

## Opportunities for rotating belt filters in novel wastewater treatment plant configurations

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2 **Opportunities for rotating belt filters in novel wastewater treatment**

3 **plant configurations**

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## 12 **Abstract**

13 Novel wastewater treatment plants (WWTPs), which are based on a partial nitrification-  
14 anammox (PN-anammox) process, enable higher chemical oxygen demand (COD)  
15 recovery to produce biogas and lower treatment costs. In this study, rotating belt filters  
16 (RBFs) were examined in different configurations to identify the opportunities for RBFs  
17 to be included in novel WWTP configurations. RBFs enable recovery of 22-37% of the  
18 influent COD and removal of 34-56% of hydrophobic organic micropollutants (OMPs).  
19 However, the effluent was not suitable for treatment in a PN-anammox process due to  
20 its high COD. Chemically enhanced settling (CES) enabled these limitations to be  
21 overcome and caused an increase in OMP removal to 73-94%. However, a dose of 300  
22 mg/L of ferric chloride was required to produce a suitable effluent for a PN-anammox  
23 reactor. The combination of RBF and CES not only derived effluents suitable for  
24 treatment in PN-anammox units but also decreased the alkalinity consumption and the  
25 required chemical dose 3-fold to achieve comparable COD recovery and OMP removal.  
26 The methane yield of the combined sludges that were produced (184 L(N) CH<sub>4</sub>/kg  
27 COD<sub>influent</sub>) was 75% higher than that obtained in conventional wastewater treatment  
28 (105 L(N) CH<sub>4</sub>/kg COD<sub>influent</sub>), and the electricity requirements decreased from 0.54 to  
29 0.41 kWh/m<sup>3</sup> of treated wastewater. The energetic calculations showed that a WWTP  
30 incorporating this combined treatment could attain energy autarky with 29% lower  
31 operational costs than that of conventional treatment (0.022 vs 0.031 €/m<sup>3</sup>) as long as a  
32 minimum alkalinity-to-ammonium ratio of 1-1.25 g IC to g NH<sub>4</sub><sup>+</sup>-N was ensured in the  
33 effluent of the combined treatment.

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

## 36 **Introduction**

37 The discovery of the autotrophic nitrogen removal process (anammox process)<sup>1</sup>, which  
38 does not require an organic carbon source for denitrification, introduces new  
39 possibilities for conceiving more energetically efficient wastewater treatment plants  
40 (WWTPs).<sup>2</sup> Although anammox-based processes are already applied at full scale to treat  
41 the supernatants of anaerobic sludge mesophilic digesters, the implementation of this  
42 technology in the mainstream of WWTPs is currently under investigation since they  
43 operate at considerably lower temperatures (10-20°C).<sup>3</sup>  
44 In the first stage of these novel WWTPs, pre-concentration technologies can recover  
45 most of the chemical oxygen demand (COD) from sewage to produce energy (methane),  
46 which enables WWTPs to gain energy self-sufficiency or even become energy-  
47 producing facilities.<sup>4</sup> Some studies have suggested that the energy contained in  
48 wastewater is nearly 5-fold the electrical energy that is used to drive conventional  
49 wastewater treatment.<sup>5</sup> Therefore, as long as 20% of the total energy in domestic  
50 wastewater can be completely converted to electrical energy, WWTPs may be  
51 energetically self-sufficient.

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

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

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

67 RBFs for municipal wastewater are commonly employed with a mesh size of 350  
68  $\mu\text{m}$ .<sup>7,16</sup> Their effluents show important COD content, which is derived not only from  
69 soluble COD that remain unaffected in the RBFs but also from particulate COD that  
70 corresponds to small TSS that pass the RBFs. Therefore, the implementation of  
71 additional steps prior to autotrophic nitrogen removal treatment is required.<sup>17</sup>

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

80 Therefore, the combination of RBF and CEPT may have a synergistic effect that  
81 overcomes the limitations of separately applying both technologies. The first effect is  
82 the incapacity of RBF to achieve high COD removal efficiencies and generate suitable  
83 effluents for autotrophic nitrogen removal process, and the second effect is the large  
84 chemical doses that are required in CES processes to achieve this goal.<sup>21</sup>  
85 The objective of this study is to assess the potential of RBFs to recover COD in novel  
86 WWTP configurations via its combination with a CES. The system was technically,  
87 energetically and economically evaluated. Considering the different characteristics of  
88 RBF sludge that influence the interaction with OMPs, an additional goal is to assess  
89 their fate in RBFs and compare it with the removal in conventional and chemically  
90 enhanced primary treatment.

## 91 **Materials and methods**

### 92 **RBF systems**

93 The technical performance of two RBF systems with a mesh size of 350  $\mu\text{m}$  and located  
94 in the Blaricum WWTP (1,600  $\text{m}^3/\text{h}$ ) and Aarle-Rixtel WWTP (2,600  $\text{m}^3/\text{h}$ ) in The  
95 Netherlands was evaluated. Influent, effluent and sludge samples were collected and  
96 stored at 4  $^{\circ}\text{C}$  in aluminium bottles prior to analysis. Wastewater samples were  
97 characterised in terms of total solids (TS, g TS/kg) and volatile solids (VS, g VS/kg),  
98 total suspended solids (TSS, g TSS/kg) and volatile suspended solids (VSS, g VSS/kg),  
99 total chemical oxygen demand ( $\text{COD}_{\text{tot}}$ , g  $\text{O}_2/\text{L}$ ) and soluble chemical oxygen demand  
100 ( $\text{COD}_{\text{sol}}$ , g  $\text{O}_2/\text{L}$ ), total Kjeldahl (TKN, g N-TKN/L), total ammonium nitrogen (g N-  
101 TAN/L) and OMPs concentrations. Dewatered RBF sludge samples were collected in

102 both WWTPs, whereas WWTP raw RBF sludge (the sludge generated in the RBF  
103 without the dewatering process) was sampled in the Aarle-Rixtel WWTP. The sludge  
104 samples were characterised in terms of TS, VS, COD<sub>tot</sub>, TKN and OMPs concentrations.  
105 Eighteen commonly employed OMPs with different physico-chemical properties were  
106 considered in this study: three musk fragrances, galaxolide (HHCB), tonalide (AHTN)  
107 and celestolide (ADBI); three anti-inflammatories, ibuprofen (IBP), naproxen (NPX)  
108 and diclofenac (DCF); four anti-biotics, sulfamethoxazole (SMX), trimethoprim (TMP),  
109 erythromycin (ERY) and roxithromycin (ROX); four neurodrugs, fluoxetine (FLX),  
110 carbamazepine (CBZ), diazepam (DZP) and citalopram (CTL); one endocrine  
111 disrupting compound, triclosan (TCS); and three hormones, estrone (E1), 17 $\beta$ -estradiol  
112 (E2) and 17 $\alpha$ -ethinylestradiol (EE2).

### 113 **CES tests**

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

### 123 **Biomethane potential tests**

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

129 The assays were conducted in 500 mL bottles (375 mL of working volume) by triplicate  
130 and were carried out with an inoculum-to-substrate ratio (ISR) in terms of VS of 2.

131 Methane production of the blank (inoculum without substrate) was also determined by  
132 triplicate. The reactors were filled with macro- and micro-nutrient solutions, and the pH  
133 was adjusted to 7.2-7.5 with NaOH or HCl when necessary. After flushing the head  
134 space with nitrogen, the bottles were incubated at 37°C. Accumulated methane  
135 production was monitored over time to determine the COD fraction that was converted  
136 into methane. The assays continued until the methane production during three  
137 consecutive days was less than 1% of the total production.<sup>23</sup> Methane production by  
138 each sludge was calculated as the difference between the average production in the  
139 bottles with substrate and the average production in the blank. BMP was calculated as  
140 the experimental ultimate methane production, which was expressed in L(N)/kg VS fed,  
141 where N denotes the normal conditions (1 atm, 0°C). Anaerobic biodegradability was  
142 expressed as the percentage of the initial COD of the substrate converted to methane.  
143 At the end of the test, bottles were opened and the pH and VFAs concentrations were  
144 measured to confirm that acidification did not occur.

145 **Solid-water distribution coefficient ( $K_d$ ) tests**

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

### 153 **Analytical methods**

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

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

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

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

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

## 188 **Results and discussion**

### 189 **Technical performance of RBF systems**

190 The physico-chemical characterisation of the influent and effluent of the two RBF  
191 sampled systems are shown in Table 1. Both influents showed similar average values of  
192 TSS (320 and 275 mg/L), VSS (300 and 255 mg /L), VS (600 and 570 mg/L), COD<sub>tot</sub>  
193 (680 and 600 mg O<sub>2</sub>/L), COD<sub>sol</sub> (230 and 260 mg O<sub>2</sub>/L) and TKN (87 and 75 mg TKN  
194 N/L), which is consistent with previously reported values for the Blaricum WWTP <sup>7</sup> and  
195 for other urban WWTPs in The Netherlands.<sup>28</sup> Conversely, the TS concentration in the  
196 influent of the Blaricum WWTP (770 mg/L) was considerably lower than that measured  
197 in the influent of the Aarle-Rixtel WWTP (1,260 mg/L), which indicates a lower salts  
198 dissolved concentration.

199 The removal efficiency of TSS (~50%), VSS (~50%), COD<sub>sol</sub> (~0%) and TKN (~10%)  
200 were similar in both RBF systems. Regarding COD<sub>tot</sub>, a higher removal efficiency  
201 (37%) was determined in the Blaricum WWTP than in the Aarle-Rixtel WWTP (22%),  
202 which is explained by its higher COD<sub>sol</sub>-to-COD<sub>tot</sub> ratio. The removal efficiencies  
203 determined in this study are similar to those reported by other authors regardless of the  
204 TKN,<sup>7,17</sup> for which the removal efficiencies achieved in both scenarios were  
205 approximately 10%—a value that is slightly higher than the that reported elsewhere  
206 (~1%).<sup>7</sup>

207 The physico-chemical properties of dewatered RBF sludge are shown in Table 2. TS  
208 (21.5-27.5%), VS (20.0-25.8%), COD<sub>tot</sub> (273-356 g O<sub>2</sub>/kg) and TKN/VS ratio (12-16  
209 mg N/g VS) are in accordance with the values reported for RBF sludge from the  
210 Blaricum WWTP <sup>15</sup>. VS represents approximately 95% of the TS of the sludge, and the  
211 COD<sub>tot</sub>-to-VS ratio was approximately 1.3, which is in accordance with the mean values

212 obtained by Paulsrud et al.<sup>29</sup> for 19 Norwegian WWTPs that apply RBF technology.  
213 Ghasimi et al.<sup>15</sup> reported higher COD<sub>tot</sub>/VS ratios (1.6-1.8), which may be indicative of  
214 a lower cellulose concentration.  
215 Raw RBF sludge of the Aarle-Rixtel WWTP was ten times less concentrated than the  
216 dewatered RBF sludge, which shows similar physico-chemical characteristics (data not  
217 shown), as expected.

### 218 **Technical performance of CES**

219 The results of applying a CES to the influent of RBFs are shown in Figure 1. Ferric  
220 chloride was selected as a coagulant rather than aluminium salts, considering its lower  
221 price<sup>18</sup> and lower required doses.<sup>22</sup> Effluent quality that is comparable to that obtained  
222 in RBFs was obtained after conventional settling (COD<sub>tot</sub> removal and TSS removal of  
223 36-38% and 47-49%, respectively), without removal of COD<sub>sol</sub>. By the addition of 100  
224 mg/L of ferric chloride, the removal of COD<sub>tot</sub> and TSS increased to 66 and 86%,  
225 respectively. This decrease was primarily attributed to a large removal of suspended  
226 matter, considering that the maximum COD<sub>sol</sub> removal achieved did not exceed 25%.  
227 Heterotrophic denitrifiers may increase nitrogen removal efficiency in anammox  
228 reactors with low influent COD/N ratios;<sup>30</sup> however, system failure was reported with  
229 COD/N ratios higher than 2 due to the growth of fast-growing heterotrophic denitrifiers,  
230 which compete with the slow-growing anammox bacteria for nitrite.<sup>31</sup> To fulfil this  
231 condition, the required ferric chloride dose should be increased to 300 mg/L, which is  
232 similar to that reported by Carballa et al.<sup>22</sup>

### 233 **Technical performance of combined RBF and CES technologies**

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

239 The combination of RBF followed by settling without chemicals addition produced a  
240 removal of almost 100% of the  $\text{COD}_{\text{part}}$  of wastewater, whereas 50% of removal was  
241 achieved when the test was carried out for the RBF influent (Figure 1), which may  
242 indicate that the presence of cellulose in wastewater limits the settlement of other  
243 suspended solids due to its tendency to float.  $\text{COD}_{\text{sol}}$  remained unaffected. When 100  
244 mg/L of ferric chloride were added,  $\text{COD}_{\text{part}}$  was totally removed, which generates an  
245 effluent with approximately 10 mg TSS/L, and more than 50% of  $\text{COD}_{\text{sol}}$  was removed  
246 (Figure 2), which accounts for  $\text{COD}_{\text{tot}}$  removal of 84%. To obtain comparable results  
247 without an RBF system, a considerably higher dose of  $\text{FeCl}_3$  (approximately 300 mg/L)  
248 was needed (Figure 1).

249 Note that a side effect exists of the addition of the coagulant on the alkalinity, with a  
250 consumption of 22 mg IC for each 100 mg of  $\text{FeCl}_3$ .<sup>32</sup> Taking into account that the  
251 further PN-anammox step requires a minimum alkalinity-to-ammonium ratio of 1-1.25  
252 g IC per g  $\text{NH}_4^+\text{-N}$ ,<sup>33</sup> the need for an external bicarbonate addition to avoid acidification  
253 in the PN-anammox unit, which considers an ammonium concentration of 67 mg  $\text{NH}_4^+\text{-}$   
254 N/L (Table 1), would be much higher if the RBF system is not present.

255 **Biomethane potential of the sludges**

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

263 Dewatered RBF sludge showed the highest BMP value (386 L(N) CH<sub>4</sub>/kg VS), which is  
264 consistent with other results in the literature.<sup>29</sup> However, the anaerobic biodegradability  
265 (80%) was higher than that the obtained by Ghasimi et al.<sup>15</sup> (64%), which is explained  
266 by its lower COD<sub>tot</sub>/VS ratio.

267 The sludges generated during conventional settling and CES after RBF showed similar  
268 BMP values (327 L(N) CH<sub>4</sub>/kg VS and 310 L(N) CH<sub>4</sub>/kg VS, which corresponds to  
269 60% of anaerobic biodegradability and 58% of anaerobic biodegradability,  
270 respectively), but values lower than those for dewatered RBF sludge. These values are  
271 comparable to those reported for conventional primary sludge (259-325 L (N) CH<sub>4</sub>/kg  
272 VS).<sup>29</sup> Thus, the installation of RBFs seems to not affect the BMP of sludge obtained by  
273 conventional settling, which may be explained by the low proportion of cellulose  
274 recovered in the latter system.<sup>7</sup> The similar results obtained for both sludges do not  
275 agree with those obtained by Kooijman et al.,<sup>34</sup> who reported an important increase in  
276 the BMP of the sludge generated during CES compared with conventional settling due  
277 to the higher readily degradable biomass removed by flocculation. However, Romero-

278 Güiza et al.<sup>35</sup> reported that  $\text{Fe}^{3+}$  reduction can limit the conversion of organics to  
279 methane as  $\text{Fe}^{3+}$  reduction is more thermodynamically favourable than methanogenesis.  
280 The data from the BMP test and the results of the CES tests enabled calculation of the  
281 methane production of each sludge in relation to the COD recovery in each treatment  
282 step. RBF enables a very limited energy recovery (62 L(N)  $\text{CH}_4/\text{kg COD}_{\text{influent}}$ ), which  
283 is explained by lower  $\text{COD}_{\text{tot}}$  recovery compared with that of other tested technologies  
284 (Figure 2).

285 The system RBF followed by settlement without chemicals enabled an increase in the  
286 energy recovery to 85 L(N)  $\text{CH}_4/\text{kg COD}_{\text{influent}}$ ). However, the highest energy recovery  
287 was achieved with the combination RBF and CES with 100 mg/L of ferric chloride,  
288 which boosted it to 122 L(N)  $\text{CH}_4/\text{kg COD}_{\text{influent}}$  due to the higher COD capture  
289 determined with the addition of chemicals (Figure 1).

#### 290 **Fate of organic micropollutants in the RBF and CES systems**

291 The concentrations of the 18 selected OMPs in the influent of both RBF systems are  
292 reported in Table S2. The highest concentrations of OMPs in both WWTPs were  
293 observed for the anti-inflammatories IBP and NPX (3.47-4.89  $\mu\text{g}/\text{L}$ ), although DCF was  
294 not detected in either of the two WWTPs. These concentrations are consistent with other  
295 concentrations in the literature.<sup>13,36,37</sup> Musk fragrances (HHCB, AHTN and ADBI) and  
296 the endocrine-disrupting compound TCS were detected in the range 0.95-2.16  $\mu\text{g}/\text{L}$ , in  
297 accordance with other authors.<sup>36,38,39</sup> The four antibiotics (SMX, TMP, ERY, and ROX)  
298 and the four neurodrugs (FLX, CBZ, DZP and CTL) were detected in the influent of  
299 Blaricum WWTP, whereas SMX and ROX were not detected in the Aarle-Rixtel

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

305 The OMP removal efficiencies achieved in the different evaluated systems (RBF, CPT,  
306 and RBF+CES using 100 mg/L of ferric chloride and CES using 300 mg/L of ferric  
307 chloride) are shown in Figure 4. Only fragrances and TCS were removed in a significant  
308 percentage in the evaluated scenarios. In the RBFs of the Blaricum WWTP (WWTP 1),  
309 the removal efficiencies of HHCB, AHTN and ADBI were 39%, 46% and 34%,  
310 respectively, and 45% for TCS. In the RBFs of the Aarle-Rixtel WWTP, the determined  
311 removal efficiencies of HHCB, AHTN and ADBI were slightly higher (53%, 54% and  
312 44%, respectively). TCS was not detected in this WWTP. In conventional settling of the  
313 Aarle-Rixtel WWTP (WWTP 2), the elimination of HHCB, AHTN and ADBI were  
314 54%, 56% and 45%, respectively, compared with those obtained during CPT of hospital  
315 wastewater.<sup>42</sup> Thus, no difference was found between RBF and CPT. These results can  
316 be explained by the similar removal efficiencies of TSS that are achieved in both  
317 systems and the similar affinity of these OMPs to the solid phase of conventional  
318 primary and RBF sludges, which is confirmed by the results of the solid-liquid  
319 distribution coefficients (Figure S1) and the comparable concentration of these OMPs in  
320 both sludges (in Supporting Information S3, a detailed discussion is included). In the  
321 Aarle-Rixtel WWTP (WWTP 2), the combination of RBF and CES enabled

322 improvement in the removal efficiencies of HHCB and AHTN to 96% and  
323 improvement in the removal efficiency of ADBI to 75%, which is similar to those  
324 achieved in the CES. For the remaining OMPs, the elimination of different RBF  
325 systems ranged from -8 to 14% (Figure 3). The increase in concentration of some OMPs  
326 was likely attributed to the analytical deviation caused by the distinctive characteristics  
327 of the wastewaters. These results show agreement with the literature.<sup>13,42,43</sup>  
328 It seems to be a consensus in the literature that most OMPs are poorly removed during  
329 coagulation–flocculation processes, however, some exceptions such as musks, a few  
330 pharmaceuticals (e.g. DCF) and nonylphenol were found.<sup>39</sup> Moreover, some authors  
331 reported that the different composition of wastewater can play a major role on OMPs  
332 removal during CES. For example, high fat content in wastewater was reported to  
333 improve the removal of hydrophobic compounds.<sup>42</sup> Dissolved humic acid could also  
334 enhance the elimination of some pharmaceutical compounds, such as DCF or IBP.<sup>44</sup> On  
335 the contrary, the presence of COD<sub>sol</sub>, especially low-molecular-weight fractions, can  
336 possibly inhibit the OMPs removal due to the preferential removal of COD<sub>sol</sub> through  
337 coagulation. Negatively charged COD<sub>sol</sub> could react with positively charged coagulants,  
338 leading to a less amount of coagulant available for elimination of OMPs.<sup>45</sup>  
339 Although the system RBF+CES of the proposed alternative did not enable extra  
340 removal of hydrophilic compounds compared with conventional settling, it enabled an  
341 increase in the removal efficiency of hydrophobic compounds, which achieved results  
342 that were as good as those obtained in the CES with higher doses of ferric chloride.

343 **Energetic and economic assessment of the proposed WWTP configuration**

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

348 In conventional WWTPs, aeration usually consumes the largest energy fraction  
349 (maximum of 70%),<sup>4,46</sup> which causes a total energy consumption of wastewater in the  
350 range 0.6-1.2 kWh/kg COD<sub>tot</sub>, with an average value of 0.9 kWh/kg COD<sub>tot</sub>.<sup>47</sup>

351 Therefore, the treatment of 0.54 kWh/m<sup>3</sup> wastewater is needed, considering 0.6 kg  
352 COD<sub>tot</sub>/m<sup>3</sup> for the Aarle-Rixtel WWTP (Table 1), in accordance with other reported  
353 values in the literature.<sup>48</sup> The potential energy in typical domestic wastewater has been  
354 estimated as 4.5 kWh/kg COD<sub>tot</sub> in the influent<sup>5,49</sup>, and the COD<sub>tot</sub> transformed into  
355 methane usually does not exceed 30%,<sup>50,51</sup> of which a maximum of 35% is converted to  
356 electricity via its combustion.<sup>47</sup> As approximately 0.47 kWh per kg of COD<sub>influent</sub> are  
357 commonly recovered, a maximum of 50% of self-produced energy can be achieved  
358 (Figure 5a). Considering an electricity cost of 0.12 €/kWh,<sup>52</sup> a treatment cost of 0.031  
359 €/m<sup>3</sup> for treated wastewater is estimated.

360 In the proposed scenario (Figure 5b), the electricity demand of the PN-anammox unit  
361 was considered to be 60% of the nitrification-denitrification electricity demand,  
362 according to Schaubroeck et al.,<sup>51</sup> which yielded 0.23 kWh/m<sup>3</sup> of treated wastewater.

363 The maximum electricity consumption of RBF was reported to be approximately 0.04  
364 kWh/m<sup>3</sup>,<sup>54</sup> and the costs due to pumping and sludge treatment were assumed to be 0.17  
365 kWh/m<sup>3</sup>, which is equivalent to those in conventional configurations<sup>47</sup>. Thus, the

366 electricity demand was 0.44 kWh/m<sup>3</sup>, which is 19% lower than that in the conventional  
367 configuration (0.54 kWh/m<sup>3</sup>). The combination of RBF followed by CEPT enabled 84%  
368 recovery of the COD<sub>tot</sub> of the influent as sludge (Figure 2). During AD, 52% of the  
369 influent COD was transformed into methane and yielded electricity generation of 0.82  
370 kWh per kg of COD<sub>influent</sub> (0.49 kWh/m<sup>3</sup> of wastewater treated), which almost doubles  
371 the electricity generation in the conventional WWTP. This fact and the lower electrical  
372 requirements of this configuration enable an electrical self-production of 100-110%.  
373 To calculate the operational costs associated with chemical addition, the FeCl<sub>3</sub> price  
374 was estimated at approximately 220 €/ton<sup>18</sup> and the sodium bicarbonate price was  
375 estimated at approximately 200 €/ton (1,400 €/ton IC). Two different scenarios were  
376 evaluated: in the first scenario, the alkalinity of wastewater was assumed to be  
377 sufficiently high bear the consumption produced in CES; thus, the influent to the PN-  
378 anammox would have an appropriate alkalinity-to-ammonium ratio; in the second  
379 scenario, an external alkalinity addition as sodium bicarbonate was considered to  
380 compensate its consumption in the CES stage. The first scenario yielded a treatment  
381 cost that was 29% lower than the treatment cost in the conventional WWTP (0.022  
382 versus 0.031 €/m<sup>3</sup>). In the second scenario, the calculated treatment costs increased to  
383 0.053 €/m<sup>3</sup>; thus, it was distinctly uncompetitive compared with the conventional  
384 WWTP.

## 385 **Conclusion**

386 The implementation of rotating belt filters before chemically enhanced settling was  
387 proven effective for generating suitable effluents for a nutrient removal stage,

388 maximising the energy recovery via the anaerobic digestion of the generated sludges,  
389 attaining 110% of the electrical autarky and achieving OMP removal that is as  
390 substantial as that obtained in chemically enhanced settling, and decreasing the required  
391 dose 3-fold. However, a minimum alkalinity level in wastewaters was shown mandatory  
392 to consider this WWTP configuration as more economically favourable with respect to  
393 the conventional WWTP configuration.

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483 **Table legends**

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

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

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

490 **Figures captions**

491 **Fig. 1.** Influence of ferric chloride dose on the removal of soluble (■) and particulate  
492 (■) COD and TSS (●) on raw wastewater of Aarle-Rixtel WWTP. 0 mg FeCl<sub>3</sub>/L refers  
493 to conventional settling without chemicals.

494 **Fig. 2.** Influence of ferric chloride dose on the removal of soluble (■) and particulate  
495 (■) COD and TSS (●) on the RBF effluent of wastewater of Aarle-Rixtel WWTP. 0 mg  
496 FeCl<sub>3</sub>/L refers to conventional settling without chemicals.

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

499 **Fig. 4.** Removal efficiencies of the organic micropollutants in RBF system in WWTP 1  
500 (■), in RBF in WWTP 2 (■), in CPT in WWTP 2 (■), RBF + CES in WWTP 2 (■),  
501 and CES in WWTP 2 (□).

502 **Fig. 5.** COD balance (in relation to 1 kg in the influent) and energy flows for the  
503 traditional WWTP configuration (adapted from Wan et al. <sup>50</sup>) and the proposed WWTP  
504 configuration. \* Represents the energy required for sludge management and pumping,  
505 ==► Refers to energy inputs for the wastewater treatment.

	<b>Blaricum WWTP</b>		<b>WWTP Aarle-Rixtel</b>	
	<b>Influent</b>	<b>Effluent</b>	<b>Influent</b>	<b>Effluent</b>
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 <sub>tot</sub> (mg O <sub>2</sub> /L)	680 ± 10	440 ± 10	600 ± 30	470 ± 10
COD <sub>sol</sub> (mg O <sub>2</sub> /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

507 TS: total solids; VS: volatile solids; TSS: total suspended solids; VSS: volatile  
508 suspended solids; COD: chemical oxygen demand; TKN-N: total Kjeldahl nitrogen,  
509 TAN-N: total ammonium nitrogen, n.d.: not determined.  
510

511 **Table 2**

	<b>Blaricum WWTP</b>	<b>Aarle-Rixtel WWTP</b>
TS (g/kg)	215 ± 10	279 ± 10
VS (g/kg)	200 ± 10	261 ± 10
COD <sub>tot</sub> (g/kg)	273 ± 18	350 ± 20
TKN-N (g/kg)	3.3 ± 0.2	4.2 ± 0.1

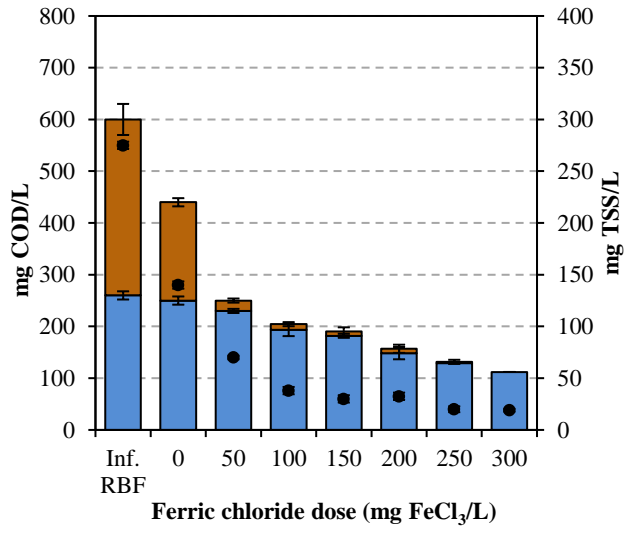
512 TS: total solids; VS: volatile solids; COD<sub>tot</sub>: total chemical oxygen demand; TKN: total

513 Kjeldahl nitrogen.

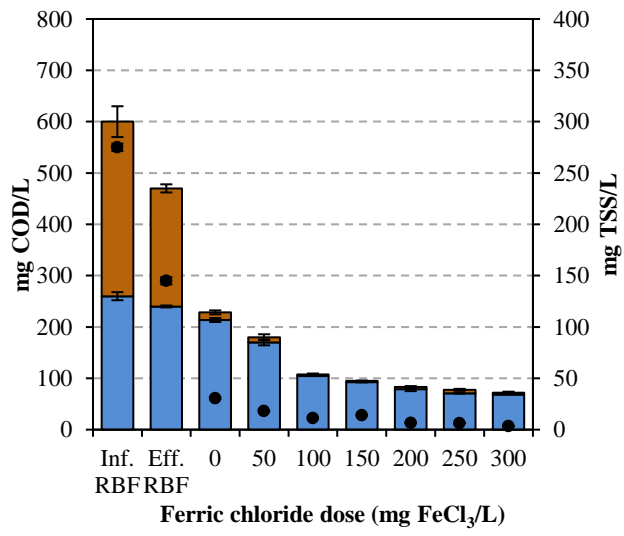
514 **Table 3**

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

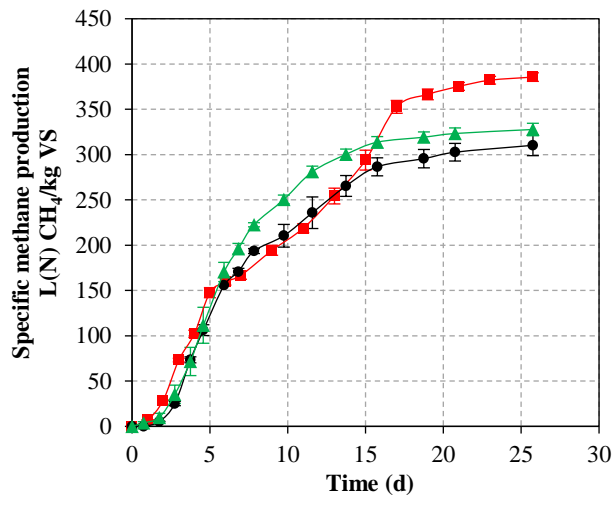
515 **Figure 1**



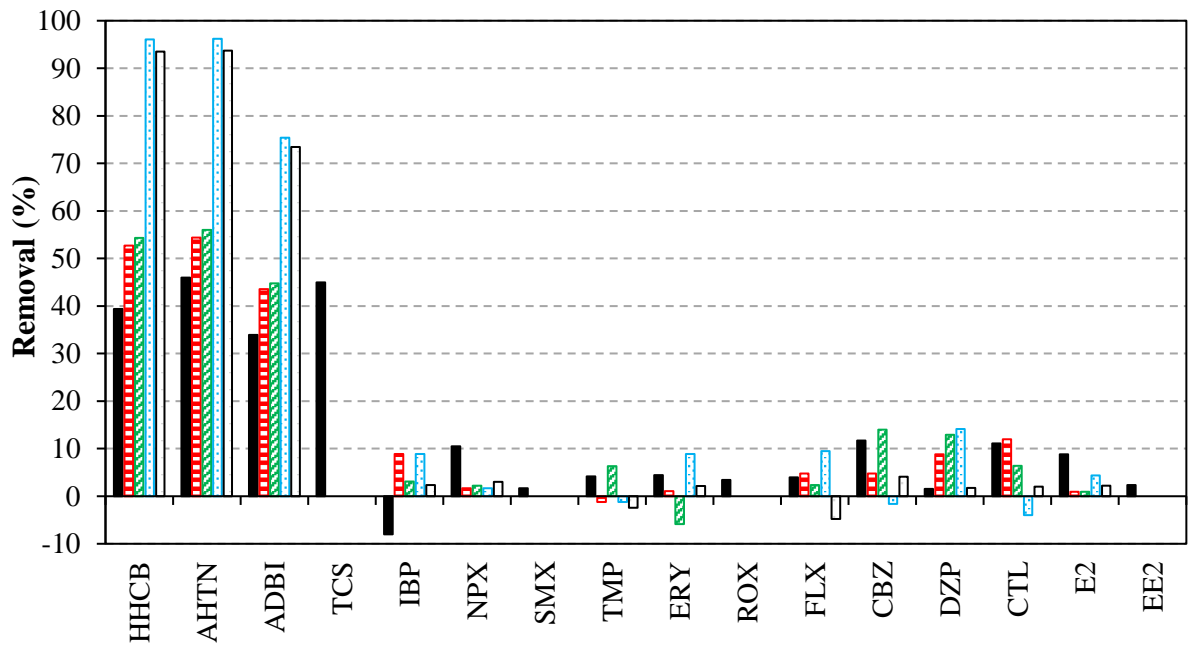
516 **Figure 2**



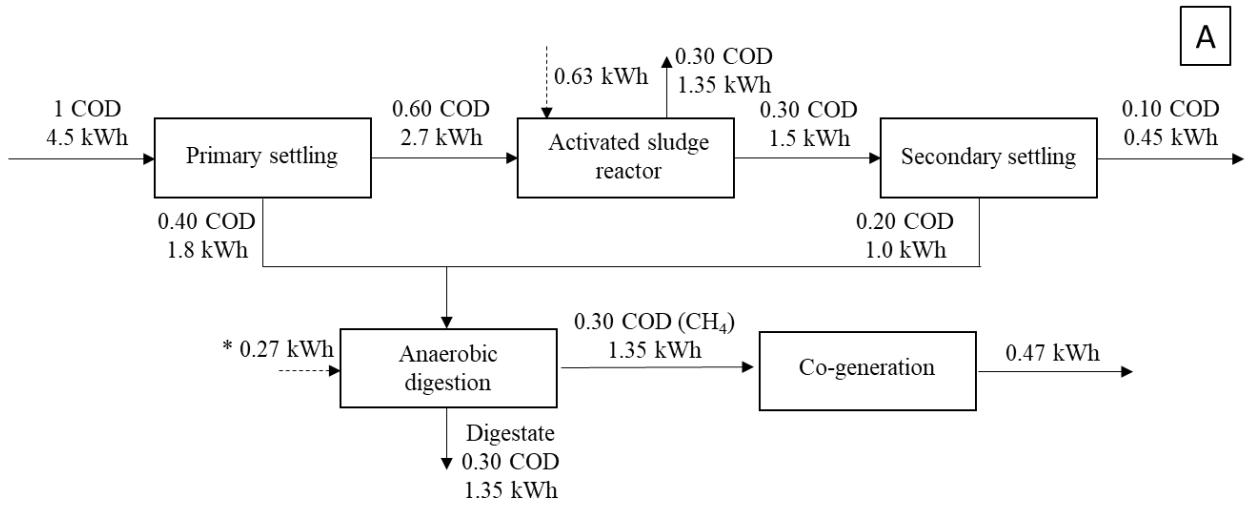
517 **Figure 3**



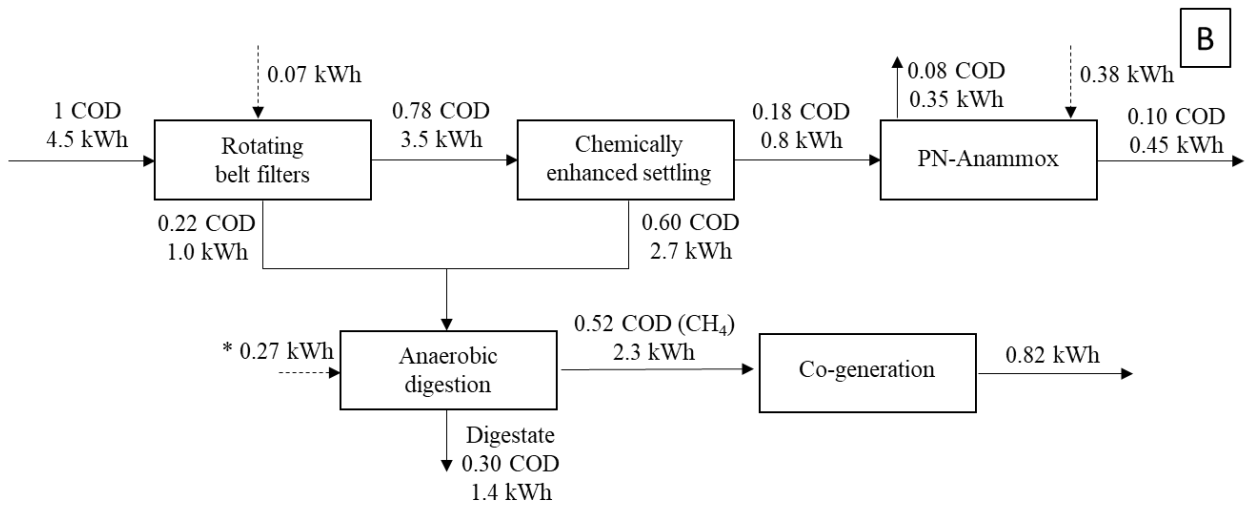
518 **Figure 4**



519 **Figure 5**



520



521