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Increasing the energy production in an urban wastewater treatment plant using a high-rate activated sludge: Pilot plant demonstration and energy balance

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ABSTRACT

The use of high-rate activated sludge (HRAS) reactors for the removal of COD in urban wastewater treatment plants (WWTPs) has been investigated because its potential contribution to energy generating WWTPs. A one-year operation period of a pilot plant treating the effluent of the primary settler of a full-scale WWTP was analyzed. The HRAS pilot plant operated without iron salts addition at temperatures between 12 and 28 °C at an average organic loading rate 2.8 ± 0.5 kg COD m^{-3} d^{-1} and with an average inflow COD concentration of 330 ± 86 mg O_2 L^{-1}. The influence of sludge retention time (SRT) on COD recovery and biomethane potential of the produced sludge was investigated and compared to the full scale WWTP performance. The highest observed sludge yield coefficient and biomethane potential of the sludge were achieved at SRT of 0.6 days. The weak point of the HRAS performance at STR of 0.6 days is the high loss of organic matter in the effluent due to the limited efficiency of the solids separation in the secondary settler. At higher SRT (in the range 1.0–2.1 days), the secondary settler efficiency and the COD recovery are higher than those achieved at SRT of 0.6 days but part of the inlet ammonium can be nitrified in the HRAS system at temperatures above 20 °C. A detailed energy balance indicated that two-thirds reduction of aeration requirements and one-third increase of biogas production could be achieved in a plant configuration in which HRAS is coupled to autotrophic biological nitrogen removal (BNR) compared to the heterotrophic BNR configuration, yielding a net energy production of ca. 0.1 kWh m^{-3} of treated water.

1. Introduction

Currently, urban wastewater treatment plants (WWTPs) are net energy-consumers systems with 8–16 kWh/person/year of electrical consumption depending on the type of treatment (removal of only organic matter or removal of organic matter and nutrients and considering the energy recovery in form of biogas from the digestion of sewage sludge) being the conventional nitrification/denitrification the most consuming process of the whole plant (Capodaglio and Olsson, 2020; Kartal et al., 2010). In the EU, with a population of 447 million persons (Eurostat, 2021a), this would mean an energy consumption of ca. 3576–7152 GWh/year for treating wastewater. Considering an average price of 0.1283 €/kWh for non-household consumers in the EU (Eurostat, 2021b), this energy consumption represents 459–918 M€/year, with an equivalent associated emission of ca. 1–2 Mtons CO_2/year considering an emission of 0.2307 kg CO_2/kWh (European Environmental Agency, 2022). Both, WWTP costs and greenhouse emissions are of great concern for stakeholders and the development of new technologies able to reduce them is of paramount importance in sustainability context (Cardoso et al., 2021; Khalkhali and Mo, 2020).

Urban WWTPs can become zero-energy consuming systems combining the chemical energy recovered by anaerobic digestion with the thermal energy recovered from the treated wastewater through heat pumps and the solar energy obtained with photovoltaic systems (Liu et al., 2021). Also, urban WWTPs can approach to the energy neutrality with aeration upgrades and using only the chemical energy recovered by anaerobic digestion if the sewage sludge is co-digested with other external organic waste (Macintosh et al., 2019; Torretta et al., 2021). However, some theoretical studies suggested that the implementation of the autotrophic biological nitrogen removal (BNR) in the mainstream of

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urban WWTPs would transform the current net-energy consumer WWTPs into self-sufficient or even net-energy producer facilities only using the chemical energy recovered by anaerobic digestion of the sewage sludge (Jetten et al., 1997; Kartal et al., 2010). This kind of technology is based in a two-stage biological process. The first stage is a high-rate activated sludge (HRAS) system for organic matter redirection. A HRAS system is a process modification of a conventional activated sludge (CAS) system. This process modification consists on operating at shorter hydraulic and sludge retention times (HRT and SRT, respectively) than those commonly applied in CAS systems (Tchobanoglous et al., 2003). This modification results in lower biomass concentration and higher volumetric and specific organic loading rates in the HRAS system. The biomass produced in this step would have, therefore, a very favourable bio-production of methane, greater than the achieved in current urban WWTPs (Rahman et al., 2020). The second stage uses autotrophic BNR for removing nitrogen in the mainstream without the need of organic matter (Juan-Díaz et al., 2021, 2022; Reino et al., 2016, 2018). The application of autotrophic BNR to the mainstream would reduce severely the aeration costs compared to current urban WWTPs where classical heterotrophic BNR (het-BNR) is applied (Kartal et al., 2010; Pérez et al., 2015).

In the HRAS process, a high fraction of the organic matter is removed through a physical process, i.e. the adsorption of this organic matter on the sludge, preserving its energy recovery potential. However, the successful implementation of HRAS process is poorly understood and it is linked to the conditions imposed, such as, among others, the addition of iron salts for improvement of organic matter removal and sludge coagulation/flocculation (de Graaff et al., 2016; de Vrieze et al., 2013).

One straight ahead way of retrofitting an existing CAS urban WWTP for organic matter redirection using the HRAS process would be to treat the effluent of the primary settler in a biological reactor in which the HRT and SRT applied are short. Indeed, it is generally assumed that HRAS process is achieved by imposing HRT and SRT in the range 1.5–3.0 h and 0.5–2.0 days, respectively (Tchobanoglous et al., 2003). When HRAS process is intended to be connected to an autotrophic BNR, the achievement of high organic matter removal is of paramount importance since it might compromise the anammox process itself (Li et al., 2020; Pijuan et al., 2020) and because organic matter removal is uniquely performed in the HRAS process.

Here, an experimental study with a HRAS pilot plant, operated on-site a full scale urban WWTP treating the effluent of the primary settler of this facility, is presented. The energy recovery with the HRAS process has been assessed through the biomethane potential of the obtained sludge and compared to the current energy production of the full scale WWTP.

In this sense, the aim of this study is to compare the performance of a pilot HRAS, treating the effluent of a primary settler, with the performance of an existing full-scale urban WWTP. Therefore the basic assumption is the retrofitting of existing WWTPs where the first settling step has been kept in the treatment scheme. The comparison of the results of a HRAS pilot plant with a full-scale CAS system treating the same influent is of interest since this comparison is not usually carried out in this kind of studies. Moreover, the use of the effluent of a primary settler as influent for the HRAS system is a significant difference with previous studies where the inlet of the HRAS system directly came from the pretreatment of an urban WWTP (Cao et al., 2020; Ge et al., 2017; Jimenez et al., 2015; Kinya et al., 2017; Liang et al., 2022; Taboada-Santos et al., 2020).

The main objectives of this study are: (i) to determine experimentally the influence of the SRT imposed in a HRAS pilot plant over the percent of COD removal and COD recovery, the sludge settleability and the nitrification process. (ii) To carry out a complete analysis of the implementation of a HRAS system in the mainstream of an urban WWTP combining the experimental data of the performance of the HRAS pilot plant, the fate of the organic matter and an energy balance.

2. Materials and methods

This section is divided in two main blocs. The first one describes the experimental set-up and the analytical methods used in the experimental part of this study. The second one describes all the calculations needed to make the mass and energy balances.

2.1. Experimental set-up and analytical methods

2.1.1. HRAS pilot plant description

The HRAS pilot plant was comprised of an aerobic biological reactor followed by a sedimentation tank for solid-liquid separation (Fig. 1). The working volumes were 250 and 470 L, respectively. Mixed liquor from the biological reactor flowed by gravity to the sedimentation tank, where solid-liquid separation took place. Dissolved oxygen (DO) concentration was controlled by means a closed control-loop that use a Hach LDO sensor (Hach Lange, Spain) and an automatic control valve to regulate the airflow rate. Temperature and pH were also monitored online. Influent and recirculation flow rates were also controlled by means a closed control-loop that used mass flowmeters and helical rotor pumps to obtain the desired flow rate. Excess sludge flow rate was controlled by two automatic on-off valves located in the recirculation line, which alternated the recirculation flow rate, either to the reactor or to the purge.

The pilot plant was located in the urban WWTP of Rubí-Valldoreix (Barcelona, Spain) and it was inoculated with activated sludge from the aerobic reactors of this facility. The mainstream line of the Rubí-Valldoreix WWTP is comprised by a pre-treatment, a primary sedimentation and a CAS process with secondary sedimentation. The full-scale CAS process was operated at SRT, HRT and DO concentration of 14 days, 8 h and 2 mg O_2 L^{-1}, respectively, throughout the period considered in this study. The sidestream of the Rubí-Valldoreix WWTP includes a mesophilic anaerobic digester where primary and secondary sludge are digested together.

The temperature was not controlled on the HRAS pilot plant, and it changed from 12 to 30 °C depending on the season. In the HRAS pilot plant, the operation started with the highest SRT (2.1 ± 0.6 days) and finished with the lowest one (0.6 ± 0.2 days). To avoid the effect of other operational parameters on the performance of the HRAS pilot plant, HRT and DO concentration were maintained throughout the study at 3 h and 2 mg O_2 L^{-1}, respectively. Iron salts were not added throughout the experimental period.

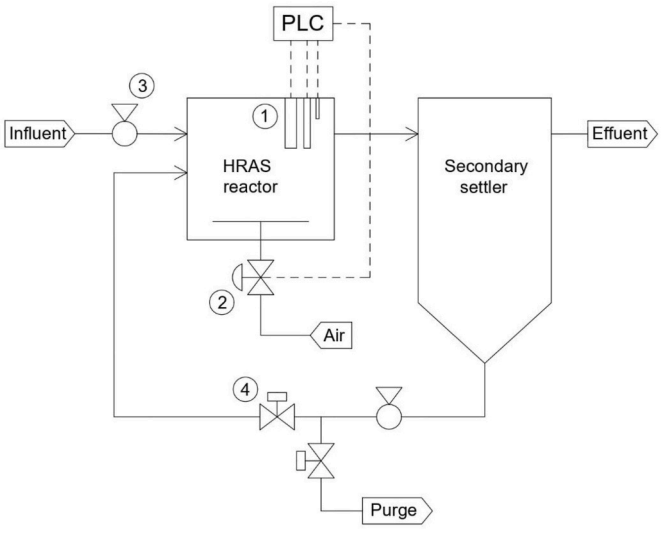

Fig. 1. Process diagram of the HRAS pilot plant: 1. DO, pH and temperature probes; 2. Automatic control valve; 3. Helical rotor pump; 4. Automatic on-off valve; PLC is a programmable logic controller.

2.1.2. Sampling and analysis

Samples were collected at least once a week from the influent of the pilot plant, the biological reactor, the sludge purge and the secondary effluent. Mixed liquor total suspended solids (TSS), mixed liquor volatile suspended solids (VSS) and sludge volumetric index (SVI) were measured following the recommendations and procedures published in Standard Methods (APHA, 1999). Total Chemical Oxygen Demand (tCOD) and ammonia nitrogen ($N–NH_4^+$) analyses were conducted using the Hach Test-in-Tube (TNT) kits (Hach Lange, Spain). The tCOD was assumed to be composed by particulate (pCOD), colloidal (cCOD) and soluble (sCOD) fractions. The sCOD fraction was measured using the flocculation-filtration ($ZnSO_4$ as flocculant, 0.45 μm) method of Mamais et al. (1993). The cCOD was measured as the COD fraction that passed through a 1.5 μm filter, from which the sCOD fraction was subtracted. The pCOD was calculated by subtracting COD filtered through 1.5 μm from tCOD.

Nitrite and nitrate analyses were conducted using the ionic chromatography ICS-2000 Integrated Reagent-Free IC system (DIONEX Corporation, USA). DO concentration, pH and temperature data of the HRAS system were online recorded throughout the whole experimental period.

2.1.3. HRAS influent characteristics

The HRAS pilot plant was fed with the effluent of the primary settlers of the full-scale WWTP. The average composition of the HRAS influent wastewater was as described in Table 1.

2.1.4. Determination of biomethane potential at standard temperature and pressure (BMP at STP)

BMP at STP tests, from now on, only BMP, were used to assess the amount of biogas produced by the anaerobic digestion of sludge produced in the HRAS pilot plant and the full-scale CAS system. The BMP tests were carried out by following the procedure proposed by Angelidaki et al. (2009). Control experiments (i.e. without added substrate) were included to recalculate the BMP accounting for residual biogas production. Control experiments were performed in triplicate, whereas substrate added tests in quintuplicate. Identical 160 mL serum bottles were used in all the tests. These bottles were filled up to 125 mL so that the headspace was 35 mL. Substrates used for the BMP tests were secondary sludge from the HRAS pilot plant operated at different SRTs and from the full-scale CAS system. The inoculum consisted of mesophilic anaerobic sludge from the full-scale anaerobic digester treating the sludge produced in the full-scale CAS system. The inoculum was degassed at 37 °C for 3–5 days before its use. In order to neglect biogas production by endogenous respiration, the substrate to inoculum ratio of 0.5 (in terms of volatile solids, VS) was maintained in all the tests. The amount of substrate and inoculum used were 1 and 2 g L^{-1} of VS respectively, per bottle. The pH of each bottle was set at 7.0 at the start of the experiments. The bottles were closed tightly with a butyl rubber septum and aluminium caps and were incubated under mesophilic conditions (37 °C). Anaerobic conditions were achieved by purging the headspace of each bottle with N_2 for 2 min. The content of each bottle was mixed once per day. The gas production was estimated by measuring the pressure increase in the headspace with a gas pressure meter. In each BMP test, the biogas composition (i.e. CH_4, CO_2 and H_2) was periodically determined by using gas chromatography. Accumulated volumetric gas production was calculated from the pressure increase in the headspace volume and expressed under standard conditions (25 °C, 1 atm) so that the results were able to be compared with other studies.

Table 1
HRAS influent characteristics.

Component	Units	Concentration	% of tCOD
tCOD	mg O_2 L^{-1}	330 ± 86	
pCOD	mg O_2 L^{-1}	155 ± 11	47
cCOD	mg O_2 L^{-1}	66 ± 30	20
sCOD	mg O_2 L^{-1}	109 ± 28	33
$N–NH_4^+$	mg N L^{-1}	51 ± 11	-
$N–NO_2^-$	mg N L^{-1}	1 ± 1	-
$N–NO_3^-$	mg N L^{-1}	1 ± 1	-

2.2. Calculations

2.2.1. Calculation of the SRT, SVI, efficiency of the secondary settler and observed sludge yield coefficient

SRT was measured by dividing the amount of VSS in the HRAS reactor by the VSS washed out with the effluent and the purge (Equation (1)).

$$SRT = \frac{V_{reactor} \cdot [VSS]_{reactor}}{Q_{purge} \cdot [VSS]_{purge} + Q_{effluent} \cdot [VSS]_{effluent}} \quad (1)$$

where SRT = sludge retention time (d); $V_{reactor}$ = reactor volume (L); $[VSS]_{reactor}$ = VSS concentration in the reactor (g VSS L^{-1}), Q_{purge} = purge flow rate (L d^{-1}), $[VSS]_{purge}$ = VSS concentration in the excess sludge (g VSS L^{-1}), $Q_{effluent}$ = effluent flow rate (L d^{-1}) and $[VSS]_{effluent}$ = VSS concentration in the effluent (g VSS L^{-1}).

Sludge Volumetric Index (SVI) was measured as described in Equation (2):

$$SVI = \frac{SV_{30}}{[VSS]_{reactor}} \quad (2)$$

where SV_{30} = settled sludge volume at 30 min (mL L^{-1}) and $[VSS]_{reactor}$ = VSS concentration in the reactor (g VSS L^{-1}).

Secondary settler efficiency (EF_{SS}) was measured as described in Equation (3):

$$EF_{SS} = \frac{[VSS]_{effluent}}{[VSS]_{reactor}} \cdot 100 \quad (3)$$

where $[VSS]_{reactor}$ = VSS concentration in the reactor (g VSS L^{-1}) and $[VSS]_{effluent}$ = VSS concentration in the effluent (g VSS L^{-1}).

Purge flow rate from the line of return activated sludge (RAS) was daily regulated to obtain the desired SRT. HRAS reactor walls were scraped twice per week to avoid the biofilm formation and the possible alteration of the applied SRT. The secondary settler was operated with a minimal sludge blanket to avoid solids accumulation and the possible alteration of the applied SRT.

The observed sludge yield coefficient (Y_{obs}) was calculated for each operational period following Equation (4).

$$Y_{obs} = \frac{Q_{purge} \cdot [VSS]_{purge} + Q_{effluent} \cdot [VSS]_{effluent}}{Q_{influent} \cdot tCOD_{influent} - Q_{effluent} \cdot tCOD_{effluent}} \quad (4)$$

where Y_{obs} = observed sludge yield coefficient (kg VSS kg^{-1} COD); Q_{purge} = volumetric flow rate in the purge (L d^{-1}), $[VSS]_{purge}$ = VSS concentration in the purge (g VS L^{-1}), $Q_{effluent}$ = volumetric flow rate in the effluent (L d^{-1}); $[VSS]_{effluent}$ = VSS concentration in the effluent (g VS L^{-1}); $Q_{influent}$ = volumetric flow rate in the influent (L d^{-1}); $tCOD_{influent}$ = total COD concentration in the influent; $tCOD_{effluent}$ = total COD concentration in the effluent.

The calculation considered that the produced sludge can be found by adding the mass flow rates of VSS in the purge and effluent, while the removed substrate was considered to be the difference between the mass flow rates of COD of the influent and the effluent.

2.2.2. Calculation of the COD mass balance for the HRAS pilot plant

COD mass balance was calculated using the average values of each operational period. Definition and related calculations for each term of COD mass balance has been indicated in Table 2.

Table 2
Definition and calculation of the COD mass balance for HRAS pilot plant.

COD in the influent (COD_{INF})	$mCOD_{INF} = Q_{influent} \cdot tCOD_{influent}$	$mCOD_{INF}$ = COD mass flow in the influent (kg O_2 d^{-1}) $Q_{influent}$ = volumetric flow rate in the influent (m^3 d^{-1}) $tCOD_{influent}$ = COD concentration in the influent (kg O_2 m^{-3})
COD as new biomass (COD_X)	$mCOD_X = Q_{influent} \cdot [N - NH_4^+]_{consumed} \frac{1\ kg\ VS}{0.12\ kg\ N} \frac{1.42\ kg\ O_2}{1\ kg\ VS}$	$mCOD_X$ = COD mass flow of new biomass formed (kg O_2 d^{-1}) $Q_{influent}$ = volumetric flow rate in the influent (m^3 d^{-1}) $[N\text{–}NH_4^+]_{consumed}$ = ammonium concentration consumed in the HRAS process (kg N m^{-3}) The ammonium oxidized to nitrate is not considered in this calculation. Assuming an empirical formula for the new biomass as: $C_5H_7NO_2$, the following ratios can be obtained: 0.12 kg N kg^{-1} VS and 1.42 kg O_2 kg^{-1} VS
COD oxidized (COD_{OX})	$mCOD_{OX} = Q_{influent} \cdot (tCOD_{influent} - tCOD_{effluent}) \cdot (1 - Y_{obs})$	$mCOD_{OX}$ = COD mass flow of oxidized organic matter (kg O_2 d^{-1}) $Q_{influent}$ = volumetric flow rate in the influent (m^3 d^{-1}) $tCOD_{effluent}$ = COD concentration in the effluent (kg O_2 m^{-3}) Y_{obs} = observed sludge yield (kg kg^{-1})
COD adsorbed (COD_{ADS})	$mCOD_{ADS} = (Q_{influent} \cdot (tCOD_{influent} - tCOD_{effluent})) - mCOD_{OX} - mCOD_X$	$mCOD_{ADS}$ = COD mass flow of adsorbed organic matter (kg O_2 d^{-1}) $Q_{influent}$ = volumetric flow rate in the influent (m^3 d^{-1}) $tCOD_{influent}$ = COD concentration in the influent (kg O_2 m^{-3}) $tCOD_{effluent}$ = COD concentration in the effluent (kg O_2 m^{-3}) $mCOD_{OX}$ = COD mass flow of oxidized organic matter (kg O_2 d^{-1}) COD_X = COD mass flow of new biomass formed (kg O_2 d^{-1})
COD in the effluent (COD_{EFF})	$mCOD_{EFF} = Q_{effluent} \cdot tCOD_{effluent}$	$mCOD_{EFF}$ = COD mass flow in the effluent (kg O_2 d^{-1}) $Q_{effluent}$ = volumetric flow rate in the effluent (m^3 d^{-1}) $tCOD_{effluent}$ = COD concentration in the effluent (kg O_2 m^{-3})
COD balance	$mCOD_{INF} = mCOD_X + mCOD_{OX} + mCOD_{ADS} + mCOD_{EFF}$	

2.2.3. Calculation of the energy balance

Energy balances for two different configurations of the full-scale WWTP were calculated using the experimental results obtained in this and other previous studies. The first configuration (CAS-hetBNR) is comprised by three process lines: (1) a water treatment line composed by a pre-treatment followed by a primary settler and finally a biological CAS process for heterotrophic BNR (a modified Luzdack-Ettinger process with anoxic and aerobic zones); (2) a sludge treatment line, where the primary and secondary sludge are treated together in an anaerobic digester and (3) an energy production line, where the produced biogas is transformed into electrical energy.

The second configuration is also comprised by three lines: (1) a water treatment line composed by a HRAS process for organic matter removal and an autotrophic BNR (partial nitritation + anammox in separated reactors) for nitrogen removal (HRAS-autBNR); (2) a sludge treatment line, where the primary and secondary sludge are treated together in an anaerobic digester and (3) an energy production line, where the produced biogas is transformed into electrical energy. For this second configuration (HRAS-autBNR), the energy balance was calculated for three different operating conditions of the HRAS process, corresponding to the three SRTs applied in the HRAS pilot plant (0.6, 1.0 and 2.1 days). Energy balance for HRAS-autBNR configuration aimed to provide what would be energy recovery in case the application of partial nitritation-anammox assuming this treatment to be feasible, therefore they do not represent any evaluation on the feasibility of the autotrophic BNR. The definition and related calculations for each term of energy balance is presented in Table 3. It should be point out that this energy balance was calculated making the following assumptions: (i) effective population equivalent, inflow and influent COD and ammonia nitrogen concentrations were considered the same for all configurations and they were assumed to the ones recorded from the current Rubí-Valldoreix WWTP, (ii) the energy consumption for physical processes: pumping, mixing, etc (Garrido et al., 2003) was the same for all configurations and finally, (iii) the biogas production estimated through BMP of the sludge would be the biogas production achieved in the digester of the full-scale WWTP.

3. Results and discussion

3.1. COD removal, settleability and ammonium oxidation: comparison between the performances of the HRAS pilot plant and the full-scale CAS

The HRAS pilot plant was operated during ca. one year treating the wastewater coming from the effluent of a primary settler of the full-scale WWTP, where a CAS process was implemented for COD removal. This is a significant difference with previous studies where the inlet of the HRAS system directly came from the pre-treatment of an urban WWTP (Cao et al., 2020; Ge et al., 2017; Jimenez et al., 2015; Kinya et al., 2017; Liang et al., 2022; Taboada-Santos et al., 2020). The whole operational period can be divided in three periods depending on the applied SRT (2.1, 1.0 and 0.6 days) as presented in Fig. 2 and Table 4. The average data of the full-scale WWTP operation for a year have been included in Table 4 for easing the comparison. The data were provided by the manager of the facility at the time of the study.

Despite the HRT was maintained at a constant value of 3 h in the HRAS pilot plant, the applied organic loading rate (OLR) varied between the three operational periods since the average influent tCOD was different in each period. As can be seen, the OLRs were 2- or 3-fold greater than the applied in the full-scale CAS process.

The COD removal in the HRAS pilot plant was between 65 and 79% and it was correlated to the applied SRT since the lower the applied SRT, the lower the total COD removal. Liang et al. (2022) found similar COD removal operating at SRT between 0.5 and 2.0 days but those authors did not found a clear relationship between the applied SRT and the achieved COD removal. However, this correlation was also found in other studies (Cao et al., 2020; Ge et al., 2017) but, in general, the

Table 3
Definition and calculation of the energy balance for CAS-hetBNR and HRAS-autBNR configurations.

Mass flow of secondary sludge (VS_{SS})	$VS_{SS} = Q_{influent} \cdot (tCOD_{influent} - tCOD_{effluent}) \cdot Y_{obs}$	VS_{SS} = mass flow of secondary sludge (kg VS d^{-1}) $Q_{influent}$ = volumetric flow rate in the influent (m^3 d^{-1}) $tCOD_{influent}$ = COD concentration in the influent (kg O_2 m^{-3}) $tCOD_{effluent}$ = COD concentration in the effluent (kg O_2 m^{-3}) Y_{obs} = observed sludge yield (kg kg^{-1})
Methane production from primary sludge ($CH4_{PS}$)	$CH4_{PS} = VS_{PS} \cdot BMP_{PS}$	$CH4_{PS}$ = methane production from primary sludge (m^3 CH_4 d^{-1}) VS_{PS} = mass flow of primary sludge (kg VS d^{-1}) BMP_{PS} (biomethane potential of primary sludge) = 0.37 m^3 CH_4 kg^{-1} VS (Baquerizo et al., 2021)
Methane production from secondary sludge ($CH4_{SS}$)	$CH4_{SS} = VS_{SS} \cdot BMP_{SS}$	$CH4_{SS}$ = methane production from secondary sludge (m^3 CH_4 d^{-1}) VS_{SS} = mass flow of secondary sludge (kg VS d^{-1}) BMP_{SS} = biomethane potential of secondary sludge (m^3 CH_4 kg^{-1} VS)
Total methane production ($CH4_T$)	$CH4_T = CH4_{PS} + CH4_{SS}$	$CH4_T$ = total methane production (m^3 CH_4 d^{-1})
Oxygen consumption for COD oxidation (OC_{COD})	$OC_{COD} = Q_{influent} \cdot (tCOD_{influent} - tCOD_{effluent}) - 1.42 \cdot VS_{SS}$	OC_{COD} = oxygen consumption for COD oxidation (kg O_2 d^{-1}) Assuming an empirical formula for the new biomass as: $C_5H_7NO_2$, the following ratio can be obtained: 1.42 kg O_2 kg^{-1} VS
Saved oxygen consumption for COD oxidation through heterotrophic denitrification (SOC_{COD})	$SOC_{COD} = Q_{influent} \cdot ([TKN]_{influent} - [NO_3^-]_{effluent}) \cdot 2.86$	SOC_{COD} = saved oxygen consumption for COD oxidation through heterotrophic denitrification (kg O_2 d^{-1}) $[TKN]_{influent}$ = TKN concentration in the influent (kg N m^{-3}) $[NO_3^-]_{effluent}$ = nitrate concentration in the effluent (kg N m^{-3}) Stoichiometric ratio between COD oxidation with oxygen or nitrate: 2.86 kg O_2 kg^{-1} N
	$OC_{NO3} = Q_{influent} \cdot NO_3 \cdot 4.3$	OC_{NO3} = oxygen consumption for complete oxidation of ammonia nitrogen to nitrate (kg O_2 d^{-1}) NO_3 = concentration of ammonia nitrogen oxidized to nitrate (kg N m^{-3}) Stoichiometric ratio for complete ammonia oxidation to nitrate considering biomass production: 4.3 kg O_2 kg^{-1} N
Oxygen consumption for partial ammonia nitrogen oxidation to nitrite (OC_{NO2})	$OC_{NO2} = Q_{influent} \cdot \frac{[TKN]_{influent}}{2} \cdot 1.6$	OC_{NO2} = oxygen consumption for partial oxidation of ammonia nitrogen to nitrite (kg O_2 d^{-1}) Stoichiometric ratio for partial ammonia oxidation to nitrite considering biomass production: 1.6 kg O_2 kg^{-1} N Assuming only half of the influent TKN is oxidized to nitrite to have a suitable influent for anammox reactor
Energy consumption for physical processes (E_{PHY})	$E_{PHY} = Q_{influent} \cdot PE_{ef} \cdot 20$	E_{PHY} = energy consumption for physical processes (kWh d^{-1}) PE_{ef} = 100000 effective population equivalent (inh-eq) Ratio of energy consumption = 20 Wh inh-eq^{-1} (Garrido et al., 2003)
Energy consumption for COD oxidation	$E_{COD} = (OC_{COD} - SOC_{COD}) \cdot 1.0$	E_{COD} = energy consumption for COD oxidation (kWh d^{-1}) Specific energy consumption for oxygen transfer = 1.0 kWh kg^{-1} O_2 (Tchobanoglous et al., 2003)
Energy consumption for complete ammonia nitrogen oxidation to nitrate	$E_{NO3} = OC_{NO3} \cdot 1.0$	E_{NO3} = energy consumption for complete ammonia nitrogen oxidation to nitrate (kWh d^{-1})
Energy consumption for partial ammonia nitrogen oxidation to nitrite	$E_{NO2} = OC_{NO2} \cdot 1.0$	E_{NO2} = energy consumption for partial ammonia nitrogen oxidation to nitrite (kWh d^{-1})
Energy recovery by combustion of biogas (E_{CH4})	$E_{CH4} = CH4_T \cdot \rho_{CH4} \cdot H_{CH4} \cdot \eta$	E_{CH4} = energy recovery by combustion of biogas (kWh d^{-1}) ρ_{CH4} = 0.657 (methane density in kg CH_4 m^{-3} CH_4) H_{CH4} = 15.425 (heat

(continued on next page)

Table 3 (*continued*)

	of methane combustion in kWh kg^{-1} CH_4) (Tchobanoglous et al., 2003) η = 0.35 (efficiency of fueled electric power generators) (Garrido et al., 2003)

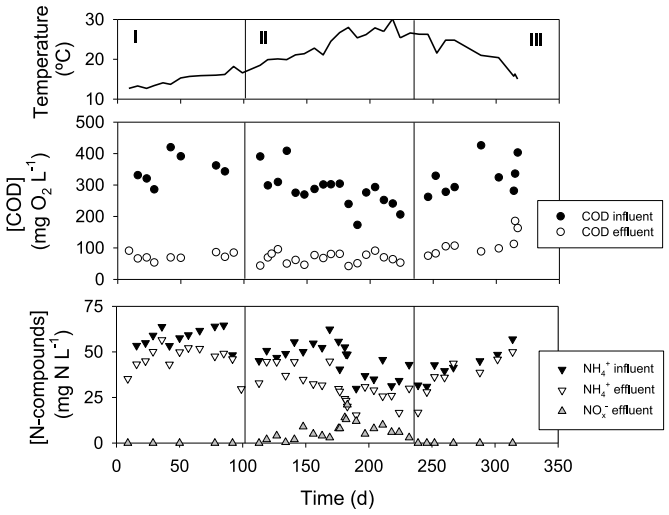

Fig. 2. Performance of the HRAS pilot plant: (i) Temperature in the HRAS reactor, (ii) influent and effluent total COD concentrations and (iii) influent and effluent N-compounds concentrations.

reported COD removal efficiencies were lower than the ones achieved in this study. However, COD removal did not show a clear correlation with the temperature of the HRAS pilot plant (Table 4). COD removal can be increased in a HRAS process up to about 90% if iron salts are added to remove phosphate since its addition improves the settleability of the sludge and, consequently the COD removal (Taboada-Santos et al., 2020). In this study, iron salts were not added for a better assessment and comparison with the full-scale CAS process, where iron salts were not added either. Moreover, if COD removal in the HRAS pilot plant is compared with the COD removal achieved in the full-scale CAS process, the correlation between COD removal and applied SRT is clear (Fig. 3). It is interesting to note that the COD removal achieved at SRT of 2.1 days in the HRAS pilot plant was similar to the maximum one achieved in the full-scale CAS process despite the applied OLR was 3-fold higher in the HRAS pilot plant compared to the full-scale CAS process. The reason behind this result could be that the operational conditions in the HRAS pilot plant (lower HRT and SRT than in the full-scale CAS process) promoted the development of an r-strategist culture in contrast to the biomass of the CAS process that could be a k-strategist culture. The selection of an r- or k-strategist culture can be achieved by modifying the operational conditions (Yu et al., 2020), as in this case. An r-strategist culture has a higher substrate consumption rate but a lower substrate affinity than a k-strategist culture (Martín-Hernández et al., 2009) and this fact would explain the higher organic removal rate (ORR) in the HRAS pilot plant compared to the full-scale CAS process (Table 4).

Sludge settleability is directly related to the performance of the HRAS process since it largely determines the amount of organic matter in the effluent. Settleability of the HRAS pilot plant sludge was estimated using two parameters: (i) SVI and (ii) EF_{SS}. SVI values of the sludge of the HRAS pilot plant were between 160 and 294 mL g^{-1}, indicating an acceptable settleability of the activated sludge throughout the study and in all the operational conditions despite no iron salts were added. The

Table 4
Main results of the performance of the HRAS pilot plant throughout the three different operational periods compared to the urban Rubí-WWTP (full-scale CAS process). The results of the full-scale CAS process are only from the secondary biological treatment. Most of the results are reported as an average value and its standard deviation in an operational period.

	HRAS pilot plant			Full-scale CAS process
Period	I	II	III	year 2015
SRT (d)	2.1 ± 0.6	1.0 ± 0.3	0.6 ± 0.2	14 ± 1
Operation time (d)	101	133	83	365
Temperature (°C)	15 ± 2	24 ± 3	20 ± 3	20 ± 5
$Q_{influent}$ (m^3 d^{-1})	2	2	2	20000
HRT (h)	3	3	3	7.6
DO (mg O_2 L^{-1})	2 ± 1	2 ± 1	2 ± 1	2 ± 1
$tCOD_{influent}$ (mg O_2 L^{-1})	394 ± 96	284 ± 97	326 ± 56	350 ± 47
$tCOD_{effluent}$ (mg O_2 L^{-1})	73 ± 12	67 ± 16	113 ± 37	50 ± 24
COD removal (%)	79 ± 6	76 ± 6	65 ± 10	85 ± 8
OLR (kg COD m^{-3} d^{-1})	3.2 ± 0.8	2.3 ± 0.5	2.6 ± 0.5	1.1 ± 0.3
ORR (kg COD m^{-3} d^{-1})	2.5 ± 0.6	1.7 ± 0.7	1.7 ± 0.6	0.9 ± 0.2
$[N–NH_4^+]_{influent}$ - $[N–NH_4^+]_{effluent}$ (mg N L^{-1})	−8 ± 3	−19 ± 6	- 6 ± 4	−11 ± 6
SVI (mL g^{-1})	214 ± 74	293 ± 96	160 ± 89	150 ± 79
$[TSS]_{eff}$ (mg L^{-1})	28 ± 16	12 ± 5	34 ± 15	25 ± 13
Secondary settler efficiency (%)	99	98	93	99
$[VSS]_{reactor}$ (mg L^{-1})	2300 ± 800	800 ± 200	500 ± 100	3000 ± 700
$[VSS]_{purge}$ (mg L^{-1})	4100 ± 1500	1800 ± 600	1500 ± 600	5600 ± 1300

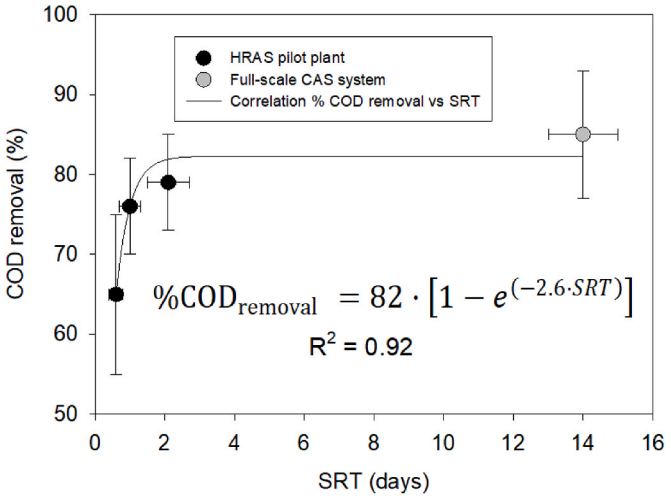

Fig. 3. Experimental COD removal in the HRAS pilot plant and the full-scale CAS process as a function of the applied SRT. A correlation between COD removal and applied SRT has been found by curve-fitting of the experimental data.

worst SVI values were measured at the highest temperatures (>25 °C) in Period II. However, SVI did not show any clear correlation with SRT (Table 4). EF_{SS} values were high (98–99%) for SRT of 1.0 and 2.1 days but it decreased up to 93% for SRT of 0.6 days. Therefore, the operation at SRT lower than 1 day clearly affected the EF_{SS}, causing a worsening of the effluent quality by the presence of solids.

If the HRAS process is designed to be connected to an autotrophic BNR process, a key point is to prevent nitrification from occurring in the

HRAS process. At low temperatures (<20 °C), nitrification was prevented at all applied SRT values since no nitrate formation was recorded and the ammonium removal matched with ammonium consumption for heterotrophic growth. At high temperatures (>20 °C), nitrification took place at SRT of 1.0 day and a significant concentration of nitrate was measured in the HRAS pilot plant effluent (Fig. 2). However, the nitrification was completely stopped when SRT was lowered to 0.6 days in spite of working at temperatures higher than 20 °C.

3.2. Fate of COD in the HRAS pilot plant compared to the full-scale CAS process

The fate of the organic matter in the HRAS pilot plant and the full-scale CAS process was evaluated through the COD-mass balance presented in Table 2 and calculated for each operational period. The comparison of the results of a HRAS pilot plant with a full-scale CAS system treating the same influent is of interest since this comparison is not usually carried out in this kind of studies (Cao et al., 2020; Ge et al., 2017; Jimenez et al., 2015; Kinya et al., 2017; Liang et al., 2022; Taboada-Santos et al., 2020).

The observed sludge yield coefficient (Y_{obs}) was calculated for each operational period as explained in section 2.2.1. Y_{obs} was found to be correlated with the applied SRT (Fig. 4A). Y_{obs} increased by 52, 61 and 77% compared to the value of a SRT of 14 days (full-scale CAS system) for SRTs of 2.1, 1.0 and 0.6, respectively (Fig. 4A).

The results of the COD mass balance are shown in Fig. 4. In the full-scale CAS process, only 38% of the COD was recovered as the sum of organic matter adsorbed over the activated sludge (COD_{ADS}) and new biomass formed (COD_X). The lost organic matter (62%) was the sum of the oxidized organic matter (COD_{OX}) and the organic matter lost with the effluent (COD_{EFF}). The percentage of recovered COD increased up to 53%, on average, in the HRAS pilot plant. That is, the HRAS pilot plant recovers, on average, 40% more organic matter than the full-scale CAS process. Regarding the composition of the recovered COD in the full-scale CAS process, only 37% was COD_{ADS} and 63% was COD_X whereas in the HRAS pilot plant, the COD_{ADS} represented, on average, 53% and COD_X was 47%. Regarding the composition of the removed COD in the full-scale CAS process, 77% was COD_{OX} and only 23% was COD_{EFF}. These percentages were, on average, 45% of COD_{OX} and 55% of COD_{EFF} for the HRAS pilot plant. Therefore, the COD recovery was higher in the HRAS process than in the full-scale CAS process because of the increase of the COD adsorption in the sludge and the significant reduction of the COD oxidation.

Our results are different than those reported in HRAS pilot plants operated at similar SRTs and temperatures (20-25 °C). Jimenez et al. (2015) and Kinya et al. (2017) reported lower COD recoveries (45% at SRT 0.5 days and 25% at SRT 1 and 2 days in Jimenez et al. (2015) and 40–46% at SRT 0.3 days and 44–55% at SRT 0.6 days in Kinya et al. (2017)) than those found in this study (51% at SRT 0.6 days and 54% at SRT 1.0 and 2.1 days). These differences on the COD recovery could be due to several factors. First, the influent of these HRAS pilot plants was different from that of the pilot plant of this study. The influent of Jimenez et al. (2015) and Kinya et al. (2017) was the effluent of a pre-treatment without primary sedimentation whereas the influent of this study was the effluent of a primary settler. Therefore, the influent COD fractionation was significantly different, having our influent a higher percentage of sCOD (33% vs 10–23%) while the influent of the other studies had a higher percentage of pCOD (60–66% vs 47%). Second, HRT in our pilot plant was 3 h and the HRTs in the other studies were 0.5–1.0 h. A HRAS treating the effluent of a pre-treatment probably has better COD removal percentages at low HRTs than a HRAS treating the effluent of a primary settler because what it removes is, basically, colloidal organic matter by adsorption and particulate organic matter by sedimentation (in the secondary settler, not in the HRAS). A HRAS treating the effluent of a primary settler has to operate at higher HRT because the percentage of particulate and colloidal fractions that receives is lower, since these fractions are mainly recovered in the primary settler. However, the combination of primary settler plus HRAS is able to achieve a global higher COD recovery than a single HRAS system. Hence, this comparison suggests that the organic matter recovery in a HRAS process would increase if the urban wastewater is previously treated in a primary settler and if the HRT is in the upper part of the range applied in HRAS processes.

The applied SRT had a limited effect on the total recovered COD in the HRAS pilot plant, as all of them were between 51 and 54%, irrespective the SRT applied. Nevertheless, there was a difference in the distribution of COD_{ADS} and COD_X for the SRTs of 0.6 and 2.1 compared to the SRT of 1.0 day. At SRT 0.6 and 2.1 days, the most important fraction of the recovered COD was the COD_{ADS} fraction, whereas at SRT of 1.0 day, the most important fraction was the COD_X fraction. Probably, this difference was related to the average temperature of each operational period rather than the applied SRT. At SRT 0.6 and 2.1 days, the average temperatures were 20 ± 3 °C and 15 ± 2 °C, respectively but at SRT 1.0 day, the average temperature was 24 ± 3 °C. This means that, at high temperatures (>20 °C), the produced biomass increased at the cost of a reduction in organic matter adsorbed in the sludge. Jia et al. (2020) predicted, in a model-based study, the decrease of the COD recovered in a HRAS process when temperature increase over 20 °C but they do not split the recovered COD in the COD_{ADS} and COD_X fractions as we did. The results of our study seem to contradict their model-based predictions since the total COD recovered did not significantly change with the increase of the temperature. Nevertheless, it seems the temperature was only affecting the distribution of COD_{ADS} and COD_X fractions and not the total recovered COD.

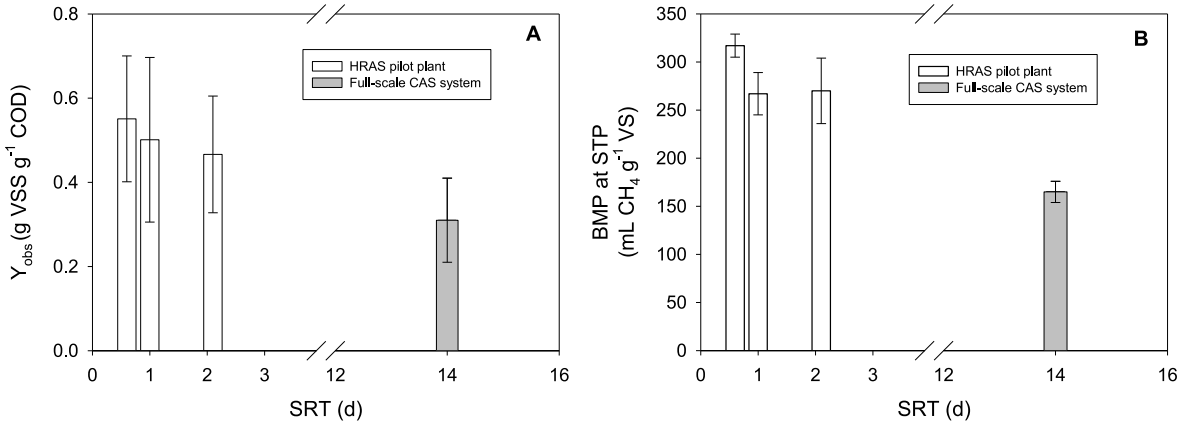

Fig. 4. (A) Observed sludge yield coefficient (Y_{obs}) in the HRAS pilot plant and full-scale CAS process as a function of the applied SRT. (B) Biomethane potential at standard temperature and pressure (BMP at STP) as a function of the SRT imposed in the HRAS pilot plant compared to that in full-scale CAS process.

However, the SRT effect was much higher on the distribution of the lost COD because COD_{OX} significantly increased (up to 93% from 0.6 to 2.1 days) with the increase of the SRT. On the contrary, COD_{EFF} significantly decreased (up to 84% from 0.6 to 2.1 days) with the increase of the SRT due to the improvement of the secondary settler efficiency, from 93% (SRT = 0.6 d) to 99% (SRT = 2.1 d). The model-based study of Jia et al. (2020) also predicted the high influence of secondary settler efficiency on COD_{EFF} in a HRAS process, with similar results to these experimentally obtained in this study.

Consequently, working at SRTs between 0.6 and 2.1 days in the HRAS process would have not a noteworthy effect on the recovery of organic matter and it has only a noticeable effect on the distribution of the lost organic matter. In any case, considering that HRAS process would be connected to a subsequent autotrophic BNR process, it seems to be a better option to lose organic matter by oxidation rather than producing an effluent with a high COD concentration, since this COD would negatively affect the subsequent autotrophic BNR (Li et al., 2020; Pijuan et al., 2020).

Overall the data gathered from the experimental campaign indicate that the SRT applied should be regulated as a function of temperature. For low temperatures, nitrification can be easily circumvented, and good effluent quality (even without iron salts addition) can be obtained at SRT of 2 days. Unexpectedly, high temperatures complicated the operation of the HRAS reactor since to avoiding nitrification required of a short SRT (lower than 1.0 day), and at such short SRT the sludge settleability is compromising the effluent quality.

3.3. Biomethane potential results

Biomethane potentials of the secondary sludge of the HRAS pilot

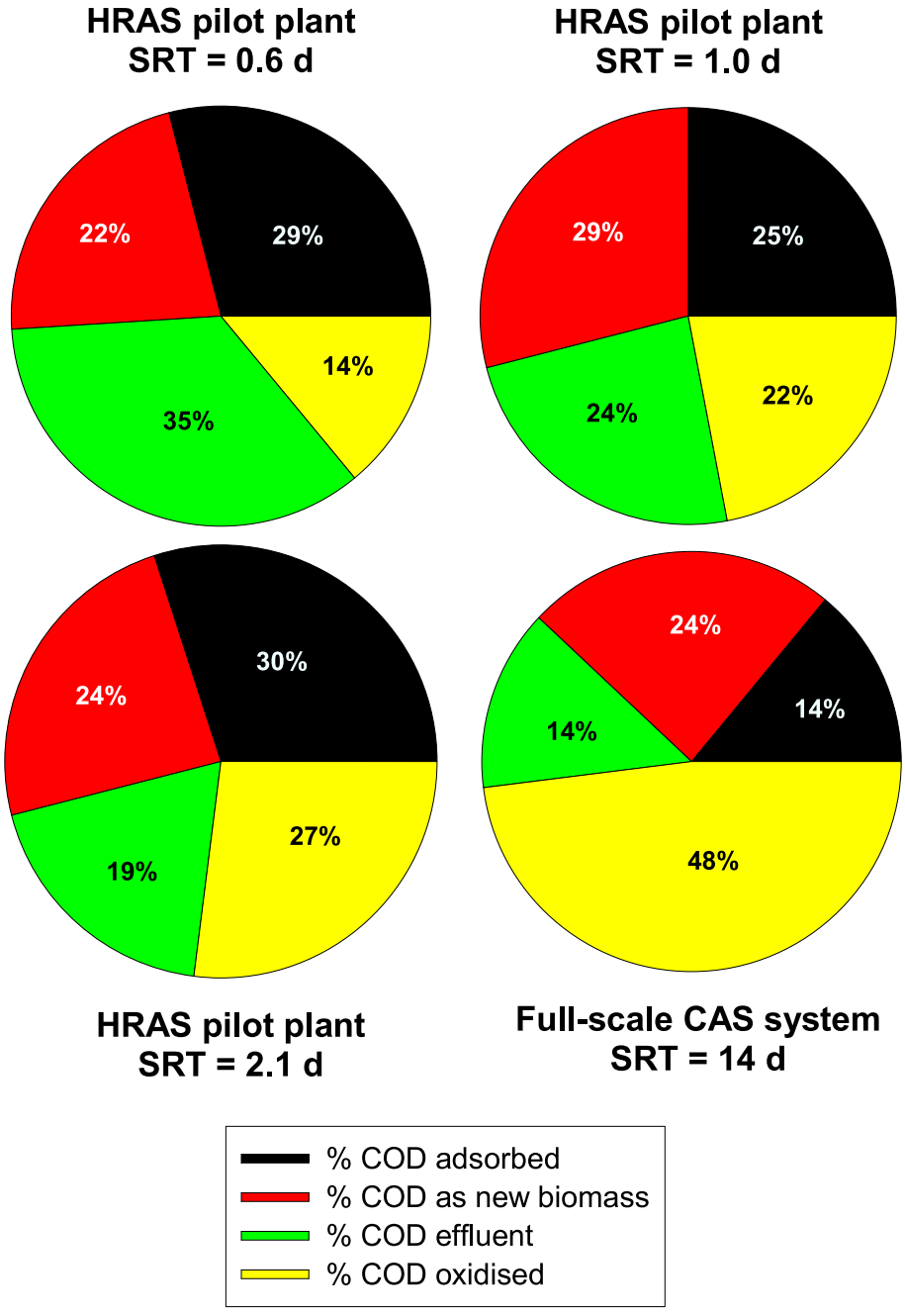

Fig. 5. COD-mass balance in the HRAS pilot plant and the full-scale CAS process.

plant and the full-scale CAS process were measured using the BMP batch tests described in section 2.1.4 (Fig. 4B). BMP of the secondary sludge of the CAS process (165 mL CH_4 g^{-1} VS at SRT 14 days) was close to the values reported for secondary sludge of other full-scale CAS systems operated at similar SRT (150 mL CH_4 g^{-1} VS at SRT 15 days; Bolzonella et al., 2005). However, the BMPs of the sludge from the HRAS system (267–317 mL CH_4 g^{-1} VS) were significantly higher than the values reported for CAS systems, regardless of the SRT applied. The maximum BMP (317 mL CH_4 g^{-1} VS) was obtained at SRT 0.6 days. In fact, the BMP of the secondary sludge produced in the HRAS system is much closer to the BMP of primary sludge (250–370 mL CH_4 g^{-1} VS; Elbeshbishy et al., 2012; Baquerizo et al., 2021) than that of secondary sludge from CAS systems and even higher than the BMP of the organic fraction of municipal waste (212 mL CH_4 g^{-1} VS; Elbeshbishy et al., 2012).

According to van Loosdrecht et al. (1997), the lower the applied SRT in an activated sludge system, the higher the BMP of the produced sludge. However, the BMP achieved at SRT 1.0 day slightly disturb the expected trend since it was similar to the BMP achieved at SRT 2.1 days (Fig. 4B). This is probably due to the composition of the recovered COD at each SRT (Fig. 5). As explained before, the COD_X fraction was the predominant one at SRT 1.0 day while the COD_{ADS} was the dominant fraction at SRT 0.6 and 2.1 days. It is well known that the COD_{ADS} fraction has higher BMP than the COD_X fraction (Baquerizo et al., 2021) and this would explain the fact that BMP achieved at SRT 1.0 day is almost the same than the achieved at SRT 2.1 days.

3.4. Energy balance: comparison between the CAS and the HRAS processes

The main results obtained from the energy balances calculated for two different WWTP configurations (as described in section 2.2.3) are presented in Table 5 and can be summarized as follows:

(i) Energy consumed in the aeration of the biological processes. The total amount of energy consumption is constituted by the aeration for COD removal and for nitrogen (N) removal. The energy consumption for COD removal is 2- to 4-fold higher for HRAS-autBNR configurations than for CAS-hetBNR configuration due to the savings in oxygen consumption through heterotrophic denitrification. However, the energy consumption for N-removal is 5-fold lower for HRAS-autBNR configurations than that of CAS-hetBNR configuration due to the greater savings in oxygen consumption for oxidation of half of ammonium to nitrite instead of oxidation of all of the ammonium to nitrate.

(ii) Energy consumed in the physical processes. This energy consumption was the same for both configurations but makes up to 26% of total energy consumption for CAS-hetBNR configuration and 42–50% for HRAS-autBNR configurations.

(iii) Energy recovered from biogas produced by anaerobic digestion of sludge. The energy recovery is 29–36% higher for the HRAS-autBNR configurations than for CAS-hetBNR configuration.

All the above results are based on the calculations presented in Table 3. One of the main items of that energy balance is the estimation of the total methane production from primary and secondary sludge. That estimation is based on the calculation of the sludge produced and the BMP of each sludge type. The data of real methane production in the full-scale CAS system were used to check the consistency of that estimation. The measured total methane production on the full-scale CAS system was 1360 m^3 d^{-1} while the estimation through our procedure was 1354 m^3 d^{-1}, less than 1% of the difference (see Table 5). Nevertheless, some values of the energy balance calculations could slightly vary, depending on if they were directly obtained from the operation of pilot- or full-scale devices (for example, an anaerobic digestor or an aeration system for N-removal).

The CAS-hetBNR configuration is a net energy consumer process while all the HRAS-autBNR configurations are net energy producer processes (a direct comparison of the total energy consumed and recovered for each configuration is depicted in Fig. 6). CAS-hetBNR configuration only recovers 63% of its energy consumption, meaning a

Table 5
Main results of the energy balance for CAS-hetBNR and HRAS-autBNR configurations.

Parameter	Acronym	Units	CAS-hetBNR	HRAS-autBNR		
			SRT = 14 d	SRT = 2.1 d	SRT = 1.0 d	SRT = 0.6 d
Influent flow	$Q_{influent}$	m^3 d^{-1}	20000 [a]	20000 [b]	20000 [b]	20000 [b]
Influent COD in the secondary treatment	$tCOD_{infliuent}$	kg COD m^{-3}	0.35 [a]	0.35 [b]	0.35 [b]	0.35 [b]
Removal efficiency	%RE	%	86 [a]	79 [a]	76 [a]	65 [a]
Effluent COD secondary treatment	$tCOD_{effluent}$	kg COD m^{-3}	0.05 [a]	0.074 [c]	0.084 [c]	0.122 [c]
Observed growth yield	Y_{obs}	kg VSS kg^{-1} COD	0.31 [a]	0.47 [a]	0.50 [a]	0.55 [a]
VS in the secondary sludge	VS_{SS}	kg VS d^{-1}	1880 [c]	2594 [c]	2660 [c]	2508 [c]
VS in the primary sludge	VS_{PS}	kg VS d^{-1}	2820 [c]	2820 [b]	2820 [b]	2820 [b]
Proportion of secondary sludge	%SS	%	40 [a]	48 [c]	49 [c]	47 [c]
VS influent anaerobic digester	VS_T	kg VS d^{-1}	4700 [a]	5414 [c]	5480 [c]	5328 [c]
Biochemical Methane Potential for secondary sludge	BMP_{SS}	m^3 CH_4 kg^{-1} VS	0.165 [a]	0.270 [a]	0.268 [a]	0.317 [a]
Methane production from primary sludge	$CH4_{PS}$	m^3 CH_4 d^{-1}	1044 [c]	1044 [b]	1044 [b]	1044 [b]
Methane production from secondary sludge	$CH4_{SS}$	m^3 CH_4 d^{-1}	310 [c]	702 [c]	710 [c]	793 [c]
Total methane production	$CH4_T$	m^3 CH_4 d^{-1}	1354 [c] 1360 [a]	1745 [c]	1754 [c]	1837 [c]
Oxygen consumption for COD oxidation	OC_{COD}	kg O_2 d^{-1}	3330 [c]	1837 [c]	1543 [c]	999 [c]
Saved oxygen consumption for COD oxidation through heterotrophic denitrification	SOC_{COD}	kg O_2 d^{-1}	2860 [c]	-	-	-
Oxygen consumption for complete ammonia nitrogen oxidation to nitrate	OC_{NO3}	kg O_2 d^{-1}	5160 [c]	-	-	-
Oxygen consumption for partial ammonia nitrogen oxidation to nitrite	OC_{NO2}	kg O_2 d^{-1}	-	960 [c]	960 [c]	960 [c]
Energy consumption for physical processes	E_{PHY}	kWh d^{-1}	2000 [c]	2000 [c]	2000 [c]	2000 [c]
Energy consumption for COD oxidation	E_{COD}	kWh d^{-1}	470 [c]	1834 [c]	1543 [c]	999 [c]
Energy consumption for complete ammonia nitrogen oxidation to nitrate	E_{NO3}	kWh d^{-1}	5160 [c]	-	-	-
Energy consumption for partial ammonia nitrogen oxidation to nitrite	E_{NO2}	kWh d^{-1}	-	960 [c]	960 [c]	960 [c]
Energy recovery by combustion of biogas	E_{CH4}	kWh d^{-1}	4801 [c]	6185 [c]	6229 [c]	6521 [c]

[a] Experimental value.
[b] Assumed value.
[c] Calculated value.

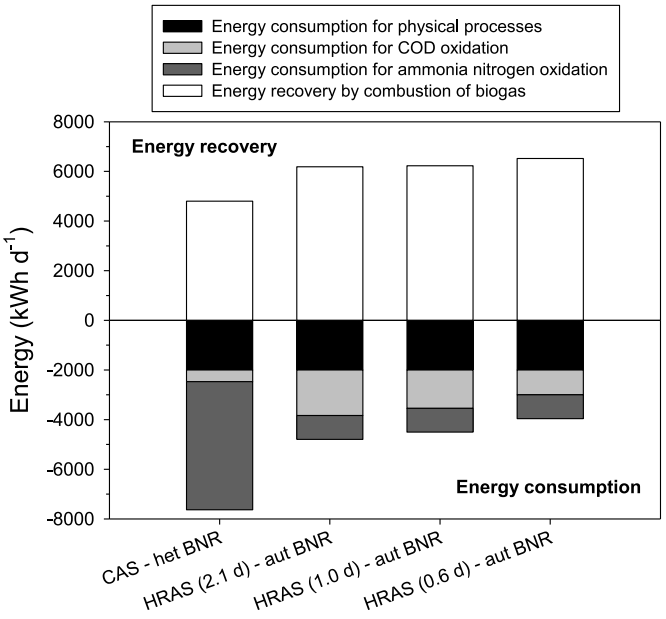

Fig. 6. Comparison of the total energy consumed and recovered for CAS-hetBNR and HRAS-autBNR configurations. The relative errors of each energy component are 5% for energy consumption components and 10% for energy recovery component.

net energy consumption of 0.14 kWh m^{-3}. On the contrary, HRAS-autBNR configurations recover from 129% up to 165% of their energy consumptions, being the HRAS-autBNR configuration with a HRAS working at SRT = 0.6 days the most favourable process since it has the lowest energy consumption and the highest energy recovery. Depending on the SRT of the HRAS process, the net energy recovery of these configurations is: 0.07 kWh m^{-3} (SRT = 2.1 days), 0.09 kWh m^{-3} (SRT = 1.0 day) and 0.13 kWh m^{-3} (SRT = 0.6 days).

The average increase in the energy recovery and the decrease of the energy consumption when passing from CAS-hetBNR to HRAS-autBNR configuration are 1510 kWh d^{-1} and 3211 kWh d^{-1}, respectively. This means that switching from a net energy consumer to a net energy producer process resulted in two-thirds reduction of aeration requirements and one-third increase of biogas production.

3.5. Practical implications

Because the results obtained include a rather wide set of SRT applied (SRTs from 0.6 to 2.1 days) with apparently similar treatment performance (recovering 51–54% of the inlet organic matter as energy, Fig. 5), a clear guideline for the recommendations derived from our study would be necessary. In fact the selection of the SRT is a complex decision and it requires for a more detailed definition of the goal of the treatment.

If the objective is to achieve the maximum energy recovery, the SRT should be around 0.6 days (Fig. 6), because at this SRT, the highest observed sludge yield coefficient and biomethane potential of the sludge were achieved (Fig. 4). At this SRT, the nitrification of the inlet ammonium is also prevented even at temperatures around 25 °C (Fig. 2). This is a determining point for maximization of energy recovery if the desired configuration is a HRAS system followed by an autotrophic BNR process, in the case that the feasibility of autotrophic BNR at mainstream full-scale conditions would be demonstrated. The weak point of the HRAS performance at STR of 0.6 days is the high loss of organic matter in the effluent (Fig. 4) due to the limited efficiency of the solids separation in the secondary settler at this SRT (Table 4). This fact could affect the subsequent autotrophic BNR process, where the presence of organic matter could compromise both the partial nitritation and the anammox processes. In this case, the HRAS should be operated at higher SRT (in the range 1.0–2.1 days), because at these SRTs, the secondary settler efficiency and the COD recovery are higher than the those achieved at SRT of 0.6 days (Table 4 and Fig. 5). Additionally, despite the observed sludge yield coefficient and biomethane potential of the sludge are lower than those achieved at SRT of 0.6 days, the energy recovery in form of biogas would be close to the achieved at SRT of 0.6 days (Fig. 6). However, part of the inlet ammonium can be nitrified in the HRAS system at temperatures above 20 °C when it is operated at SRTs from 1.0 to 2.1 days.

4. Conclusions

- The removal of COD in the HRAS pilot plant depended on the SRT imposed, ranging from 65% at SRT 0.6 days to 79% at SRT 2.1 days, with temperatures between 12 and 28 °C. Moreover, these COD removals were achieved without iron salts addition for improving settleability in the HRAS system. The maximum COD removal in the HRAS pilot plant was close to the COD removal achieved in the full-scale CAS system used as reference (85% at SRT 14 days).
- The observed sludge yield coefficients achieved in the HRAS pilot plant ranged from 0.47 kg VSS kg^{-1} COD at SRT 2.1 days to 0.55 kg VSS kg^{-1} COD at SRT 0.6 days, being in all cases higher than the achieved in the full-scale CAS system (0.31 kg VSS kg^{-1} COD at SRT 14 days).
- The recovery of COD in the HRAS pilot plant ranged from 51% at SRT 0.6 days to 54% at SRT 2.1 days, being in all cases higher than the achieved in the full-scale CAS system (38% at SRT 14 days).
- The performance of the HRAS process was found to be directly linked to the sludge settleability, which in turn depended on the SRT imposed.
- Avoiding nitrification in the HRAS system at temperatures above 20 °C is required. Imposing low SRT at high temperatures easily prevented nitrification (e.g., an SRT of 0.6 days completely suppressed nitrification at 25 °C).
- The biomethane potential of the sludge of the HRAS pilot plant ranged from 270 mL g^{-1} VS at SRT 2.1 days to 317 mL g^{-1} VS at SRT 0.6 days, being in all cases higher than the achieved with the secondary sludge of the full-scale CAS system (165 mL g^{-1} VS at SRT 14 days).
- A detailed energy balance indicated that two-thirds reduction of aeration requirements and one-third increase of biogas production could be achieved in a WWTP configuration in which an HRAS system is coupled to an autotrophic BNR (HRAS-autBNR) process compared to the CAS-hetBNR configuration. This would yield on average a net energy production of ca. 0.1 kWh per cubic meter of wastewater treated in a HRAS-autBNR configuration.

CRediT authorship contribution statement

Julián Carrera: Writing – original draft, Supervision. **Oriol Carbó:** Experiments. **Silvia Doñate:** Idea development. **María Eugenia Suárez-Ojeda:** Idea development, Writing. **Julio Pérez:** Writing – original draft, Supervision.

Declaration of competing interest

The authors declare that they have not financial and personal relationships that could inappropriately influence (bias) their work.

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