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Opportunities for rotating belt filters in novel wastewater treatment plant configurations

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Abstract

Novel wastewater treatment plants (WWTPs), which are based on a partial nitritation-anammox (PN-anammox) process, enable higher chemical oxygen demand (COD) recovery to produce biogas and lower treatment costs. In this study, rotating belt filters (RBFs) were examined in different configurations to identify the opportunities for RBFs to be included in novel WWTP configurations. RBFs enable recovery of 22-37% of the influent COD and removal of 34-56% of hydrophobic organic micropollutants (OMPs). However, the effluent was not suitable for treatment in a PN-anammox process due to its high COD. Chemically enhanced settling (CES) enabled these limitations to be overcome and caused an increase in OMP removal to 73-94%. However, a dose of 300 mg/L of ferric chloride was required to produce a suitable effluent for a PN-anammox reactor. The combination of RBF and CES not only derived effluents suitable for treatment in PN-anammox units but also decreased the alkalinity consumption and the required chemical dose 3-fold to achieve comparable COD recovery and OMP removal. The methane yield of the combined sludges that were produced (184 L(N) CH_4/kg $COD_{influent}$) was 75% higher than that obtained in conventional wastewater treatment (105 L(N) CH_4/kg $COD_{influent}$), and the electricity requirements decreased from 0.54 to 0.41 kWh/m^3 of treated wastewater. The energetic calculations showed that a WWTP incorporating this combined treatment could attain energy autarky with 29% lower operational costs than that of conventional treatment (0.022 *vs* 0.031 €/m^3) as long as a minimum alkalinity-to-ammonium ratio of 1-1.25 g IC to g NH_4^+-N was ensured in the effluent of the combined treatment.

Keywords: cellulosic sludge, chemically enhanced settling, energy self-sufficiency, organic matter recovery, organic micropollutants.

Introduction

The discovery of the autotrophic nitrogen removal process (anammox process)[1], which does not require an organic carbon source for denitrification, introduces new possibilities for conceiving more energetically efficient wastewater treatment plants (WWTPs).[2] Although anammox-based processes are already applied at full scale to treat the supernatants of anaerobic sludge mesophilic digesters, the implementation of this technology in the mainstream of WWTPs is currently under investigation since they operate at considerably lower temperatures (10-20ºC).[3]

In the first stage of these novel WWTPs, pre-concentration technologies can recover most of the chemical oxygen demand (COD) from sewage to produce energy (methane), which enables WWTPs to gain energy self-sufficiency or even become energy-producing facilities.[4] Some studies have suggested that the energy contained in wastewater is nearly 5-fold the electrical energy that is used to drive conventional wastewater treatment.[5] Therefore, as long as 20% of the total energy in domestic wastewater can be completely converted to electrical energy, WWTPs may be energetically self-sufficient.

The energy contained in wastewater can be recovered either directly in an anaerobic reactor in moderate climates[6] or indirectly in an organic matter pre-concentration step in the form of sludge, which is subsequently treated by anaerobic digestion. Several pre-concentration alternatives exist: physical (e.g., sieving),[7] chemical (e.g., precipitation),[8] biological (e.g., A-stage)[9] or combinations of these alternatives.

Fine mesh rotating belt filters (RBFs) offer a very low footprint solution for recovering

COD. They have been successfully applied as a replacement for conventional primary treatment (CPT) in traditional WWTPs[10,11] and achieve total suspended solids (TSS) removals that are similar to those reported for CPT (~50%).[12,13] A maximum of 50% dry matter content of RBF sludge (also known as cellulosic sludge) can be achieved with a very high percentage of cellulose (maximum of 79% of TSS),[7] which facilitates its use as a soil conditioner in agriculture, fuel in a biomass-based power plant, and feed stock in the fermentation industry for the production of biofuels[6] or chemicals, such as volatile fatty acids (VFA).[14] However, the most straightforward method for onsite valorisation is energy recovery by mesophilic AD.[15]

RBFs for municipal wastewater are commonly employed with a mesh size of 350 µm.[7,16] Their effluents show important COD content, which is derived not only from soluble COD that remain unaffected in the RBFs but also from particulate COD that corresponds to small TSS that pass the RBFs. Therefore, the implementation of additional steps prior to autotrophic nitrogen removal treatment is required.[17]

Chemically enhanced primary treatment (CEPT) or chemically enhanced settling (CES) is an alternative that overcomes the limitations of RBF. In CEPT processes, using some chemical additives (coagulants and/or flocculants), TSS and COD removal can eliminate a maximum of 90% and 70%, respectively, of TSS and COD, and an increase in the sedimentation rate decreases the size of the settling tank.[18] Chemical coagulation has been shown to completely eliminate viruses from wastewater.[19] However, these processes require a considerable amount of chemicals and generate large volumes of sludge, with subsequent excessive costs of reagents and sludge disposal.[20]

Therefore, the combination of RBF and CEPT may have a synergistic effect that overcomes the limitations of separately applying both technologies. The first effect is the incapacity of RBF to achieve high COD removal efficiencies and generate suitable effluents for autotrophic nitrogen removal process, and the second effect is the large chemical doses that are required in CES processes to achieve this goal.[21]

The objective of this study is to assess the potential of RBFs to recover COD in novel WWTP configurations via its combination with a CES. The system was technically, energetically and economically evaluated. Considering the different characteristics of RBF sludge that influence the interaction with OMPs, an additional goal is to assess their fate in RBFs and compare it with the removal in conventional and chemically enhanced primary treatment.

Materials and methods

RBF systems

The technical performance of two RBF systems with a mesh size of 350 µm and located in the Blaricum WWTP (1,600 m^3/h) and Aarle-Rixtel WWTP (2,600 m^3/h) in The Netherlands was evaluated. Influent, effluent and sludge samples were collected and stored at 4 ºC in aluminium bottles prior to analysis. Wastewater samples were characterised in terms of total solids (TS, g TS/kg) and volatile solids (VS, g VS/kg), total suspended solids (TSS, g TSS/kg) and volatile suspended solids (VSS, g VSS/kg), total chemical oxygen demand (COD_{tot}, g O_2/L) and soluble chemical oxygen demand (COD_{sol}, g O_2/L), total Kjeldahl (TKN, g N-TKN/L), total ammonium nitrogen (g N-TAN/L) and OMPs concentrations. Dewatered RBF sludge samples were collected in both WWTPs, whereas WWTP raw RBF sludge (the sludge generated in the RBF without the dewatering process) was sampled in the Aarle-Rixtel WWTP. The sludge samples were characterised in terms of TS, VS, COD_{tot}, TKN and OMPs concentrations. Eighteen commonly employed OMPs with different physico-chemical properties were considered in this study: three musk fragrances, galaxolide (HHCB), tonalide (AHTN) and celestolide (ADBI); three anti-inflammatories, ibuprofen (IBP), naproxen (NPX) and diclofenac (DCF); four anti-biotics, sulfamethoxazole (SMX), trimethoprim (TMP), erythromycin (ERY) and roxithromycin (ROX); four neurodrugs, fluoxetine (FLX), carbamazepine (CBZ), diazepam (DZP) and citalopram (CTL); one endocrine disrupting compound, triclosan (TCS); and three hormones, estrone (E1), 17β-estradiol (E2) and 17α-ethinylestradiol (EE2).

CES tests

Chemically enhanced settling (CES) assays were carried out with both RBF influent and RBF effluent of the Aarle-Rixtel WWTP in a Jar-Test device with vessels that contain 1 L of liquid volume following the protocol described by Carballa et al. [22], but without pH correction. The influence of the dose of ferric chloride (0-300 mg/L) on the removal of TSS, COD and OMPs was analysed at 25ºC. The test included an initial 3 min period of rapid stirring (150 rpm) after the addition of the coagulant, followed by 5 min of slow mixing (50 rpm) for emulsion breaking and floc formation and a 1 hour period without mixing for floc separation, after which 500 mL of supernatant were collected for the characterisation.

Biomethane potential tests

The biomethane potential (BMP) of the RBF sludge and of the sludges generated after RBF (settling without chemicals and chemically enhanced settling using 100 mg/L of ferric chloride) was carried out following a protocol that was described elsewhere.[23] The inoculum was flocculant biomass (11.8 g VS/L) from the sludge anaerobic digester of a WWTP.

The assays were conducted in 500 mL bottles (375 mL of working volume) by triplicate and were carried out with an inoculum-to-substrate ratio (ISR) in terms of VS of 2. Methane production of the blank (inoculum without substrate) was also determined by triplicate. The reactors were filled with macro- and micro-nutrient solutions, and the pH was adjusted to 7.2-7.5 with NaOH or HCl when necessary. After flushing the head space with nitrogen, the bottles were incubated at 37ºC. Accumulated methane production was monitored over time to determine the COD fraction that was converted into methane. The assays continued until the methane production during three consecutive days was less than 1% of the total production.[23] Methane production by each sludge was calculated as the difference between the average production in the bottles with substrate and the average production in the blank. BMP was calculated as the experimental ultimate methane production, which was expressed in L(N)/kg VS fed, where N denotes the normal conditions (1 atm, 0ºC). Anaerobic biodegradability was expressed as the percentage of the initial COD of the substrate converted to methane. At the end of the test, bottles were opened and the pH and VFAs concentrations were measured to confirm that acidification did not occur.

Solid-water distribution coefficient (K_d) tests

A common approach to determining the fraction of OMPs sorbed onto sludge is the use of the solid–water distribution coefficient (K_d, L/kg). A spike of the 18 selected compounds was performed on raw RBF sludge at different concentrations in the three tests. Sodium azide (10 mg/L) was added to avoid biological activity. After 12 hours of mixing at room temperature to achieve equilibrium conditions, the samples were centrifuged and liquid and solid phases were separately analysed, as explained in the section analytical methods of this document.

Analytical methods

COD, pH, PA, TA, TSS, VSS, TS, VS, N-TKN and N-TAN were determined according to standard methods.[24] Total inorganic carbon (IC) concentrations were measured with a Shimadzu analyser (TOC-5000). In BMP tests, biogas production was measured by a pressure transducer (Centrepoint Electronics) and its composition was determined by gas chromatography (HP 5890 Series II). VFAs were measured by gas chromatography with flame ionisation detection (FIC, HP 5890A).

To determine the OMP concentrations in the wastewater samples, the latter were centrifuged, pre-filtered (AP4004705, Millipore) and filtered by 0.45 mm (HAWP04700, Millipore) before performing solid phase extraction (SPE) with 200 mg OASIS HLB cartridges (Waters, Milford, MA, USA), as described by Fernandez-Fontaina et al.[25] The quantification of musk fragrances (HHCB, AHTN, ADBI), anti-inflammatories (IBP, NPX, DCF) and endocrine disrupting compound TCS was accomplished using a gas chromatograph (Varian CP-3900) coupled with an ion trap spectrometer (Varian CG-2100). Antibiotics (ERY, ROX, SMX, TMP), neurodrugs

(FLX, CBZ, DZP, CTL) and hormones (E1, E2, EE2) were quantified using an Agilent G1312A liquid chromatograph with a binary pump and automatic injector HTC-PAI (CTC Analytics) connected to a mass spectrometer API 4000 triple quadrupole (Applied Biosystems).[26]

For influents and effluents, the sample volume that was analysed was 1 L, and the final volume of the extract was 3 mL, which generated an enrichment factor (concentration in the extract compared with the source) of 333 $L_{supernatant}/L_{extract}$. For the liquid phase of RBF sludge, the analysed volume was 100 mL and the final volume of extract was 3 mL, which yielded an enrichment factor of 33 $L_{supernatant}/L_{extract}$. The limits of quantification for each case are shown in Table S1 in Supporting Information.

The frozen solid phases of the influent and effluent of RBF and raw and dewatered SS were lyophilised to perform ultrasonic solvent extraction following a procedure based on the procedure described by Alvarino et al.[27] Three sequential extractions with methanol and two sequential extractions with acetone were performed on the freeze-dried samples (0.5-1 g). In each extraction, samples were sonicated for 15 min and centrifuged at 1500 rpm for 5 min. The resulting supernatants were combined and filtered through glass wool. The resulting volume was evaporated to 1 mL (TurboVap LV, Biotage) flowing nitrogen (200 kPa, 30 ºC) and resuspended in 100 mL of Milli-Q water prior to SPE. SPE and OMPs quantification were performed as previously described for liquid samples. The enrichment factor was 166 $g_{sludge}/L_{extract}$.

Results and discussion

Technical performance of RBF systems

The physico-chemical characterisation of the influent and effluent of the two RBF sampled systems are shown in Table 1. Both influents showed similar average values of TSS (320 and 275 mg/L), VSS (300 and 255 mg /L), VS (600 and 570 mg/L), COD_{tot} (680 and 600 mg O_2/L), COD_{sol} (230 and 260 mg O_2/L) and TKN (87 and 75 mg TKN N/L), which is consistent with previously reported values for the Blaricum WWTP [7] and for other urban WWTPs in The Netherlands.[28] Conversely, the TS concentration in the influent of the Blaricum WWTP (770 mg/L) was considerably lower than that measured in the influent of the Aarle-Rixtel WWTP (1,260 mg/L), which indicates a lower salts dissolved concentration.

The removal efficiency of TSS (~50%), VSS (~50%), COD_{sol} (~0%) and TKN (~10%) were similar in both RBF systems. Regarding COD_{tot}, a higher removal efficiency (37%) was determined in the Blaricum WWTP than in the Aarle-Rixtel WWTP (22%), which is explained by its higher COD_{sol}-to-COD_{tot} ratio. The removal efficiencies determined in this study are similar to those reported by other authors regardless of the TKN,[7,17] for which the removal efficiencies achieved in both scenarios were approximately 10%—a value that is slightly higher than the that reported elsewhere (~1%).[7]

The physico-chemical properties of dewatered RBF sludge are shown in Table 2. TS (21.5-27.5%), VS (20.0-25.8%), COD_{tot} (273-356 g O_2/kg) and TKN/VS ratio (12-16 mg N/g VS) are in accordance with the values reported for RBF sludge from the Blaricum WWTP [15]. VS represents approximately 95% of the TS of the sludge, and the COD_{tot}-to-VS ratio was approximately 1.3, which is in accordance with the mean values obtained by Paulsrud et al.[29] for 19 Norwegian WWTPs that apply RBF technology. Ghasimi et al.[15] reported higher COD_{tot}/VS ratios (1.6-1.8), which may be indicative of a lower cellulose concentration.

Raw RBF sludge of the Aarle-Rixtel WWTP was ten times less concentrated than the dewatered RBF sludge, which shows similar physico-chemical characteristics (data not shown), as expected.

Technical performance of CES

The results of applying a CES to the influent of RBFs are shown in Figure 1. Ferric chloride was selected as a coagulant rather than aluminium salts, considering its lower price [18] and lower required doses. [22] Effluent quality that is comparable to that obtained in RBFs was obtained after conventional settling (COD_{tot} removal and TSS removal of 36-38% and 47-49%, respectively), without removal of COD_{sol}. By the addition of 100 mg/L of ferric chloride, the removal of COD_{tot} and TSS increased to 66 and 86%, respectively. This decrease was primarily attributed to a large removal of suspended matter, considering that the maximum COD_{sol} removal achieved did not exceed 25%. Heterotrophic denitrifiers may increase nitrogen removal efficiency in anammox reactors with low influent COD/N ratios;[30] however, system failure was reported with COD/N ratios higher than 2 due to the growth of fast-growing heterotrophic denitrifiers, which compete with the slow-growing anammox bacteria for nitrite.[31] To fulfil this condition, the required ferric chloride dose should be increased to 300 mg/L, which is similar to that reported by Carballa et al. [22]

Technical performance of combined RBF and CES technologies

RBFs are suitable to partial removal of COD_{part} from wastewater but they are unable to remove COD_{sol}. CES enables complete removal of COD_{part} and partial removal of COD_{sol} with a requirement of high chemical doses. Thus, the combination of RBF and CES was analysed (Figure 2) to attempt to overcome the limitation of both technologies and compare with the CES system (Figure 1).

The combination of RBF followed by settling without chemicals addition produced a removal of almost 100% of the COD_{part} of wastewater, whereas 50% of removal was achieved when the test was carried out for the RBF influent (Figure 1), which may indicate that the presence of cellulose in wastewater limits the settlement of other suspended solids due to its tendency to float. COD_{sol} remained unaffected. When 100 mg/L of ferric chloride were added, COD_{part} was totally removed, which generates an effluent with approximately 10 mg TSS/L, and more than 50% of COD_{sol} was removed (Figure 2), which accounts for COD_{tot} removal of 84%. To obtain comparable results without an RBF system, a considerably higher dose of $FeCl_3$ (approximately 300 mg/L) was needed (Figure 1).

Note that a side effect exists of the addition of the coagulant on the alkalinity, with a consumption of 22 mg IC for each 100 mg of $FeCl_3$.[32] Taking into account that the further PN-anammox step requires a minimum alkalinity-to-ammonium ratio of 1-1.25 g IC per g NH_4^+-N,[33] the need for an external bicarbonate addition to avoid acidification in the PN-anammox unit, which considers an ammonium concentration of 67 mg NH_4^+-N/L (Table 1), would be much higher if the RBF system is not present.

Biomethane potential of the sludges

Figure 3 shows the results of the BMP tests of RBF sludge, which comprise the sludges generated after RBFs (settling without chemicals and settling with the addition of 100 mg/L of ferric chloride). Three of the sludges showed similar methane production rates and needed 26 days to complete the test, following the criteria proposed by Holliger et al. [23] The neutral pH values (7.3-7.7) and the absence of VFA (<2.5 ppm acetic acid) at the end of the tests (data not shown) indicated that the performance of the tests was adequate and acidification did not occur.

Dewatered RBF sludge showed the highest BMP value (386 L(N) CH_4/kg VS), which is consistent with other results in the literature.[29] However, the anaerobic biodegradability (80%) was higher than that the obtained by Ghasimi et al. [15] (64%), which is explained by its lower COD_{tot}/VS ratio.

The sludges generated during conventional settling and CES after RBF showed similar BMP values (327 L(N) CH_4/kg VS and 310 L(N) CH_4/kg VS, which corresponds to 60% of anaerobic biodegradability and 58% of anaerobic biodegradability, respectively), but values lower than those for dewatered RBF sludge. These values are comparable to those reported for conventional primary sludge (259-325 L (N) CH_4/kg VS).[29] Thus, the installation of RBFs seems to not affect the BMP of sludge obtained by conventional settling, which may be explained by the low proportion of cellulose recovered in the latter system.[7] The similar results obtained for both sludges do not agree with those obtained by Kooijman et al.,[34] who reported an important increase in the BMP of the sludge generated during CES compared with conventional settling due to the higher readily degradable biomass removed by flocculation. However, Romero-

Güiza et al. [35] reported that Fe^{3+} reduction can limit the conversion of organics to methane as Fe^{3+} reduction is more thermodynamically favourable than methanogenesis. The data from the BMP test and the results of the CES tests enabled calculation of the methane production of each sludge in relation to the COD recovery in each treatment step. RBF enables a very limited energy recovery (62 L(N) CH4/kg $COD_{influent}$), which is explained by lower COD_{tot} recovery compared with that of other tested technologies (Figure 2).

The system RBF followed by settlement without chemicals enabled an increase in the energy recovery to 85 L(N) CH_4/kg $COD_{influent}$). However, the highest energy recovery was achieved with the combination RBF and CES with 100 mg/L of ferric chloride, which boosted it to 122 L(N) CH_4/kg $COD_{influent}$ due to the higher COD capture determined with the addition of chemicals (Figure 1).

Fate of organic micropollutants in the RBF and CES systems

The concentrations of the 18 selected OMPs in the influent of both RBF systems are reported in Table S2. The highest concentrations of OMPs in both WWTPs were observed for the anti-inflammatories IBP and NPX (3.47-4.89 µg/L), although DCF was not detected in either of the two WWTPs. These concentrations are consistent with other concentrations in the literature. [13,36,37] Musk fragrances (HHCB, AHTN and ADBI) and the endocrine-disrupting compound TCS were detected in the range 0.95-2.16 µg/L, in accordance with other authors.[36,38,39] The four antibiotics (SMX, TMP, ERY, and ROX) and the four neurodrugs (FLX, CBZ, DZP and CTL) were detected in the influent of Blaricum WWTP, whereas SMX and ROX were not detected in the Aarle-Rixtel

WWTP. In general, the measured concentrations (LOD-235 ng/L) were in the lower range of the literature. [36,37,39,40] This fact can be explained by the fact that the Netherlands has the lowest human antibiotic consumption rate of Europe.[41] The concentrations of hormones ranged between LOQ and 57 ng/L, which is the same range of those reported in the literature).[39]

The OMP removal efficiencies achieved in the different evaluated systems (RBF, CPT, and RBF+CES using 100 mg/L of ferric chloride and CES using 300 mg/L of ferric chloride) are shown in Figure 4. Only fragrances and TCS were removed in a significant percentage in the evaluated scenarios. In the RBFs of the Blaricum WWTP (WWTP 1), the removal efficiencies of HHCB, AHTN and ADBI were 39%, 46% and 34%, respectively, and 45% for TCS. In the RBFs of the Aarle-Rixtel WWTP, the determined removal efficiencies of HHCB, AHTN and ADBI were slightly higher (53%, 54% and 44%, respectively). TCS was not detected in this WWTP. In conventional settling of the Aarle-Rixtel WWTP (WWTP 2), the elimination of HHCB, AHTN and ADBI were 54%, 56% and 45%, respectively, compared with those obtained during CPT of hospital wastewater.[42] Thus, no difference was found between RBF and CPT. These results can be explained by the similar removal efficiencies of TSS that are achieved in both systems and the similar affinity of these OMPs to the solid phase of conventional primary and RBF sludges, which is confirmed by the results of the solid-liquid distribution coefficients (Figure S1) and the comparable concentration of these OMPs in both sludges (in Supporting Information S3, a detailed discussion is included). In the Aarle-Rixtel WWTP (WWTP 2), the combination of RBF and CES enabled improvement in the removal efficiencies of HHCB and AHTN to 96% and improvement in the removal efficiency of ADBI to 75%, which is similar to those achieved in the CES. For the remaining OMPs, the elimination of different RBF systems ranged from -8 to 14% (Figure 3). The increase in concentration of some OMPs was likely attributed to the analytical deviation caused by the distinctive characteristics of the wastewaters. These results show agreement with the literature.[13,42,43]

It seems to be a consensus in the literature that most OMPs are poorly removed during coagulation–flocculation processes, however, some exceptions such as musks, a few pharmaceuticals (e.g. DCF) and nonylphenol were found.[39] Moreover, some authors reported that the different composition of wastewater can play a major role on OMPs removal during CES. For example, high fat content in wastewater was reported to improve the removal of hydrophobic compounds. [42] Dissolved humic acid could also enhance the elimination of some pharmaceutical compounds, such as DCF or IBP.[44] On the contrary, the presence of COD_{sol}, especially low-molecular-weight fractions, can possibly inhibit the OMPs removal due to the preferential removal of COD_{sol} through coagulation. Negatively charged COD_{sol} could react with positively charged coagulants, leading to a less amount of coagulant available for elimination of OMPs.[45]

Although the system RBF+CES of the proposed alternative did not enable extra removal of hydrophilic compounds compared with conventional settling, it enabled an increase in the removal efficiency of hydrophobic compounds, which achieved results that were as good as those obtained in the CES with higher doses of ferric chloride.

Energetic and economic assessment of the proposed WWTP configuration

Among the evaluated alternatives, the combination of RBF and CES drove the maximum energy production with the lowest ferric chloride and alkalinity consumption and to the highest OMPs removal. Figure 5 shows a comparison of this alternative with the conventional WWTP scheme in terms of energy production/consumption.

In conventional WWTPs, aeration usually consumes the largest energy fraction (maximum of 70%),[4,46] which causes a total energy consumption of wastewater in the range 0.6-1.2 kWh/kg COD_{tot}, with an average value of 0.9 kWh/kg COD_{tot}.[47] Therefore, the treatment of 0.54 kWh/m^3 wastewater is needed, considering 0.6 kg COD_{tot}/m^3 for the Aarle-Rixtel WWTP (Table 1), in accordance with other reported values in the literature.[48] The potential energy in typical domestic wastewater has been estimated as 4.5 kWh/kg COD_{tot} in the influent [5,49], and the COD_{tot} transformed into methane usually does not exceed 30%, [50,51] of which a maximum of 35% is converted to electricity via its combustion.[47] As approximately 0.47 kWh per kg of $COD_{influent}$ are commonly recovered, a maximum of 50% of self-produced energy can be achieved (Figure 5a). Considering an electricity cost of 0.12 €/kWh,[52] a treatment cost of 0.031 €/m^3 for treated wastewater is estimated.

In the proposed scenario (Figure 5b), the electricity demand of the PN-anammox unit was considered to be 60% of the nitrification-denitrification electricity demand, according to Schaubroeck et al.,[51] which yielded 0.23 kWh/m^3 of treated wastewater. The maximum electricity consumption of RBF was reported to be approximately 0.04 kWh/m^3,[54] and the costs due to pumping and sludge treatment were assumed to be 0.17 kWh/m^3, which is equivalent to those in conventional configurations [47]. Thus, the electricity demand was 0.44 kWh/m^3, which is 19% lower than that in the conventional configuration (0.54 kWh/m^3). The combination of RBF followed by CEPT enabled 84% recovery of the COD_{tot} of the influent as sludge (Figure 2). During AD, 52% of the influent COD was transformed into methane and yielded electricity generation of 0.82 kWh per kg of $COD_{influent}$ (0.49 kWh/m^3 of wastewater treated), which almost doubles the electricity generation in the conventional WWTP. This fact and the lower electrical requirements of this configuration enable an electrical self-production of 100-110%. To calculate the operational costs associated with chemical addition, the $FeCl_3$ price was estimated at approximately 220 €/ton [18] and the sodium bicarbonate price was estimated at approximately 200 €/ton (1,400 €/ton IC). Two different scenarios were evaluated: in the first scenario, the alkalinity of wastewater was assumed to be sufficiently high bear the consumption produced in CES; thus, the influent to the PN-anammox would have an appropriate alkalinity-to-ammonium ratio; in the second scenario, an external alkalinity addition as sodium bicarbonate was considered to compensate its consumption in the CES stage. The first scenario yielded a treatment cost that was 29% lower than the treatment cost in the conventional WWTP (0.022 versus 0.031 €/m^3). In the second scenario, the calculated treatment costs increased to 0.053 €/m^3; thus, it was distinctly uncompetitive compared with the conventional WWTP.

Conclusion

The implementation of rotating belt filters before chemically enhanced settling was proven effective for generating suitable effluents for a nutrient removal stage, maximising the energy recovery via the anaerobic digestion of the generated sludges, attaining 110% of the electrical autarky and achieving OMP removal that is as substantial as that obtained in chemically enhanced settling, and decreasing the required dose3-fold. However, a minimum alkalinity level in wastewaters was shown mandatory to consider this WWTP configuration as more economically favourable with respect to the conventional WWTP configuration.

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Table legends

Table 1. Physicochemical characteristics of influent and effluent in rotating belt sieves from Blaricum and Aarle-Rixtel wastewater treatment plants (n=3).

Table 2. Physicochemical characteristics of dewatered sieved sludge generated in rotating belt sieves of Blaricum and Aarle-Rixtel wastewater treatment plants (n=3).

Table 3. Calculated electricity and chemical operational costs of the proposed WWTP configuration.

Figures captions

Fig. 1. Influence of ferric chloride dose on the removal of soluble (🟦) and particulate (🟫) COD and TSS (●) on raw wastewater of Aarle-Rixtel WWTP. 0 mg $FeCl_3$/L refers to conventional settling without chemicals.

Fig. 2. Influence of ferric chloride dose on the removal of soluble (🟦) and particulate (🟫) COD and TSS (●) on the RBF effluent of wastewater of Aarle-Rixtel WWTP. 0 mg $FeCl_3$/L refers to conventional settling without chemicals.

Fig. 3. Average BMP results of dewatered sieved sludge (🟥), conventional settling sludge after RBF (▲) and chemically enhanced settling sludge after RBF (●).

Fig. 4. Removal efficiencies of the organic micropollutants in RBF system in WWTP 1 (■), in RBF in WWTP 2 (▤), in CPT in WWTP 2 (▨), RBF + CES in WWTP 2 (▦), and CES in WWTP 2 (□).

Fig. 5. COD balance (in relation to 1 kg in the influent) and energy flows for the traditional WWTP configuration (adapted from Wan et al. [50]) and the proposed WWTP configuration. * Represents the energy required for sludge management and pumping, - - ▶ Refers to energy inputs for the wastewater treatment.

Table 1

	Blaricum WWTP		WWTP Aarle-Rixtel	
	Influent	**Effluent**	**Influent**	**Effluent**
TS (mg/L)	770 ± 30	610 ± 20	1260 ± 0	1140 ± 10
VS (mg/L)	600 ± 20	440 ± 20	570 ± 5	450 ± 20
TSS (mg/L)	320 ± 10	160 ± 0	275 ± 5	145 ± 10
VSS (mg/L)	300 ± 20	150 ± 0	255 ± 10	130 ± 5
COD_{tot} (mg O_2/L)	680 ± 10	440 ± 10	600 ± 30	470 ± 10
COD_{sol} (mg O_2/L)	230 ± 10	220 ± 10	260 ± 20	240 ± 10
TKN-N (mg/L)	87 ± 2	75 ± 1	75 ± 4	69 ± 6
TAN-N (mg/L)	nd	nd	67 ± 3	61 ± 4

TS: total solids; VS: volatile solids; TSS: total suspended solids; VSS: volatile suspended solids; COD: chemical oxygen demand; TKN-N: total Kjeldahl nitrogen, TAN-N: total ammonium nitrogen, n.d.: not determined.

Table 2

	Blaricum WWTP	**Aarle-Rixtel WWTP**
TS (g/kg)	215 ± 10	279 ± 10
VS (g/kg)	200 ± 10	261 ± 10
COD_{tot} (g/kg)	273 ± 18	350 ± 20
TKN-N (g/kg)	3.3 ± 0.2	4.2 ± 0.1

TS: total solids; VS: volatile solids; COD_{tot}: total chemical oxygen demand; TKN: total Kjeldahl nitrogen.

Table 3

	Alkalinity supply	**No alkalinity supply**
Electricity requirements (kWh/m^3)	0	0
Ferric chloride dosage (kg/m^3)	0.1	0.1
Alkalinity supply (g IC/m^3)	0.022	0
Ferric chloride cost (€/m^3)	0.022	0.022
Sodium bicarbonate cost (€/m^3)	0.031	0
Operational costs (€/m^3)	0.053	0.022

Figure 1

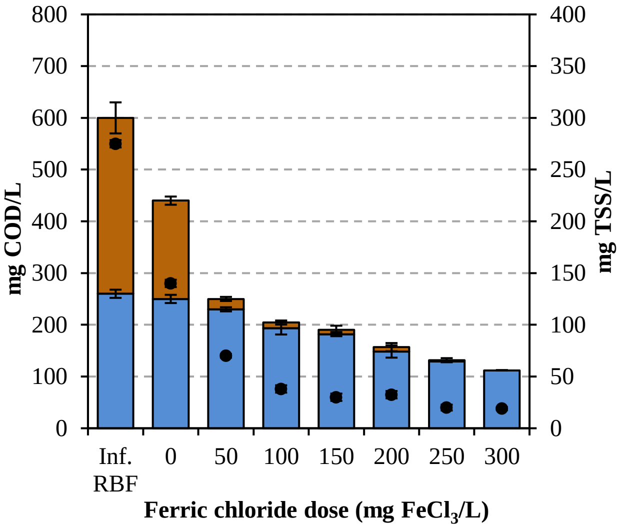
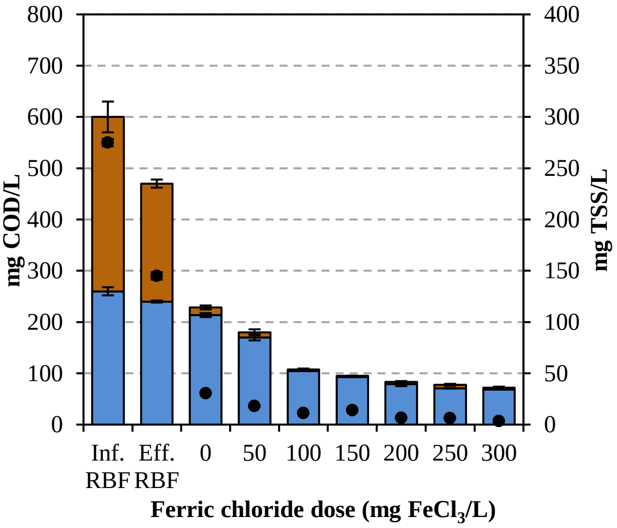
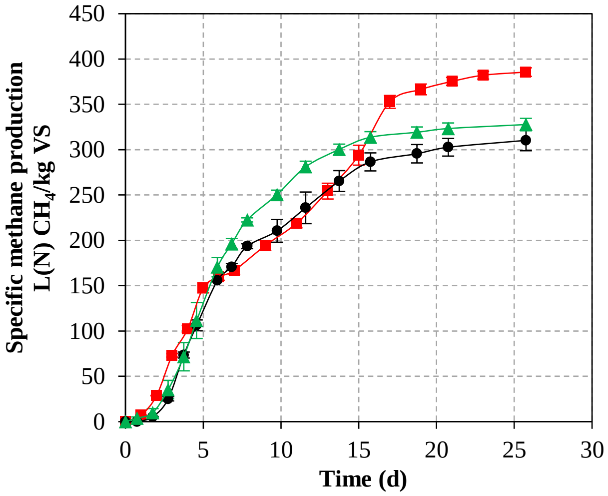

800
700
600
500
400
300
200
100
0
mg COD/L
400
350
300
250
200
150
100
50
0
mg TSS/L
Inf. RBF
0
50
100
150
200
250
300
Ferric chloride dose (mg $FeCl_3$/L)

Figure 2



800
700
600
500
400
300
200
100
0
mg COD/L
400
350
300
250
200
150
100
50
0
mg TSS/L
Inf. RBF
Eff. RBF
0
50
100
150
200
250
300
Ferric chloride dose (mg $FeCl_3$/L)

517 **Figure 3**


Specific methane production L(N) CH_4/kg VS
0
50
100
150
200
250
300
350
400
450
0
5
10
15
20
25
30
Time (d)

518 **Figure 4**

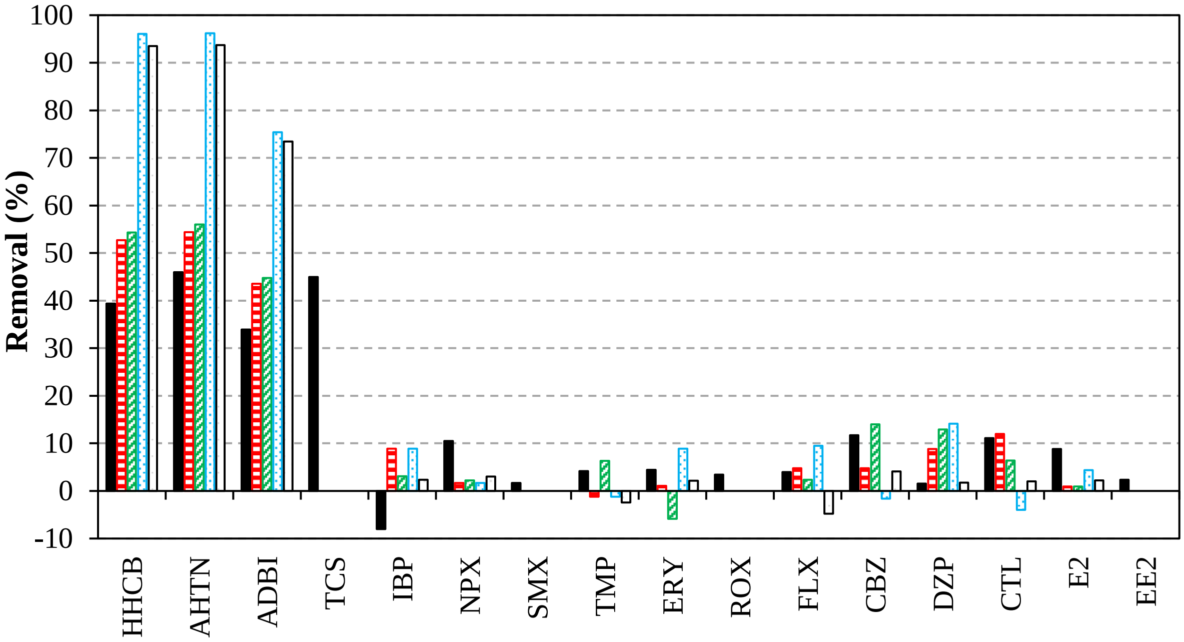
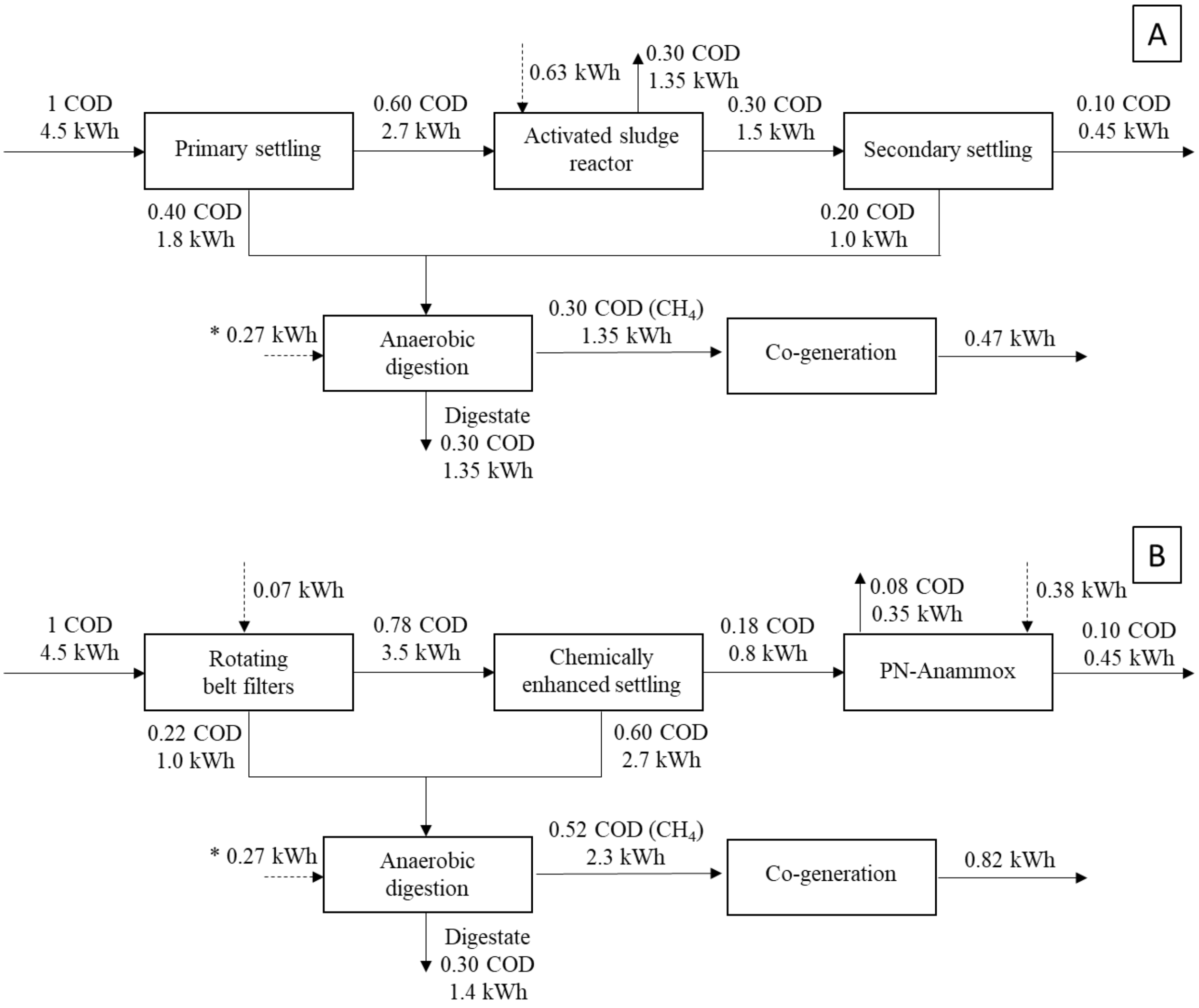

Removal (%)
100
90
80
70
60
50
40
30
20
10
0
-10
HHCB
AHTN
ADBI
TCS
IBP
NPX
SMX
TMP
ERY
ROX
FLX
CBZ
DZP
CTL
E2
EE2

Figure 5


A
1 COD
4.5 kWh
Primary settling
0.60 COD
2.7 kWh
0.63 kWh
0.30 COD
1.35 kWh
Activated sludge reactor
0.30 COD
1.5 kWh
Secondary settling
0.10 COD
0.45 kWh
0.40 COD
1.8 kWh
0.20 COD
1.0 kWh
* 0.27 kWh
Anaerobic digestion
0.30 COD (CH4)
1.35 kWh
Co-generation
0.47 kWh
Digestate
0.30 COD
1.35 kWh
B
0.07 kWh
1 COD
4.5 kWh
Rotating belt filters
0.78 COD
3.5 kWh
Chemically enhanced settling
0.18 COD
0.8 kWh
0.08 COD
0.35 kWh
0.38 kWh
PN-Anammox
0.10 COD
0.45 kWh
0.22 COD
1.0 kWh
0.60 COD
2.7 kWh
* 0.27 kWh
Anaerobic digestion
0.52 COD (CH4)
2.3 kWh
Co-generation
0.82 kWh
Digestate
0.30 COD
1.4 kWh