Supplementary information

Evaluation of the integration of P recovery, polyhydroxyalkanoate production and short cut nitrogen removal in a mainstream wastewater treatment process

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Table S1. Configuration of the four reactors of the pilot plant with 8 h cycle length.

R1-HET (heterotrophic SBR)		**R2-AUT** (autotrophic SBR)	
Time (min)	Phase	Time (min)	Phase
0 - 37	Feeding from influent	0 - 178[1]	Aerobic
37 – 175	Anaerobic	178[1]- 233	Settling
175-180	Purge	233 - 261	Extraction to R1-HET
180 - 205	Settling	261 - 285	Feeding from R4-INT
205 - 233	Extraction to R4-INT	287 - 290	Purge to R1-HET
233 - 261	Feeding from R2-AUT + R3-PRE	290 - 480	Idle
261 - 301	Anoxic		
301 - 421	Aerobic		
421 - 451	Settling		
451 - 480	Extraction to effluent		
R3-PRE (precipitation reactor)		**R4-INT** (interchange vessel)	
Time (min)	Phase	Time (min)	Phase
205 – 233	Settling	205 – 233	Feeding from R1-HET
233 - 245	Extraction to R1-HET	233 - 245	Idle
245 – 255	Feeding from R4-INT	245 - 255	Extraction to R3-INT
255 – 205[2]	Precipitation: Mg^{2+} addition	261 - 285	Extraction to R2-AUT
		285 – 205[2]	Idle

[1]Maximum value (the real value depends on the control of the aeration phase length)

[2]Time of the following cycle

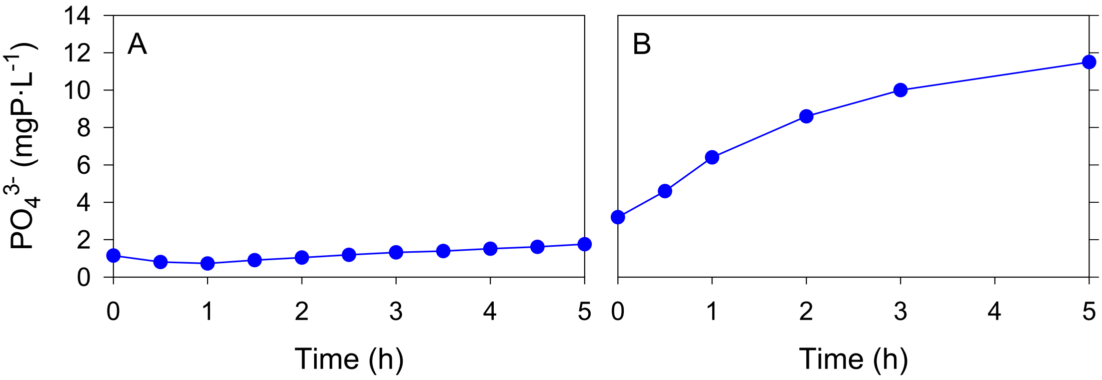

Figure S1. P-release activity tests in the anaerobic phase of R1-HET. A: no VFA addition. B: Addition of acetic acid (100 mg COD·L^{-1}).

Anaerobic EBPR activity was low without external acid acetic dosage due to the limited COD available in the influent. P-release was very low, almost negligible, even after 5 hours of anaerobic conditions. When 100 mg COD·L^{-1} of acetic acid were added at the start of the anaerobic phase, anaerobic EBPR activity was enhanced and the soluble PO_4^{3-}-P concentration increased from 3.2 to 11.5 mg·L^{-1}.

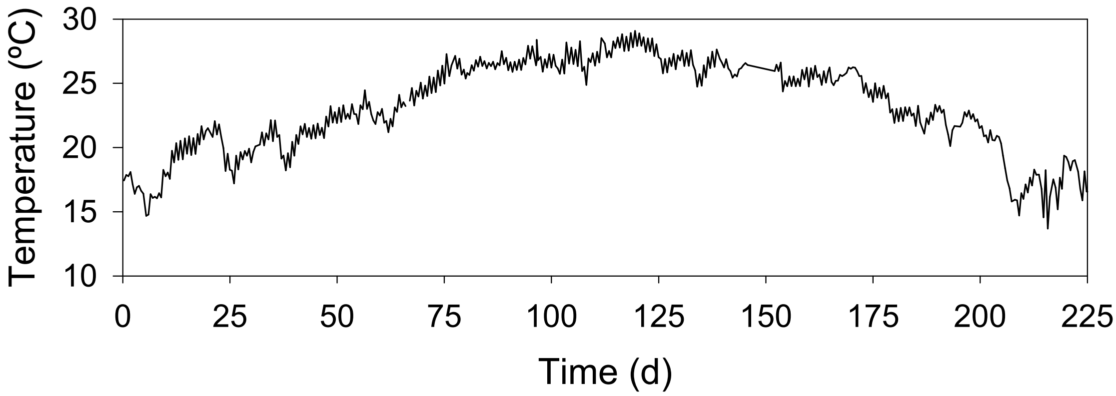

Figure S2. First long-term monitoring period. Temperature profile for R1-HET.

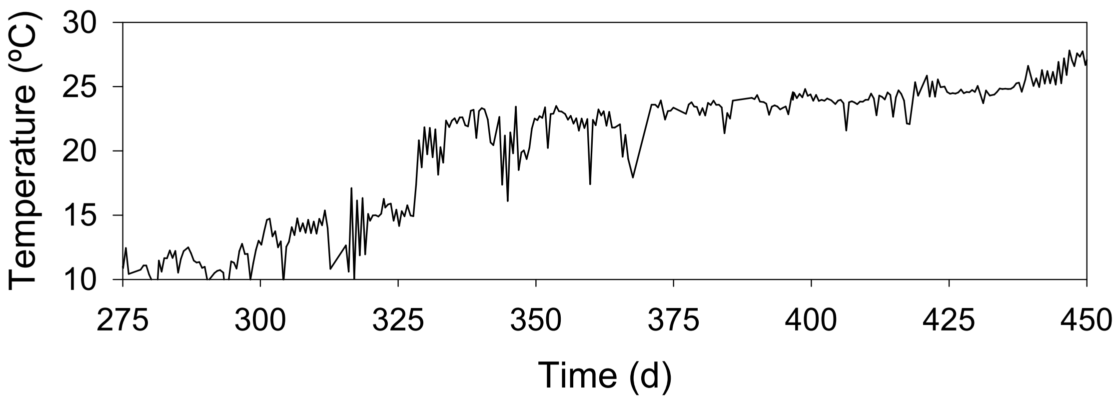

Figure S3. Second long-term monitoring period. Temperature profile for R1-HET.

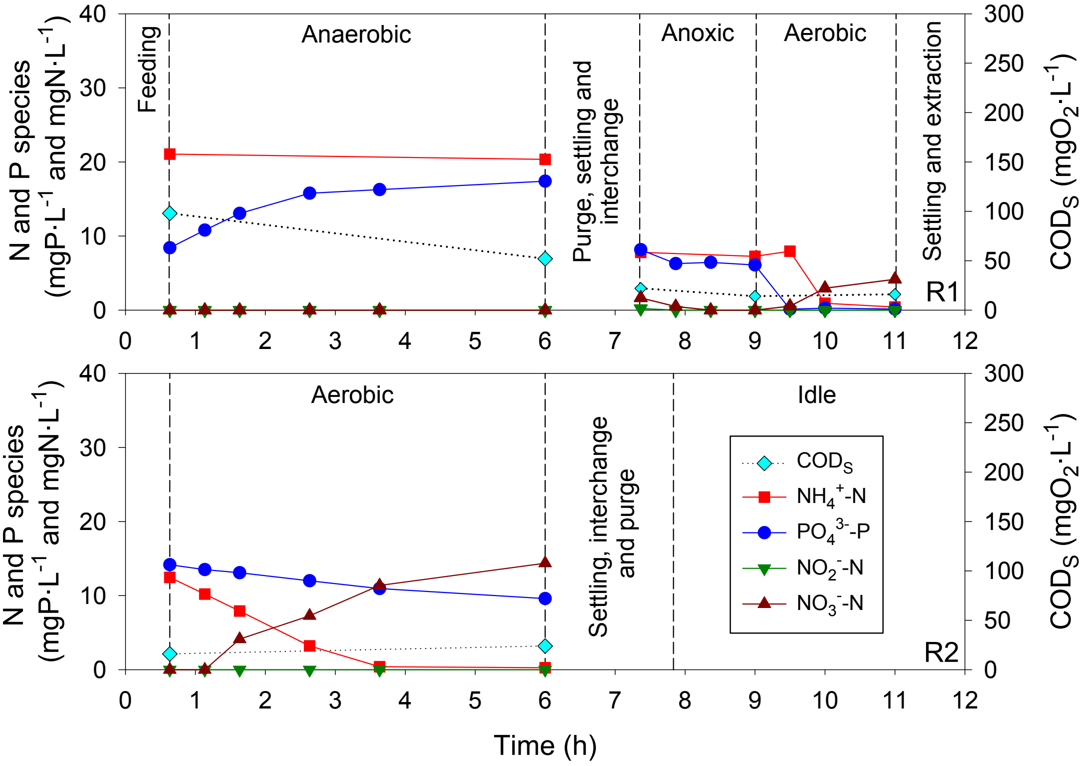

Figure S4. SCEPPHAR cycle with complete nitrification obtained at day 362 of operation for R1-HET and R2-AUT.

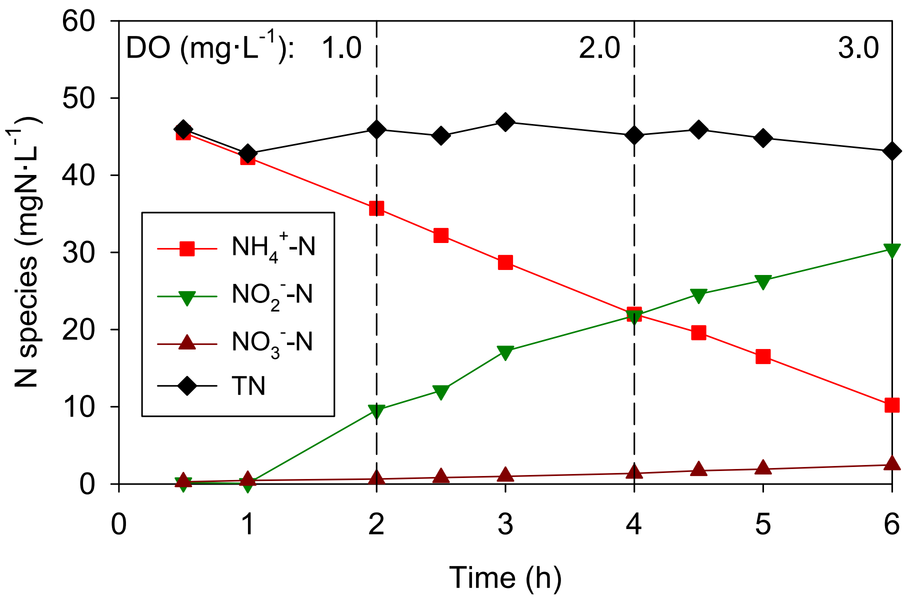

Figure S5. Experimental ammonium, nitrite and nitrate concentrations at different DO values.

Economic evaluation of the mainstream SCEPPHAR configuration

MATERIALS AND METHODS

SCEPPHAR technology was benchmarked against a conventional full-scale WWTP with an A^2/O configuration. The plant was designed to treat the average raw wastewater composition (see Table S2) for the period 2016-2017 of the municipal WWTP of Manresa with an average inflow of 21840 m^3d^{-1}. The major design assumptions were: (i) primary and secondary settlers are not needed for SCEPPHAR plant while they are considered for the A^2/O plant, (ii) there are three independent SCEPPHAR process lines to guarantee continuous operation and ease of maintenance, and (iii) just one warehouse spare equipment unit (i.e. blower and pumps) for all process lines is purchased as a backup. The standard handbook of Metcalf&Eddy (Tchobanoglous et al., 2014) was used for design of cylindrical settlers (Table 5-19), biomass growth and aeration requirements (equations in Table 8-10 and design procedure in Table 8-21), SBR parameters (Example 8-5 adapted to the SCEPPHAR case) and sludge treatment by digestion, cogeneration and dewatering units (Example 13-5). Calculations were performed in a Python script with a dimensional unit control. The code is available upon request and enables to reproduce the results relative to the economic evaluation presented in this study.

Plant costing was evaluated with the net present value (NPV) (equation S1) and internal rate of return (IRR) performance. IRR was calculated by solving the non-linear equation S2, which was obtained from equation S1 setting the NPV to zero.

$$NPV = CF_0 + \sum_{n=1}^{T} \frac{CF_n}{(1+i)^n} \qquad \text{(S1)}$$

$$0 = CF_0 + \sum_{n=1}^{T} \frac{CF_n}{(1+IRR)^n} \qquad \text{(S2)}$$

CF_n is the cash flow in year n, T is project life in years and i is the interest (or discount) rate.

We followed the guidelines of the European Commission for cost-benefit analysis in the water supply/sanitation sector (European Commission, 2014) and set for both technologies a project life and an interest rate of 30 years and 4%, respectively. We assumed that the plant was built at time zero, thus capital expenditures (CAPEX) were not distributed over the construction period (CAPEX equals CF_0). Such a practice often causes less than 5% error in evaluating project alternatives (Garrett, 1989). The cash-flow term CF_n is a sum of annual incomes and operational expenditures (OPEX). CAPEX is the sum of total module equipment costs (TM), where this last is estimated as a free on board (FOB) equipment cost multiplied by an installation factor (L), which accounts for costs of labour, freight, insurance, indirect, contractor fees, contingencies and start-up. Both CAPEX and OPEX estimates for equipment are scale dependent with an overall accuracy of ±50% (Towler and Sinnott, 2013). An overview of the major equipment FOB costs and installation factors used for our study is given in Table S3, while the costs relative to items and chemicals are given in Table S4. All the cost values given in US Dollar ($) were converted to Euro (€) by applying the $ to € Foreign Exchange Rate (DEXUSEU). Historical equipment cost estimates were updated to year 2019 within the Chemical Engineering Plant Cost Index (CE), which is reported in Figure S6. CE values for 2018 and 2019 were estimated with a correlation model (Mignard, 2014) with two exogenous variable: crude oil prices and interest rate on U.S. bank prime loans. We assumed that for the wastewater treatment sector, any equipment cost relative to the U.S. Gulf Coast (USGC) was approximately equal to any location inside the European zone and, thus, location factors were not applied as it is the case for the chemical industry.

Incomes were derived from the net production of electricity (i.e. biogas) and wastewater tariff. Taxes deductions on incomes were not accounted for (i.e. pre tax-NPV). We assumed an average Spanish wastewater tariff of 0.73 €/m^3 (Gallego Valero et al., 2018) and electricity price of 0.1098 €/kWh (Eurostat, non-household consumers, second half 2018). Cash-flows relative to struvite were calculated, although they were negligible compared to the other costs. The total incomes were heavily dependent on the tariff value. We performed a screening analysis to find the tariff value that would give an IRR of 4%. We did not account for any grant or project co-financing. PHA recovery incomes were excluded because of the low PHA-sludge concentrations found in the current pilot-plant SCEPPHAR set-up. However, we accounted for the increase in biogas production in relation to the PHA concentration in the sludge by assuming that 0.59, 0.45, 0.65 Nm^3 of methane was produced for each kg of VSS removed relative to proteins, carbohydrate and PHA, respectively (Chan et al., 2020). Primary and activated sludge content of proteins for the A^2/O was set to 35%, while in case of SCEPPHAR proteins was 32% and PHA was 9%.

The main OPEX costs were electrical energy consumption, equipment maintenance, sludge treatment/disposal and personnel. Sludge transportation costs were not considered since we assumed that digestate was taken by nearby farmers. We assumed that no external thermal energy was needed for digester heating because the cogeneration unit (CHP) provided the necessary heat from burning the biogas. Equipment maintenance costs were related to TM costs: 1% for tanks; 3% for pumps with low TSS concentrations, settlers, mixers and blowers; 6% for pre-treatment and sludge pumps. Higher ratios between maintenance and TM costs were given to equipment that work under harsh conditions. After 10 years of workhours, pumps, mixers, blowers and diffusers were replaced (FOB cost). The annual insurance premium was fixed to 1% of equipment TM costs. External carbon addition was not accounted in OPEX since the ratio between the readily biodegradable carbon (i.e. VFA, BOD5, etc.) to TP concentration was considered high enough to promote P-removal (Tchobanoglous et al., 2014).

RESULTS AND DISCUSSION

The feasibility study for SCEPPHAR and A^2/O with a wastewater tariff of 0.73 €/m^3 is presented in Figure S7. The NPVs for SCEPPHAR and A^2/O were 58.2 and 63.4 M€, respectively. IRR was very positive for both SCEPPHAR and A^2/O: 21% and 29%, respectively, due to the high tariff of 0.73 €/m^3 applied. The slightly better outcome for the A^2/O technology was mainly due to its lower CAPEX cost (15.9 M€) compared to SCEPPHAR (21.8 M€). SCEPPHAR is a discontinuous process, and hence all the liquid/gas displacement units such as pumps, blowers and diffusers need to have a higher flow capacity than the A^2/O equipment (Figure S8). The cost advantage of missing settler units in SCEPPHAR was off-set by the higher total tank volumes and mixing units. Cost of piping was 15% higher for SCEPPHAR than A^2/O because of its more complex liquid interchange system.

In relation to OPEX (Figure S9), both had similar sludge treatment and disposal costs (55% of total OPEX). If we consider only the mainstream related OPEX, costs were higher for SCEPPHAR because the maintenance costs were proportional to TM costs. The electricity consumption was similar, around 0.22 kWh/m^3. Pumping pressure heads (losses) for SCEPPHAR were higher than for A^2/O because of the SBR height (6 m) with filling and discharge periods, but on the other hand, aeration costs were lower because of the higher efficiency of nutrient removal per energy use. The workload of employees was similar but insurance costs were higher for SCEPPHAR because of its higher CAPEX.

The screening over the wastewater tariff in relation to IRR is shown in Figure S10. An interest rate of 4% was obtained if the tariff was set to 0.27 and 0.31 €/m^3 for A^2/O and SCEPPHAR, respectively. Those values were close to the current tariff of 0.23 €/m^3 applied in the WWTP of Manresa. Note, that the current tariff does not account for the CAPEX of the plant, but it only covers its OPEX. On the other hand, our scenario assumes that the tariff should cover both the costs without any grant or co-financing. If we set the new more realistic tariffs, the share of incomes from biogas for A^2/O increases from 4.9 to 10.7%, while for SCEPPHAR increases from 6.1 to 14.9%.

The feasibility study shows that SCEPPHAR technology is outcompeted by a conventional A^2/O if only the incomes from biogas production and struvite are considered. However, the difference in terms of wastewater tariff aid for SCEPPHAR is only 15% higher than for A^2/O, which could justify its implementation if one considers its strategic advantage in terms of resource recovery and incentives are legislated. The current study did not consider incomes from bio-plastic production from PHA-rich sludge because of sub-optimal PHA concentrations found during SCEPPHAR' pilot-plant operation. However, evidence from similar pilot-plant projects like PHARIO (Bengsston et al., 2017; Werker et al., 2018) suggest that accumulations of PHA up to 40% for activated sludge are possible after a short enrichment period, although at the expense of an additional reactor and additional VFA needs. This would open the possibility to consider in the future incomes from PHA recovery in SCEPPHAR that would potentially improve its economic feasibility.

Table S2. Average composition of the raw wastewater at the Manresa WWTP in the period 2016-2017.

Compound	Concentration	Units
TP	7.0	$mgP \cdot L^{-1}$
TN	56	$mgN \cdot L^{-1}$
NH_4^+-N	42	$mgN \cdot L^{-1}$
TKN	56	$mgN \cdot L^{-1}$
COD_T	592	$mgCOD \cdot L^{-1}$
BOD5	250	$mg \cdot L^{-1}$
Alkalinity	140	$mgCaCO3 \cdot L^{-1}$

Table S3. Major equipment FOB costs and installation factors (L). TM = FOB×L and $CEF_n = CE_{2019}/CE_n$ (see Figure S6).

Equipment	FOB	Units	L	Reference
Tank	CEF_{2016} 2842.2 $V^{-0.48}$ L^{-1}	€/m^3	4	(Aeris, 2019)
Digester	CEF_{2012} 485 $V^{-0.2}$ L^{-1}	€/m^3	4	(Assentoft, 2019)
Settler	CEF_{2007} 3470 $A^{-0.3827}$ L^{-1}	\$/ft^2	4	(McGivney and Kawamura, 2008)
Pre-treat.	CEF_{1978} 10^4 6.43 $Q^{-0.24}$ L^{-1}	\$/Mgpd*	4	(Huang, 1980)
Mixer	CEF_{2010} 27.8	€/m^3	4	(Verrecht et al., 2010)
Diffusers	CEF_{1988} 1022.7 $N^{-0.345}$ L^{-1}	\$/disc	4	(Campbell and Boyle., 1989)
Pump	CEF_{2009} 0.024 $Q^{-0.22}$	K\$/gpm*	4.8	(Couper et al., 2012)
Blower	CEF_{2010} $(4450+57Q^{0.8})$ Q^{-1}	\$/(m^3/h)	2.5	(Towler and Sinnott, 2013)

CHP	CEF_{2016} 1650	€/kWh	1.7	(US DOE, 2017)
Belt press	CEF_{2007} (433972/Q+146) L^{-1}	\$/gph*	4	(McGivney and Kawamura, 2008)
Electrical sys.	CEF_{1978} 10^5 1.67 $Q^{-0.25}$ L^{-1}	\$/Mgpd	1	(Huang, 1980)
IAC**	CEF_{1978} 10^4 7.78 $Q^{-0.22}$ L^{-1}	\$/Mgpd	1	(Huang, 1980)
Piping	CEF_{1978} 10^5 2.23 $Q^{-0.22}$ L^{-1}	\$/Mgpd	4	(Huang, 1980)

*Mgpm: mega gallons per day; gpm: gallons per minute; gph: gallons per hour.

**Instrumentation and control.

Table S4. Items and chemicals costs.

Items	Cost	Units	Reference
Electricity	0.1098	€/kWh	(Eurostat, 2019) Spain, non-household consumers, 2nd half 2018
Wastewater tariff	0.73	€/m^3	(Gallego Valero et al., 2018)
Sludge treatment	150	€/Mg	(Foladori et al., 2010)
Sludge agro-disposal	139	€/Mg	(Foladori et al., 2010)
Wage ordinary worker	25000	€/year	-
Wage specialized worker	45000	€/year	-
Lime	100	\$/Mg	-

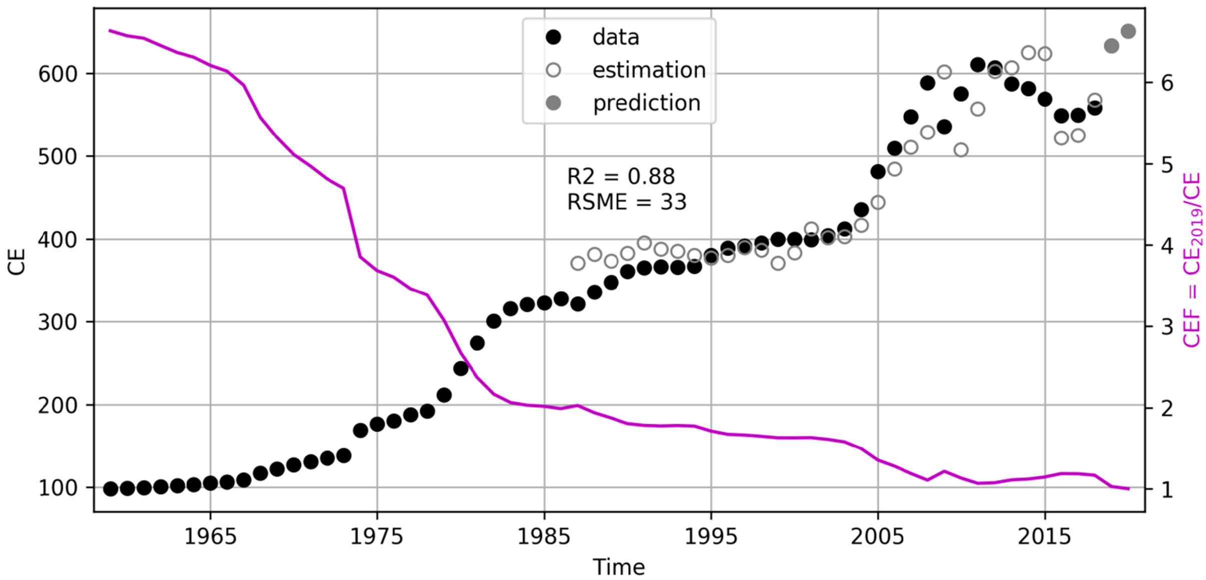

Figure S6. Chemical Engineering Plant Cost Index (CE) data from 1957 to 2017 and estimated values of CE for 2018 and 2019 based on a correlation model (Mignard, 2014). The model is calibrated on the period 1987 to 2017.

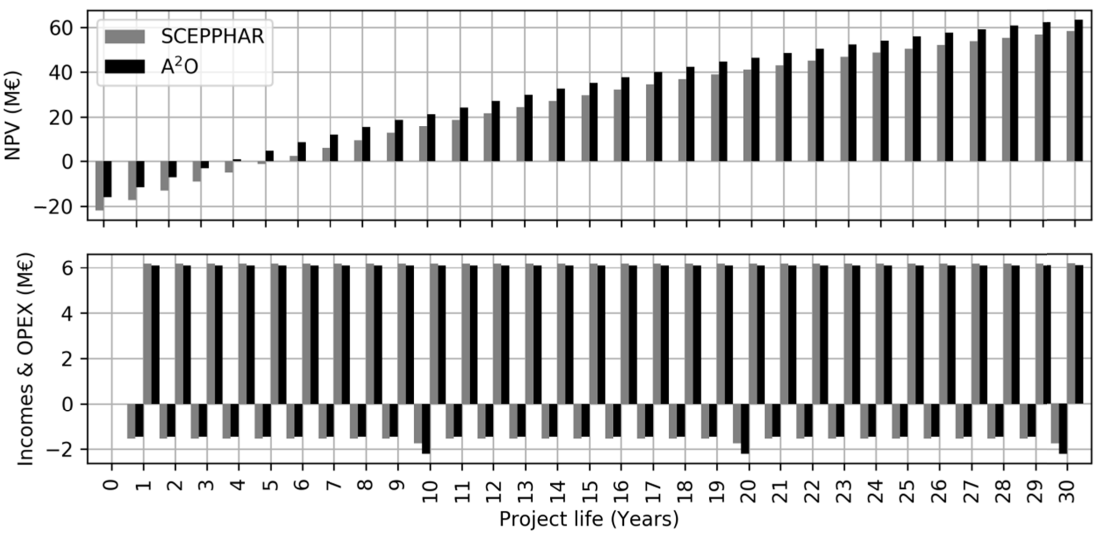

Figure S7. Feasibility study of SCEPPHAR and A^2/O for a wastewater tariff of 0.73 €/m^3. The OPEX and the Incomes are not discounted while a 4% interest rate is applied for the NPV estimation.

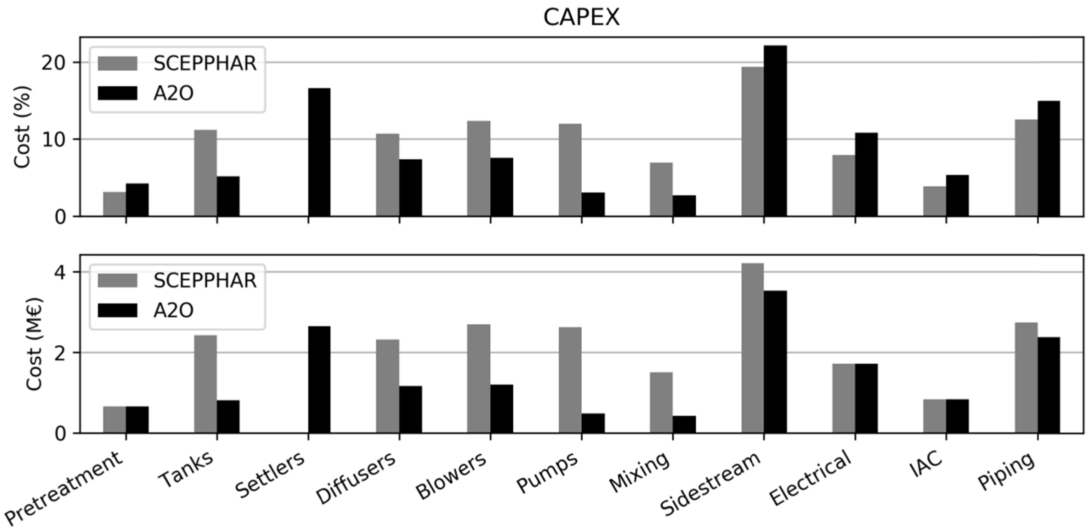

Figure S8. CAPEX and percentage costs for equipment.

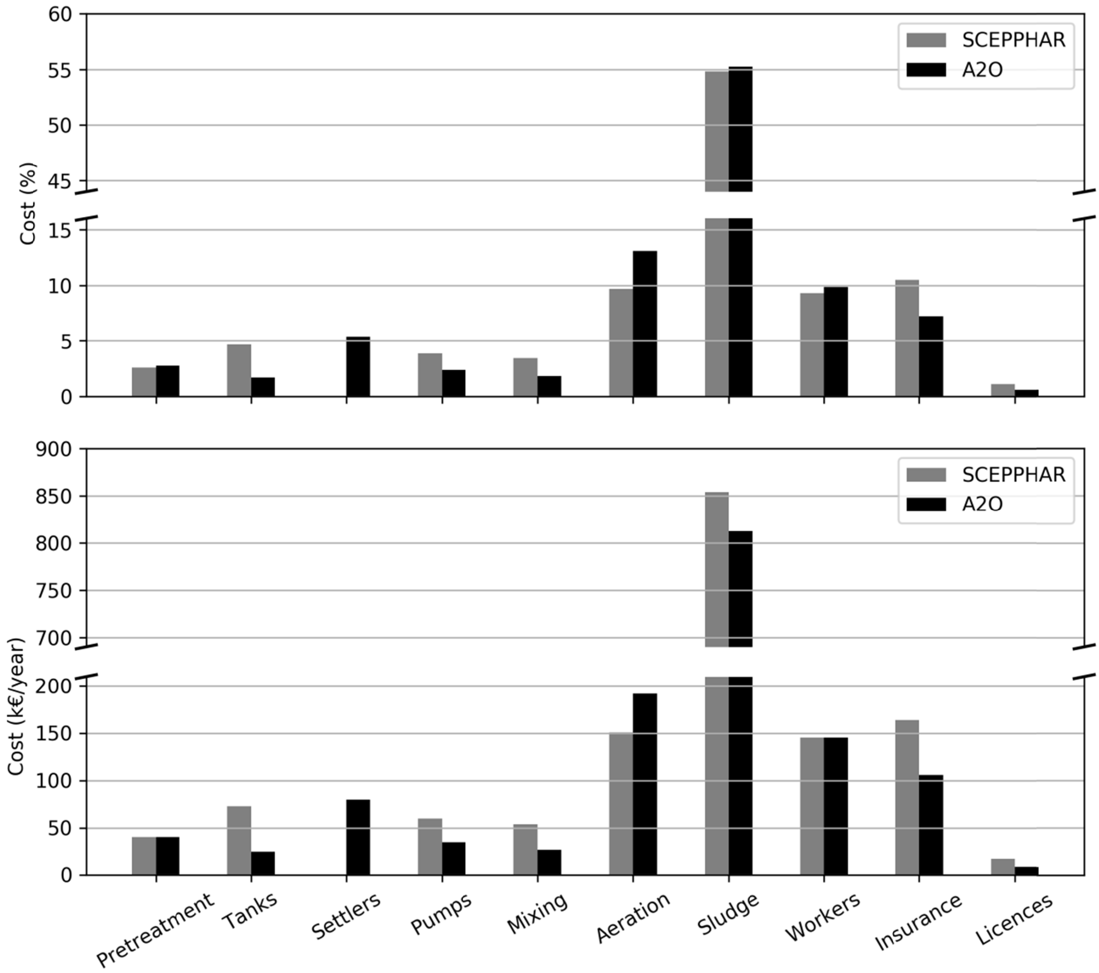

Figure S9. OPEX and percentage costs for equipment and non-consumable items.

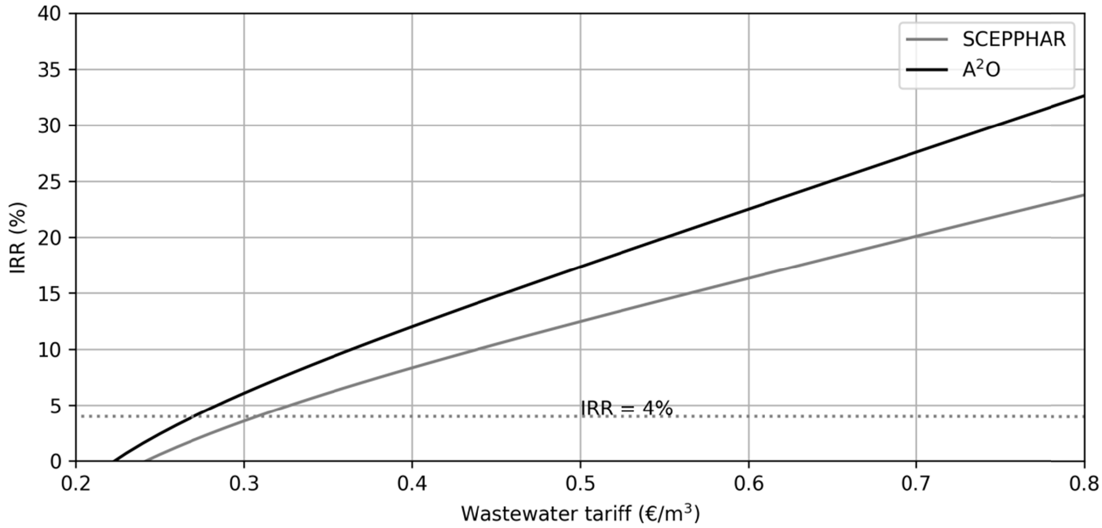

Figure S10. Screening analysis of wastewater tariff in relation to IRR. An interest rate of 4% (dot line) is possible if the tariff is set to 0.27 and 0.31 €/m^3 for the A^2/O and SCEPPHAR, respectively.

REFERENCES

Aeris, 2019. AERIS Tecnologías Ambientales S.L [WWW Document]. URL http://aeris.es/services/idi/

Assentoft, 2019. ASSENTOFT SILO A/S [WWW Document]. URL http://www.assentoftsilo.dk/aviva/media/biogas/biogas._engelsk.pdf

Bengsston, S., Werker, A., Visser, C., Korving, L., 2017. PHARIO Stepping stone to a sustainable vaue chain for PHA bioplastic using municipal activated sludge. STOWA Rep. https://doi.org/Rapport 2017-15

Campbell, H., Boyle., W., 1989. Design manual: fine pore aeration systems. EPA/625/1-89/023.

Chan, C., Guisasola, A., Baeza, J.A., 2020. Correlating the biochemical methane potential of bio-P sludge with its polyhydroxyalkanoate content. J. Clean. Prod. 242, 118495. https://doi.org/10.1016/j.jclepro.2019.118495

Couper, J.R., Penney, W.R., Fair, J.R., Walas, S.M., 2012. Chemical process equipment : selection and design. Elsevier/Butterworth-Heinemann.

European Commission, 2014. Guide to Cost-benefit Analysis of Investment Projects: Economic appraisal tool for Cohesion Policy 2014-2020, Publications Office of the European Union. https://doi.org/10.2776/97516

Eurostat, 2019. Electricity prices for non-household consumers - bi-annual data [WWW Document]. URL https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_205&lang=en

Foladori, P., Andreottola, G., Ziglio, G., 2010. Sludge Reduction Technologies in Wastewater Treatment Plants, Water Intelligence Online. IWA Publishing. https://doi.org/10.2166/9781780401706

Gallego Valero, L., Moral Pajares, E., Román Sánchez, I., 2018. The Tax Burden on

Wastewater and the Protection of Water Ecosystems in EU Countries. Sustainability 10, 212. https://doi.org/10.3390/su10010212

Garrett, D.E., 1989. Chemical Engineering Economics. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-94-011-6544-0

Huang, W., 1980. Construction Costs for Municipal WWTP: 1973-1978. EPA/430/9-80-003.

McGivney, W., Kawamura, S., 2008. Cost Estimating Manual for Water Treatment Facilities. John Wiley & Sons, Inc., Hoboken, NJ, USA. https://doi.org/10.1002/9780470260036

Mignard, D., 2014. Correlating the chemical engineering plant cost index with macro-economic indicators. Chem. Eng. Res. Des. 92, 285–294. https://doi.org/10.1016/j.cherd.2013.07.022

Tchobanoglous, G., Stensel, H.D., Tsuchihashi, R., Burton, F., 2014. Wastewater Engineering: Treatment and Resource Recovery, 5th ed, McGraw-Hill , New York, USA.

Towler, G., Sinnott, R., 2013. Chemical Engineering Design. Elsevier. https://doi.org/10.1016/C2009-0-61216-2

US DOE, 2017. Combined heat and power (CHP) Technology Fact Sheet Series [WWW Document]. URL https://www.energy.gov/eere/amo/combined-heat-and-power-basics

Verrecht, B., Maere, T., Nopens, I., Brepols, C., Judd, S., 2010. The cost of a large-scale hollow fibre MBR. Water Res. 44, 5274–5283. https://doi.org/10.1016/j.watres.2010.06.054

Werker, A., Bengtsson, S., Korving, L., Hjort, M., Anterrieu, S., Alexandersson, T., Johansson, P., Karlsson, A., Karabegovic, L., Magnusson, P., Morgan-Sagastume, F., Sijstermans, L., Tietema, M., Visser, C., Wypkema, E., van der Kooij, Y., Deeke, A., Uijterlinde, C., 2018. Consistent production of high quality PHA using activated sludge harvested from full scale municipal wastewater treatment – PHARIO. Water Sci. Technol. 78, 2256–2269. https://doi.org/10.2166/wst.2018.502