advantage of having built already the decentralized model's MBR for grey water treatment, we repurposed this modular unit within a second centralized model. For this adaptation, the MBR receives a combined brown water, food waste, and grey water feed that simulates centralized sewage composition. Notably, this repurposed design retains the original MBR block, characterization, aeration, and control strategies, providing a truly apples-to-apples comparison with the decentralized system.

23.1.2.1 Distribution and collection system

The centralized approach requires piping networks for wastewater collection, discharge to the environment after treatment, extraction of new water from water bodies, transport to potable water treatment plants, and distribution to end users. In accordance with observed proximities of wastewater treatment plants (WWTPs) to city centers across various European cities (including Barcelona, Berlin, Bucharest, Girona, Madrid, Oslo, Paris, Rome, Stockholm, Trondheim, Vienna, and Warsaw), the European average scenario considers a distance of 10 km to the nearest conventional centralized water treatment plant. Additionally, the distance from WWTPs to the nearest local freshwater systems where discharge takes place is considered to be 2 km (Shahmoradi and Isalou, 2013). Finally, the average distance from the source of potable water to the potable water treatment plant is 36 km (as observed for the cities listed previously for distances to WWTPs).

Table S16: Inventory details for the annualized construction and annual operation of the centralized pipeline and pumping (FU: water treatment for 300 people during a year).

Element	Amount	Unit	Ecoinvent dataset	
Sourcing pipeline	3.98E-04	km	market for water supply network	GLO
Wastewater collection and discharge, urban	551.65	m ³	market for sewer grid, urban	GLO
Wastewater collection and discharge, rural	37.58	m ³	market for sewer grid, rural	GLO
Pumping requirements	31,506.06	MJ	market for water pump operation, electric	GLO

23.1.2.2 The volumetric losses in sewer networks

relevant volumetric losses are associated with sewer networks, therefore their inclusion in the study is crucial for fair comparison. In fact, large volumetric losses of up to 55% of total water are associated with current water distribution networks, resulting in nearly 50 billion m³ of potable water being lost annually worldwide (Ociepa et al., 2019). While volumetric losses in sewer networks depend on the several factors (e.g., pipe condition, leak and cracks, overall deterioration, system age, groundwater levels, intense rainfall, insufficient maintenance practices, etc.), in the current Centr scenario, a typical range of 5% of total wastewater volume was used. In older, poorly maintained systems, or those experiencing high infiltration/inflow, losses could reach 25% or higher.

On the other hand, regarding clean water distribution, losses of 20% of total supply along the transport system are considered, matching data for the losses associated with large distribution networks considering good condition and active monitoring and control of leakages (Brandt et al., 2017). Lengths of pipes necessary per cubic meter of water are allocated considering the ratio established by the European datasets, for both freshwater and wastewater.

Pumping is modelled considering standardized energy intensities of sourcing, conveyance, and distribution provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2020), considering 50% of total distance is covered by gravity sewers. Private pumping inside the FU building is also added to match the boundaries of the decentralized approach.

Pipeline aimed at the distribution of potable water is included in the market for tap water employed to model the production of drinking water. Sourcing of freshwater and wastewater collection and discharge are added using the ecoinvent datasets for water supply network and sewer grid, respectively. The sewer grid for transport to and from the WWTP is modelled with a urban:rural pipeline ratio of 0.83:0.17 following the grid composition in ecoinvent for Europe. Lifespan of the pipeline in the datasets is adapted to match that of the FU of the study.

- Ociepa, E., Mrowiec, M., Deska, I., 2019. Analysis of Water Losses and Assessment of Initiatives Aimed at Their Reduction in Selected Water Supply Systems. Water 11. <https://doi.org/10.3390/w11051037>
- Brandt, M.J., Johnson, K.M., Elphinston, A.J., Ratnayaka, D.D., 2017. Chapter 1 - The Demand for Potable Water, in: Twort's Water Supply (Seventh Edition). Butterworth-Heinemann, Boston, pp. 1–36. <https://doi.org/10.1016/B978-0-08-100025-0.00001-6>

23.2 Comparing centralized versus decentralized

To establish a fair baseline, we compared our decentralized model against both a detailed 1) conventional activated sludge (CAS) system using a membrane bioreactor (MBR) and 2) detailed conventional activated sludge system with a modified Ludzack-Ettinger (MLE) configuration – arguably the most prevalent biological nutrient removal approach.

Shared Parameters: Both models utilized the same influent (originating from different streams, of course), co-digestion approach, aeration system, and control strategies (airflow, valve opening, blower settings, etc.). Environmental conditions were identical.

Robustness and Accuracy: 5 different operational strategies were subjected to the CAS model. Averaged results were rigorously checked against findings from an extensive literature review covering various control scenarios (ammonia-based control, bubble size, diffuser settings, energy options, etc.). This validated model accuracy; however, it was primarily used for confirmation, with the literature review ultimately providing the core reference for comparison.

4550 23.2.1 Two Centralized Models

4551 To comprehensively assess a conventional treatment scenario, we employed two centralized models for
4552 robust comparison, both built and calibrated on well-established design principles:

- 4553 • **Traditional Activated Sludge (CAS) with MLE Configuration:** The Modified Ludzack-Ettinger
4554 (MLE) process serves as a cornerstone of biological nutrient removal. For both centralized-based
4555 models and the decentralized model, we ensured an identical influent (though drawn from different
4556 streams within the overall system), a shared co-digestion approach, identical aeration setup and
4557 control parameters (ABAC, airflow/valve-opening logic, blower settings, etc.), plus matched
4558 environmental conditions. This carefully standardized approach enables the most direct
4559 comparison for a variety of treatment performance aspects.
- 4560 • **MBR as Conventional Activated Sludge (CAS):** Recognizing the inherent advantage of having
4561 built already the decentralized model's MBR for Greywater treatment, we repurposed this modular
4562 unit within a second centralized model. For this adaptation, the MBR receives a combined Brown
4563 water, Food waste, and Greywater feed that simulates centralized sewage composition. Notably,
4564 this repurposed design retains the original MBR block, characterization, aeration, and control
4565 strategies, providing a truly apples-to-apples comparison with the decentralized system.

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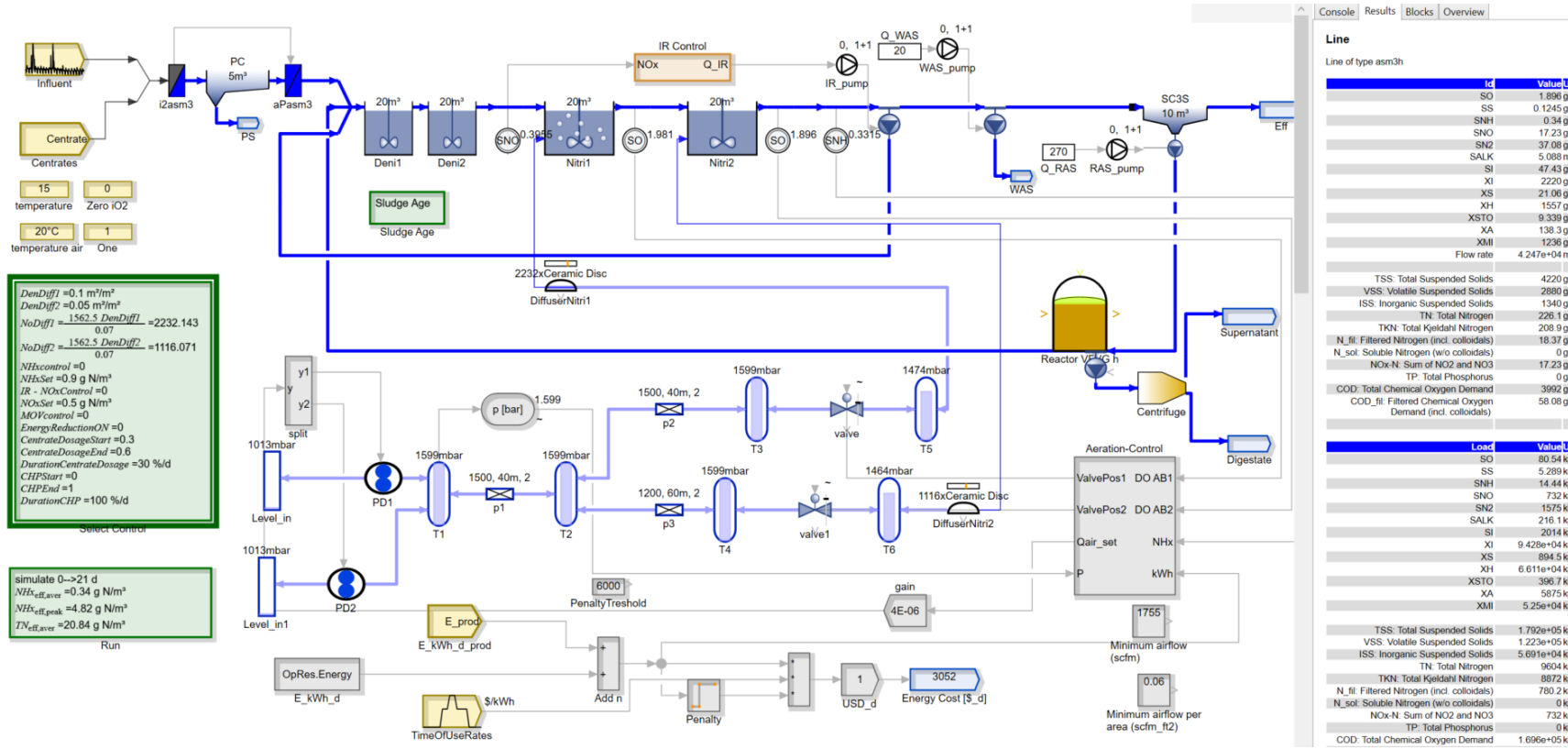
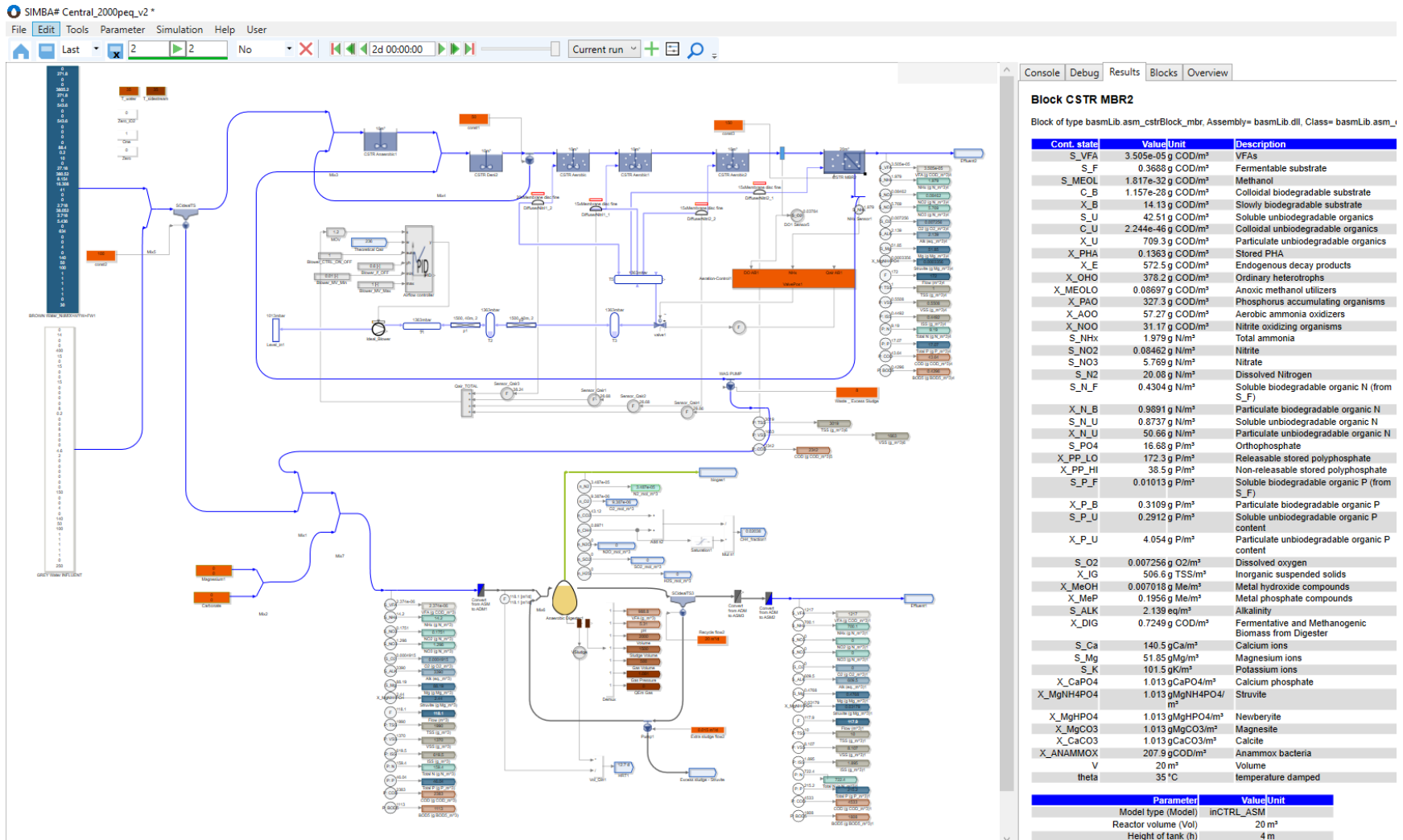


Table S23-2:: Screen captures of the SIMBA# model representing a small (centralized) municipal wastewater treatment facility (WWTP) with an influent flow rate of 250 m³/d (0.065 MGD) to study and compare the energy consumption and cost at centralized WWTPs. The plant has primary clarifiers, an MLE activated sludge process, secondary clarifiers, and anaerobic digesters. Wasting is done from the aeration tanks. An internal mixed liquor recycle (IMLR) stream is used to recycle nitrate back to the anoxic zone from the aerobic zone. The return streams from anaerobic digestion are represented by an influent stream that can be fed intermittently or continuously. The WWTP has combined heat and power (CHP) generation to extract energy from the biogas produced in the anaerobic digesters. The daily energy production rate derived from the WWTP process is assumed constant, but food waste co-digestion feed is based on the same scheduled used for the decentralized system.

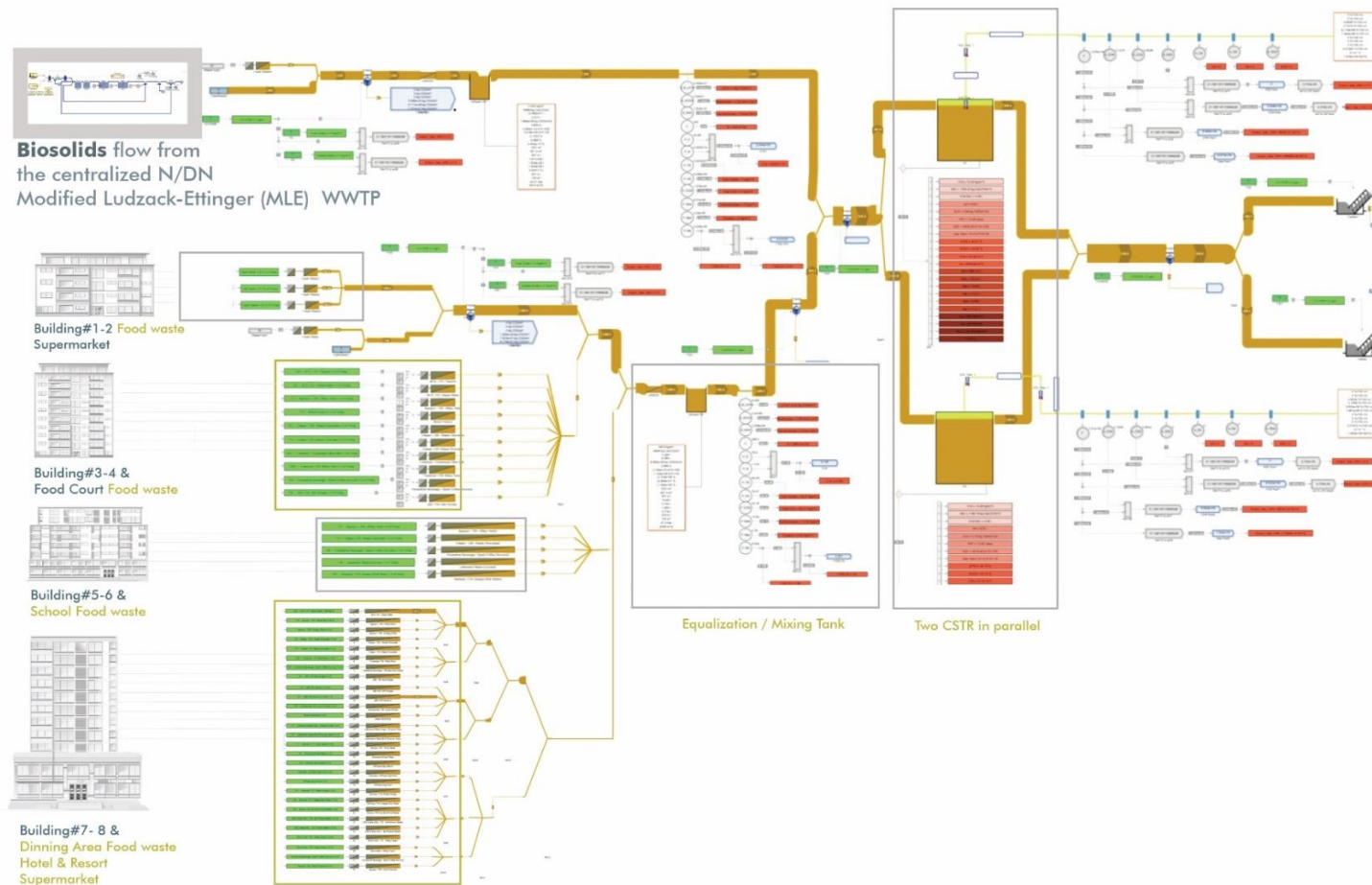
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Table S23-3: Screen captures of the SIMBA# MBR-based model representing a small (centralized) municipal wastewater treatment facility (WWTP) with an influent flow rate of 250 m³/d (0.065 MGD) to study and compare the energy consumption and cost at centralized WWTPs. The plant was evaluated with and without primary clarifiers, an MLE activated sludge process, secondary clarifiers, and anaerobic digesters. The WWTP has combined heat and power (CHP) generation to extract energy from the biogas produced in the anaerobic digesters. The daily energy production rate derived from the WWTP process is assumed constant, but food waste co-digestion feed is based on the same scheduled used for the decentralized system.

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4589 Table S23-4: The modeled anaerobic digestion process corresponds to two CSTR in parallel. The anaerobic digestion system is both fed from the WWTP facility
 4590 biosolids (the NDN – MLE process depicted above) and from the same co-digestion materials and regime used for the decentralized (DSS) model. The planned
 4591 operation of the co-digestion modules basically consists of an equalization tank that will achieve partial degradation of hauled-in waste, while allowing time for mixing
 4592 and nutrient/composition balance. Other necessary equipment as grinders, storage tanks, etc. were not modeled but considered in the technoeconomic assessment.
 4593 Effluent from these two digesters will flow into screw presses, which are modelled with a single separator block operating at a fixed 40% (w/v) TSS concentration in
 4594 the centrifuge solids (Figure 19). The screw press solids flow rate was assuming that the specific gravity of the solids was approximately equal to water. A gas
 4595 analysis subsystem was added to calculate the production rate of total gas, methane, and carbon dioxide.

Key Considerations

- **Fair Comparison:** This dual-model approach is strategically designed to neutralize performance disparities stemming solely from treatment technology differences (i.e., CAS vs. MBR). The two centralized cases were evaluated with the same pre-treatment, sludge handling, and disinfection.
- **Literature Validation:** As an additional robustness check, the results of both centralized models were cross-referenced with findings from an extensive literature review covering CAS systems under various operational and control variables (ammonia-based control, bubble size, energy optimization strategies, etc.). [see Costs Comparison: Literature Review]

23.2.1.1 Model Description:

The two models of the centralized CAS include diurnal influent flow and patterns for COD, ammonia and ammonium nitrogen (NH_x), and soluble phosphorus (SP) concentrations (Diurnal Influent block). It also models primary clarifiers, bioreactors in series, and a layered clarifier (Secondary Clarifiers block).

Each bioreactor has a separate dissolved oxygen (DO) controller; these controllers send airflow set points to lower-level flowrate controllers that manipulate control valves (contained within the Ammonia and SRT Controllers block). A detailed aeration system sub-model (Schraa et al. 2017) provides a realistic test environment (also within the Ammonia and SRT Controllers block). The aeration system model includes turbo blowers, aeration piping (based on a typical layout), and membrane disc diffusers. A total airflow controller adjusts blower output and the number of operating blowers to match the sum of the three-airflow controller set points.

The diurnal patterns were created using the influent generation tool developed by the HSG group (Langergraber et al. 2008, 2009). On weekends, the pattern is adjusted: loadings are reduced by 10% and the patterns are delayed by one hour. Proportional recycle is used, and wasting is done from the third bioreactor to provide an SRT of 11 days at design conditions. This 11-day SRT was calculated as the minimum for nitrification at 10 °C, considering a desired steady-state effluent NH_x concentration of 1 mgN/L, and a safety factor of 1.5 days. The calculation used the design equation presented by van Haandel & van der Lubbe (2012).

The model of the centralized scenario developed in SIMBA# uses the inCTRL-ASM biokinetic model, the Otterpohl & Freund (1992) model for the primary clarifier, and the Takács et al. (1991) layered clarification model for the secondary clarifiers. Dynamic simulations were conducted, and the simulations occurred at a wastewater temperature of 10 °C. To initialize the simulations, a 100-day simulation with a diurnal loading pattern at 10 °C was run to achieve a stable operating point. Following this, 60-day diurnal simulations were conducted.

23.2.2 Costs Comparison: Literature Review

A detailed and impartial comparison of centralized vs. decentralized systems is a core focus of this analysis. Our study goes well beyond simple case-to-case model comparisons, aiming to inform decision-making with the most holistic and objective information possible.

23.2.2.1 *Challenges: Idealized vs. Real-World CAS Performance*

Real-world implementations of conventional activated sludge (CAS) frequently face operational inefficiencies, budget restrictions, and design flaws. These factors can drastically undercut performance. Conversely, academic studies may illustrate optimized CAS with near-ideal conditions, skewing performance unrealistically high. To bridge this gap, we designed a strategy centered on fairness and representative real-world results:

- **Comprehensive Literature Review:** Reviewing over 50 authoritative sources for current CAS performance provides a broad, grounded reference point. This helps avoid ambiguities from the sheer variety of CAS implementations and ensures our model contrasts capture the core differences between centralized and decentralized systems.
- **Deliberate Focus on System-Level Differences:** We carefully kept specific CAS configurations, influent characteristics, and effluent requirements outside the immediate modeling scope. This ensures focus stays on the inherent contrasts between a decentralized approach and conventional centralized treatment, free from biases that could be introduced by one specific CAS example.

23.2.2.2 *References used in the literature review.*

- Arif, A. U. A., Sorour, M. T., & Aly, S. A. (2020). Cost analysis of activated sludge and membrane bioreactor WWTPs using CapdetWorks simulation program: Case study of Tikrit WWTP (middle Iraq). *Alexandria Engineering Journal*, 59(6), 4659–4667.
- Belloir, C., Stanford, C., & Soares, A. (2014). Energy benchmarking in wastewater treatment plants: the importance of site operation and layout. *Environmental Technology*, 36(2), 260–269.
- Benedetti, L., Bixio, D., & Vanrolleghem, P. A. (2006). Benchmarking of WWTP design by assessing costs, effluent quality and process variability. *Water Science and Technology*, 54(10), 95–102.

- Castellet, L., Hernández, V., Hernandez, F., Poch, M., & Rigola, M. (2017). Performance Indicators to support the optimal management of wastewater treatment facilities. *Pi* 2017 - Specialist Conference on Benchmarking and Performance Assessment.
file:///C:/Users/Manel/Downloads/D2.Manel%20Poch%20(2).pdf
- Garrido-Baserba, M., Vinardell, S., Molinos-Senante, M., Rosso, D., & Poch, M. (2018). The Economics of Wastewater Treatment Decentralization: A Techno-economic Evaluation. *Environmental Science & Technology*, 52(15), 8965–8976.
- Gernaey, K., Jeppsson, U., Vanrolleghem, P., & Copp, J. (2014). Benchmarking of control strategies for wastewater treatment plants.
- Haslinger, J., Krampe, J., & Lindtner, S. (2016). Operating costs and energy demand of wastewater treatment plants in Austria: benchmarking results of the last 10 years. *Water Science and Technology*, 74(11), 2620–2626.
- Herman, J. G., Scruggs, C. E., & Thomson, B. M. (2017). The costs of direct and indirect potable water reuse in a medium-sized arid inland community. *Journal of Water Process Engineering*, 19, 239–247.
- Jafarinejad, S. (2016). Cost estimation and economical evaluation of three configurations of activated sludge process for a wastewater treatment plant (WWTP) using simulation. *Applied Water Science*, 7(5), 2513–2521.
- Kehrein, P., Jafari, M., Slagt, M., Cornelissen, E., Osseweijer, P., Posada, J., & van Loosdrecht, M. (2021). A techno-economic analysis of membrane-based advanced treatment processes for the reuse of municipal wastewater. *Water Reuse*, 11(4), 705–725.
- Keller, A. A., Su, Y., & Jassby, D. (2021). Direct Potable Reuse: Are We Ready? A Review of Technological, Economic, and Environmental Considerations. *ACS ES&T Engineering*, 2(3), 273–291.
- Molinos-Senante, M., Hernández-Sancho, F., & Sala-Garrido, R. (2010). Economic feasibility study for wastewater treatment: A cost–benefit analysis. *Science of The Total Environment*, 408(20), 4396–4402.
- Roux, A., & Walker Hazen, T. (2010). The Western Corridor Recycled Water Project-Challenges in Ensuring Water Quality on a large Indirect Potable Reuse Scheme.
- Sarpong, G., Gude, V. G., Magbanua, B. S., & Truax, D. D. (2020). Evaluation of energy recovery potential in wastewater treatment based on codigestion and combined heat and power schemes. *Energy Conversion and Management*, 222, 113147.
- Sim, A., & Mauter, M. S. (2021). Cost and energy intensity of U.S. potable water reuse systems. *Environmental Science: Water Research & Technology*, 7(4), 748–761.
- Tow, E. W., Hartman, A. L., Jaworowski, A., Zucker, I., Kum, S., AzadiAghdam, M., Blatchley 3rd, E. R., Achilli, A., Gu, H., Urper, G. M., & Warsinger, D. M. (2021). Modeling the energy consumption of potable water reuse schemes. *Water Research X*, 13, 100126.
- Vaccari, M., Foladori, P., Nembrini, S., & Vitali, F. (2018). Benchmarking of energy consumption in municipal wastewater treatment plants – a survey of over 200 plants in Italy. *Water Science and Technology*, 77(9), 2242–2252.
- Walker, N. L., Williams, A. P., & Styles, D. (2021). Pitfalls in international benchmarking of energy intensity across wastewater treatment utilities. *Journal of Environmental Management*, 300, 113613.

Direct indirect potable water reuse "Tow et al., 2016" "conventional WWT energy consumption not included since it is needed whether reuse happens or not; same with energy consumption at domestic use"

ENERGY DEMAND

Advanced treatment

Pre-treatment

MF0.16 kWh/m3

UF0.2 kWh/m3

RO0.6 kWh/m3 permeate

*SEEC of brine disposal considered negligible

0.85 recovery ratio

*concordance w/ Giammar et al

Advanced oxidation processes (AOP)

UV-based0.11 kWh/m3

Ozone-based0.5 kWh/m3 (range) mg ozone/dg dissolved organic matter

6 kWh/m3 (range) kWh/m3 ozone

UV-030.15 kWh/m3

Grasslar media filtration (GMF)0.16 kWh/m3

Grasslar activated carbon (GAC)0.32 kWh/m3

0.37 kWh/m3

Additional treatments

Soil aquifer treatment (SAT) - IPR0.48 kWh/m3

Distribution of potable water

0.14 kWh/m3

0.85 recovery ratio

Conventional drinking water treatment0.23 kWh/m3

Alternative augmentation techniques

RO desalination3.5 kWh/m3

4.5 kWh/m3 (range) kWh/m3

Long distance water transfer0.5 kWh/m3

1.4 kWh/m3 (range) kWh/m3

W/O W/WT CAS

SEEC FAT continuous0.31 kWh/m3

SEEC FAT batch0.78 kWh/m3

SEEC FAT semi-batch0.82 kWh/m3

SEEC DPR w/o DvT1.21 kWh/m3

SEEC DPR + DvT (considered redundant)1.48 kWh/m3

SEEC IPR RO2.05 kWh/m3

SEEC IPR BAF1.41 kWh/m3

Groundwater desalination1.4 kWh/m3

Seawater desalination4 kWh/m3

Long distance transportation2.6 kWh/m3

Decentralized approach0.05 kWh/m3

1 Wastewater treatment plant effluent

2 Advanced treatment - wAWT

3 (Drinking water treatment) - wDwT

4 W/ter conveyance

5 W/ter conveyance

WATER

RR_W

W_{WWT}

W_{AWT}

W_{DwT}

W_{W/ter}

RR_{W/ter}

W_{AWT}

W_{SAT}

W_{DwT}

W_{W/ter}

Table 1

Table of parameters used in model evaluation.

Parameter

Default value

SEEC sensitivity

Overall permeate0.7 bar^a

0.06

Membrane permeability0.36 m² s⁻¹ Pa⁻¹

0.28

Flow0.26 m³ s⁻¹

0.26

Pump efficiency0.75

0.75

RO efficiency0.9

0.9

Number of RO stages2

2

Number of inter-stage pumps3

3

RO recovery ratio0.8

0.8

Water transport recovery ratio^b0.85

0.85

WWT SEEC0.2 kWh/m³

0.18

UV AOP SEEC1.11 kWh/m³

0.06

GAC-based AWT SEEC0.37 kWh/m³

0.12^c

GAC-based AWT SEEC0.22 kWh/m³

0.21^c

UV-related SEEC0.48 kWh/m³

0.22

DPR SEEC0.23 kWh/m³

0.13

Local water conveyance SEEC0.14 kWh/m³

0.02

Table 2

Energy consumption of conventional on-site water treatment stages.

Country

Energy consumption (kWh/m³)

Reference

Australia0.01-0.2

[98]

Spain0.11-1.3

[94]

New Zealand0.15-0.44

[99]

US0.184-0.47

[100]

Canada0.18-1.31

[101]

Taiwan0.16-0.25

[102]

SEEC

Specific electrical energy consumption

SEEC

Specific electrical energy consumption

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FIND \$/m3	\$/m3				
11,431,250.00 CAPEX (I) F	0.40	*plant life of 20 yrs > Giammar et al; Herman et al 2017			
581,250.00 OPEX (I/yr)	0.41				
12,206,250.00 CAPEX (I) C	0.43				
*Keller et al 2022		*method B			
Advanced treatment train		CAPEX (I)	OPEX (I/yr)	for capacity	
		MF+RO+UV combination	8,908,000.00	529,820.00	3,875.00
		\$/m3	0.31	0.37	0.63
		MF+RO+UV system	15,500,000.00	904,000.00	
		\$/m3	0.55	0.64	1.19
SEEC FAT continuous					
SEEC FAT batch					
SEEC FAT semi-batch					
SEEC DPR w/o DWT					
SEEC DPR + DWT (considered redundant)					
SEEC IPR RO					
SEEC IPR BAF					
*Framework for Direct Potable Reuse					
	CAPEX (I/annualized) + OPEX (I/yr)				
Groundwater desalination	0.46	2.10	range (\$/m3)		Treatment + residuals/concentrate management+ conveyance
Seawater desalination	1.38	3.57	range (\$/m3)		Treatment + residuals/concentrate management+ conveyance
Long distance transportation					
Advanced treatment with RO +	0.70	2.20	range (\$/m3)		: SEEC DPR w/o DWT
Conveyance	0.10	0.81	range (\$/m3)		in range with calculations
SEEC FAT continuous				0.63	Total \$/m3
SEEC FAT batch				0.82	Total \$/m3
SEEC FAT semi-batch					
SEEC DPR w/o DWT		Capacity	" 4000 (AVG)	100000	m3/day
		Lower bound		0.79	0.60
		Higher bound		1.63	1.43
SEEC DPR + DWT (considered redundant)		Capacity	" 4000 (AVG)	100000	m3/day
		Lower bound		0.94	0.74
		Higher bound		1.65	1.57
SEEC IPR RO		Capacity		100000	m3/day
SEEC IPR BAF					0.87
					0.53
SEEC FAT continuous				1.86	Total \$/m3
SEEC FAT batch				2.24	Total \$/m3
SEEC FAT semi-batch					
SEEC DPR w/o DWT		Capacity	" 4000 (AVG)	100,000.00	m3/day
		Lower bound		1.96	1.77
		Higher bound		3.05	2.85
SEEC DPR + DWT (considered redundant)		Capacity	" 4000 (AVG)	100,000.00	m3/day
		Lower bound		2.11	1.91
		Higher bound		3.08	2.99
	100,000.00	m3/day	lower bound	upper bound	
SEEC IPR RO				2.04	2.29
SEEC IPR BAF				1.70	1.95
Seawater desalination			low	high	
			1.67	3.42	withhals et al.

Table S23-6: Overview of the data extraction, analysis, standardization, and comparison processes during the literature review to evaluate CAS costs..

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4722 23.2.3 Cost Comparison: CapdetWorks

4723 The results from a previous work where we used the commercially available software
4724 CapdetWorks, to obtained detailed costs comparison of costs were also used a reference in the
4725 cost comparison. CapdetWorks is a software tool specifically designed for preliminary design and
4726 cost estimation of wastewater treatment plants.

4727 The aim of this study was to advance the understanding of decentralization and source-separation
4728 economics in wastewater systems. We employed standardized economic modeling approaches,
4729 specifically the commercially available software CapdetWorks, to assess feasibility. The software
4730 allowed industry-standard algorithms generating process designs and estimated construction,
4731 operation, and maintenance costs. The study focused on providing a:

- 4732 ▪ Reliable Methodology: Construction and operation cost estimations leverage
4733 CapdetWorks (Hydromantis, Inc.) and established literature.
- 4734 ▪ Realistic Technologies: Focus is on field-ready technologies accepted by wastewater
4735 experts, ensuring immediate applicability.
- 4736 ▪ Income Potential: Analysis incorporates potential revenue streams from source-
4737 separated alternatives.
- 4738 ▪ Broad Scenarios: Application addresses both new wastewater infrastructure
4739 development and retrofits within developed and developing contexts.

4740 This approach delivers a comprehensive economic analysis encompassing sewer systems,
4741 existing and alternative treatment options, and resource efficiency.

4742

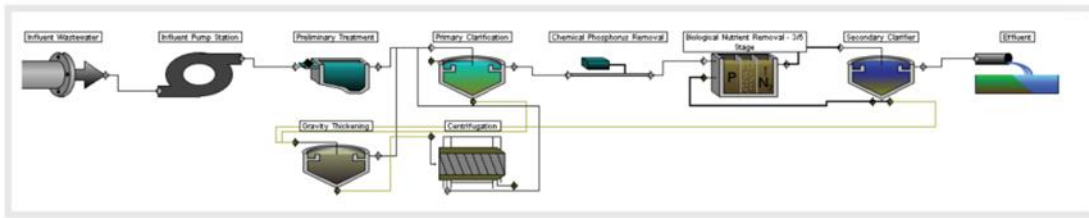
4743 23.2.3.1 *Alternative A: Centralized Wastewater Treatment*

4744

4745 This centralized treatment system utilizes an influent pump station, preliminary screening, and a
4746 primary clarification tank with aluminum dosing (for inorganic phosphorus removal). The
4747 biological treatment stage employs a Modified Ludzack-Ettinger configuration for organic matter
4748 and nitrogen reduction. Collected sludge undergoes thickening and centrifuge processing.
4749 CapdetWorks software determines appropriate equipment dimensions.

4750

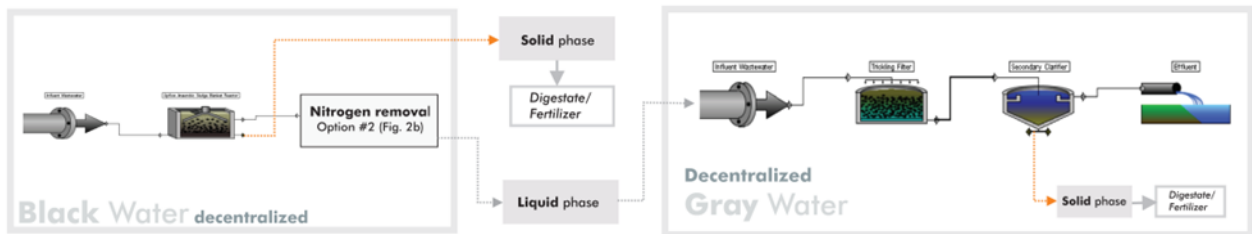
A) Centralized alternative



23.2.3.2 Alternative B: Decentralized Wastewater Treatment

This decentralized alternative mirrors the structure of the presented hybrid system. The key difference lies in its decentralized greywater (GW) treatment, employing district-scale trickling filter technology rather than a centralized facility. Component volumes (UASB units, Oland reactors, struvite reactors, clarifiers) were calculated similarly to the hybrid options. CapdetWorks software was used to estimate trickling filter and associated clarifier dimensions.

C) Decentralized alternative



4762 23.2.3.3 Design of centralized wastewater alternative

4763 The economic and sizing parameters used as input for CapdetWorks are shown.

4764 Table S23-8: Economic parametres used as input in CapdetWorks

Bulding Cost	822.88	€/m ²
Excavation	7.27	€/m ³
Wall concrete	590.85	€/m ³
Slab concrete	318.15	€/m ³
Crane rental	172.74	€/hr
Canopy roof	149.61	€/m ²
Hand rail	171.01	€/m
Construction labor rate	27.79	€/hr
Operator labor rate	35.79	€/hr
Administration labor rate	35.79	€/hr
Laboratory labor rate	35.79	€/hr
Hydrated Lime	0.27	€/kg
Al ₂ (SO ₄) ₃ ·14H ₂ O	0.41	€/kg
Ferric chloride	0.55	€/kg
Polymer	1.99	€/kg
Citric acid 50%	0.79	€/kg
NaOCl 14%	239.54	€/m ³
Electricity	0.13	€/KWh
Land Costs	34,346.3	€/ha
Interest rate	5	%
Construction period	3	years
Operating life of plant	30	years
Engineering Design Fee	15	%
Miscellaneous	5	%
Administration/Legal	2	%
Inspection	2	%
Contingency	10	%
Technical	2	%
Profit and Overhead	15	%

4765

4766

4767 Table S23-9: Dimensioning parametres used as input in CapdetWorks

Influent pump station	Depth to influent sewer	4.57	m
	Static Head	12.19	m
	Number of pumps	2	-
	Type of pumps	Constant speed pumps	-
Preliminary treatment	Cleaning method	Mechanically cleaned	-
	Cleaned depht	0.3048	m
	Bars width	0.6357	cm
	Bars space	3.81	cm
	Bars slope	30	degrees
	Bars shape factor	2.42	-
	Approach velocity	0.762	m/s
Primary clarifier	Design basis	Average Flow	-
	Surface Overflow Rate	41	m ³ /(m ² ·day)
	Sidewater Depth	2.74	m
	Specific Gravity	1.05	-
	Underflow concentration	4	%
	Weir overflow rate	186	m ³ /(m·day)
	Type of clarifier	Circular	-
	Ion used for P elimination	Equivalent aluminium	-
Activated sludge process (3 stages)	Aeration Type	Diffused Aeration	-
	Safety Factor for calculated SRT	1.5	-
	SS concentration in mixed liquor	3000	mg/L
	Maximum heterotrophic specific growth rate	6	1/day
	Heterotrophic decay rate	0.24	1/day
	Maximum autotrophic specific growth rate	0.75	1/day
	Autotrophic decay rate	0.08	1/day
	Biomass yield	0.5	-
	Alpha factor for oxygen transfer in wastewater	0.7	-
	Beta factor for oxygen saturation in wastewater	0.95	-

	Standard oxygen transfer efficiency	20	%
Secondary clarifier	Surface overflow rate	20.5	m ³ /(m ² ·day)
	Maximum solid loading rate	117.18	kg/(m ² ·day)
	Specific gravity	1.03	-
	Underflow concentration	1	%
	Weir overflow rate-maximum	186	m ³ /(m·day)
	Type of clarifier	Circular	
	Efluent suspended solids	20	mg/L
Gravity Thickening	Underflow concentration	5	%
	Depth	2.74	m
	Mass Loading	50	kg/(m ² ·day)
Centrifuge	Cake solids content	19	%
	Power Requirement	0.137	KW/m ³ /day
	Number of units	2	

4768

4769 In the following table S3, the results obtained for an adequate dimensioning and
4770 material/operational requirements obtained through CapdetWorks are shown (economic results
4771 are not included).

4772 *Table S23-10: Results obtained for CAS option through CapdetWorks.*

Influent pump Station	Volume of wet well	256	m ³
	Width of wet well	25.2	m
	Depth of the pumping station	7.94	m
	Length of the pumping station	5.49	m
	Width of the pumping station	33.5	m
	Minimum depth of water in wet well	1.54	m
	Area of pump building	47.7	m ²
	Total dynamic head - average conditions	13.8	m
	Operation labor required	532	pers-hrs/yr
	Maintenance labor required	448	pers-hrs/yr
	Electrical energy required	101,000	kWh/yr
	Volume of earthwork required	7.570	m ³
	Volume of slab concrete required	447	m ³
	Volume of wall concrete required	262	m ³

	Capacity per pump	16,700	m ³ /d
	Number of constant speed pumps	2	
	Number of variable speed pumps	0	
	Diameter of discharge header pipe	31.8	cm
	Total dynamic head	22.2	m
	Size of selected pump	30.5	cm
	Specific speed of pump	3,990	
	Pump rotating speed	1.810	rpm
	Motor size required	59.7	kW
	Size of selected motor	74.6	kW
	Width of pump system	0.914	m
	Length of pump system	5.54	m
	Length of the dry well	5.49	m
	Width of the dry well	8.28	m
Preliminary treatment	Bar size	0.636	cm
	Bar spacing	3.81	cm
	Slope of bars from horizontal	30	°
	Head loss through screen	0.00628	m
	Approach velocity	0.762	m/s
	Average flow through velocity (screen)	0.762	m/s
	Maximum flow through velocity (screen)	0.914	m/s
	Screen channel width	0.218	m
	Average channel depth	0.305	m
	Maximum flow	4.780	m ³ /d
	Average flow	4.380	m ³ /d
	Minimum flow	3.980	m ³ /d
	Temperature	10	° C
	Maximum flow through velocity	0.457	m/s
	Average flow through velocity	0.305	m/s
	Size of smallest particle 100% removed	0.02	cm
	Specific gravity of particle	2.65	
	Number of units	2	
	Maximum flow/unit	2.390	m ³ /d

	Width of channel	0.0496	m
	Depth of channel	1.22	m
	Length of channel	44	m
	Settling velocity of particle	0.0215	m/s
	Slope of channel bottom	0.016	
	Manning coefficient	0.035	
	Hydraulic retention time	1.6	min
	Volume of grit	0.132	m ³ /d
Primary clarifier	Surface area	112	m ²
	Surface area per circular clarifier	55.9	m ²
	Diameter of each circular clarifier	8.53	m
	Number of clarifiers per battery	2	
	Number of batteries	1	
	Solids loading rate	22.4	kg/(m ² ·d)
	Hydraulic retention time	1.61	hr
	Weir length	26.8	m
	Volume of sludge generated	36.6	m ³ /d
	Operation labor required	371	pers-hrs/yr
	Maintenance labor required	211	pers-hrs/yr
	Electrical energy required	7.500	kWh/yr
	Volume of earthwork required	462	m ³
	Slab thickness	25.8	cm
	Volume of slab concrete required	40.5	m ³
	Wall thickness	29.2	cm
	Volume of wall concrete required	56.3	m ³
	Chemical dosage	19.7	g/m ³
	Mass of chemical per year	32,700	kg/yr
	Chemical sludge production	98.1	g/m ³
	Organic sludge production	10.8	g/m ³
Activated Sludge	Max. specific growth of nitrifiers at winter temperature	0.374	1/d
	Death rate of nitrifiers at winter temperature	0.0601	1/d
	Total reactor SRT	10.5	d
	Design SS	2,470	g/m ³
	Calculated VSS	1,100	g/m ³

Calculated VSS:TSS ratio	0.446	mg VSS/mg SS
Total volume of anaerobic reactors	53.6	m ³
Total volume of anoxic reactors	3,400	m ³
Total volume of aerobic reactors	3,560	m ³
Total volume of all reactors	7,010	m ³
Width of parallel train	10	m
Sidewater depth	5	m
Number of batteries	1	
Number of parallel trains per battery	2	
Number of anoxic cells within one train	2	
Number of aerobic cells within one train	2	
Anaerobic hydraulic retention time	0.283	hr
Anoxic hydraulic retention time	17.9	hr
Aerobic hydraulic retention time	18.8	hr
Amount of sludge generated	1,650	kg/d
Sludge recycle ratio	32.7	%
Sludge recycle rate	1,490	m ³ /d
Nitrogen required for biomass growth	19.1	g/m ³
Phosphorus required for biomass growth	3.81	g/m ³
Oxygen required to meet average demand	1,700	kg/d
Air flow required to meet average demand	2,650	N m ³ /hr
Design air flow	12.4	N m ³ /min/1000 m ³
Design air flow	2.07	L/s/m ²
Operation labor required	2,460	pers-hrs/yr
Maintenance labor required	1.220	pers-hrs/yr
Electrical energy required	1,010,000	kWh/yr
Volume of earthwork required	3,930	m ³
Volume of slab concrete required	883	m ³
Volume of wall concrete required	570	m ³
Handrail length	165	m

	Number of diffusers per train	391	
	Fine bubble diffuser floor coverage	4.5	%
	Number of swing arm headers per train	10	
	Required mixing power	44.9	kW
	Total number of mixers	18	
	Design mixing power per mixer	3.73	kW
	Mixing power for each unaerated tank	7.48	kW
	Minimum air flow capacity	2,650	N m ³ /hr
	Safety factor	1.5	
	Requested air flow capacity	3,980	N m ³ /hr
	Total capacity of blowers	3,980	N m ³ /hr
	Number of blowers in use	1	
	Total number of blowers	2	
	Capacity of individual blowers	3,980	N m ³ /hr
	Blower building area	86.7	m ²
Secondary clarifier	Surface area	222	m ²
	Surface area per circular clarifier	111	m ²
	Diameter of each circular clarifier	11.9	m
	Number of clarifiers per battery	2	
	Number of batteries	1	
	Solids loading rate	67.1	kg/(m ² ·d)
	Hydraulic retention time	3.21	hr
	Designed surface overflow rate	20.5	m ³ /(m ² ·d)
	Weir length	26.6	m
	Volume of wasted sludge	160	m ³ /d
	Operation labor required	464	pers-hrs/yr
	Maintenance labor required	254	pers-hrs/yr
	Electrical energy required	7,960	kWh/yr
	Volume of earthwork required	837	m ³
	Slab thickness	25.8	cm
	Volume of slab concrete required	73.1	m ³
	Wall thickness	29.2	cm
	Volume of wall concrete required	76	m ³
Thickener	Initial concentration	1.56	%
	Thickened concentration	5	%

	Mass loading	50	kg/(m ² ·d)
	Hydraulic loading	3.21	m ³ /(m ² ·d)
	Hydraulic retention time	20.5	hr
	Number of tanks	2	
	Tank volume	168	m ³
	Depth	2.74	m
	Surface area per tank	30.6	m ²
	Tank diameter	6.4	m
	Amount of sludge generated	3,060	kg/d
	Volume of thickened sludge	52.5	m ³ /d
	Operation labor required	340	pers-hrs/yr
	Maintenance labor required	271	pers-hrs/yr
	Electrical energy required	6,490	kWh/yr
	Volume of earthwork required	289	m ³
	Slab thickness	25.8	cm
	Volume of slab concrete required	24.7	m ³
	Wall thickness	29.2	cm
	Volume of wall concrete required	43.8	m ³
Centrifuge	Total power required	8.99	kW
	Power required per unit	4.5	kW
	Excess capacity factor	1.25	
	Number of units	2	
	Chemical dose	1	% dry wt
	Chemicals required	27.6	kg/d
	Sludge flow	52.5	m ³ /d
	Initial solids concentration	5	%
	Power required per unit	4.5	kW
	Area of building	22.3	m ²
	Dry solids produced	2,620	kg/d
	Operation labor required	2,580	pers-hrs/yr
	Maintenance labor required	440	pers-hrs/yr
	Electrical energy required	88,100	kWh/yr

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4775 23.3 Centralized (CAS) - LCA

4776 Conventional Treatment Inventory

4777 Pipeline and Pumping

- 4778 • **Potable Water Sourcing:** The inventory for the pipeline delivering potable water is included in
4779 the market for tap water. This models the production of drinking water. Sourcing of freshwater
4780 and wastewater collection and discharge are added using the ecoinvent datasets for water supply
4781 network and sewer grid, respectively. The sewer grid for transporting wastewater to and from the
4782 WWTP is modelled with an urban:rural pipeline ratio of 83:17, following the grid composition in
4783 ecoinvent for Europe. The lifespan of the pipeline in the datasets is adapted to match that of the
4784 FU of the study. Losses of 25% of the total supply along the transport system are considered, in
4785 line with data for losses associated with large distribution networks that are in good condition and
4786 have active monitoring and control of leakages (Brandt et al., 2017). The lengths of pipes
4787 required per cubic meter of water are allocated considering the ratio established by the European
4788 datasets, for both freshwater and wastewater.
- 4789 • **Pumping:** Pumping is modelled considering standardized energy intensities for
4790 sourcing, conveyance, and distribution provided by the United Nations Framework Convention on
4791 Climate Change (UNFCCC, 2020). It is assumed that 50% of the total distance is covered by
4792 gravity sewers. Private pumping inside the FU building is also added to match the boundaries of
4793 the decentralized approach.

4794

4795 Potable Water Production and Wastewater Treatment

- 4796 • **Potable Water Production:** Following research by Garfí et al. (2016), potable water is modelled
4797 from the “market for tap water” dataset in ecoinvent, matching the volume of recycled wastewater
4798 and collected rainwater of each scenario. The dataset for a European setting is used, which
4799 provides the weighted inventory for all drinking water treatment routes in Europe with gate-to-gate
4800 boundaries in the potable water plants (including infrastructure). The “market for” dataset
4801 additionally includes the distribution of the treated effluent to households.
- 4802 • **Wastewater Treatment:** The impacts related to the treatment of wastewater are obtained from
4803 Risch et al. (2014), who modelled an average, centralized WWTP within a European
4804 setting, considering both infrastructure and operation with a lifespan of 30 years, consistently with
4805 this thesis. They reported gate-to-gate impacts for the WWTP with a FU of 60 g BODd-1, *which*
4806 *has been adapted to the BOD content of the present study of 65 g VODd-1* (slightly higher due to
4807 the inclusion of OFSMW in the treatment mix) and to the FU of this study to account for the total
4808 amount of BOD produced by the inhabitant of the studied building during a year. The WWTP in

4809 Risch et al. (2014) considers conventional treatment by the activated sludge process, with
 4810 enhanced P-removal and clarification. Results for their S2 scenario, including tertiary
 4811 treatment, are used, and sludge stabilization and treatment are within boundaries. They consider
 4812 70% of anaerobic digestion, 20% of incineration, and 10% of landfilling. Data for endpoint impacts
 4813 has been complemented by results provided by Heimersson et al. (2014), who use the same
 4814 boundaries for a conventional European WWTP and consider sludge treatment uniquely through
 4815 anaerobic digestion. For the water consumption potential (WCP) and marine eutrophication
 4816 (MEP) midpoints, the impacts are obtained from Besson et al. (2021), as no information is given
 4817 for the former indicator in the two aforementioned studies, and the value for MEP provided is on
 4818 the upper range of impacts for the reviewed literature and might lead to an overestimation of
 4819 impacts.

4820 *Table S23-11. Inventory details for the annualized construction and annual operation of the centralized*
 4821 *pipeline and pumping (FU: water treatment for 300 people during a year).*

4822

Element	Amount	Unit	Ecoinvent dataset	
Sourcing pipeline	3.98E-04	km	market for water supply network	GLO
Wastewater collection and discharge, urban	551.65	m ³	market for sewer grid, urban	GLO
Wastewater collection and discharge, rural	37.58	m ³	market for sewer grid, rural	GLO
Pumping requirements	31,506.06	MJ	market for water pump operation, electric	GLO

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4825 23.3.1 Assessment of the conventional treatment model

4826 The influence of site-specific variations on transport distances and water treatment on the scores for
 4827 conventional treatment is studied. To do so, the characteristics of each city listed below are collected and
 4828 used to modify the Conventional treatment inventory.

4829 Barcelona's water currently originates mainly from Ter and Llobregat river basins. The former is stored in
 4830 the Sau, Susqueda, and El Pastoral reservoirs and treated in Cardedeu, while the reservoirs for water from
 4831 the Llobregat river are La Baells, La Llosa del Cavall, and Sant Ponç, which is then treated in Abrera and
 4832 Sant Joan Despí. The main wastewater plants in the city are located in Prat del Llobregat, Besós,

Vallvidrera, Montcada, and Sant Feliu de Llobregat, and most of the city's water is discharged to sea after treatment (Ajuntament de Barcelona, 2023). Freshwater sourcing and wastewater collection distances estimated are 52.5 km and 6 km, respectively.

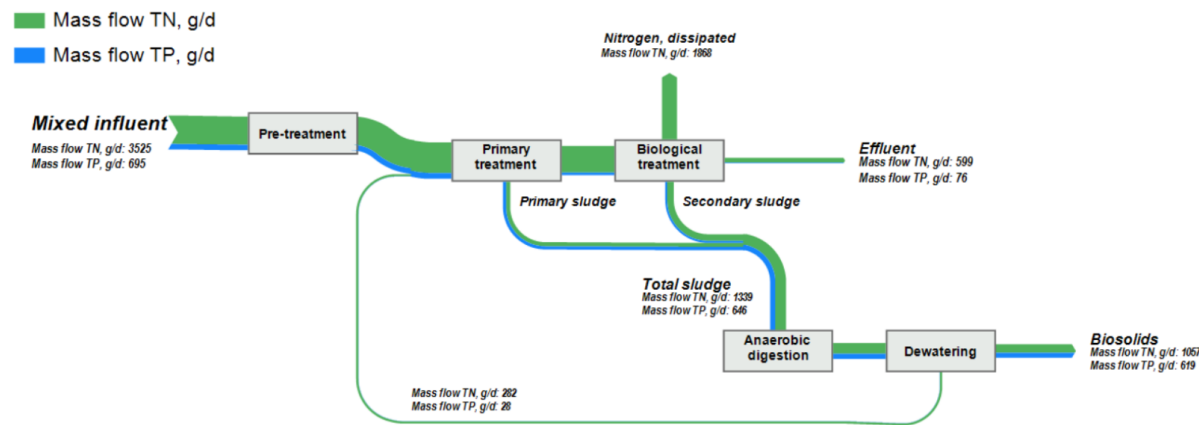
Trondheim's potable water is collected from Jonsvatnet lake located south of the city. The main wastewater treatment plants for the city are those of Høvringen and Ladehammeren. Other treatment plants within the municipality are Bromstadtrøa, Brøttemsåsen, Byneset aldershjem, Hyttfossen, Leirfallet, Ostangen, and Vassfjellet skisenter avløpsrenseanlegg. Treated wastewater is discharged either to Trondheim bay or Nidelva river (Trondheim Kommune, 2023). Sourcing and wastewater collection distances are estimated at 15 km and 4 km, respectively.

Vienna obtains its freshwater from the Alps through two main gravity pipes of 150 km and 180 km which conduct water directly to the city. The protection of the sourcing areas allows Vienna to distribute water without any potabilization treatment beyond chlorination. Distance to wastewater treatment is calculated for the Vienna Main Wastewater Treatment Plant in Simmering. Water is discharged to the Danube River (City of Vienna, 2021; Wandl et al., 2006). Sourcing distance is an average of the two main pipes, consisting of 165 km, and wastewater collection distance is 9 km. No pumping of water from the source to the city is considered in Vienna's case as they rely solely on gravity when working under regular conditions. Vienna's water also undergoes minimal modification, thus the potable water production for the city is modelled considering no further treatment other than chlorine disinfection.

Table S23-12. MFA of the conventional system showcasing mass flows for total nitrogen (TN) and total phosphorus (TP) in g/d, for the reference population of 300 people.

Material Flow Analysis for conventional treatment

Nutrient balance

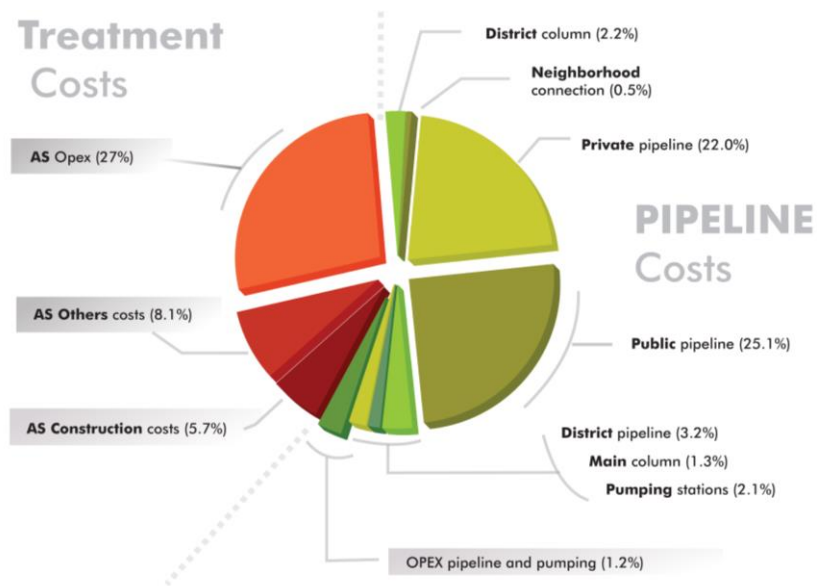


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Table S23-13: Breakdown of costs for centralized wastewater treatment (Alternative A). The broken lines separate costs related to treatment and those related to pipeline.

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24 Process Monitoring

To ensure public acceptance, the highest standards on monitoring need to be satisfied. Grey water reuse should satisfy the most stringent of the quality requirements, demanding an advanced, robust, and safe treatment system able to comply with the tighter standards.

To avoid a negative perception towards this type of approach, the presented system must yield the highest water qualities (such as potable water), even if none of the reused water will be recycled as a direct potable source. A very conservative estimation of the monitoring requirements was purposely chosen to demonstrate that the most rigorous and advanced monitoring routine could be achieved, avoiding concerns about safety and control. The monitoring costs were calculated as in three main blocks: 1) Laboratory tests (outside lab); 2) Sensors CapEx and OpEx (external service contract); 3) Real-time online monitoring (external service contract).

The monitoring cost calculation for minimizing risk considers three main blocks:

- **Laboratory tests:** We carry out different calculations, from the consideration of external lab(costliest scenario) to in-situ analysis and optimization which could significantly reduce operational costs. See Table S24-1 for detailed costs.
- **Sensors (CapEx & OpEx):** Real-time remote monitoring via external service contracts allows centralized management and expert intervention, but optimizing processes and maintenance can lead to cost reductions. See Table S24-2 for detailed costs.
- **Real-time remote monitoring:** This external service ensures optimal control but can be revisited based on system performance and budget constraints. See Table S24-3 and See Table S24-4 for detailed costs.

The laboratory test routine designed follows the guidelines from the sampling workbook "Sampling Questionnaire and Matrix" developed by the Water Environment Federation (WEF) task group on Wastewater Treatment Plant Data Collection. The workbook indicates the required sampling locations within the treatment process and the type and frequency of analyses required to meet the process control goals (including the requirements for process simulators). The compiled laboratory costs were obtained from several commercial laboratories, and costs should be updated and adapted accordingly. It must be noted that the cost of using outside laboratories is the most expensive option, and it was selected to reflect the worst economic scenario and to assume no need for further investment or space requirements.

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4902 Table S24-1: The laboratory test routine designed follows the guidelines from the sampling workbook "Sampling
 4903 Questionnaire and Matrix" developed by the Water Environment Federation (WEF) task group on Wastewater
 4904 Treatment Plant Data Collection

Preliminary Guideline of Costs ¹ for Analyses, Assuming Use of Outside Laboratories							
Parameter	Total Weekly Analyses		Estimated Cost Per Test		Total Cost Per Week ²	Total lab analyses by type, per week	
Flow	-		--		--	TSS	4
TSS	4		\$10.0		\$40	VSS	4
VSS	4		\$10.0		\$40	COD	6
COD	4		\$17.0		\$68	BOD	0
sCOD (0.45 micron)	1		\$17.0		\$17	cBOD	0
ffCOD	1		\$17.0		\$17	TKN	4
TBOD5	0		\$25.0		\$0	NH3-N	1
sBOD (0.45 micron)	0		\$25.0		\$0	NO3-N	1
CBOD5	0		\$25.0		\$0	NO2-N	0
sCBOD (0.45 micron)	0		\$25.0		\$0	TP	2
TKN	2		\$27.0		\$54	PO4-P	1
sTKN (0.45 micron)	2		\$27.0		\$54	VFA	1
NH3-N	1		\$24.0		\$24	Alk	4
NO3-N	1		\$15.0		\$15		
NO2-N	0		\$15.0		\$0		
TP	1		\$20.0		\$20		
sTP (0.45 micron)	1		\$20.0		\$20		
PO4-P	1		\$18.0		\$18		
VFAs	1		\$100.0		\$100		
SVIs	1		--		--		
Alk	4		\$8.0		\$32		
pH	0		--		--		
Temp	0		--		--		
Turbidity	0		--		--		
DO	0		--		--		
				TOTAL	\$519		
¹ Estimated costs are averages from three commercial labs (2011). Costs need to be verified!							
² Estimated costs only apply when outside labs are used for all or some of the analyses.							

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4907 The operating budget could be significantly reduced by analyzing in situ some of them and, especially,
 4908 decreasing the number of lab tests from the recommended sampling routine once a stable performance is
 4909 obtained. In parallel, some service contracts could be reduced depending on process performance,
 4910 maintenance routine, etc.

4911 Nevertheless, we anticipate monitoring costs to further decrease in upcoming years with cheaper and better
 4912 sensors capabilities, new development of reliable soft sensors, and more breakthroughs in control theory
 4913 (Vanrolleghem and Lee, 2003).

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4917 Table S24-2: Sensors CapEx and OpEx (external service contract).

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Annual Sensor Costs			
New advanced control solution			
Annual Costs			
Investment costs			
#			
4	ISE probe with control box	\$	20,000
	Misc	\$	2,000
	Sensor installation	\$	2,000
	Compressed air piping	\$	400
	Connection of sensor to PLC	\$	2,000
	Implementation control strategies	\$	5,000
	Total investments (without taxes)	\$	31,400
	Total investments with taxes (15%)	\$	36,110
	Expected lifetime of sensor	yr	10
	Interest rate	%	5
	Annuity (without taxes)	\$/yr	4,066
	Annuity (including taxes of 15%)	\$/yr	4,676
	Yearly investment costs (including taxes)	\$/yr	4,676
			CAPEX 10 years
O&M costs			
3	Measuring electrodes (\$500 per electrode)	\$/yr	1,500
1	Reference electrodes (\$500 per electrode)	\$/yr	500
	Calibration Standards and cleaning solution (\$100 per se	\$/yr	400
	Other Consumables (\$50 per sensor)	\$/yr	200
	Yearly consumable costs	\$/yr	2,600
10	Price per test kit	\$	
50	Yearly consumable costs for QA/QC	\$/yr	2,000
	Yearly O&M costs (without personnel)	\$/yr	4,600
1	Weekly maintenance and QA/QC hours per sensor	hr	
30	Personnel cost	\$/hr	
	Service and QA/QC: Personnel (1h/week per sensor)	\$/yr	6,240
500	Service Contract with Supplier (per sensor)	\$/yr	2,000
	Yearly O&M costs (internal & external persc	\$/yr	8,240
	Yearly O&M costs	\$/yr	12,840
	Yearly costs (without personnel)	\$/yr	11,276
	Yearly costs	\$/yr	17,516

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4925 Table S24-3: Implementation of an On-line Monitoring System for Black, Grey and Rain Water System.

Project Info						Budget Summary		
Project lead : Senior Process Engineer						Project Cost		TOTAL
Project technical lead: Process Engineer						\$ 8,700.00		\$ 12,300.00
Project Manager: Process Engineer						w/o buf		
Start date : TBD								
Project duration : TBD								
No.	Tasks	Labor						
		Senior Expert		Data Analytics/ IT expert		Process engineer		Total working Hrs/task
		\$250		\$250		\$150		Total working Cost/task
		Hrs	Cost	Hrs	Cost	Hrs	Cost	
Work package 1 : Project Management								
1	Project mobilization (project no, timeline, payment details etc)							
a	kickoff Project Preparations	1	\$ 250.00		\$ -	1	\$ 150.00	2 \$ 400.00
b	Organize the kick-off meeting, data sharing, permits, especifications		\$ -		\$ -	1	\$ 150.00	1 \$ 150.00
c	Organization (Agenda, project structure, tasks, etc.)	0	\$ -		\$ -	1	\$ 150.00	1 \$ 150.00
2	Specification of the building systems (BW, GW, RW)	1	\$ 250.00		\$ -	1	\$ 150.00	2 \$ 400.00
	Admin		\$ -		\$ -		\$ -	
3	Project management	0	\$ -		\$ -	1	\$ 150.00	1 \$ 150.00
Individual working hrs and cost (Without Software)		2	\$ 500.00	0	\$ -	5	\$ 750.00	7 \$ 1,250.00
Work package 2 : Refinement of Process Control Solutions								
	Assess and refine project control solutions							
1	Design typical load and temperature scenarios based on hystorical/similar data	0	\$ -		\$ -	1	\$ 150.00	1.00 \$ 150.00
2	Adjust Model template of BW_GW_RW to seize and characteristics	1	\$ 250.00		\$ -	1	\$ 150.00	
3	Refine process control strategies and run scenario simulations.	0	\$ -		\$ -	2	\$ 300.00	2.00 \$ 300.00
4	Evaluate and share the results of the modeling efforts.	0	\$ -		\$ -	1	\$ 150.00	1.00 \$ 150.00
	On-line monitoring platform and model delivery:		\$ -		\$ -		\$ -	
	Deliver on-line monitoring instructions		\$ -		\$ -	1	\$ 150.00	1.00 \$ 150.00
	Excel file with input data		\$ -		\$ -	1	\$ 150.00	1.00 \$ 150.00
Individual working hrs and cost (Without Software)		1	\$ 250.00	0	\$ -	7	\$ 1,050.00	6 \$ 900.00
Work package 3 : Sensor Initialization and Monitoring								
	Validate calibration of sensors, configure sensors in opsCTRL, and start monitoring program							
1	Identify sensors used in the selected aeration control solutions.	0	\$ -	0	\$ -	2	\$ 300.00	2 \$ 300.00
2	Configure the sensors in monitoring platform	0	\$ -	2	\$ 500.00	2	\$ 300.00	4 \$ 800.00
3	Support Snsor initialization.	0	\$ -	0	\$ -	1	\$ 150.00	1 \$ 150.00
4	Train staff in collecting reference measurements and input into monitoring software	0	\$ -	4	\$ 1,000.00	0	\$ -	4 \$ 1,000.00
Individual working hrs and cost (Without Software)		0	\$ -	6	\$ 1,500.00	5	\$ 750	11 \$ 2,250.00
Work package 4 : Implementation of Control Solutions								
	Connect, configure, and implement C control strategies							
1	Define a detailed implementation procedure and define relevant tags (connections to sensors and process variables) for control and monitoring.	0	\$ -	0	\$ -	1	\$ 150.00	1 \$ 150.00
2	Implement selected/customized control solutions.	0	\$ -	1	\$ 250.00	1	\$ 150.00	2 \$ 400.00
3	Establish the required connections for the monitoring platform software to operate the control solutions inside the SCADA network	0	\$ -	5	\$ 1,250.00	1	\$ 150.00	6 \$ 1,400.00
4	Ensure access rights to the SCADA Network (for configuration and process monitoring).	0	\$ -	1	\$ 250.00	1	\$ 150.00	2 \$ 400.00
5	Support the establishment of the control strategies	0	\$ -	0	\$ -	1	\$ 150.00	1 \$ 150.00
6	Support effective use of the monitoring software.	0	\$ -	0	\$ -	1	\$ 150.00	1 \$ 150.00
Individual working hrs and cost (Without Software)		0	\$ -	7	\$ 1,750.00	6	\$ 900.00	13 \$ 2,650.00
Work package 5 : Monitoring and Assessment of Control Solutions								
	Continuous monitoring and assessment after the control solution implementation.							
1	Set up monitoring control procedures.	0	\$ -		\$ -	1	\$ 150.00	1 \$ 150.00
2	Continuous assessment of the control solutions key process indicators such as oxygen transfer efficiency, energy consumption, effluent quality, etc.	0	\$ -		\$ -	10	\$ 1,500.00	10 \$ 1,500.00
2	Monitoring Platform Keys Delivery:				\$ -			
Individual working hrs and cost (Without Software)		0	\$ -	0	\$ -	11	\$ 1,650	11 \$ 1,650.00
Total project hrs and cost		3	\$ 750.00	13	\$ 3,250.00	34	\$ 5,100.00	48 \$ 8,700.00

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4929 Table S24-4: Implementation of an On-line Monitoring System for Black, Grey and Rain Water System.

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SOFTWARE COSTS	
Visualization Module	\$ 1,200.00
Functionality to select and plot any signal (e.g. as time series plot, bar chart, pie chart, etc.).	
Controller Status Module	\$ 1,200.00
Calculates controller performance metrics and provides a framework to set criteria for alarming.	
Softsensor Module	\$ 1,200.00
Framework to generate data-driven models and integration into general alarming system.	
Model Input Generation Module	\$ 1,200.00
Module to generate customized inputs to SIMBA# models.	
Equipment Monitoring Module	\$ 1,200.00
Module to monitor performance of equipment.	
Process Monitoring Module	\$ 1,200.00
Module to monitor performance of processes.	
Advanced Data Analytics Module (under development)	\$ 1,200.00
Total	8,400

Essential Packages for Monitoring	\$ 3,600.00
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4936 *Table S24-5: Summary of the annual cost related to process performance and effluent quality monitoring.***Annual Sensor Costs**

Yearly investment costs (including taxes, 5% interest rate)	\$3,700/y
4 ISE probes with control box (10 years)	\$18,000
Misc., Sensor installation, compressed air piping	\$3,500
Connection of sensor to PLC, Implementation control strategies	\$3,500
 Yearly O&M costs	 \$2,800/y
4 Measuring electrodes, 2 Reference electrodes (\$500 per electrode),	\$1,500
Calibration Standards and cleaning solution (\$100 per sensor)	\$300
Test kit, Consumable costs for QA/QC, Other Consumables (\$50 per sensor)	\$400
Service Contract with Supplier (per sensor)	\$500

Annual Lab Tests Costs

Preliminary costs for analyses, assuming the use of outside laboratories	\$15,360/y
VSS, COD, sCOD,, ffCOD, TKN, sTKN, NH ₃ , NO ₃ , TP, sTP, PO ₄ -P.	340/
VFA, Alkalinity, pH, temp, turbidity.	week

On-line Monitoring System (BW, GW and RW)

	\$9,300
Project mobilization	\$1,250
Process control solutions, model development, and delivery	\$1,500
Sensor initialization and monitoring	\$2,250
Implementation of customized control solutions	\$2,650
Monitoring and Assessment of Control Solutions	\$1,650/y

Essential Packages for Monitoring

	\$3,600/y
Controller status module, soft sensor module, equipment monitoring, and process monitoring module (\$1,200 per module)	\$1,200/y

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25 Risk Assessment

The level of risk each process was evaluated and used to determine the specific treatment requirements. Risk evaluation was not only a central consideration in our study, but the entire system and monitoring was built around risk mitigation strategies to minimize risk and deliver the highest service to ensure public trust.

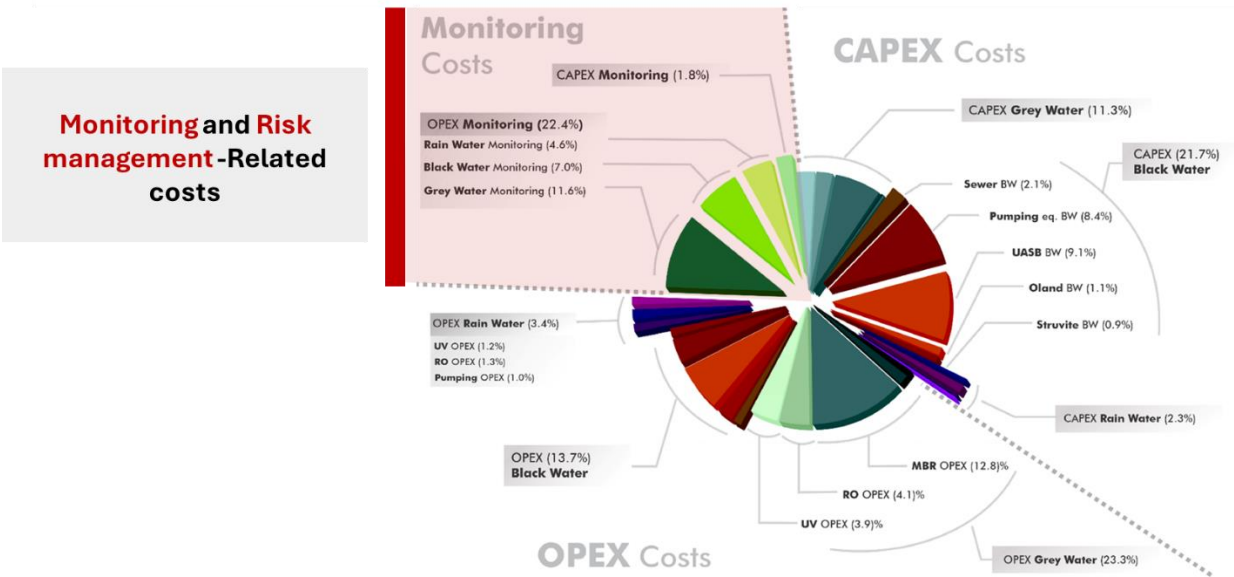
Regarding the risk assessment for each process:

- **Comprehensive Risk Matrix (Figure 1):** We employed a detailed risk matrix that assessed the potential hazards associated with each water source and reuse pathway (treated rainwater, greywater, biosolids, etc.). This matrix considered factors like microbial contamination, chemical pollutants, and emerging contaminants. The approximate costs of implementation are also accounted for and incorporated in the techno-economic analysis.
- **Treatment Tailoring:** Based on the identified risks, we tailored treatment processes for each water source and reuse application [e.g., advanced monitoring, high-TS processes, confined gases management, etc.]. This ensured that the level of treatment aligned with the specific risk profile, optimizing both resource recovery and environmental sustainability.
- **Impact Quantification:** The environmental and cost implications of the chosen treatment strategies were comprehensively evaluated. This included quantifying energy consumption, greenhouse gas emissions, and other relevant impacts associated with risk mitigation measures, which were accordingly included in the techno-economic analysis and in the Life Cycle Assessment.

The presented system prioritizes advanced, robust treatment, satisfying the most stringent water quality requirements even if reuse doesn't directly involve drinking water. This conservative approach minimizes health risks and fosters public trust, even if it increases the cost of monitoring in comparison to centralized treatment plants. Nevertheless, as we will discuss below, even if costs and energy are effectively expected to increase before the economies of scale for such approaches start to kick in (in case of a theoretical implementation), this increase in energy and costs dwarfed by the benefits obtained by source separation and having anaerobic digestion as the main treatment.

While the current system follows internationally recognized guidelines such as the World Health Organization's (WHO) "Guidelines for the Safe Reuse of Wastewater, Excreta and Greywater" or the USEPA's "Water Reuse Guidance Framework." Additionally, incorporating robust quantitative microbial risk assessment (QMRA) tools could help determine the likelihood and severity of potential health risks associated with reuse applications balancing risk mitigation with cost-effectiveness. (Hunter et al., 2009).

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4975 *Table S25-1: Cost breakdown highlighting the importance given to risk management through monitoring and risk*
4976 *management preparedness. While monitoring could be easily considered as OpEx we decided to provide exclusive*
4977 *focus to all the requirements need to ensure a comprehensive monitoring and risk of such systems.GW, BW and RW*
4978 *are shown in blue, red, and purple, respectively. CapEx, OpEx, and monitoring costs are separated to compare the*
4979 *three categories.*

4980

4981 A very conservative estimation of the monitoring requirements was purposely chosen to demonstrate that
4982 the most rigorous and advanced monitoring routine could be achieved, avoiding concerns about safety and
4983 control. The monitoring costs were calculated as in three main blocks: 1) Laboratory tests (outside lab); 2)
4984 Sensors CapEx and OpEx (external service contract); 3) Real-time remote monitoring (external service
4985 contract). The real-time remote monitoring was selected to enable remote monitoring of these decentralized
4986 systems, allowing the necessary technical and operational expertise to operate and maintain in real-time
4987 such complex systems. Centralized management of these different decentralized units was considered to
4988 allow experts to control and coordinate with technicians.

4989 Beyond traditional parameters, the presence of emerging contaminants in water sources poses new
4990 challenges for risk assessment and monitoring. These include pharmaceuticals, personal care products,
4991 microplastics, and endocrine disrupting chemicals (EDCs). While regulatory frameworks for some emerging
4992 contaminants are still evolving, proactive monitoring is essential. Implementing advanced analytical
4993 techniques like liquid chromatography-mass spectrometry (LC-MS) and next-generation sequencing (NGS)
4994 allows for comprehensive detection and quantification of these potential threats (Eschauzier et al., 2016).
4995 Moreover, real-time sensor technology for specific contaminants can provide early warning indicators,
4996 enabling swift mitigation measures (Rodriguez et al., 2020).

4997

While VUV disinfection offers minor reductions in oxygen demand and nitrogen concentrations (Piras et al., 2022), its primary objective in this system is pathogen inactivation. This is crucial for ensuring that reused water complies with microbial safety standards (Adams, 2015). Our combination of MBR+RO+UV creates a highly effective multi-barrier treatment process for potable water reuse. Research supports that this is a more sustainable option than alternative systems (Akhoundi and Nazif, 2018; Tarpani and Azapagic, 2023). Let's break down how each treatment component contributes:

- **MBR (Membrane Bioreactor):** Provides preliminary pathogen removal (especially protozoa and bacteria) through several mechanisms including size exclusion and adsorption. It also effectively pre-treats water for RO.
- **RO (Reverse Osmosis):** Ensures consistent high-quality water and serves as a second line of defense against microbes.
- **UV:** Provides the final disinfection stage.

We aim for this system to meet both water reuse and drinking water quality standards (Ghernaout, 2019; Tang et al., 2018).

The Challenge of Public Perception

Despite a clear focus on the safety and quality of treated water, public acceptance of direct water reuse and current reuse legislation pose challenges. While recycled water is well-accepted for non-personal uses (e.g., irrigation), acceptance rates drop significantly for uses involving contact or consumption (Al-Saidi, 2021; Nkhoma et al., 2021). Key factors driving rejection include disgust, distrust, and misinformation. Overcoming this resistance is crucial for the widespread adoption of recycling measures.

Addressing these concerns through education, awareness initiatives, and institutional action can build trust and acceptance. Furthermore, if reused water is intended for potable purposes, careful monitoring, remineralization to match drinking water's mineral content, and attention to aesthetic elements (appearance, taste, and odor) will be vital in influencing consumer perception (WHO, 2022). In our layout, potable water is derived from rainwater, with reused treated water used only for non-potable purposes.

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Process	Hazard	Likelihood (L/M/H)	Severity (Minor/Moderate/Major)	Risk Score (L/M/H)	Mitigation Strategies	Residual Risk	Cost Impact (%)	Materials	Production Processes	Resource Recovery
UASB Reactor:	Incomplete organic matter removal	M	M	M	Optimized loading rates, pH control, granulation monitoring	M	Moderate (5-15%)	Steel, concrete	Primary, UASB	N/A
	Washout of granular sludge	M	H	M	Proper design, operation at optimal conditions, shock load prevention	L	Moderate (5-15%)	Steel, concrete	UASB	N/A
	Sulfide accumulation and toxicity	M	M	M	pH control, proper ventilation, worker safety protocols	L	Moderate (5-15%)	Steel, concrete	UASB	N/A
OLAND (deammonification) Reactor:	Incomplete nitrogen removal	M	M	M	Optimized pH and temperature control, organic carbon availability	M	Moderate (5-15%)	Steel, concrete	OLAND	N/A
	Nitrite accumulation and toxicity	M	M	M	Alkalinity addition, process control to avoid nitrite buildup	L	Moderate (5-15%)	Steel, concrete	OLAND	N/A
	Bioclogging of membranes	M	M	M	Regular cleaning, proper membrane selection and operation	L	Moderate (5-15%)	Polymeric membranes	OLAND	N/A
Digestate treatment:	Pathogen regrowth	M	H	M	Proper disinfection, storage conditions, controlled solids content	L	Moderate (5-15%)	Concrete, steel	Digestate treatment	N/A
	Odor emissions	M	M	M	Covered storage, odor control measures, proper ventilation	L	Low (1-5%)	Concrete, steel	Digestate treatment	N/A
Supernatant treatment:	Nutrient overload in receiving water	M	M	Nutrient management practices, controlled discharge or reuse	L	Low (1-5%)	Concrete, plastic	Supernatant treatment	N/A	
	Inadequate solids removal	M	M	M	Pre-treatment measures, appropriate filter selection	L	Moderate (5-15%)	Concrete, plastic	Supernatant treatment	N/A
Struvite collection:	Incomplete struvite precipitation	M	M	Optimized pH and magnesium availability, proper reactor design	L	Moderate (5-15%)	Steel, concrete	Struvite precipitation	Struvite	
	Sludge handling and disposal	- Pathogen exposure to workers	M	H	Personal protective equipment, proper handling procedures	L	Moderate (5-15%)	Steel, plastic	Varies depending on method	Sludge handling
	- Air or soil pollution from land application	M	M	M	Land application following regulations, monitoring soil quality	L	Low (1-5%)	N/A	Sludge handling	N/A
Food waste management:	Odor emissions and insect attraction	M	M	Proper storage and processing methods, enclosed facilities	L	Low (1-5%)	Varies depending on method	Food waste management	N/A	
	Incomplete organic matter conversion	M	M	M	Optimized process parameters, monitoring and adjustments	L	Moderate (5-15%)	Varies depending on method	Food waste management	N/A
Electrochemical disinfection:	Chemical spills or leaks	M	M	M	Safe handling procedures, spill containment measures, redundant systems	L	Moderate (5-15%)	Steel, plastic	Disinfection	N/A
	System malfunction	M	M	M	Regular maintenance, alarms, redundant systems	L	Low (1-5%)	Steel, plastic	Disinfection	N/A
MABR (Membrane Aerated Bio-reactor):	Electrocution hazard	M	H	M	Proper grounding, safety protocols, signage	L	Low (1-5%)	Steel, plastic	Disinfection	N/A
	Membrane fouling	H	M	M	Regular cleaning procedures, proper operation and maintenance	M	Moderate (5-15%)	Polymeric membranes	Secondary	N/A
	Aerator failure	M	M	M	Redundant aerators, alarms, maintenance protocols	L	Moderate (5-15%)	Steel, plastic	Aeration	N/A
Toilets:	Bioclogging of membranes	M	M	M	Regular cleaning, proper membrane selection and operation	L	Moderate (5-15%)	Polymeric membranes	Secondary	N/A
	Blockage and overflows	M	M	M	Proper design and maintenance, user education	L	Low (1-5%)	Ceramics, plastic	N/A	N/A
	Disease transmission (if not properly maintained)	M	H	M	Proper hygiene practices, regular maintenance	L	Moderate (5-15%)	Ceramics, plastic	N/A	N/A
Vacuum toilets:	Odor emissions (conventional toilets)	M	M	M	Proper ventilation, odor control measures	L	Low (1-5%)	Ceramics, plastic	N/A	N/A
	Vacuum system failure	M	M	M	Backup power, alarms, maintenance protocols	L	Moderate (5-15%)	Plastic, steel	Collection	N/A
	Blockage and leaks	M	M	M	Proper design and maintenance, user education	L	Low (1-5%)	Plastic, steel	Collection	N/A
	Noise pollution from vacuum pumps	M	M	M	Proper pump selection, soundproofing measures	L	Low (1-5%)	Steel, plastic	Collection	N/A
Brown water sewer:	Pipe leaks or blockages: - Physical damage	M	M	M	Proper design, installation, and maintenance, leak detection systems	L	Low (1-5%)	PVC, HDPE, concrete	N/A	N/A
	- Corrosion	M	M	M	Proper material selection, corrosion protection, maintenance	L	Moderate (5-15%)	Steel, concrete	N/A	N/A
	- Root intrusion	M	M	M	Trenchless installation, proper pipe materials, root barriers	L	Low (1-5%)	Concrete, HDPE	N/A	N/A
	- Sediment buildup	M	M	M	Regular cleaning, proper pipe slopes and velocities	L	Low (1-5%)	Concrete, HDPE	N/A	N/A
Yellow water sewer:	Pipe leaks or blockages: - Physical damage	M	M	M	Proper design, installation, and maintenance, leak detection systems	L	Low (1-5%)	PVC, HDPE, concrete	N/A	N/A
	- Corrosion	M	M	M	Proper material selection, corrosion protection, maintenance	L	Moderate (5-15%)	Steel, concrete	N/A	N/A
	- Root intrusion	M	M	M	Trenchless installation, proper pipe materials, root barriers	L	Low (1-5%)	Concrete, HDPE	N/A	N/A
	- Nutrient overflow and pollution in receiving water	M	M	M	Nutrient management practices, controlled discharge or reuse	L	Low (1-5%)	Concrete, HDPE	N/A	N/A
Pipeline and pumping:	Pipe leaks or blockages: - Physical damage	M	M	M	Proper design, installation, and maintenance, leak detection systems	L	Low (1-5%)	PVC, HDPE, ductile iron, concrete	Installation, pumping	N/A
	- Corrosion	M	M	M	Proper material selection, corrosion protection, maintenance	L	Moderate (5-15%)	Steel, concrete	N/A	N/A

Table S25-2: Screen capture of a section of the developed risk matrix, which identifies and prioritizes potential hazards associated with key processes and components in the decentralized wastewater treatment system. Process: Identifies the specific process or component within the system where the risk might arise. Hazard: Describes the potential event or condition that could cause harm or disruption. Likelihood (L/M/H): Assesses the probability of the hazard occurring, with H indicating high likelihood and L signifying low likelihood. Severity (Minor/Moderate/Major): Evaluates the potential consequences of the hazard, with Major representing significant impacts and Minor implying limited consequences. Risk Score (L/M/H): Combines likelihood and severity to categorize the overall risk level, highlighting areas needing prioritized action. Mitigation Strategies: Proposes specific actions and procedures to reduce the likelihood or severity of the hazard, ensuring system safety and reliability. Residual Risk: After considering mitigation strategies, this column indicates the remaining level of risk, aiming for minimal residual risk for optimal system performance. Cost Impact (%): Estimates the potential financial implications of implementing the mitigation strategies, providing a transparent view of resource allocation. Treated Water Type (Before/After): Clarifies whether the risk is associated with water before or after a treatment process. Specific Human Health/Environmental Exposure Risk: Directly outlines the specific risk to human health or the environment associated with the hazard. Regulatory Reference: Includes relevant regulations or standards associated with the identified human health or environmental exposure risk.

26 Vertical farming

26.1 Why Vertical farming

While vertical farming is one approach within resource recovery, it's not the only option. However, it offers unique advantages, particularly in urban settings:

- **Reduced land footprint:** Vertical farms require minimal land compared to traditional agriculture, making them ideal for space-constrained urban environments.
- **Controlled environment:** Vertical farms offer precise control over temperature, humidity, and lighting, leading to higher yields and reduced reliance on pesticides and herbicides.
- **Water efficiency:** Advanced irrigation systems in vertical farms can significantly reduce water usage compared to open-field agriculture.
- **Nutrient recycling:** Vertical farms can integrate with wastewater treatment systems, utilizing nutrients from treated wastewater for crop growth, promoting circularity and resource recovery.

Energy and water consumption are valid concerns for vertical farming. However, advancements in technology and renewable energy integration are continuously reducing these footprints. Additionally, the reduced transportation needs for locally produced food in vertical farms can offset some of the energy consumption.

The safety of using recovered resources like nutrients and struvite in vertical farming is paramount.

- **Nutrient/struvite health risks:** Stringent regulations and guidelines govern the use of treated wastewater and recovered nutrients in agriculture. The US EPA's Guidelines for Water Reuse and the European Union's Wastewater Treatment Directive set strict limits on contaminants and pathogens, ensuring safe food production.
- **Struvite and 503 regulations:** Struvite is not currently classified as a biosolid under 503 regulations, as it's not a sewage sludge product. However, struvite for agricultural use falls under specific regulations depending on its origin and processing methods. These regulations address potential contaminants and ensure its suitability for safe food production.
- **Chemical risks:** Emerging contaminants like PFAS are a concern for any agricultural practice, not just vertical farming using recovered resources. Rigorous testing and monitoring of both resources and crops are crucial to mitigate risks. Additionally, advancements in wastewater treatment technologies are continuously improving the quality of treated wastewater and recovered nutrients.

Open communication and ongoing research are vital to address concerns and ensure the safe and sustainable integration of vertical farming in resource recovery. Continuous monitoring, data sharing, and research collaborations can build trust and inform further regulatory development.

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5079 *26.1.1 Economic feasibility (Market): Overview*

5080 independent vertical farms can thrive financially has sparked lively debate within the vertical farm
5081 industry. While challenges exist, mounting evidence suggests that independent vertical farms not
5082 only can be profitable, but many are already demonstrating impressive success, paving the way
5083 for a more sustainable and localized food system.

5084 Several key factors underpin the financial viability of independent vertical farms:

- 5085 ▪ **Cost Optimization:** Advancements in LED lighting, automation, and hydroponic
5086 systems are continuously reducing energy and resource consumption, leading to lower
5087 operational costs (Despommier, 2013; Kozai et al., 2016). Additionally, strategically
5088 sourcing inputs and integrating resource recovery can further minimize expenses
5089 (Nguyen et al., 2020).
- 5090 ▪ **Targeted Production:** Cultivating high-value crops like leafy greens, berries, and
5091 microgreens, often with premium varieties, allows for competitive pricing and lucrative
5092 market opportunities (Kowall et al., 2017; Benke et al., 2020).
- 5093 ▪ **Diversifying Revenue Streams:** Beyond direct produce sales, independent farms are
5094 exploring innovative models like subscription services, partnerships with restaurants
5095 and retailers, and value-added products like packaged salads and ready-to-eat meals,
5096 generating multiple income streams (Gómez-Luciano et al., 2020; Specht et al., 2021).

5097 Market Drivers: Fueling Growth and Profitability

5098 Consumer demand for locally grown, sustainable, and fresh produce is steadily rising, creating a
5099 fertile market for vertical farming (Teitelbaum et al., 2020). This, coupled with growing awareness
5100 of the environmental benefits of vertical farming compared to traditional agriculture, is driving
5101 increased consumer willingness to pay a premium for vertically-grown products (Benke et al.,
5102 2020; Specht et al., 2021).

5103 Real-World Success Stories:

5104 Numerous independent vertical farms are already thriving across the globe, demonstrating the
5105 practicality and profitability of this innovative approach:

- 5106 ▪ **Plenty Unlimited (USA):** This large-scale vertical farm operates multiple facilities,
5107 supplying fresh produce to major retailers and generating significant revenue (Plenty,
5108 2023).
- 5109 ▪ **Gotham Greens (USA):** This company operates several rooftop farms in major cities,
5110 supplying high-quality leafy greens to supermarkets and restaurants, achieving financial
5111 success through strategic partnerships and efficient operations (Gotham Greens, 2023).

5112 ▪ **InFarm (Germany):** This Berlin-based startup operates indoor vertical farms within
5113 supermarkets, providing hyper-local, fresh produce directly to consumers, experiencing
5114 rapid growth and profitability (InFarm, 2023).

5115 The future of independent vertical farming is not guaranteed success, but rather a journey filled
5116 with both opportunities and challenges. By acknowledging the potential pitfalls alongside the
5117 exciting possibilities, we can foster a more realistic and grounded perspective on this
5118 transformative agricultural technology.

5119 References:

- 5120 ▪ Benke, M., Oosting, M., & Vejlegaard, M. (2020). Assessing the economic feasibility of
5121 vertical farming for leafy greens production in the Netherlands. *Journal of Cleaner*
5122 *Production*, 269, 122093.
- 5123 ▪ Despommier, D. (2013). *The vertical farm: Feeding the world in the 21st century*. St.
5124 Martin's Press.
- 5125 ▪ Gómez-Luciano, M. Á., de los Ángeles Camacho, M., Montero-Barrientos, A. I., &
5126 Baeza, E. J. (2020). Economic feasibility of a closed-loop vertical farm for leafy green
5127 production in a mediterranean climate. *Journal of Cleaner Production*, 270, 122481.
- 5128 ▪ Gotham Greens (2023). Retrieved from <https://gothamgreens.com/>
- 5129 ▪ InFarm (2023). Retrieved from <https://www.infarm.com/>
- 5130 ▪ Kozai, T., Niu, G., Takagaki, M., Ohyama, K., & Kitaya, A. (2016). Vegetable production
5131 under LED lights: Current status and perspectives. *Frontiers in plant science*, 7, 1417.
- 5132 ▪ Kowall, M., Shahbazi, A., Datta, A., & Van Iersel, M. (2017). Financial viability of

5133

5134 26.1.2 Centralized versus decentralized.

5135 We discuss potential limitations of struvite recovery within individual superblocks versus a
5136 centralized system.

5137 **Strengths of Centralized Struvite Recovery:**

5138 Economy of Scale: centralized systems benefit from larger processing volumes, potentially
5139 leading to lower per-unit costs for struvite recovery compared to individual superblocks. Many
5140 centralized systems already have established infrastructure for nutrient and wastewater
5141 treatment, potentially facilitating easier integration of struvite recovery processes. Depending on
5142 the city size and population density, transportation distances from a central facility to vertical farms
5143 might not be a significant drawback, especially considering the growing urban adoption of vertical
5144 farming.

5145 **Strengths of Decentralized Struvite Recovery within Superblocks:**

- 5146 ▪ **Reduced Reliance on Transportation:** Minimizing transportation needs for both
5147 wastewater and recovered nutrients contributes to lower energy consumption and
5148 carbon footprint.
- 5149 ▪ **Hyper-local Nutrient Recycling:** Creates a closed-loop system within the superblock,
5150 promoting resource recovery and self-sufficiency.
- 5151 ▪ **Improved Nutrient Quality:** Decentralized struvite recovery might offer greater control
5152 over nutrient quality and purity, potentially appealing to specific vertical farming needs.
- 5153 ▪ **Enhanced Social and Community Benefits:** Local nutrient recovery and vertical
5154 farming can foster community engagement and awareness about sustainable practices.

5155 It's crucial to recognize that decentralized and centralized approaches are not necessarily
5156 mutually exclusive. Synergistic strategies are emerging, where centralized systems handle larger
5157 wastewater volumes and basic treatment, while individual superblocks implement decentralized
5158 solutions for finer treatment, resource recovery, and integration with vertical farming. Moreover,
5159 the decentralized wastewater treatment and vertical farming industries are rapidly evolving.
5160 Technological advancements, economic considerations, and policy changes might shift the
5161 balance between centralized and decentralized struvite recovery in the future.

5162 While centralized struvite recovery currently holds advantages in terms of economy of scale, the
5163 decentralized approach offers unique benefits and aligns well with the principles of circularity and
5164 resource recovery within superblocks. Ultimately, the optimal approach will depend on various
5165 factors, including city size, population density, existing infrastructure, and specific goals for
5166 resource management and sustainability. The future likely lies in exploring synergies and adapting
5167 strategies based on local contexts and ongoing advancements in both centralized and
5168 decentralized systems.

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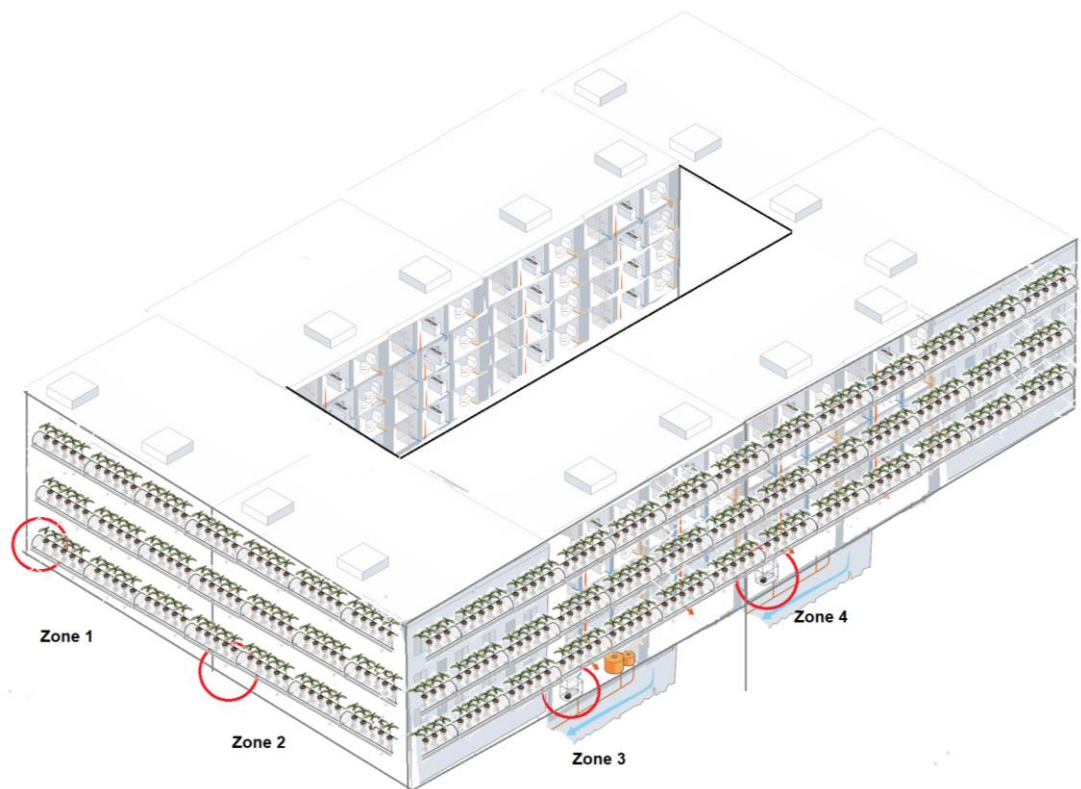
26.2 Vertical farming System Description

Market for nitrogen- and phosphate- based fertilizers recovered from the wastewater treatment and urine-diversion systems including (i) K-struvite, (ii) urine precipitate-Ca and (iii) urine liquid concentrate to be sold at prices comparable to other commercially available fertilizers is limited (Chipako & Randall, 2020). In the present study the wastewater reuse infrastructure integrates a vertical farm based on hydroponic soil-less culture allowing for the application of the fertilizers to produce vegetables in the urban environment. Hydroponic systems are capable of drastically reducing water consumption in comparison to open field agriculture, as well as cutting supply chain emissions, and facilitating cultivation in all environments (Al-Kodmany, 2018; Avgoustaki & Xydis, 2020; Bafort et al., 2022; Burak & Margat, 2016; Clark & Mousavi-Avval, 2022; Donnell et al., 2011; Joseph & Muthuchamy, 2014; Kahu et al., s.d.; Kalantari et al., 2018; Kawser et al., 2017; Lam et al., 2015; Linsley-Noakes et al., 2006; Maboko, 2013; Magwaza, 2020; P. Hilton et al., s.d.; Son et al., 2020, p. 20; Van Gerrewey et al., 2021). The proposed vertical farm is based on a closed-loop concept where water and nutrients are recycled, allowing to further reduce input requirements, and employs a nutrient film technique (NFT) configuration (Asgarov et al., 2021; Christie, 2014; Guzmán-Valdivia et al., 2019; Van Gerrewey et al., 2021).

The combination of wastewater treatment and hydroponics has been backed by numerous studies as urine-diverted fertilizers and struvite have been proved to be suitable for the cultivation of leafy greens (Asaduzzaman et al., 2022; Avgoustaki & Xydis, 2020; El-Nakhel et al., 2021; Halbert-Howard et al., 2021; Magwaza, 2020). In the studied system all P and Mg demand from the vertical farm can be supplied solely by the wastewater treatment system, as well as 56% and 31% of N and Ca, respectively. To provide the plants with the missing nutrients and to ensure optimal growth, fertilizer supplements (Rolfes Agri, Gauteng, South Africa) are assumed to be incorporated in the mix (Magwaza, 2020). The vertical farm is destined to the cultivation of lettuce (*Lactuca sativa*), strawberries (*Fragaria × ananassa*), and cherry tomatoes (*Solanum lycopersicum*). The possibility to include spinach as a fourth crop was studied but discarded since the economic analysis showed a negative contribution margin (Al-Kodmany, 2018; El-Nakhel et al., 2021; Van Gerrewey et al., 2021). The distribution of production area per crop is obtained from an optimization model considering capital and operational costs, marketable weight per plant and harvest cycle for each crop, consumer price, and per capita consumption (Ali et al., 2013; Asgarov et al., 2021; Cardoso et al., 2018; Donnell et al., 2011; Favaro et al., 2011; Hwang et al., 2021; Joseph & Muthuchamy, 2014; Kahu et al., s.d.; Lages Barbosa et al., 2015; Ors & Suarez, 2016, 2004, 2019a, 2019b, 2019c, 2022). The operation of the farm can meet the per total consumption of all cultivated vegetables for the block and produce an additional annual 29,000 kg of cherry tomatoes which could be destined for sale. If sold at a market price of 4\$/kg the operational costs of the farm could be offset.

Total cultivation area is that of 913 m² distributed across two facades of the block in a greenhouse-like structure, and divided into four areas, each of which with an independent recirculation loop to facilitate pumping and nutrient uptake. The positioning of the vertical farm is subject to the local

sun path in each location (e.g., in Barcelona the two facades of the block where to place the installation should be those facing NE to SW). The closed-loop system solution based on RO-demineralized tap water is to be replaced every 10 days (Christie, 2014) and is pumped at a flowrate of 1.5 L/min from supply tanks located within the shared basement together with wastewater treatment and germination area.



Capital and operational costs are calculated based on literature and supplier data. Eighteen levels of rowing racks (1 m high) containing three rows of trays (e.g., NatureHydro, Shanghai, China) contiguous to glass windows equipped with irrigation and runoff drainpipes for a closed-loop water circulation system, artificial LED lightning (e.g., ChilLED Tech, USA), and recirculating pumps are considered. Additional elements include pH and EC sensors and a control unit for independent system operation (European horticulture, Prague, Czech Republic), HVAC system (Asgarov et al., 2021), air pumps to minimize aerobic zones responsible for undesired increases in N₂O emissions and nitrogen losses (Magwaza, 2020), nutrient collection and mixing tanks (Mixer Direct, Jeffersonvill, IN, USA), valves, and RO + UV disinfection to prevent microbial growth within the circuit (Son et al., 2020; DuPont, Wilmington, DE, USA; Applied Membranes Inc., Vista, CA). Crop harvesting is assumed to be carried out by building inhabitants. Daylight sensors (e.g., Lutron, Coopersburg, PA, USA) are installed to adjust artificial lightning to complement sunlight, allowing for 20% reductions in electricity consumption for the hydroponic system (Asgarov et al.,

2021; Halbert-Howard et al., 2021). Resulting CAPEX of 2,500,000 \$ are elevated as expected in hydroponic installations (Harris & Kountouris, 2020; Magwaza, 2020). A life span of 30 years is assumed. OPEX consider supplementary nutrient mix purchase, UV, and RO operation, electrical consumption for the complete system, and seed purchase. Resulting costs of production are those of 2.2 \$/kg, 3.70 \$/kg, and 1.68 \$/kg for lettuce, strawberry, and tomatoes, respectively.

Besides creating an on-site application for urine-diverted fertilizers and offering an optimized and sustainable cultivation option, vertical farming has been discussed as a BioEnergy with Carbon Capture and Storage (BECCS) deployment enabler (Harris & Kountouris, 2020). Lower land footprint of vertical farms compared to conventional horizontal farming allows to reduce land destined for open field agriculture. Among all climate change forest mitigation options (incl. reforestation, afforestation, landscape restoration), preventing deforestation and ecosystem degradation offers the highest short-term potential (IPCC, 2007).

As calculated from open field cultivation yields and the total annual harvest mass of each crop for the proposed system, 0.085 km² would be required to produce the same amount through conventional agriculture (Clark & Mousavi-Avval, 2022; Gonzaga et al., 2017; Maureira et al., 2022; Molin & Martin, 2018). Two scenarios are considered where the environmental benefits of the vertical farm are calculated considering (i) the spare land avoids the conversion of the equivalent surface area of a selection of natural ecosystems to agricultural fields, and (ii) the land is employed for bioenergy supply.

5263 *Table S26-1: Vertical farming description.*

Height of storey	3.00	m	
Height of building	36.00	m	
Surface of façade 1 (front)	2,282.54	m ²	
Surface of façade 2 (side)	3,804.31	m ²	
2 façades (one each): surface	6,086.85	m ²	
% surface of façade occupied by VF	0.70		
Total VF surface	4,260.80	m ²	
Fertilizers available from WWT			
kg Ca ₃ (PO ₄) ₂ /yr	663.28		
		6,415,137.23	mmol Ca/yr
		4,276,758.15	mmol P/yr
Struvite production (kg/yr); (NH ₄)MgPO ₄	2677.11		
		19,496,158.45	mmol Mg/yr
		19,496,158.45	mmol N/yr
		19,496,158.45	mmol P/yr
Concentrate (L/yr)	114,975.00		
NO ₃ -N (mg/l)	3,885.50	62.66	mmol/l
PO ₄ -P (mg/l)	74.80	0.79	mmol P/l
Volume needed			
1.50	L/min	0.000025	m ³ /s
4.12E-03	Area tube m ²	36.5	10 day periods in a year
0.01	m/s	10	days
864,000.00	s in chosen period	3	number of rows of trays
	s full loop	Volume in trays (m³)	Loops in 10 days
Larger façade	168,603.06	11.76	5.12
Smaller façade	105,906.41	7.05	8.16
Dilutions/weekly			
	Required nutrients all façades (mmol total/week)	mmol fertilizer available from WWT	Surplus (+) or lack (-) of fertilizer
P	56,425.11	23,863,471.58	21,803,955.04
NO ₃ -N	1,297,777.54	26,700,998.11	-20,667,882.26
Ca	564,251.11	6,415,137.23	-14,180,028.15
Mg	253,913.00	19,496,158.45	10,228,334.03
Fruit growth			
Total production area	913.03	m ²	Total trays (1 m length per tray)
Plants/m ²	25.00	45	25
Plants/tray	3	4	3

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5266 26.3 Vertical Farming costs

5267 *Table S26-2: The detailed breakdown of operational costs over a one-year period for theoretical urban*
 5268 *vertical farming implementations for the container-based scenario. Please note that the complete economic*
 5269 *assessment for this system extends 20 years into the future and incorporates a discounted rate to adjust for*
 5270 *the time value of money.*

OpEx	OpEx [\$ /year]	Selected References [SI]
Additional Ca, Zn, Mn, Ro		
3.0	ml/L	Al-Kodmany, 2018
169.3	L total	Rolfes Agri, Gauteng, South Africa
1,029.8	L total yr only once/6 weeks	Van Gerrewey et al., 2021
5.0	L bottle	
40.0	€ bottle	
5,672.0	OPEX €/yr	DuPont (Wilmington, DE, USA)
UV		Lutron (Coopersburg, PA, USA):
0.2	€/m3	Christie, 2014
1.4	OPEX €/day	
1,504.6	OPEX €/yr	
RO dem water		Son et al., 2020
0.2	€/m3	Applied Membranes Inc. (Vista, CA)
1.5	OPEX €/day	Guzmán-Valdivia et al., 2019
1,536.1	OPEX €/yr	
Chemicals		Donnell et al., 2011
pH regulation	10	Joseph & Muthuchamy, 2014
1.0	ml/L solution	
2,059,516.5	ml/total	
11,595.2	OPEX €/yr	
Power consumption (option 1)	15,521.47	Lam et al., 2015
15,521.5	kWh/yr [Method 1]	Asgarov et al., 2021
17,470.4	kWh/yr [Power consum. Method 2]	Magwaza, 2020
55,155.5	OPEX €/yr	Al-Kodmany, 2018
Seeds		Halbert-Howard et al., 2021
0.020	€/plant	Ors & Suarez, 2016, 2004, 2019a, 2019b, 2019c, 2022
0.020	(2 years per plant)	Cardoso et al., 2018
0.020	€/plant	Favaro et al., 2011
0.300	€/plant (duration of 1 year)	Hwang et al., 2021
3,190.7	OPEX €/yr	Lages Barbosa et al., 2015
N- Fertilizers need (No recovery scenario)		Bafort et al., 2022
3.0	€/L	Kalantari et al., 2018:
0.0	l/L	
141.1	L/week	
2,246.5	L/yr	
6,739.5	OPEX €/yr	
****Water (closed system)	0.75 complete renewal water	Son et al., 2020
1,544,637.4	L/yr	Van Gerrewey et al., 2021
1,544.6	m3/yr	Guzmán-Valdivia et al., 2019
73,962.3	m3/yr recycled from DSS	Christie, 2014
2.1	% of recycled water needed in VF	
2.1	% of recycled water needed in VF	
CO2		
Not used in the system for safety and ventilation		
Labor		Labor Cost Survey Report - 2021 Update" by CEA
40,102.9	Method 1. \$0.60 to \$1.20 per kilogram of produce	CEA Facility Benchmarking 2021 Report
55,831.9	Method 2. \$40 to \$60 per sq meter growth	https://sustainablefoodcenter.org/reports
Others (Rent, Insurance,)		Kabir, 2023
13,027.1	CEA, 2021; NET 2023	Faraz, 2021
Maintenance		https://ifarm.fi/blog/vertical-farming-costs
8,684.7	CEA, 2021; NET 2023	Burak & Margat, 2016
TOTAL \$/ year		
80,611.8	OPEX €/yr	

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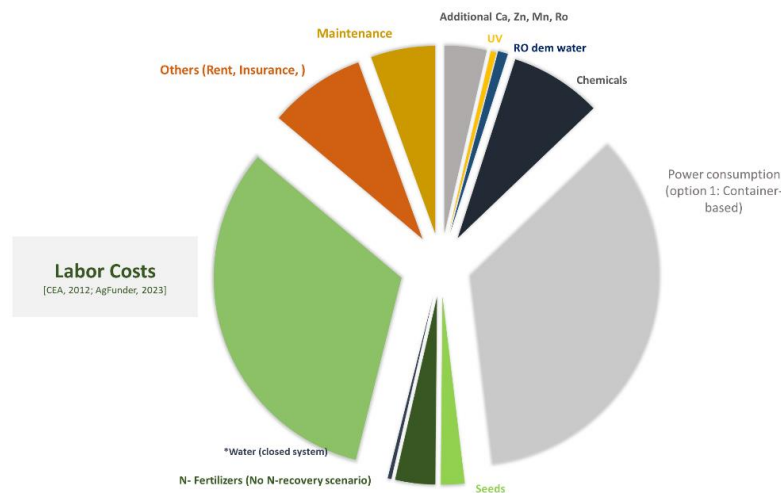


Table S26-3: Breakdown of operational costs for theoretical urban vertical farming implementations. Power consumption dominates the container-based scenario (up to 35%), followed by labor costs (around 30%). In contrast, the facade-based scenario (see SI for details) boasts significantly lower power consumption (5%), making labor the main expense driver at 42%. This highlights the dramatic impact of implementation choice on cost distribution in vertical farming systems.

References

- "Controlled Environment Agriculture Production Costs and Profitability" by CEA Alliance:
- <https://www.agritecture.com/blog/2023/4/26/beyond-price-parity-cea-must-focus-more-on-consumer-demand-to-truly-scale>
- "Labor Costs in Controlled Environment Agriculture (CEA)" by AgFunder:
- <https://agfundernews.com/tag/vertical-farming>
- "Labor Cost Survey Report - 2021 Update" by CEA Food:
- <https://par.nsf.gov/servlets/purl/10206750>
- "CEA Facility Benchmarking 2021 Report" by Green Business:
- <https://sustainablefoodcenter.org/reports>
- "Economic feasibility of vertical farming for leafy greens production in the tropics" by Sustainable Horticulture: https://link.springer.com/chapter/10.1007/978-981-16-9001-3_20
- "Vertical Farming: Economics and Profits"
- <https://rbr.business.rutgers.edu/sites/default/files/documents/rbr-060111.pdf>
- "The economics of rooftop and containerized urban agriculture: An international review" by Urban Agriculture: <https://www.frontiersin.org/articles/10.3389/fsufs.2020.00076>
- "Emerging Trends in Vertical Farming: Economic Considerations and Future Opportunities" by Frontiers in Plant Science:
- <https://blogs.nicholas.duke.edu/env212/economic-viability-of-vertical-farming-overcoming-financial-obstacles-to-a-greener-future-of-farming/>

- 5304 ▪ "Vertical Farming Cost Model: A Tool for Economic Feasibility Analysis" by Journal of
5305 Agricultural and Food Business Management: <https://ifarm.fi/blog/vertical-farming-costs>
5306 ▪ Asgarov, R., MacLaren, D., Hannan, M. A., & Khandelwal, P. (2021). A Sustainable,
5307 Integrated Multi-Level Floating Farm Concept: Singapore Perspective [Preprint].
5308 ENGINEERING. <https://doi.org/10.20944/preprints202011.0181.v2>
5309 ▪ Kabir, M. S. N., Reza, M. N., Chowdhury, M., Ali, M., Samsuzzaman, Ali, M. R., ... &
5310 Chung, S. O. (2023). Technological trends and engineering issues on vertical farms: A
5311 review. Horticulturae, 9(11), 1229.

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5315 **26.4 Vertical Farming Production**5316 *Table S26-4:Vertical farming.*

	Romaine lettuce	Strawberries	Spinach	Tomatoes (cherry)	Total
% of plants	0.36	0.25	0.01	0.39	1.00
Total plants per type	9,784.74	9,086.76	273.91	7,194.02	
Harvest cycle (days)	25.00	120.00	35	150	
Fruit/plant (g/lettuce;strawberries/plant)	140.00	300.00	40	1650	
Harvest kg/yr	20,000.00	8,291.67	114.26	28,883.98	
Per capita consumption (kg/yr)	10.00	4.15	1.08	9.40	
All PE consumption (kg/yr)	20,000	8,291	2,168	18,800	231,184
Consumer price (€/kg)	3.20	6.02	8.4	4.06	
Sales (€/yr)	0.00	0.00	17,252.87	40,940.95	
mcu	1.00	2.32	5.93	2.38	
<i>Savings vegetables/fruit per capita/yr</i>	<i>32.00</i>	<i>24.96</i>	<i>9.11</i>	<i>38.16</i>	
MCT (€/yr)	107,979	OBJ CELL		Total sales (€/yr)	40,940
	Romaine lettuce	Strawberries	Spinach	Tomatoes (cherry)	
m2	27,557	11,425	157	39,797	1,984
Acres	6.810	2.823	0.03890	9.836	0.490
container eq.	5.45	2.26	0.03	7.87	0.39
	55,555.56	23,032.41	317.39	80,233.27	4000
					TOTAL
If SOLD (\$/year)	64,000.	49,915	959	117,268	232,144
%	27.57	21.50	0.41	50.52	
\$/m3	0.827	0.6450	0.0124	1.515	

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26.5 Equivalent Production: A Daily (organic) Salad

To understand the overall amount of available nutrients produced by the system, we need to focus into two key linked processes that is important to clarify. First, there is the mass balance between the total amount of nutrients entering into the residential complex or urban setting (in the form of food) and the nutrients excreted by the residents (in the form faeces and urine). Later there is the mass balance between the nutrient content in the corresponding influent streams (i.e., YW, BW and GW) and the different removal or recovery efficiencies for each of the processes involved.

Table S26-5: Approximated summary of the recovery efficiencies of nutrients from consumption, excretion to recovery. Combining available literature characterizing the average energy and nutrient daily intake of a human adult with the average energy and nutrient content on adult human faeces and urine and adding the removal/recovery efficiencies obtained using these study results and available literature on selected similar technologies.

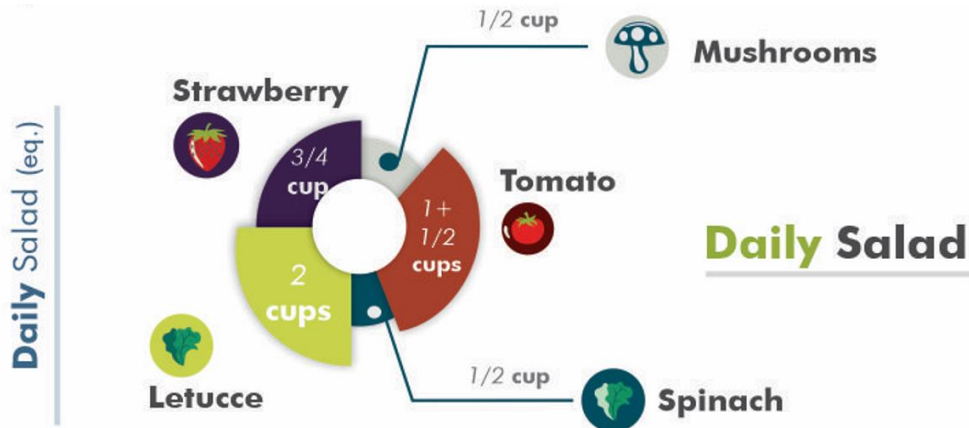


The residents will not obviously live only of the selected crops, but they will certainly complement their diet with other food sources bringing larger quantities of nutrients to the system. The nutrients that residents will consume will be largely metabolized for growth and energy, and only a fraction of the consumed nutrients will be discarded by the feces and urine. We created the previous figure to exemplify the approximate uptake efficiency of an average adult metabolizing nutrients. While we can see our body is pretty good at consuming energy (with around a 80% efficiency), is less efficient in the uptake of nitrogen, and even less, phosphorus, which is in accordance to the metabolic needs (i.e., production of protein, etc.).

On the other hand, current nutrient recovery technologies are not completely efficient processes and not all the nutrients can be recovered, even if the process is highly efficiently enhanced by source separation. Therefore, in the case of recovering energy from brown water stream, less than 5% of the total energy consumed by the residents can be recovered in the form of heat and electricity. Similarly, from all the nutrients entering the urban setting, only an approximate 20-30% can be recovered from food in the case of nitrogen and approximately 50-60% in the case of phosphorus.

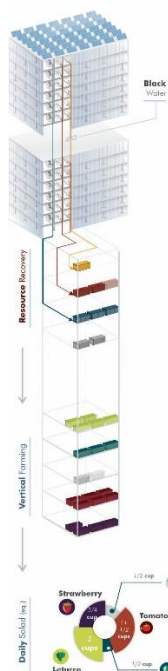
While we agree further studies are needed to quantify the vertical farming contribution, its theoretical potential to provide daily lettuce, tomato, spinach, strawberry, and mushroom needs could roughly equate to a daily salad, potentially representing a significant portion (around 5-10%) of daily nutritional needs (assuming a 2000 calories day diet). Furthermore, an approximate 30-40% of the obtained produce for two of the selected crops (i.e., tomatoes and lettuce) exceeds the daily demand of residents and is expected to be sold or distributed. Therefore, a significant portion of the harvest being distributed also contributes to the overall nutrient recovery efficiency.

Table S26-6: Approximated theoretical potential to provide daily lettuce, tomato, spinach, strawberry, and mushroom is equivalent to a daily salad.



On those lines, even if the suggested concept of farming may not fully meet a city's food needs, this type of urban farms can significantly contribute to improving local food systems, support the transformation of urban spaces into greenspaces, and increase local biodiversity by developing cluster of urban farms, gardens, and other green initiatives. Which could coordinate to obtain different crops and harvests and create the support infrastructure to get local producers selling.

Inhabitants: 2,000
Eq. households: 830
[2.4 hab./household]
Treated flow: 300 m³/day



From Source to Harvest: Transforming urban nutrient-rich sources into healthier, sustainable, and economically feasible harvests

Decentralized source-separation systems have the potential to generate water, energy and nutrients where are needed.

Advances in automated hydroponic farms built inside shipping containers provide controlled environments to grow local produce 365 days a year, which can offset the economic and environmental cost of the urban food-water cycle.

Urban Clusters as Nutrient Factories

Coupling decentralized systems [nutrient factories] to vertical farming can contribute to the community demand of greens while enabling a potential payback mechanism able to offset the water and wastewater cycle costs.

Nutrient Removal

The recovery of nutrients can be increased by an "stepping-stone" approach (from complex and higher concentration of nutrients).

Nutrient Recovery

Recovering half of the main nutrients from urban wastewater provides almost 100% of the farm requirements.



Wastewater Streams

Daily Loadings from source separated streams (g/day)



Main Technologies

Technologies to treat source separated streams (g/day)



Recovered Sources

Recovered sources from urban streams (g/day)



Nutrient Usage

Due to the low market price of fertilizers together with new innovations in vertical farming, the recovered nutrients can be used to grow a wide variety of produce to satisfy community demand.

The farm can meet the yearly consumption* of the cultivated vegetables for the block.

Daily Produce

Estimated daily production of vegetables, fruits, greens and mushrooms (g/day) from daily nutrient generation in urban environments



Yearly Harvest: 20,000 kg/Year
Yearly Value: 50,000\$/Year
Equivalent Crop Area: 25,000m² (7 Acres)
Satisfies 100% of community yearly demand (10 kg per capita per year)



Yearly Harvest: 20,000 kg/Year
Yearly Value: 30,000\$/Year
Equivalent Crop Area: 40,000m² (9 Acres)
Satisfies 100% of community yearly demand (10 kg per capita per year)



Yearly Harvest: 1,000 kg/Year
Yearly Value: 6,500\$/Year

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5377 26.6 Risk Management in Vertical Farming

5378 We emphasize the necessity of thorough risk assessment and mitigation for high-value crops in
5379 vertical farming (VF). A comprehensive risk analysis was fundamental to our system design and
5380 is currently under review in a separate publication. Here's a summary of our approach:

- 5381 ▪ **Hazard Identification:** Potential hazards including biological contaminants (pathogens
5382 from source-separated wastes), chemical residues (pharmaceuticals, cleaning agents),
5383 and operational disruptions (power failures, nutrient imbalances) were thoroughly
5384 scrutinized.
- 5385 ▪ **Risk Characterization and Mitigation:**
- 5386 ▪ **Prevention at Source:** Stringent pretreatment at the decentralized system (DSS)
5387 minimizes hazards prior to VF integration. This multi-barrier approach significantly
5388 reduces biological load.
- 5389 ▪ **VF Operational Controls:** Sensors and automation enable tight control over nutrient
5390 inputs, water quality, and environmental parameters, reducing contamination risks
5391 within the VF itself.
- 5392 ▪ **Product Testing:** Pre-harvest and post-harvest protocols confirm produce meets the highest
5393 food safety standards.

5394 Balancing Risks and Benefits: While attaining absolute zero risk is often unfeasible, our rigorous
5395 controls aim to make residual risks acceptable, especially when considering the environmental
5396 and resource recovery benefits compared to conventional agriculture.

5397 Our risk assessment framework is meant to be iterative, incorporating new insights, technological
5398 advancements, and evolving regulatory standards.

5399 While additional treatment steps may increase energy and material inputs, a holistic lifecycle
5400 analysis (LCA) provides a fair comparison. Our analysis, which currently factors in water, energy,
5401 and nutrient efficiency, will be expanded to incorporate all treatment steps within the LCA
5402 framework., highlighting the importance of robust risk management alongside sustainability
5403 assessments in high-value VF applications.

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26.6.1 Salinity Considerations

Salinity monitoring while using digestate and fertilizers can lead to increased salinity over time, potentially impacting plant growth and system performance. Vertical farming also faces challenges compared to traditional methods in areas like soil health and microbial ecology. While this study hasn't explicitly studied salinity tracking in our current design, understanding it is crucial. We propose implementing regular monitoring of the soil/solution mixture's electrical conductivity (EC) to track salinity levels. Based on these readings, we can implement strategies like:

- **Controlled irrigation practices:** Using low-salinity water sources and optimizing irrigation frequency to prevent salt accumulation.
- **Nutrient source selection:** Opting for low-salt digestate and using alternative nutrient sources like biochar or hydrochar to balance nutrient supply while minimizing salinity increase.
- We acknowledge the challenges you mentioned regarding soil health and microbial ecology in vertical farming. To address these, we are exploring:
 - **Substrate selection:** Researching alternative growing media that promote beneficial microbial communities and maintain long-term soil health, like biochar-based mixes or engineered substrates.
 - **Microbial augmentation:** Introducing specific microbial strains to enhance nutrient cycling and decomposition processes, mimicking natural soil functions.
 - **Controlled environments:** Optimizing temperature, humidity, and light conditions to favor beneficial microbial activity and suppress the growth of potential pathogens.

Furthermore, we recognize the need for further research in optimizing salinity management and promoting soil health in container-style vertical farming. Our ongoing research plans include studying long-term salinity management strategies and investigating the effectiveness of different mitigation techniques over extended periods, and a better understanding of the dynamics of microbial communities in vertical farming systems and identifying strategies to enhance their diversity and functionality.

26.7 Decentralized Production, Centralized Management

While the primary intention is to utilize recovered nutrients within the urban environment (vertical farms, parks, community gardens), a successful concept might generate a surplus. In this scenario, recovered nutrients would offer two advantages: (1) they are produced in higher concentrations and smaller volumes compared to biosolids from traditional wastewater treatment, reducing transport requirements. (2) Their value lies in their sustainable origin rather than direct competition with artificial fertilizers. Excess nutrients can be distributed without cost for environmental projects or sold at lower prices to agricultural users to progressively displace reliance on artificial fertilizers. Government support for transitioning infrastructure and fostering

5443 local, sustainable nutrient supply chains is crucial for managing this potential surplus while
5444 facilitating a paradigm shift in resource management.

5445 Although the vertical farm's design is directly linked to wastewater nutrient flow, meaning its
5446 nutrient needs are sized specifically to match the incoming streams, different configurations,
5447 changes in population, or other factors could easily disrupt this delicate balance between
5448 production and demand. Therefore, exploring the concept of a centralized management system
5449 for decentralized source separation satellite stations becomes crucial. These stations would act
5450 as citywide nutrient recovery points, capable of coordinating with areas requiring additional
5451 nutrients, landscaping projects, or independent urban farms.

5452 Addressing Potential Nutrient Surplus: While it's true that a significant portion of nutrients within
5453 urban areas will continue to come from existing food supply chains, this concept aims to recover
5454 a substantial amount for a variety of local uses: from selected crop cultivation to enriching parks,
5455 community gardens, and forestry initiatives. In a successful scenario, a surplus of recovered
5456 nutrients could arise. Addressing this, consider that nutrients recovered in this manner have
5457 advantages over biosolids common in current wastewater treatment:

5458 In a successful implementation scenario, even with a potential nutrient surplus, several factors
5459 favor this concept over existing practices:

- 5460 ▪ **Reduced Transport Volume:** Due to the elimination of aeration (CAS), the nutrient
5461 recovery process yields a far more concentrated product than aerobic biosolids. This
5462 means smaller volumes would need to be transported back to agricultural areas.
- 5463 ▪ **Higher Nutrient Concentration:** Since nutrients aren't chemically destroyed in
5464 anaerobic processes, higher concentrations are achievable, further reducing transport
5465 burdens.
- 5466 ▪ **Local Utilization:** A significant portion of the recovered nutrients can be directly utilized
5467 within the urban environment (gardens, forestry, community projects), decreasing the
5468 amount that needs to be transported out.

5469 Therefore, even while a more comprehensive study is needed, this approach likely demonstrates
5470 reduced transport requirements when compared to the large quantities of biosolids generated by
5471 the current system, even when accounting for a potential nutrient surplus. A portion of these
5472 recovered nutrients would be immediately used within the urban environment. Even with a net
5473 excess, transport needs back to agricultural areas would likely be less than current biosolid-based
5474 practices.

5475 Sustainable Fertilizer as a Valuable By-product: The primary value of recovered nutrients lies in
5476 their sustainable origin, not direct market competition with commercially-produced fertilizers. This
5477 creates flexibility in a surplus scenario: excess nutrients could be offered without cost to support
5478 environmentally focused agriculture and promote resilience in vulnerable regions. These efforts
5479 offer the potential to gradually reduce our reliance on artificial fertilizers with known environmental
5480 detriments.

5481 Evolving Demand and Supply: Even in a surplus situation, local demand for sustainable fertilizer
5482 could grow considerably over time. Parks, landscaping initiatives, urban agriculture, and
5483 environmentally conscious residents provide increasing possibilities for nutrient absorption. As
5484 locally recovered fertilizers become more abundant, new supply chains would likely emerge.
5485 While competing with established systems initially may raise transport costs, this must be weighed
5486 against the long-term environmental benefits of reducing reliance on traditional, artificial fertilizer
5487 production.

5488 Governmental Support is Key: A successful adoption of this model requires governmental support
5489 at multiple levels. Policies must focus on aiding the transition to source separation, fostering local
5490 nutrient supply chains, and incentivizing a long term view that emphasizes the importance of
5491 environmental sustainability over a purely cost-focused approach.

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27 Photovoltaic Energy

27.1 Solar Energy Potential: Scenarios.

This study investigates the capacity for solar energy to power critical urban infrastructure. Specifically, it examines the potential of solar panels to offset energy needs within a multi-use block. This block integrates a water reuse system, vertical farm, and domestic energy components. The analysis covers the cited diverse cities under various Köppen-Geiger climate classifications (Barcelona, Amsterdam, Santiago de Chile, Hong Kong, Seoul, Toronto, and Miami), suggesting an exploration of solar viability across varying geographical and climatic conditions.

Table S27-1:: Average solar irradiance (kWh/m²/day) across diverse locations selected to represent a variety of climates based on the Köppen-Geiger classification.

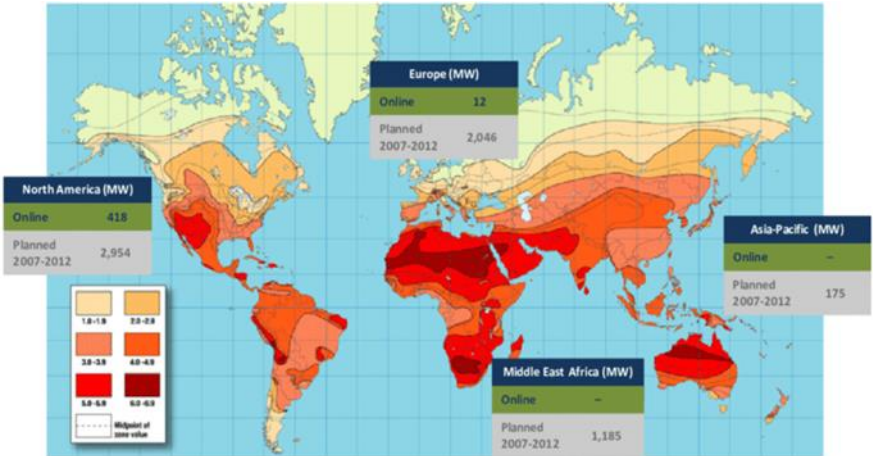


Table S27-2: Solar energy analysis for each city depending in the various climatic regions.

	Electricity consumption per capita (average)	For All (2000 PE) kWh/yr	Monthly req (kWh)	Sun hours/ mo	kWh system/ hh [load sizing]	kW system/ house [consumption]	Total kW system	Nº 400Wp panels	Nº 425Wp panels	kwh/yr produced
World	3,128	6,256,000	521,333							
EU	6,022	12,044,000	1,003,667							
Barcelona	5,356	10,712,000	892,667	105	8	10	1,063	2,657	2,501	1,135,260
Amsterdam	6,713	13,426,000	1,118,833	45	18	30	3,108	7,770	7,313	486,540
Chile (Santiago)	3,880	7,760,000	646,667	90	9	9	898	2,246	2,114	973,080
Hong Kong	6,083	12,166,000	1,013,833	105	8	12	1,207	3,018	2,840	1,135,260
Seoul	10,497	20,994,000	1,749,500	165	5	13	1,325	3,314	3,119	1,783,980
Toronto	15,588	31,176,000	2,598,000	75	11	42	4,330	10,825	10,189	810,900
Miami	12,994	25,988,000	2,165,667	263	3	10	1,031	2,579	2,427	2,838,150

27.2 PV System description

The installation of solar panels can offset a geographically dependant fraction of the total requirements and is found to be capable of supplying the necessary electricity for the operation of the water reuse system and the vertical farm for all the studied cities (i.e., Barcelona, Amsterdam, Santiago de Chile, Hong Kong, Seoul, Toronto, and Miami, in representation of a range of Köppen-Geiger climates). Energy consumption from the block is divided into three categories according to demand source: (i) water reuse system, (ii) vertical farm, and (iii) domestic energy.

DC monocrystalline 425W panels (SunPower, Silicon Valley, CA, US) with a 20% efficiency distributed across 75% of block roof surface are assumed. Calculations for yearly electricity output from solar installation are based on average available sun hours per country and solar panel performance (H. Chen et al., 2022; Fthenakis et al., 2012; Huld et al., 2012; Oyedepo et al., 2019; Santamouris et al., 2015; Taşçioğlu et al., 2016; H. Walker et al., 2020; Zaini et al., 2015). Domestic demands are estimated according to electric load sizing and verified by comparison to existent per capita electricity consumption per country (International Energy Agency, 2014). Size of solar system is that of 900 kW and occupied area on roof is of around 4,000 m².

Lithium batteries (Dragonfly energy, Reno, NV, US) are assumed and sizing accounts for 1.5 backup days. Power demand of the facility and sizing of DC to AC inverters is dependent on the maximum expected load size considering coincidence factors per household and between all dwellings in block. The power requirement of the selected inverters is calculated with an oversizing factor of 1.25 (Oyedepo et al., 2019),

CAPEX and OPEX include the described elements plus maintenance costs (H. Walker et al., 2020). It is expected that the installation can cover up to 12% of the total annual electricity demand including domestic consumption. Environmental benefits minus solar system impacts are included in the environmental analysis.

5536

5537 Table S27-3:: Battery sizing according to typical household power demand.

BATTERY SIZING

1.5	backup		
	days		
Electric load 1 hh	W	h	LOAD kWh/d
Lights+fan+TV	205		0.99
Air conditioner	1100	1.00	1.10
Coffee maker	900	0.17	0.15
Fridge	140	24	3.36
Hair blow dryer	2200	0.08	0.18
Freezer	100	24.00	2.40
Dehumidifier	240	4.00	0.96
Desktop computer	450	3.00	1.35
Stove	2000	0.50	1.00
Automatic garage door	350	0.08	0.03
Printer	25	0.08	0.00
Extractor fan	200	1.00	0.20
Microwave	800	0.13	0.11
Oven	2150	0.75	1.61
Phone charger	6	2.00	0.01
Vacuum cleaner	600	1.00	0.60
Washing machine	500	2.00	1.00
WiFi router	6	14.00	0.08
Additional	600	5.00	3.00
Inverter			
Total load W/kWh	12,572.00		18.14
Total battery size Wh			27,203.63
Coef. simultaneitat	0.39		
Load w coef	4897		

5538

5539 Table S27-4: Aggregate electricity consumption of the entire housing development and the three concepts (DSS, VF and PV) described in our study.

Total demand (kWh/yr)	DSS	VF	Domestic energy use	Total	% covered off grid
Barcelona	111,678	15,521	10,712,000	10,839,200	10
Amsterdam	111,678	15,521	13,426,000	13,553,200	4
Chile (Santiago)	111,678	15,521	7,760,000	7,887,200	12
Hong Kong	111,678	15,521	12,166,000	12,293,200	9
Seoul	111,678	15,521	20,994,000	21,121,200	8
Toronto	111,678	15,521	31,176,000	31,303,200	3
Miami	111,678	15,521	25,988,000	26,115,200	11

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kWh saved/m3 REUSE	kWh saved/m3 TREATED	kg CO2 eq/kWh to add	kg CO2 eq/kWh avoided	Net kg eq CO2/m3 REUSE	Net kg eq CO2/m3 TREATED
15.35	12.49	0.87	8.54	-7.67	-6.24
6.58	5.35	0.37	3.66	-3.29	-2.67
13.16	10.71	0.75	7.32	-6.57	-5.35
15.35	12.49	0.87	8.54	-7.67	-6.24
24.12	19.63	1.37	13.42	-12.05	-9.81
10.96	8.92	0.62	6.10	-5.48	-4.46
38.37	31.23	2.19	21.36	-19.17	-15.60

*not considering demand in buildings, if all electricity produced is destined to WWT system

**solar could offset the WWT system's demand in all cases

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5543

5544 The “total domestic electricity demand” refers to the estimated aggregate electricity consumption
5545 of the entire housing development described in our study. Here's the breakdown:

- 5546 ▪ Residential Units: Electricity use within individual housing units for appliances, lighting,
5547 and HVAC.
- 5548 ▪ Common Areas: Consumption for shared spaces like lobbies, hallways, and any
5549 amenities buildings.
- 5550 ▪ Decentralized Systems: The power requirements for the decentralized source
5551 separation (DSS) system.
- 5552 ▪ Vertical Farming: Electrical demands specific to lighting, climate control, and associated
5553 technology within the vertical farm.

5554 **Clarifying the Percentage and Comparisons:**

5555  $2 \pm 0.7\%$ (DSS): The DSS consumes approximately this percentage of the
5556 development's total electricity demand.

5557  $2.4 \pm 0.2\%$ (VF): The vertical farm's consumption relative to the development's total
5558 electricity demand.

5559 Combined: Together, the DSS and VF components represent an additional demand of roughly
5560 4.4% on top of the baseline residential and common area usage.

5561 **Photovoltaic Offset:** Our analysis indicates that solar panel integration could offset
5562 approximately 10% of the entire development's energy use, including the additional demand from
5563 VF and DSS. Photovoltaics (PV) Payback period would range from 6 to 15 years depending on
5564 location. In this study, we assumed that the PV energy is free after the PV's payback.

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28 Payback Mechanisms

28.1 Supporting payback mechanisms description

28.1.1 From net loss to payback/investment

The most crucial aspect is comprehending the true nature of the 7-10% figure as initial costs of the concept. This study employed the total costs of a building to establish a comparison with the estimated price of the decentralized source separation system (DSS). This comparison intended to provide readers with an accessible understanding of the order of magnitude of the DSS's costs and benefits. However, we should have explicitly stated that this comparison wasn't meant to dictate who should bear the costs.

This percentage incorporates the estimated initial costs of three components: the DSS (3.5%), photovoltaic infrastructure (4%), and vertical farming (3.5%).

Let's focus first on the initial costs regarding the photovoltaic infrastructure. Anyone pursuing a solar panel installation anticipates a payback period, typically around 7-10 years, where electricity bill savings offset the initial cost. Similarly, the current vertical farming boom operates on this principle, with private companies aiming to recoup their investment (3-6 years) through more efficient and reliable produce sales.

The DSS is also aimed to recoup the initial investment, albeit in more indirect manner. Unlike traditional wastewater treatment, viewed as a "net loss" requiring sustained investment with no return in sight, the DSS offers the potential for two distinct paybacks powered by synergies. While existing infrastructure demands continuous financial input with no expected payback, the DSS opens the door to a novel, positive economic outlook.

This article proposes a first payback mechanism through indirect savings generated by extremely local, water efficient and completely organic harvests. While food production might not be the first goal of DSSs, the example of local food production will be used to show the potential of the approach. The concept is simple: recover a portion of residents' discarded nutrients and energy on-site (from food, blackwater, and hot water) and enable an efficient use of the nutrients to produce valuable organic harvests able to provide an approximate 10% of the daily needs of the residents (in the form of a healthy salad). This harvest (or daily salad) if sold or priced at market prices (and considering all the related costs to produce it), can indeed provide a payback for the system.

While initial DSS implementations might not use the produced fertilizers for vertical farming (VF), directing them towards landscaping, forestry, or community gardens, the high price on organic local food still offers value. The synergy with VF truly exemplifies the potential and scale of this approach. Studies have shown that source separation techniques, with similar fertilizer production from urine-derived fertilizers and together with energy savings, hold promise for economic

5612 feasibility (Chipako & Randall, 2020; M. Gao et al., 2019; Lohman et al., 2020; Volpin et al., 2019;
5613 Watabe et al., 2023). Nevertheless, widespread implementation remains elusive.

5614

5615 The main obstacle lies in the long-standing dependency on artificially produced fertilizers*. Their
5616 invention, while enabling human progress, led to decades of mass production that drove down
5617 costs and stifled serious consideration of nutrient recovery alternatives. Recovering fertilizer from
5618 centralized systems cannot compete economically with such an optimized process (Patel et al.,
5619 2021; Volpin et al., 2019). Compared to DSS, centralized systems not only lack source separation
5620 efficiencies but also require vast land areas to use the fertilizers in situ— a stark contrast to the
5621 distributed nature of modular containers throughout the territory. The utilization of the nutrients
5622 right at the production center would allow bypassing the need to sell the obtained fertilizers at
5623 uncompetitive market prices and grow, instead, a high-valued harvest that can support the
5624 system's payback.

5625

5626 **The latest report from the United Nations Food and Agriculture Organisation (FAO) estimates that between 2015 and*
5627 *2018, the world demand for fertilisers (N, P₂O₅, K₂O) has increased, on an average, 1.8 percent per annum (FAO, 2017).*
5628 *As in 2015, the demand was estimated to be 184'017'000 tonnes, every year the fertiliser consumption increases of about*
5629 *3'351'300 tonnes. With a world population expected to reach 11.2 billion people by 2100, this trend is expected to keep*
5630 *rising (United Nations, 2017). The rise in the need for fertilisers would affect both the raw material availability as well as*
5631 *the greenhouse gas (GHG) emissions and eutrophication.*

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5633

5634 Typical wastewater treatment plants biosolids often include the leftover nutrients recovered from
5635 centralized systems. They are use in agriculture as fertilizer, but they involve further drawbacks:
5636 transportation, contamination runoff, low purity, and they are mostly attached to practices such
5637 as pesticide and herbicide use, inefficient water usage (>90% water consumption compared to
5638 VF), poor labor conditions, weather dependence, and more. Conversely, the DSS minimizes solid
5639 waste production, recovers a larger portion of nutrients, eliminates transportation needs, uses
5640 less than the 3% of the DSS-treated water, avoids pesticides, offers maximized control, is
5641 weather-resilient, and employs skilled labor. Therefore, even excluding these positive
5642 externalities from cost calculations, the revenue generated from the harvested produce, even if it
5643 constitutes only a portion of residents' total food consumption, is sufficient to support the system's
5644 payback.

5645

5646 This article proposes an even more exciting second payback mechanism: avoided cost in potable
5647 water production. Similar to how separating blackwater facilitates nutrient recovery through
5648 energy-generating systems, separating greywater allows 80% of household wastewater to be
5649 cheaply purified to drinking water quality. This has two major implications:

- 5650 ▪ **Traditional water infrastructure is outdated and unsustainable:** The current system
5651 of collecting, purifying, and transporting water relies on crumbling infrastructure
5652 designed for different weather and hydrological conditions. As droughts become more
5653 frequent, this outdated system struggles to keep up, requiring constant investment and
5654 failing to adapt to changes.
- 5655 ▪ **Potable water reuse is a growing trend:** From California's recent legislation allowing
5656 full-scale potable reuse to similar initiatives in drought-stricken regions like Spain and
5657 Brazil, regulations are rapidly evolving to embrace direct and indirect potable water
5658 reuse.

5659 While directly comparing the DSS to traditional water production (sourced from reservoirs,
5660 groundwater, etc.) is practically impossible, it can be effectively compared to the functionality of
5661 direct and indirect potable water initiatives (DPR or IPR). Even if the comparison only applies to
5662 these specific applications, the rapid growth of this field makes the discussion highly relevant.
5663 Here's why the DSS offers two advantages:

5664 **2.1) Cheaper potable water production:** While both the DSS and DPR (or desalination plants
5665 too) primarily use Reverse Osmosis (RO) technology, the source-separated stream in the DSS
5666 enables more efficient treatment. So, even if desalination becomes cheaper, the same improved
5667 technology can be applied to the DSS for purification, which treats an easier to purify water
5668 (greywater has fewer ions and cations than seawater and 10 times less pollutants the raw
5669 wastewater).

5670 **2.2) Avoiding centralized system expansion:** reuse avoids expanding the centralized system,
5671 which is crucial considering the significantly higher unit costs of adding capacity compared to the
5672 average costs used in the centralized system comparison. This is important because expanding
5673 existing systems is much more expensive per unit of water than the average cost used in
5674 comparisons. This underestimates the economic value of the DSS, as it doesn't reflect the higher
5675 incremental cost of expanding the centralized system, which is offset by the additional capacity
5676 provided by the decentralized DSS.

5677 Therefore, if the recovered water from the DSS is valued at the avoided cost of expanding the
5678 existing system, it would offer an additional avenue to recoup the initial 3.5% investment in the
5679 DSS. This effectively increases the payback potential of the system compared to just considering
5680 energy and water savings and fertilizers at market price. In summary, for the scenario analyzed
5681 in this study, implementing the entire concept (DSS+VF+PV) represents an approximate 10%
5682 upfront investment compared to conventional building costs. Nevertheless, each of the synergetic
5683 components has the potential to transform costs to investments:

- 5684 📍 **Vertical farming (VF):** Could recoup its investment in roughly 12-15 years.
- 5685 📍 **Photovoltaics (PV):** Payback period would range from 6 to 15 years depending on
5686 location.

5687  **Decentralized wastewater system (DSS):** In this study, assuming that the revenue
5688 from the VF after its corresponding payback goes to the DSS and that the PV energy is
5689 free after the PV's payback, an estimated payback period of 18-22 years was found. It's
5690 important to note that this payback could drastically be shortened depending on the
5691 assigned value for avoiding expansion of the existing centralized infrastructure, but a
5692 conservative estimate assuming the saved costs of not using DPR (which is almost two
5693 times more expensive), could already decrease the payback to approximately 11-14
5694 years.

5695 Overall, the initial costs of the three main components (PV - 4%, VF - 3.5%, DSS - 3.5%) could
5696 be recovered within approximately 15 years, making this approach potentially attractive for utilities
5697 managing such integrated concepts.

5698 This raises the question of who truly benefits from transitioning to such concepts. While residents
5699 and owners reap immediate gains like reliable and tailored water access, pesticide-free produce,
5700 and personalized water quality, the DSS's impact extends far beyond individual users. By offering
5701 public utilities a novel approach to enhance their financial viability and embrace sustainable
5702 practices, the DSS unlocks wider societal benefits:

- 5703 **Improved financial health:** By circumventing costly expansions and retrofits of
5704 traditional wastewater systems, the DSS helps utilities achieve better financial
5705 standings.
- 5706 **Enhanced sustainability:** The system facilitates the integration of sustainable
5707 practices like potable water reuse, aligning utilities with environmental objectives.
- 5708 **Increased resilience:** By diversifying water management strategies, the DSS
5709 strengthens the overall resilience of the system against disruptions and challenges.

5710 The DSS paves the way for utilities to transition from "net cost" to "payback" by strategically
5711 avoiding new infrastructure, particularly for potable reuse, and minimizing ongoing operational
5712 expenses. Therefore, this transition yields benefits for all stakeholders:

5713 Residents and owners: Enjoy direct advantages like access to fresh local produce and reliable
5714 water sources.

5715 Utilities: Achieve financial stability and implement sustainable practices, aligning with societal
5716 expectations.

5717 Community: Gains a more resilient and environmentally friendly water system, contributing to a
5718 healthier and more sustainable future.

5719 By recognizing the wider benefits enjoyed by residents, utilities, and the community at large, we
5720 can identify the main players that should be responsible to finance the transition to these
5721 innovative, decentralized water management solutions.

5722

5723 28.2 Total costs of synergetic strategies

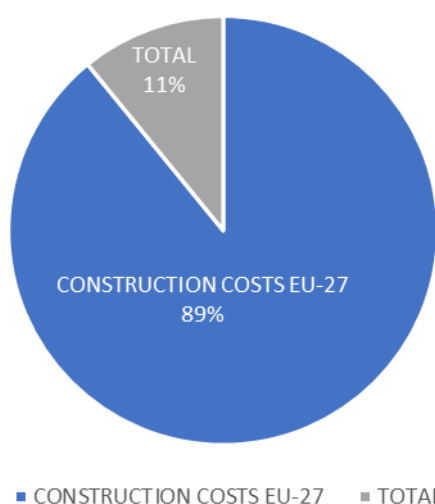
5724 Table S28-1: Total Capital costs (CapEx) and Operational costs (OpEx) including the synergetic strategies.

	Building costs		CAPEX			CAPEX + OPEX
	CONSTRUCTION COSTS EU-27	CAPEX [\$/30y]	%	OPEX [\$/30y]	CapEx + OpEx	%
D-SS	65,075,251	2,377,421	3.26	2,043,168	4,420,589	6.05
	CONSTRUCTION COSTS EU-27	Rainwater				
RW	65,075,251	58,571	0.08	116,565	175,136	0.24
	CONSTRUCTION COSTS EU-27	Vertica Farming				
VF	65,075,251	2,468,709	3.38	3,097,675	5,566,384	7.62
	CONSTRUCTION COSTS EU-27	Solar Energy				
PV	65,075,251	3,043,618	4.17	268,440	3,312,058	4.54
	CONSTRUCTION COSTS EU-27	TOTAL (NO Paybacks)				
Total (No Payback)	65,075,251	7,948,320	10.88	5,525,847	13,474,168	18.45
	CONSTRUCTION COSTS EU-27	TOTAL (With Paybacks)				
Total (Payback)	65,075,251	-324,435	-0.50	1,381,462	1,718,733	2.57

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5727 Table S28-2: Total initial costs (CapEx) when including the synergetic strategies.



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Table S28-3: Total Capital costs depending on location for when including the different payback mechanisms.

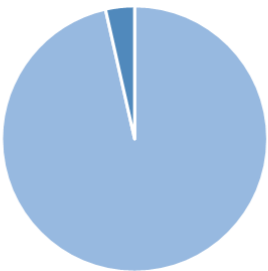
	D-SS CAPEX	Benefits after payback							
		VF	PV	RW	CAPEX [30 years]	%			
Barcelona	2,377,421	1,100,319	857,890	28,426	390,787	16.4			
Amsterdam	2,377,421	1,100,319	-1,371,543	159,672	2,488,974	104.7			
Chile (Santiago)	2,377,421	1,100,319	300,532	-21,945	998,515	42.0			
Hong Kong	2,377,421	1,100,319	857,890	479,573	-60,360	-2.5			
Seoul	2,377,421	1,100,319	3,087,323	-14,896	-1,795,325	-75.5			
Toronto	2,377,421	1,100,319	-256,827	195,250	1,338,680	56.3			
Miami	2,377,421	1,100,319	6,710,153	199,267	-5,632,317	-236.9			
AVG	2,377,421	1,100,319	1,455,060	146,478	-324,435	-14			

	D-SS CapEx	D-SS OpEx	Total [CapEx +OpEx]	Benefits [30y]	Cost - Benefits [30y]	%	Wo Benefits	W Benefits
							\$/m3	\$/m3
Barcelona	2,377,421	2,043,168	4,420,589	1,986,635	2,433,955	45	1.62	0.89
Amsterdam	2,377,421	2,043,168	4,420,589	-111,553	4,532,142	-3	1.62	1.66
Chile (Santiago)	2,377,421	2,043,168	4,420,589	1,378,906	3,041,683	31	1.62	1.12
Hong Kong	2,377,421	2,043,168	4,420,589	2,437,782	1,982,807	55	1.62	0.73
Seoul	2,377,421	2,043,168	4,420,589	4,172,747	247,843	94	1.62	0.09
Toronto	2,377,421	2,043,168	4,420,589	1,038,742	3,381,847	23	1.62	1.24
Miami	2,377,421	2,043,168	4,420,589	8,009,739	-3,589,150	181	1.62	-1.32
AVG	2,377,421	2,043,168	4,420,589	2,701,857	1,718,733	61	1.62	0.63

VF					PV			
	COST	NET	Wo Benefits		W Benefits		Wo Benefits	W Benefits
			\$/m3	\$/m3	COST	NET	\$/m3	\$/m3
Barcelona	3,097,675	- 1,100,319	1.14	-0.40	3,276,424	-857,890	1.20	-0.31
Amsterdam	3,097,675	- 1,100,319	1.14	-0.40	3,143,392	1,371,543	1.15	0.50
Chile (Santiago)	3,097,675	- 1,100,319	1.14	-0.40	3,243,166	-300,532	1.19	-0.11
Hong Kong	3,097,675	- 1,100,319	1.14	-0.40	3,276,424	-857,890	1.20	-0.31
Seoul	3,097,675	- 1,100,319	1.14	-0.40	3,409,457	3,087,323	1.25	-1.13
Toronto	3,097,675	- 1,100,319	1.14	-0.40	3,209,908	256,827	1.18	0.09
Miami	3,097,675	- 1,100,319	1.14	-0.40	3,625,634	6,710,153	1.33	-2.46
AVG	3,097,675	- 1,100,319	1.14	-0.40	3,312,058	1,455,060	1.21	-0.53

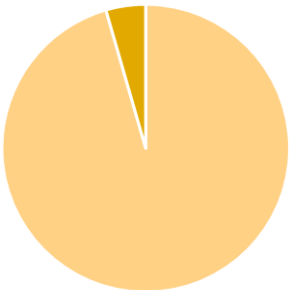
5733

5734 Table S28-4: Total initial costs (CapEx) for the decentralized source separation.



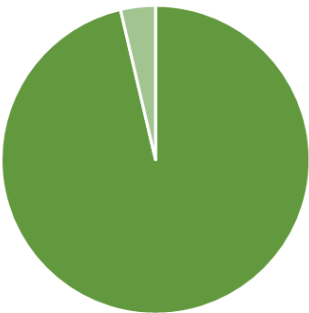
5735 CONSTRUCTION COSTS EU-27 CAPEX [\$ / 30y]

5736 Table S28-5: Total initial costs (CapEx) for the photovoltaic installation.



5737 CONSTRUCTION COSTS EU-27 SOLAR ENERGY CAPEX

5738 Table S28-6: Total initial costs (CapEx) for the vertical farming.



5739 CONSTRUCTION COSTS EU-27 VF CAPEX

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28.3 Centralized vs Decentralized (preliminary results)

Therefore, the difference between the main water costs (i.e., treatment, potabilization, and sewer) and the billed water costs in different cities not only illustrates the complexity of water economics, but also that when excluding regional disparities and recognizing societal services as resilience or recycling, the costs between the centralized and decentralized approaches are comparable. The conventional centralized system has an approximate cost of $1.2 \pm 0.5 \$/\text{m}^3$ without considering any recycling capability and taking advantage of an already-built infrastructure and the economies of scale (SS). Even if the D-SS can lower the overall operational costs (due to higher recovery efficiencies) when compared to the conventional approach, the need to adapt the infrastructure (i.e., NoMix toilets, brown-yellow lines, remote monitoring and control, etc.) still results in higher overall costs $1.8 \pm 0.3 \$/\text{m}^3$. Nevertheless, as the D-SS approach enables the recycling of 85-95% of the water, a more realistic comparison with the centralized paradigm should also consider the cost of either direct or indirect potable reuse to account for such resilience-enhancing capability. Centralized potable reuse strategies also vary significantly in cost and type, but the most common and benchmarked alternatives are in the range of $1.2\text{-}2 \$/\text{m}^3$ (Keller et al., 2021). The addition of potable reuse would significantly increase the overall cost of water ($2 \pm 0.5 \$/\text{m}^3$), but it would allow a more comprehensive comparison with the D-SS approach given they would provide the same societal service (i.e., drinking-quality water without tapping on traditional supply sources). Using this comparison, the costs of the decentralized system would be lower than the combination of the conventional system when augmented with reuse potable strategies.

28.4 Public subsidies.

28.4.1 From “lock-in” to the next green transition

Despite numerous innovative decentralised urban water solutions being described over many years, their practical application remains largely anecdotal despite the claimed benefits (H+ projektet, 2023; NEREUS, 2023; Run4Life, 2023). While technical demonstrations have proven the feasibility and scalability of innovative solutions (Badeti et al., 2022; Ledezma et al., 2017; Maurer, 2009; Maurer et al., 2005; Volpin et al., 2019; Wilsenach & Loosdrecht, 2006), translating these successes from small trials to widespread adoption remains a significant challenge (Aliahmad et al., 2023; D. M. Fam & Mitchell, 2013a; Gunnarsson et al., 2023; Watabe et al., 2023; Yan et al., 2021). As Reviewer#1 correctly indicates, the techno elements are rarely the determining factor for the success or failure of new initiatives.

Keller, 2020 offer a comprehensively exploration to the various barriers impacting such concepts. Arguably the most important one, is the lack of institutional support, which is primarily rooted in a system-wide legacy of technological inertia. Several factors can be accounted for the slow progression of these type of concepts, from the difficult uptake in building projects (separate piping), public risk perception and associated “yuck factor”, and, especially, due to limited innovation in the water sector, especially from technology “lock-in” effects (Keller, 2023; Mankad, 2012; Rabaey et al., 2020; Van de Walle et al., 2023). The latter entails the phenomenon where a “random” early lead in innovation (as happened with conventional activated sludge) is sufficient for a certain technology to acquire dominance within a market, leading to a restricted advancement of other technologies (Arthur et al., 1989). Thus, investments in large-scale, centralized water systems can cause a lock-in due to their associated high infrastructure costs.

Equally significant is the current incapacity to weigh in the societal, economic, and environmental aspects this paradigm shift could bring as a long-term solution on a whole-of-system basis. This has happened before, and even with a more obvious case as it is the solar power, even when costs, paybacks and energy production efficiencies were above fossil fuel it is implementation remained scarce. Like the early days of solar adoption, the lack of general recognition of societal and economic benefits creates a blind spot for source separation concepts. As with other successful historical transitions like solar power, widespread adoption of decentralized water systems will need the support from key institutions to improve existing infrastructure and optimize the long-term

5805 economic feasibility supporting the creation of a new and necessary thriving green
5806 economy.

5807 The proposed transition to decentralized source separation systems shares similarities
5808 with the ongoing success story of photovoltaics (PV). Similar to how PV benefits extend
5809 beyond individual users to encompass broader goals of resilience, payback,
5810 decentralization, and environmental improvements, the decentralized management
5811 concept holds similar potential. On those lines, vertical farming, also aspires to achieve
5812 those same positive outcomes of payback, resilience, and decentralization, however, this
5813 approach lays in the other type of the spectrum, where investors are flocking to VFs in
5814 the believe that urban farming will eventually be engrained in urban food supply chains.

5815 The advantages of DSS concepts resonates with the urgent need for solutions to water
5816 and sanitation challenges addressed by the United Nations. In its Sustainable
5817 Development Goal 6 (SDG 6), the UN emphasizes closed water cycles and zero-
5818 emission principles by 2030 (UN, 2023a). This aligns perfectly with the decentralized
5819 approach, which conserves water and minimizes waste. Furthermore, other SDGs
5820 support the shift towards a circular economy (CE) in the water industry, where
5821 technologies like source separation, urine-derived fertilizers and recycled water
5822 contribute to SDG 12 (Responsible Consumption and Production) by promoting resource
5823 conservation and waste minimization (UN, 2023b). Additionally, SDG 11, focused on
5824 sustainable cities and communities, finds synergy with this approach as it can create jobs
5825 and resource recovery opportunities within local communities (UN, 2023c).

5826 Therefore, even if the growing number of studies on source separation technology
5827 suggest these alternatives can be financially attractive for businesses, due to the
5828 theoretical revenue from selling recovered nutrients, potentially reduced water bills, less
5829 consumption of chemicals, lower energy requirements and less waste management
5830 (Badeti et al., 2022; Larsen et al., 2015; Ledezma et al., 2017; Van de Walle et al., 2023;
5831 Watabe et al., 2023). The presented approach seeks to transcend business opportunities
5832 and be considered as solid alternative (or complement) to the existing water and
5833 wastewater paradigm. Given the decentralized source separation alignment with global
5834 sustainability goals and potential for broader societal benefits, it should deserve similar
5835 support from society and government as other transformative technologies like solar
5836 power have received. This support can accelerate its development and integration,
5837 paving the way for a more resilient and sustainable future for our water systems.

5838

5839 28.4.2 A transition success story

5840 Rabaey et al., 2020 extensively elaborated how the production of potable water by rain
5841 harvesting should mirror other successful transitions that have happened in other
5842 sectors, as in the case of solar power, and find a credible reference model. The paper
5843 describes how the expansion of household solar power offers valuable lessons for future
5844 urban water systems giving the example of Germany's approach to solar power adoption.
5845 Starting with a single house in 1983, they gradually scaled up trials to 1,000 homes in
5846 1990 and 100,000 by 1998. Each step saw installation costs fall, allowing for reduced
5847 subsidies and eventually, self-sustaining economics. Early adopters, motivated by
5848 environmental concerns, accepted higher costs, but as the market grew, innovation
5849 driven by investor interest dramatically reduced costs. By 2017, solar was cost-
5850 competitive in many places, eliminating the need for subsidies.

5851

5852 This success wasn't without challenges (Rabaey et al., 2020). Rooftop solar users
5853 benefited from the existing grid without fully contributing to its upkeep. However, it also
5854 spurred advancements like home energy storage and electric vehicles. Individualized
5855 power generation became a driver for rapid innovation, surpassing the conventional
5856 sector economically and creating new applications. However, when considering the
5857 transition to decentralized source separation schemes in the water sector, it is important
5858 to acknowledge some key differences between water and electricity generation. Although
5859 both seek an overall efficiency through close proximity by distributed but coordinate
5860 decentralized systems, the production of key sources is obviously quite different. Unlike
5861 the guaranteed sun for solar panels, droughts pose serious threats to local water
5862 supplies, or inadequacies in the PV sector would not pose major public health concerns
5863 whereas the potential for disease transmission or illness must be considered in any effort
5864 to alter water supplies.

5865

5866

5867 28.4.3 A hybrid transition.

5868 Despite hurdles like subsidized traditional systems and ensuring safe, scaled-up
5869 operations, technological advancements are making off-the-grid household systems
5870 increasingly viable. Combining water use efficiency, rainwater collection, and water
5871 reuse, these systems could indeed offer promising solutions for both water supply and
5872 sanitation. Thus, as in the case of solar power, the future of water management likely
5873 lies in a hybrid approach, where centralized and decentralized solutions work together
5874 to optimize water use, minimize environmental impact, and guarantee public health.
5875 During a transition, both centralized and decentralized water systems should coexist and
5876 collaborate, with centralized systems eventually losing ground in low-population areas to
5877 fully household or building-scale systems. Therefore, water decentralization could be
5878 initially achieved through hybrid systems complementing existing centralized
5879 infrastructure. From decentralized processes that selectively up-concentrate household
5880 collected nutrients (e.g., urine-diverting, anaerobic co-digestion for black water and
5881 organic waste, etc.), where the remaining low-nutrient stream is still discharged into the
5882 centralised wastewater system (Freguia et al., 2021; Rabaey et al., 2020; Wilsenach et
5883 al., 2007) to other strategies like rainwater harvesting, combined with graywater
5884 recycling, or many other distributed water supply options (Keller, 2023). Such an
5885 approach requires active and genuine collaboration between many entities, as it hold the
5886 potential to generate benefits and value to multiple stakeholders.

5887

5888 28.4.4 How to finance a successful transition

5889 We acknowledge the economic barrier of higher upfront costs for developers
5890 implementing decentralized water systems, while the benefits fall mainly on users
5891 (creating a financing mismatch, as it also happened in the solar power transition). As
5892 stated, is our perspective these systems should deserve public support as they represent
5893 a shift in the existing water and wastewater management paradigm. The shift will not
5894 only benefit users, but the overall water sector, society, and could trigger a new economy
5895 based on enhancing resilience and sustainability of water, food, and energy sources.

5896

5897

5898 There are two key components to financing this transition:

A unified narrative with shared understanding and clear benefits. All stakeholders - from government officials to citizens - need to agree on the need for this change. This requires a clear narrative based on real-world data from successful pilot projects. By analyzing the entire system's economics (including both direct costs and indirect benefits), a deeper understanding of the advantages should support informed investments decisions.

Innovative financial models. Subsidies are coordination mechanisms that when designed properly can become effective tools to meet adoption target levels (Cohen et al., 2015). Studies show that government support can reduce uncertainty for companies developing green technologies, motivating them to bring solutions to market (Chemama et al., 2019; Cohen et al., 2015; Jung & Feng, 2020). Therefore, a targeted set of subsidies, agreed upon by all key stakeholders should be put in place to bridge the gap between upfront costs and users benefits. This will unlock the broader societal benefits of DSS while avoiding continued investment in unsustainable, outdated infrastructure.

28.4.5 Unified narrative and regulatory support

Institutions and water stakeholders need to come together once again (as with solar) to craft a unified narrative placing water at the center of the agenda, from food security, and economic development, to health and well-being. In recent years, we have seen how institutional support and public educational initiatives can influence social acceptance into adopting better solutions as the growing number of potable reuse implementations has repeatedly shown how fast the public adapts to innovation when there is transparency and legitimate goals (Gheraot et al., 2019; Keller, 2023; Kenney, 2019; OCWD, 2021). Decentralized water and wastewater solutions imply much less of a change in the mental framework than most of the already implemented worldwide wastewater potable reuse alternatives, and there's an overall acceptance of these innovations (Contzen et al., 2023; Lamichhane & Babcock, 2013; Lienert & Larsen, 2006, 2010; Poortvliet et al., 2018; Simha & Ganesapillai, 2017) . Public acceptance is often misused as an excuse to avoid change in the current technology “lock-in” situation, hindering the consideration of more sustainable alternatives that, once implemented, prove their value.

Regulatory aspects are often cited as potential barriers to broader adoption, which emphasize the need for institutional arrangements and new regulatory frameworks to facilitate the mainstreaming of these new sanitation technologies (Beal et al., 2020; D. Fam & Lopes, 2015; Seleman & Bhat, 2016; Yan et al., 2021; Yang et al., 2021). Collaborative policies at local and national levels will be crucial for large-scale transformation in wastewater management. Therefore, to achieve real progress, our institutions' structural barriers must be overcome by ensuring that the claimed benefits of decentralized systems are well understood and aligned through all the necessary stakeholders. Regulators, urban planners, property developers, water utilities, and customers need to be exposed to these new concepts and allow the right conditions to prove these concepts. The pressing climate crisis has already permeated many societal levels leading to wide recognition for a paradigm shift. These emerging solutions offer a more effective response to the escalating challenges and will be well-received as their advantages can be proven (as is happening with potable reuse, solar power, and urban farming).

28.4.6 Financing models

We share the same understanding that reviewer# 2 and financing models should be in place to encourage widespread adoption. We agree that providing upfront subsidies directly to developers would offset their higher CAPEX and level the playing field with traditional systems. This could be in the form of grants, low-interest loans, or tax breaks based on the water and energy savings projected by the system.

Government subsidies could reduce uncertainty regarding adoption levels uncertainty, thereby motivating and therefore encourage suppliers to stimulate the adoption of green technologies (Chemama et al., 2019; Cohen et al., 2015). Fam and Mitchell (2013) argued that local level economic subsidies at the local level are necessary to support the installation of source separation initiatives. Nevertheless, they argued that this economic incentive alone could not ensure a higher and long-term adoption, as because manufacturers tend to be more likely to focus on market size. Therefore,

it's important to acknowledge past experiences with financial incentives. While studies suggest they can influence adoption (Meriggi et al., 2021; Tilley et al., 2014), some existing incentive systems for source separation technologies fell short of attracting residents (D. M. Fam & Mitchell, 2013b; H. Gao et al., 2017; Woods et al., 2013). This highlights the need for careful consideration and realistic expectations when setting subsidy levels. Therefore, the exploration of innovative financing models and tailoring financial incentives to the unique value proposition of DSS, should be considered.

Options like green building certifications, grants, or subsidies specifically designed to consider the long-term savings and benefits of decentralized systems.

4.2.1. Direct subsidies: Grants, low-interest loans, or tax breaks based on projected water and energy savings can directly offset developers' CAPEX, making decentralized systems competitive with traditional approaches.

4.2.2. Shared benefits: Splitting subsidies between developers and occupants incentivizes both parties. Developers can offer lower rents or share OPEX savings, while users enjoy reduced water bills and ecological harvests.

4.2.3. Green building codes/incentive schemes: Regulations requiring or incentivizing decentralized systems in new buildings can shift the market towards sustainability. This clarifies benefits for developers and minimizes risk.

4.2.4. Transparent classification systems: Robust systems like "green star ratings" that accurately assess CAPEX and OPEX benefits can inform decisions for all stakeholders, ensuring fair returns on investments. Even system that could prove an overall reduced maintenance cost and infrastructure upgrades could further incentivize long-term investments.

28.4.7 Subsidies Accounting for externalities.

Beyond direct user benefits, decentralized systems offer broader societal benefits like reduced strain on centralized infrastructure and environmental advantages. Subsidies can factor in these externalities, recognizing the value created beyond individual cost savings. A progressive and coordinated implementation could help to develop improved systems of cost-sharing mechanisms among stakeholders while demonstrating through actual implementations the benefit-cost analysis when compared to the real long-term cost of continuing with the existing inefficient paradigm. This comparison analysis should include externalities like contribution to a circular economy, life cycle benefits, flood and drought resilience, food production, urban landscaping, and overall community benefits, as decentralized solutions offer multiple local values. These comprehensive approaches should be mandatory in project planning and evaluation, and new projects should be supported to give them the chance to prove their claims.

Institutions should not only support and craft new societal frameworks, when necessary, but they should also revise their long-term priorities and assess project development and

decision-making through different lenses. Institutions and other key stakeholders need to gravitate toward long-term and system-wide solutions. The real cost of continuing with the existing paradigm needs to be evaluated with a long-term and circular vision that includes economic, environmental, and societal values, including a holistic optimization of the entire system and its quantifiable externalities (Molinos-Senante et al., 2012, 2014; Sun et al., 2020).

28.4.7.1 First steps: Collaboration with utilities

Including local water utilities in discussions is crucial. Exploring alternative "development fee" structures that consider reduced demand on their systems due to decentralized solutions can create a win-win for developers and utilities. Therefore, an alliance between institutions, public health regulators, and water providers should boost their technical and risk management capabilities and allow the creation of a network of shared experiences and pilot implementations to learn, optimize, and consolidate these solutions as an integral part of a more sustainable urban planning. First, institutions and regulators need to coordinate to allow stronger incentives, facilitate legal requirements, remove barriers across the industry, and, very importantly, they should empower local water and wastewater providers. Local service providers possess the necessary technical and organizational capabilities to lead collaboratively. They should be politically and legally empowered for this role while engaging in the process researchers and technology developers.

28.4.7.2 Evolving collaboration and cost sharing between Stakeholders.

The first key stakeholders, public health regulators, could raise high expectations and demands for these novel decentralized solutions. A higher acceptance bar could not only be justified due to the innovative nature of these approaches but could also help gain public and institutional acceptance. However, increased sampling and monitoring requirements could imply an increased economic burden. Nevertheless, these new solutions are based on decades-long design optimization meant to achieve impressive reductions in energy, chemicals, and biosolids-related costs compared to existing systems (Larsen et al., 2009, 2016; Wald, 2022) which frees enough economic resources to appease conservative and risk-averse voices by offering the highest quality controls. Additionally, the whole industry is entering the so-called fourth revolution (or digitalization era) where remote monitoring solutions, digital twins, soft sensors, systems integrations, IoT, and a long number of innovations are paving the way to not only cheaper but also more efficient monitoring strategies (Garrido-Baserba et al., 2020).

6035 Summarizing, we completely agree that a comprehensive discussion on the main
6036 barriers hindering wider adoption of more sustainable investments, despite their claimed
6037 benefits, is crucial. You raise two valuable points, and we agree that due to their
6038 importance further discussion was necessary. Decentralized systems offer the
6039 opportunity to galvanize the much-needed paradigm shift in the water-energy-food nexus
6040 and could play a pivotal role in helping society navigate the complex challenges posed
6041 by the mounting human-induced environmental crisis.

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28.5 Vertical Farming (Payback 1)

28.5.1 VF payback description

This article proposes a first payback mechanism through indirect savings generated by extremely local, water efficient and completely organic harvests. While food production might not be the first goal of DSSs, the example of local food production will be used to show the potential of the approach. The concept is simple: recover a portion of residents' discarded nutrients and energy on-site (from food, blackwater, and hot water) and enable an efficient use of the nutrients to produce valuable organic harvests able to provide an approximate 10% of the daily needs of the residents (in the form of a healthy salad). This harvest (or daily salad) if sold or priced at market prices (and considering all the related costs to produce it), can indeed provide a payback for the system.

While initial DSS implementations might not use the produced fertilizers for vertical farming (VF), directing them towards landscaping, forestry, or community gardens, the high price on organic local food still offers value. The synergy with VF truly exemplifies the potential and scale of this approach. Studies have shown that source separation techniques, with similar fertilizer production from urine-derived fertilizers and together with energy savings, hold promise for economic feasibility (Chipako & Randall, 2020; M. Gao et al., 2019; Lohman et al., 2020; Volpin et al., 2019; Watabe et al., 2023). Nevertheless, widespread implementation remains elusive.

The main obstacle lies in the long-standing dependency on artificially produced fertilizers*. Their invention, while enabling human progress, led to decades of mass production that drove down costs and stifled serious consideration of nutrient recovery alternatives. Recovering fertilizer from centralized systems cannot compete economically with such an optimized process (Patel et al., 2021; Volpin et al., 2019). Compared to DSS, centralized systems not only lack source separation efficiencies but also require vast land areas to use the fertilizers in situ— a stark contrast to the distributed nature of modular containers throughout the territory. The utilization of the nutrients right at the production center would allow bypassing the need to sell the obtained fertilizers at uncompetitive market prices and grow, instead, a high-valued harvest that can support the system's payback.

*The latest report from the United Nations Food and Agriculture Organisation (FAO) estimates that between 2015 and 2018, the world demand for fertilisers (N, P₂O₅, K₂O) has increased, on an average, 1.8 percent per annum (FAO, 2017). As in 2015, the demand was estimated to be 184'017'000 tonnes, every year the fertiliser consumption increases of about 3'351'300 tonnes. With a world population expected to reach 11.2 billion people by 2100, this trend is expected to keep rising (United Nations, 2017). The rise in the need for fertilisers would affect both the raw material availability as well as the greenhouse gas (GHG) emissions and eutrophication.

Typical wastewater treatment plants biosolids often include the leftover nutrients recovered from centralized systems. They are use in agriculture as fertilizer, but they involve further drawbacks:

transportation, contamination runoff, low purity, and they are mostly attached to practices such as pesticide and herbicide use, inefficient water usage (>90% water consumption compared to VF), poor labor conditions, weather dependence, and more. Conversely, the DSS minimizes solid waste production, recovers a larger portion of nutrients, eliminates transportation needs, uses less than the 3% of the DSS-treated water, avoids pesticides, offers maximized control, is weather-resilient, and employs skilled labor. Therefore, even excluding these positive externalities from cost calculations, the revenue generated from the harvested produce, even if it constitutes only a portion of residents' total food consumption, is sufficient to support the system's payback.

6095 Table S28-7: Production of the vertical farming at market price.

6096

	Romaine lettuce	Strawberries	Spinach	Tomatoes (cherry)	Total
% of plants	0.36	0.25	0.01	0.39	1.00
Total plants per type	9,784.74	9,086.76	273.91	7,194.02	
Harvest cycle (days)	25.00	120.00	35	150	
Fruit/plant (g/lettuce;strawberries/plant)	140.00	300.00	40	1650	
Harvest kg/yr	20,000.00	8,291.67	114.26	28,883.98	
Per capita consumption (kg/yr)	10.00	4.15	1.08	9.40	
All PE consumption (kg/yr)	20,000	8,291	2,168	18,800	231,184
Consumer price (€/kg)	3.20	6.02	8.4	4.06	
Sales (€/yr)	0.00	0.00	17,252.87	40,940.95	
mcu	1.00	2.32	5.93	2.38	
Savings vegetables/fruit per capita/yr	32.00	24.96	9.11	38.16	
MCT (€/yr)	107,979	OBJ CELL		Total sales (€/yr)	40,940
	Romaine lettuce	Strawberries	Spinach	Tomatoes (cherry)	
m2	27,557	11,425	157	39,797	1,984
Acres	6.810	2.823	0.03890	9.836	0.490
container eq.	5.45	2.26	0.03	7.87	0.39
	55,555.56	23,032.41	317.39	80,233.27	4000
					TOTAL
If SOLD (\$/year)	64,000.	49,915	959	117,268	232,144
%	27.57	21.50	0.41	50.52	
\$/m3	0.827	0.6450	0.0124	1.515	

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6099

6100 Table S28-8: Total initial costs (CapEx) and operational costs (OpEx) for the vertical farming when including
 6101 production at market price.

6102

Pay Back VF		
CAPEX TOTAL (€)	2,468,709	\$
OPEX (€/yr)	102,730	\$/year
OPEX TOTAL (€)	628,965	\$
Total [30 years]	3,097,675	\$
	CAPEX - Benefit (if sold at Market price)	
NET Benefit:	1,100,319	\$
Time for payback CAPEX	16	Years
Benefit if all is sold at Market price		
If SOLD (\$/year)		
64,000	Romaine lettuce	
49,916	Strawberries	
960	Spinach	
117,269	Tomatoes (cherry)	
232,145	\$/year	
40,941	\$/year (sold extra tomato and lettuce)	
4,197,994	benefits after 30 years	
r=0.05		

6103

6104

6105

6106 **28.6 Solar Photovoltaic (Payback 2)**

6107 Photovoltaics (PV): Payback period would range from 6 to 15 years depending on
 6108 location. Assuming PV energy is free after the PV's payback, the payback of the
 6109 decentralized source separation system could be further shortened.

6110

6111 *Table S28-9: Total initial costs (CapEx) and operational costs (OpEx) for the photovoltaic installation and*
 6112 *expected payback periods for the different locations.*

6113

Total demand (kWh/yr)	Water reuse system	VF	Domestic energy use	Total	% covered off grid	kWh/year	\$/Year	\$ [30 years]	\$ [30 years] r:0.05
Barcelona	111,678	15,521	10,712,000	10,839,200	10	1,135,260	268,943	8,068,293	4,134,315
Amsterdam	111,678	15,521	13,426,000	13,553,200	4	486,540	115,261	3,457,840	1,771,849
Chile (Santiago)	111,678	15,521	7,760,000	7,887,200	12	973,080	230,523	6,915,680	3,543,698
Hong Kong	111,678	15,521	12,166,000	12,293,200	9	1,135,260	268,943	8,068,293	4,134,315
Seoul	111,678	15,521	20,994,000	21,121,200	8	1,783,980	422,625	12,678,746	6,496,780
Toronto	111,678	15,521	31,176,000	31,303,200	3	810,900	192,102	5,763,066	2,953,082
Miami	111,678	15,521	25,988,000	26,115,200	11	2,838,150	672,358	20,170,732	10,335,786
Payback									
	Years for pay back	SOLAR CAPEX	Benefits (in 30 years) after payback	Total Benefits [30 years]	SOLAR OPEX [30 years]	OPEX \$/year	Benefits (in 30 years) after payback - CAPEX - OPEX		
Barcelona	17	3,043,618	1,090,696	4,134,315	232,806	15,144	857,890	Barcelona	
Amsterdam	40	3,043,618	-1,271,769	1,771,849	99,774	6,490	-1,371,543	Amsterdam	
Chile (Santiago)	22	3,043,618	500,080	3,543,698	199,548	12,981	300,532	Chile (Santiago)	
Hong Kong	17	3,043,618	1,090,696	4,134,315	232,806	15,144	857,890	Hong Kong	
Seoul	9	3,043,618	3,453,162	6,496,780	365,838	23,798	3,087,323	Seoul	
Toronto	30	3,043,618	-90,537	2,953,082	166,290	10,817	-256,827	Toronto	
Miami	6	3,043,618	7,292,168	10,335,786	582,015	37,861	6,710,153	Miami	
AVG	20		1,723,499	4,767,118	268,440	17,462	1,455,060		

6114

6115

6116 **28.7 Providing potable Water (Payback 3)**

6117

6118 *Table S28-10: Total initial costs (CapEx) and operational costs (OpEx) for the rainwater installation and*
6119 *expected payback periods for the different locations.*

6120

	Rainwater CAPEX	Total Benefits [30 years]	Benefits (in 30 years) after payback	Unit
Barcelona	58,571	86,997	28,426	\$
Amsterdam	58,571	218,243	159,672	\$
Chile (Santiago)	58,571	36,626	-21,945	\$
Hong Kong	58,571	538,144	479,573	\$
Seoul	58,571	43,675	-14,896	\$
Toronto	58,571	253,821	195,250	\$
Miami	58,571	257,838	199,267	\$
	AVERAGE	% of yearly covered demand	€ saved per city/yr	Water /Price \$/m3
Concepción (Chile)	337.28	20.53	4,047.34	1
Temuco (Chile)	595.76	36.26	7,149.17	1
Santiago (Chile)	207.83	12.65	2,494.01	1
Barcelona	246.83	15.02	5,923.87	2
Amsterdam	339.29	20.65	14,860.81	3.65
Hong Kong	734.05	44.68	36,643.88	4.16
Toronto	339.69	20.67	17,283.43	4.24
Seoul	495.67	30.17	2,974.00	0.5
Miami	447.43	27.23	17,557.00	3.27

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6122

28.8 Avoiding centralized system expansion: (Payback 4)

This article proposes an even more exciting second payback mechanism: avoided cost in potable water production. Similar to how separating blackwater facilitates nutrient recovery through energy-generating systems, separating greywater allows 80% of household wastewater to be cheaply purified to drinking water quality. This has two major implications:

Traditional water infrastructure is outdated and unsustainable: The current system of collecting, purifying, and transporting water relies on crumbling infrastructure designed for different weather and hydrological conditions. As droughts become more frequent, this outdated system struggles to keep up, requiring constant investment and failing to adapt to changes.

Potable water reuse is a growing trend: From California's recent legislation allowing full-scale potable reuse to similar initiatives in drought-stricken regions like Spain and Brazil, regulations are rapidly evolving to embrace direct and indirect potable water reuse.

While directly comparing the DSS to traditional water production (sourced from reservoirs, groundwater, etc.) is practically impossible, it can be effectively compared to the functionality of direct and indirect potable water initiatives (DPR or IPR). Even if the comparison only applies to these specific applications, the rapid growth of this field makes the discussion highly relevant. Here's why the DSS offers two advantages:

2.1) Cheaper potable water production: While both the DSS and DPR (or desalination plants too) primarily use Reverse Osmosis (RO) technology, the source-separated stream in the DSS enables more efficient treatment. So, even if desalination becomes cheaper, the same improved technology can be applied to the DSS for purification, which treats an easier to purify water (greywater has fewer ions and cations than seawater and 10 times less pollutants than raw wastewater).

2.2) Avoiding centralized system expansion: reuse avoids expanding the centralized system, which is crucial considering the significantly higher unit costs of adding capacity compared to the average costs used in the centralized system comparison. This is important because expanding existing systems is much more expensive per unit of water than the average cost used in comparisons. This underestimates the economic value of the DSS, as it doesn't reflect the higher incremental cost of expanding the centralized system, which is offset by the additional capacity provided by the decentralized DSS.

observations where we see a rapidly changing landscape with an unstoppable growth of direct and indirect potable reuse projects around the globe meant to tackle the growing challenges providing potable water and to address climate change impacts on water supplies, ranging from changes in weather patterns, droughts, groundwater depletion, salt intrusion, failing infrastructure, etc.

We have rephrased the statement to ensure that comparison is only done for those cases that potable reuse is also done. While recycling domestic water for drinking purposes potable reuse is still not widely use, its implementation is already far from an infancy state, as exemplified by the enacted new laws in Colorado (Colorado.gov) and California (Waterboard.gov) that allow local water agencies to take wastewater and put it right back into the drinking water system after the corresponding treatment. Many other states (e.g., Arizona, Nevada, and New Mexico) and a plethora of many other countries around the world (i.e., Spain, Greece, etc.) are actively working to pass new legislation, triggered by historical drought in southern Europe, south America, and east Africa. Although the concept may seem new and while not yet ubiquitous, there are already mass-scale implementations of potable reuse projects, including examples such as the mentioned in Singapore, but also as Orange County (CA), Los Angeles (CA), San Diego (CA), Windhoek (Namibia), Wichita Falls (TX), and Altamonte Springs (FL), Queensland (AUS), Victoria (AUS), and Israel among others (OCWD, 2021; Van Rensburg, 2016; Tortajada and Nambiar, 2019; WRF, 2019; Watereuse, 2019). For example, according to Water Reuse Association estimates that the number of potable reuse projects worldwide could increase from around 100 currently to over 500 by 2035 and according to global Water Recycle and Reuse this market is expected to reach USD 30.5 Billion by 2030, growing at 14.1%. Figure 1 shows only a fraction of the projects that were projected by the EPA report the year 2019. While challenges exist, the growth potential for potable reuse projects is significant due to the increasing need for sustainable water management solutions. As technology advances, costs decrease, and public perception improves, we can expect to see a continued rise in the number and scale of these projects worldwide.

World Health Organization; Potable reuse:
Guidance for producing safe drinking water (2017)



https://www.epa.gov/sites/default/files/2018-01/documents/potablereusecompendium_3.pdf

Table S28-11. Direct and Indirect Potable Reuse Projects around the world based on 2017 EPA report:

https://www.epa.gov/sites/default/files/2018-01/documents/potablereusecompendium_3.pdf

Furthermore, the comparison to direct or indirect Potable Reuse (DPR) is triggered by the fact that the Decentralized Source Separation systems taps in the territory of potable water recycling. The connection has been further explored in comment#1. While the DSS function is to manage wastewater by recovering nutrients and recycling water, the latter is not just more efficiently obtained through the application of source separation concept but also goes a step further and it can achieve drinking water quality.

Therefore, when the same functionality is considered (i.e., providing drinking-quality water without developing new forms of traditional supplies), the DSS has the potential to drastically decrease the overall treatment cost when compared to growing implementations of the conventional treatment followed by direct or indirect potable reuse, an alternative that is expected to steadily growing as climate changes impacts water supplies. DSS could offering a powerful alternative, or complementary tool, to centralized approaches by not only providing clean water but also fostering resource recovery and a circular economy, paving the way for a more sustainable water future.

References:

- https://www.waterboards.ca.gov/press_room/press_releases/2023/pr20231219-dpr-regulations-adoption.pdf
- https://cdphe.colorado.gov/Regulation_11_Direct_Potable_Reuse
- WateReuse Association: WateReuse Association Website: <https://www.watereuse.org/>
- International Desalination Association: International Desalination Association Website: <https://idadesal.org/>

6211 ▪ US Environmental Protection Agency: EPA Potable Water Reuse Website:
6212 <https://www.epa.gov/ground-water-and-drinking-water/potable-water-reuse-and->
6213 [drinking-water](https://www.epa.gov/ground-water-and-drinking-water/potable-water-reuse-and-)

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6236

6237

6238

6239

6240 **29 Bibliography**

6241

6242 Ariunbaatar, J., Bair, R., Ozcan, O., Ravishankar, H., Esposito, G., Lens, P.N.L., Yeh, D.H., 2021.
6243 Performance of AnMBR in Treatment of Post-consumer Food Waste: Effect of Hydraulic
6244 Retention Time and Organic Loading Rate on Biogas Production and Membrane Fouling.
6245 Front. Bioeng. Biotechnol. 8, 1–15. <https://doi.org/10.3389/fbioe.2020.594936>

6246 Casey, E., Syron, E., Shanahan, J.W., Semmens, M.J., Syron, E., Shanahan, J.W., 2008.
6247 Comparative economic analysis of full scale MABR configurations Comparative economic
6248 analysis of full scale MABR configurations. IWA North Am. Membr. Res. Conf. Univ.
6249 Massachusetts, Amherst, USA 1–7.

6250 Chipako, T.L., Randall, D.G., 2020. Investigating the feasibility and logistics of a decentralized
6251 urine treatment and resource recovery system. J. Water Process Eng. 37, 101383.
6252 <https://doi.org/10.1016/j.jwpe.2020.101383>

6253 Courtens, E.N.P., Meerburg, F., Mausen, V., Vlaeminck, S.E., 2014. When the smoke disappears:
6254 dealing with extinguishing chemicals in firefighting wastewater. Water Sci. Technol. 69,
6255 1720–1727. <https://doi.org/10.2166/wst.2014.081>

6256 de Graaff, Temmink, H., Zeeman, G., Buisman, C.J.N., 2010. Anaerobic Treatment of
6257 Concentrated Black Water in a UASB Reactor at a Short HRT. Water 2, 101–119.
6258 <https://doi.org/10.3390/w2010101>

6259 De Paepe, J., Lindeboom, R.E.F., Vanoppen, M., De Paepe, K., Demey, D., Coessens, W.,
6260 Lamaze, B., Verliefde, A.R.D., Clauwaert, P., Vlaeminck, S.E., 2018. Refinery and
6261 concentration of nutrients from urine with electrodialysis enabled by upstream precipitation
6262 and nitrification. Water Res. 144, 76–86. <https://doi.org/10.1016/j.watres.2018.07.016>

6263 De Paepe, J., Pryck, L. De, Verliefde, A.R.D., Rabaey, K., Clauwaert, P., 2020. Electrochemically
6264 Induced Precipitation Enables Fresh Urine Stabilization and Facilitates Source Separation.
6265 <https://doi.org/10.1021/acs.est.9b06804>

6266 Etter, B., Tilley, E., Khadka, R., Udert, K.M., 2011. Low-cost struvite production using source-
6267 separated urine in Nepal. Water Res. 45, 852–862.
6268 <https://doi.org/10.1016/j.watres.2010.10.007>

6269 Fletcher, H., Mackley, T., Judd, S., 2007. The cost of a package plant membrane bioreactor.
6270 Water Res. 41, 2627–2635. <https://doi.org/10.1016/j.watres.2007.02.038>

6271 Foglia, A., Akyol, Ç., Frison, N., Katsou, E., Eusebi, A.L., Fatone, F., 2020. Long-term operation
6272 of a pilot-scale anaerobic membrane bioreactor (AnMBR) treating high salinity low loaded

6273 municipal wastewater in real environment. *Sep. Purif. Technol.* 236, 116279.
6274 <https://doi.org/10.1016/j.seppur.2019.116279>

6275 Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, 2016. Guideline: Vacuum
6276 sewer systems.

6277 Gouveia, J., Plaza, F., Garralon, G., Fdz-Polanco, F., Peña, M., 2015. Long-term operation of a
6278 pilot scale anaerobic membrane bioreactor (AnMBR) for the treatment of municipal
6279 wastewater under psychrophilic conditions. *Bioresour. Technol.* 185, 225–233.
6280 <https://doi.org/10.1016/j.biortech.2015.03.002>

6281 Gritti, M.C., 2019. From Earth To Space and Back - Nutrient Recovery From Urine for a Circular
6282 Economy 2018–2019.

6283 Kujawa-Roeleveld, K., Zeeman, G., 2006. Anaerobic Treatment in Decentralised and Source-
6284 Separation-Based Sanitation Concepts. *Rev. Environ. Sci. Bio/Technology* 5, 115–139.
6285 <https://doi.org/10.1007/s11157-005-5789-9>

6286 Lema, J.M., Martinez, S.S. (Eds.), 2017. Innovative wastewater treatment & resource recovery
6287 technologies: impacts on energy, economy and environment. International Water
6288 Association publishing.

6289 Lin, H., Chen, J., Wang, F., Ding, L., Hong, H., 2011. Feasibility evaluation of submerged
6290 anaerobic membrane bioreactor for municipal secondary wastewater treatment.
6291 *Desalination* 280, 120–126. <https://doi.org/10.1016/j.desal.2011.06.058>

6292 Liu, R., Huang, X., Chen, L., Wen, X., Qian, Y., 2005. Operational performance of a submerged
6293 membrane bioreactor for reclamation of bath wastewater. *Process Biochem.* 40, 125–130.
6294 <https://doi.org/10.1016/j.procbio.2003.11.038>

6295 Lo, C.H., McAdam, E., Judd, S., 2015. The cost of a small membrane bioreactor. *Water Sci.*
6296 *Technol.* 72, 1739–1746. <https://doi.org/10.2166/wst.2015.394>

6297 Lozano, J., Sabaté, F., Subiranas, J., 2007. Anàlisi comparativa dels processos emergents
6298 SHARON i ANAMMOX pel tractament d'aigües amb una alta càrrega de nitrogen 1–116.

6299 Maurer, Scheidegger, A., Herlyn, A., 2013. Quantifying costs and lengths of urban drainage
6300 systems with a simple static sewer infrastructure model. *Urban Water J.* 10, 268–280.
6301 <https://doi.org/10.1080/1573062X.2012.731072>

6302 Maurer, Wolfram, M., Anja, H., 2010. Factors affecting economies of scale in combined sewer
6303 systems. *Water Sci. Technol.* 62, 36–41. <https://doi.org/10.2166/wst.2010.241>

6304 Mazuki, N.I., Teow, Y.H., Ho, K.C., Mohammad, A.W., 2020. Techno-economic analysis of single
6305 disinfection units and integrated disinfection systems for sewage effluent reclamation. *J.*
6306 *Water Process Eng.* 36, 101398. <https://doi.org/10.1016/j.jwpe.2020.101398>

6307 Metcalf, Eddy, 2013. Wastewater Engineering: Treatment and Resource Recove.

6308 Pretel, R., Robles, A., Ruano, M. V., Seco, A., Ferrer, J., 2014. The operating cost of an anaerobic
6309 membrane bioreactor (AnMBR) treating sulphate-rich urban wastewater. *Sep. Purif.*
6310 *Technol.* 126, 30–38. <https://doi.org/10.1016/j.seppur.2014.02.013>

6311 Ribera-Pi, J., Campitelli, A., Badia-Fabregat, M., Jubany, I., Martínez-Lladó, X., McAdam, E.,
6312 Jefferson, B., Soares, A., 2020. Hydrolysis and Methanogenesis in UASB-AnMBR Treating
6313 Municipal Wastewater Under Psychrophilic Conditions: Importance of Reactor Configuration
6314 and Inoculum. *Front. Bioeng. Biotechnol.* 8. <https://doi.org/10.3389/fbioe.2020.567695>

6315 Roefs, I., Meulman, B., Vreeburg, J.H.G., Spiller, M., 2017. Centralised, decentralised or hybrid
6316 sanitation systems? Economic evaluation under urban development uncertainty and phased
6317 expansion. *Water Res.* 109, 274–286. <https://doi.org/10.1016/j.watres.2016.11.051>

6318 S. Puig, personal communication, 2017, n.d.

6319 Shin, C., McCarty, P.L., Kim, J., Bae, J., 2014. Pilot-scale temperate-climate treatment of
6320 domestic wastewater with a staged anaerobic fluidized membrane bioreactor (SAF-MBR).
6321 *Bioresour. Technol.* 159, 95–103. <https://doi.org/10.1016/j.biortech.2014.02.060>

6322 Shoener, B.D., Zhong, C., Greiner, A.D., Khunjar, W.O., Hong, P.Y., Guest, J.S., 2016. Design of
6323 anaerobic membrane bioreactors for the valorization of dilute organic carbon waste streams.
6324 *Energy Environ. Sci.* 9, 1102–1112. <https://doi.org/10.1039/c5ee03715h>

6325 Siciliano, A., Limonti, C., Curcio, G.M., Molinari, R., 2020. Advances in struvite precipitation
6326 technologies for nutrients removal and recovery from aqueous waste and wastewater.
6327 *Sustain.* 12. <https://doi.org/10.3390/su12187538>

6328 Tarragó, E., Puig, S., Rusalleda, M., Balaguer, M.D., Colprim, J., 2016. Controlling struvite
6329 particles' size using the up-flow velocity. *Chem. Eng. J.* 302, 819–827.
6330 <https://doi.org/10.1016/j.cej.2016.06.036>

6331 Van Voorthuizen, E.M., Zwijnenburg, A., Wessling, M., 2005. Nutrient removal by NF and RO
6332 membranes in a decentralized sanitation system. *Water Res.* 39, 3657–3667.
6333 <https://doi.org/10.1016/j.watres.2005.06.005>

6334 Verrecht, B., Maere, T., Nopens, I., Brepols, C., Judd, S., 2010. The cost of a large-scale hollow
6335 fibre MBR. *Water Res.* 44, 5274–5283. <https://doi.org/10.1016/j.watres.2010.06.054>

6336 Wang, K.M., Cingolani, D., Eusebi, A.L., Soares, A., Jefferson, B., McAdam, E.J., 2018a.
6337 Identification of gas sparging regimes for granular anaerobic membrane bioreactor to enable
6338 energy neutral municipal wastewater treatment. *J. Memb. Sci.* 555, 125–133.
6339 <https://doi.org/10.1016/j.memsci.2018.03.032>

6340 Wang, K.M., Jefferson, B., Soares, A., McAdam, E.J., 2018b. Sustaining membrane permeability
6341 during unsteady-state operation of anaerobic membrane bioreactors for municipal

6342 wastewater treatment following peak-flow. J. Memb. Sci. 564, 289–297.
 6343 <https://doi.org/10.1016/j.memsci.2018.07.032>

6344 Wen, X. hua, Xing, C. hong, Qian, Y., 1999. A kinetic model for the prediction of sludge formation
 6345 in a membrane bioreactor. Process Biochem. 35, 249–254. [https://doi.org/10.1016/S0032-](https://doi.org/10.1016/S0032-9592(99)00058-8)
 6346 9592(99)00058-8

6347 Xing, Wen, X.-H., Qian, Y., Tardieu, E., 2001. Microfiltration-membrane-coupled bioreactor for
 6348 urban wastewater reclamation. Desalination 141, 63–73. [https://doi.org/10.1016/S0011-](https://doi.org/10.1016/S0011-9164(01)00389-7)
 6349 9164(01)00389-7

6350 Xing, Wu, W.-Z., Qian, Y., Tardieu, E., 2003. Excess Sludge Production in Membrane Bioreactors:
 6351 A Theoretical Investigation. J. Environ. Eng. 129, 291–297.
 6352 [https://doi.org/10.1061/\(ASCE\)0733-9372\(2003\)129:4\(291\)](https://doi.org/10.1061/(ASCE)0733-9372(2003)129:4(291))

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