Long-term operation of a novel electrically-enhanced biomass concentrator reactor for wastewater treatment

D. Cecconet, A. Callegari and A. G. Capodaglio

ABSTRACT

Membrane biological reactors (MBRs) are a key technology in wastewater treatment nowadays. However, due to their high construction cost and energetic requirements, alternatives based on the same principle of biomass retention have been designed and operated. Amongst these, biomass concentrator reactors (BCRs), using a coarser filter medium instead of a membrane, have shown to be able to remove a wide range of contaminants from wastewater and groundwater. A new BCR-derived technology enhanced with an electric field, called the electrically-enhanced biomass concentrator reactor (E_2BCR), was designed and tested for urban wastewater treatment at different organic loads for a period of 180 days. The electrically-enhanced reactor showed better chemical oxygen demand (COD) removal performances than a non-enhanced control reactor (92.4% and 83.6% respectively) thanks also to electrocoagulation effects, and a lower fouling tendency, and proved to be more energy efficient in comparison with the control reactor in terms of energy consumption per mass of COD removed.

Key words | BCR, biomass retention, electrically-enhanced process, fouling, MBR, wastewater

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INTRODUCTION

Among new process technologies developed in the last decades to enhance wastewater treatment performance and effectiveness, improve energy footprint, sustainability and compliance with new water management paradigms of reuse and recycle (Capodaglio 2017; Capodaglio *et al.* 2017), membrane bioreactors (MBRs) (Judd & Judd 2011) are currently one of the most attractive treatment technologies for both industrial and municipal wastewater, on account of many advantages such as operation at higher mixed liquor suspended solids (MLSS), longer sludge retention time (SRT), lower space/tank size requirements, much higher quality effluents, and the capacity to remove a wide range of contaminants, from organic matter and nutrients to some contaminants of emerging concern (CECs) and pharmaceutically active compounds (PhACs) (Cecconet *et al.* 2017a).

Energy consumption and fouling of the membrane medium are the principal drawbacks of this technology: the energy consumption is estimated to be the highest in comparison with other secondary treatments, and up to three times in comparison with conventional activated sludge (Longo *et al.* 2016); the fouling of the membrane medium limits the filtration efficiency in time and leads to the requirement for a cleaning and/or substitution of the membrane itself, increasing the cost of the technology (Judd 2004). Membrane fouling and its prevention is in fact one of the most investigated topics in the wastewater treatment literature today, with about 80 papers published each year on this subject in 2000, steadily increasing to over 600 in 2016, as reported by the ScienceDirect database. Although many factors such as particle size, surface charge of floc, extracellular polymeric substances (EPS), and MLSS concentration are mentioned as affecting membrane fouling, it has been specifically shown that particle size of MLSS has the greatest impact on fouling (Huang & Wu 2008).

Addition of coagulants or adsorbents, ozone oxidation, and electrocoagulation (EC) are among the methods mentioned in literature for dealing with filterability and particle size enhancement; this, however, has to be achieved avoiding any possible negative/toxic effect on microbial activity. When a stress such as a strong electric current is applied to a biomass population, cells' metabolism, physiology, shape and movement are impacted; however, Wei *et al.* (2011) showed that bacterial viability was not significantly affected (less than 10% death rate) when the

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applied electric current density (CD) was less than 6.2 A/m^2, after 4 hrs. Ibeid *et al.* (2015) showed that CD between 15–35 A/m^2 enhanced sludge filterability up to 200 times, and that electrically 'enhanced' sludge exhibited membrane fouling rates 6 times lower, compared to unaffected sludge. This may be explained by the fact that biological sludge is negatively charged (Lee *et al.* 2003), and thus attracted by the anode and repulsed by the cathode in a polarized system. By placing a cathode in proximity to the membrane medium and the anode at a certain distance from it, the suspended solids in an MBR/BCR reactor will be kept away from the filtering surface and have a lesser chance of impacting, and being caked onto it. Zeyoudi *et al.* (2015) indicated that introducing low intermittent or constant electrical current densities into existing biological treatment processes had the potential to lead to more efficient, improved reactors for wastewater treatment. Furthermore, they showed that supplying a reactor with an intermittent, rather than continuous, electric current causes some species of microorganisms to grow better than others, and that longer OFF cycles increased soluble chemical oxygen demand (COD) removal efficiency, reaching 99% at a 5-to-30 ratio. It has also been shown that EC, induced by oxidation at the anode generating metallic hydroxides, enhances biomass flocculation, and therefore the system's COD removal (Sirés & Brillas 2012), since flocs with dimensions bigger than filter pores are retained in the reactor (Al-Shannag *et al.* 2014), where they can undergo further extended degradation. Modification of the physico-chemical characteristics of MLSS (Bani-Melhem & Elektorowicz 2010), reduction of the volatile suspended solids (VSS) to MLSS ratio, due to formation of metallic hydroxides (Ibeid *et al.* 2015), and modification of shape and dimension of sludge flocs (Hua *et al.* 2015), are all factors that could contribute to overall process performance enhancement.

As a consequence of the high investment and operation costs of MBRs, alternatives based on similar biomass retention and filtration principles have been developed, notably biomass concentrator reactors (BCRs). These are processes that use high (>5–10 μm), instead of low (≤1 μm) porosity filtration media to achieve a lower degree of solid-liquid separation. Their main advantages lie in lower cost of the medium, lower energetic requirements, due to gravity-driven flow, and greater operational ease. Even though their particle retention capacity is evidently lower than MBRs', it is sufficient to significantly retain active biomass and obtain an MBR-like MLSS concentration in the reactor. BCRs were successfully tested for the treatment of domestic (Capodaglio & Callegari 2016) and industrial wastewater (Capodaglio & Callegari 2015), biological nitrogen removal (Scott *et al.* 2013), and even removal of poorly-degradable groundwater contaminants such as methyl tert-butyl ether (MTBE) and other gasoline-derived compounds (Zein *et al.* 2004a; Zein *et al.* 2004b; Zein *et al.* 2006a, 2006b; Capodaglio *et al.* 2010). An overview of reported BCR applications in the literature is summarized in Table 1.

BCRs, much like MBRs, allow high active biomass concentrations to be achieved in the reactor at low HRTs and high SRT, by fostering ideal growth and retention conditions for biomass concentration, and allowing its specialization into a microbiome more adapted to quickly degrade even contaminants that are usually considered poorly biodegradable (i.e. MTBE).

BCRs have been shown to be able to operate continuously at gravity flow in field conditions for up to 1 year without severe fouling (Zhang 2009; Capodaglio & Callegari 2015). Usually, low pressure backwash proved sufficient to restore their capacity to almost initial conditions.

In this study, a new-type BCR was built using a stainless steel (SS) filter, instead of UHMWPE (ultra-high molecular weight polyethylene), as described by Cecconet *et al.* (2017b), enhanced with electric field application to reduce fouling phenomena, to verify treatment performance in long-term operation. New results confirmed previously obtained indications.

MATERIALS AND METHODS

An electrically-enhanced BCR (E_2BCR) was built for this study, similar to the one previously described by Cecconet *et al.* (2017b), except for some constructive improvements introduced concerning better connections, more robust waterproof seams, and an improved effluent extraction system. The reactor is a single stage, aerated cylindrical vessel (V = 1.5 L), with a stainless steel (SS 316) wound wedge wire filter (Figure 1) (Federal Screen Products Inc., Canada) immersed within (Figure 2). A sacrificial iron anode (A = 37.5 cm^2), which had previously demonstrated better performance than an aluminum one in aiding biomass coagulation and flocculation by ion release, is also contained in the reactor; the SS filter is electrically connected to the anode, doubling as cathode and filtration medium. Table 2 summarizes filter medium characteristics. Feeding and extraction are provided by peristaltic pumps. A programmable DC supply (Velleman LABPS3005D) connected anode and cathode, provides intermittent 5 V current to the system in 5 min on/20 min off cycles. The

Table 1 | BCR applications in current literature

Substrate	Filter type	Experimental conditions	Contaminants	Removal (%)	Reference
Municipal WW	316 SS, slot size 25 μm, A = 226 cm^2	V = 1.5 L, aerobic	COD	94.5%	Cecconet *et al.* (2017b)
Groundwater	UHMWPE, d = 18–28 μm, A = 120 m^2	V = 8 m^3, aerobic	MtBE	>99	Capodaglio *et al.* (2010)
	UHMWPE, d = 20 μm, A = 45 m^2	V = 1.2 m^3, aerobic		>99	
Ship tanks rinse WW	UHMWPE, d = 20 μm, A = 45 m^2	V = 4 L, aerobic	BOD_5 COD SS	~100 >85% >95%	Capodaglio & Callegari (2015)
Municipal WW	UHMWPE, d = 20 μm, A = 1.24 m^2	V = 60 L , HRT = 2–2.4 d, COD_{in} = 0,35 kg/m^3 d Aerobic	COD TN	>93% 37%	Capodaglio & Callegari (2016)
Synthetic WW	UHMWPE, d = 18–28 μm, A = 0.6 m^2	V_{conv} = 28 L, V_{hybrid} = 17.5 l, HRT = 9 h, SRT = 6–15 d, aerobic/anaerobic	SS COD NH_4 N	~100 >90% 100% 67%	Scott *et al.* (2013)
Groundwater	HDPE, d = 18–28 μm, A = 25 m^2	V = 1 m^3, HRT = 4 h, $MtBE_{in}$ = 5 mg/l, aerobic	MtBE	~100	Zein *et al.* (2004a)
Groundwater	HDPE, d = 18–28 μm, A = 120 m^2	V = 8 m^3, HRT = 6 h, $Contaminants_{in}$ = 12 mg/l, aerobic	MtBE TBA TBF BTEX	99,85 99,14 99,94 ~100	Zein *et al.* (2004b)
Groundwater	HDPE, d = 18–28 μm, A = 120 m^2	V = 8 m^3, HRT = 6 h, $MtBE_{in}$ = 1.5–12.5 mg/l aerobic	MtBE TBA TBF BTEX	99,91 99,75 99,94 ~100	Zein *et al.* (2006a)
Groundwater	HDPE, d = 18–28 μm	V = 8 L, HRT = 15–32 h aerobic	BTEX MTbE PAH	>99.7 >99.7 >99%	Zein *et al.* (2006b)

HRT = Hydraulic Retention Time.

Figure 1 | Stainless steel filter medium (before and after use).

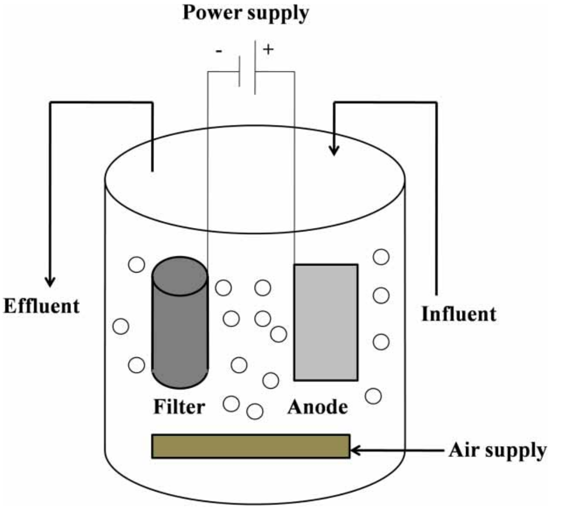

Figure 2 | Scheme of the E2BCR reactor.

Table 2 | Characteristics of the filter medium used in the study

Filter characteristics	
Material	Stainless steel 316
Slot size	25 μm
Diameter	2.4 cm
Height	15 cm
Surface area	226.2 cm^2

whole system was operated under computerized control, connected to a data acquisition system (National Instruments USB6008). An identical control reactor was operated in parallel, without electric enhancement (this unit will be referred to as Control BCR, or CBCR).

Both systems were run under continuous feeding for 180 days after inoculation and startup with sludge from the local wastewater treatment plant, using substrate from the same source.

Inflow was set to 10 L/day, achieving an HRT = 3.6 hrs, 20% lower than in previous trials. As the filter media used is an innovative material for this kind of application, the search for an optimal hydraulic loading rate, rather than the solids loading, is quite important to evaluate the practical operational limits of this process, and further tests are being planned on this issue. Operating parameters were measured every 3–4 days. COD measurements were performed on inflow and both outflows using Hanna Instruments measurements kits, following ISO 15705 standard, analyzed using a desk spectrophotometer (Hanna Instruments HI 83224). Conductivity and pH were measured using probes (IntelliCAL™ PHC101 Standard pH Electrode; IntelliCAL™ CDC401 Standard Conductivity Probe; Hach Lange, Italy) connected to a digital multimeter (HQd™ Digital Meter, Hach Lange, Italy).

Energy consumption was assessed initially in terms of overall energy needs, calculated as the sum of energy consumption of pumps and aerators (standard tag values times operating time), and total energy provided to the E_2BCR with applied voltage. However, this value turned out to be less relevant than initially thought, the reason being that, after careful evaluation, it turned out to depend almost exclusively (>97%) on pumping and aeration, present and of similar value in both systems: pumps and aeration equipment were in fact taken from the current laboratory supply, and the specific prototype reactor design relied on excessive pumping action.

On the other hand, the specific energy consumption (SEC) index, in terms of energy provided to the E_2BCR reactor (and not to the CBCR) through the applied voltage, turned out to be the key discerning parameter for assessing system performance as a function of COD removed, calculated using the formula:

$$SEC = \frac{V \times I \times t}{COD_{rem}}$$

modified from Al-Shannag *et al.* (2014), where V is the applied voltage [V], I is the current [A], t is the time the voltage is applied [sec] and COD_{rem} is the amount of COD removed during treatment [kg COD].

Both the E_2BCR and the CBCR were run continuously for over 6 months.

The fouling tendency was characterized using the percentage of reduction in flux permeate (PRPF), similarly to that reported in Bani-Melhem & Elektorowicz (2010):

$$PRPF = \frac{(J_i - J)}{J_i} \times 100\%$$

where J is the permeate flux at the beginning of the experiment and J_i is the permeate flux at any time.

RESULTS AND DISCUSSION

Organic matter removal

Table 3 shows COD, pH and conductivity average values for influent and effluents. No other parameters were tested in these experiments as they were deemed not relevant for the purpose of assessing the general reactor's relative

Table 3 | COD, pH and conductivity values for influent and effluents

	Influent			**E_2BCR effluent**		**CBCR effluent**	
	COD (mg/L)	**pH –**	**Conductivity (μS/cm)**	**COD (mg/L)**	**pH –**	**COD (mg/L)**	**pH –**
Average	553 ± 221	7.6 ± 0.55	715.73 ± 77.7	40 ± 31	7.8 ± 0.8	85 ± 35	7.8 ± 0.5

performance. The purpose of this study was in fact to verify the long term performance of BCR efficiency augmentation by the applied direct current in comparison to a standard system (CBCR). The E_2BCR showed high COD removal since the beginning of the continuous feeding mode (Figure 3). COD removal performance was 92.4% in the electro-assisted reactor, while it was about 10% lower (at 83.6%) in the control reactor. No accumulated solids were detected in the effluent in either case, an indication of the instrinsic efficiency of the filter medium. Compared to the CBCR, the E_2BCR showed a better performance, obtaining an 8.8% average higher COD removal than the CBCR. E_2BCR performance offset that of the CBCR's since the beginning of the test, due to the immediate positive effects of the voltage supply, such as sludge flocs' improved electrocoagulation, as also observed by Vijayakumar *et al.* (2015). During the whole experimentation period, COD effluent value from the E_2BCR never exceeded the 125 mg/L limit prescribed by the European Water Treatment Directive, demonstrating its potential suitability to real-life application. A reduction of effluent conductivity in both reactors was observed, mainly due to the almost complete removal of solids by the filter; no significant pH variations were noticed in the effluent of either reactor.

The increase of performance obtained from the E_2BCR versus the CBCR is significant and better than the ones previously obtained by Cecconet *et al.* (2017b) with an almost identical system (8.8 vs. the previous 6%), run at slightly higher HRT (4.5 instead of the current 3.6 hrs), showing that the BCR hydraulic capacity is yet to be reached at the current level of 0.044 L/cm^2-day, and is coherent with those reported in literature with electrically-assisted MBRs

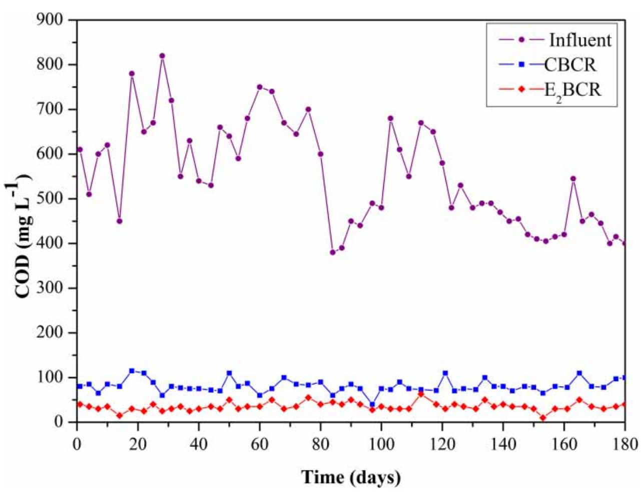

Figure 3 | COD concentrations in the influent and in both reactors' effluents.

(Table 4). These results may be due to better electrocoagulation of sludge flocs due to the iron anode ion release, a more efficient on/off current cycle (in the previous work a 5'/15' cycle was used, while in the present this was shifted to 5'/20', closer to the optimum indicated by Zeyoudi *et al.* (2015) as 5'/30' for an MBR-based system), and augmented organics adsorption onto sludge flocs, which are then retained in the reactor due to physical barrier filtration (Hosseinzadeh *et al.* 2015). During the study, no sludge wastage was operated on either system, therefore SRT was theoretically infinite, and retained excess biomass produced by the process and flocculated organics were eventually endogenously degraded in this 'ultra-extended' aeration phase. Electrolysis in the assisted reactor could have led to a further increase of the biodegradable fraction of COD as reported by Keerthi *et al.* (2013).

In comparison with the systems reported in Table 4, the performance increase of the E_2BCR is similar to those described by Keerthi *et al.* (2013) and Hosseinzadeh *et al.* (2015). A better improvement was reported by Bani-Melhem & Elektorowicz (2010), perchance due to a more effective voltage supply cycle (in their case, 15' on/45' off).

Filtering medium fouling

Both systems were operated for 180 days; the CBCR suffered severe fouling by day 69, with significantly reduced effluent discharge, and again by day 155. In both cases, the filter was extracted, manually rinsed with a hard brush and tap water, restoring discharge to pre-fouled conditions. E_2BCR showed similar signs around day 107, when it was cleaned

Table 4 | Difference in COD removal between electrically-enhanced and control reactor in MBR/ BCR systems

Reference	COD removal, electrically-assisted	COD removal, control reactor	Difference
This work	92.45%	83.64%	8.8%
Cecconet *et al.* (2017b)	89,6%	83.7%	6%
Bani-Melhem & Elektorowicz (2010)	85–95%	75–90%	+10% (~)
Yan *et al.* (2016)	89,4%	87,6%	+2,2%
Hosseinzadeh *et al.* (2015)	85%	80%	5%
Keerthi *et al.* (2013)	94%	90%	4%
Vijayakumar *et al.* (2015)	96.11%	89.05%	+7.06%

by the same procedure. A simplified scheme was adopted to approximate the trend of fouling tendency achieved by the E_2BCR in comparison with the CBCR, determined as the difference between the time integral of the PRPF of the two systems, shown in Table 5 (scheme illustrated in Figure 4). The ratio between the areas (% fouling vs. time) calculated for the two reactors, assuming the trend was linear (only the data reported in Table 5 were recorded), gives a fouling reduction tendency between the two systems of −30.4%. To compensate for observed fouling, the extraction pumping speed was manually adjusted during the experiments.

Compared with values reported in literature (Table 6), the fouling reduction of the electrically-assisted system is definitely higher. This discrepancy could be attributed to the fact that, in this study, there is no distinction between the cathode and the filter: the cathode is actually the filter itself and this could translate into better, more efficient sludge repulsion.

Energy consumption

The total energy consumption of the system during the experimental period was calculated at first taking into account the actual energy consumption of aeration, pumping and, in the case of the E_2BCR, the voltage supplied to the system. The energy used for filter cleaning is not considered, as this operation was performed manually; however, since the CBCR was cleaned twice and the E_2BCR only once, the missed accounting works in favor of the electrically-assisted system. The overall energy consumption value in relation to volume treated is clearly lower for the CBCR (2.35×10^{-3} vs. 2.42×10^{-3} kWh/m^3), due to the lack of voltage supply.

These values may seem high at first sight; however, it should be kept in mind that pumping and aeration accounted for more than 97% of these values, and, clearly, this being an experimental study, they were by no means optimized during design and operation (standard laboratory pumps and aeration equipment were used). By taking into account only the additional energy requirements of electrically-assisted operation (SEC), which is the parameter specifically characterizing the E_2BCR system (SEC = 0 in the CBCR system), this leads to the consideration that, while the operation of E_2BCR is marginally more convenient in terms of removal of organic matter (as seen by the total calculated energy supplied), the process enhancement of electrically-assisting the reactor does not actually imply significant, additional energy inputs.

The SEC value was in fact calculated as 0.83 kWh/$kgCOD_{rem}$. Comparing the system's SEC value with those found in literature, the value is below the range reported in Hanafi *et al.* (2010) (3.41–2.63 kWh/$kgCOD_{rem}$) and Hanafi *et al.* (2011) (2.54–2.63 kWh/$kgCOD_{rem}$), which dealt with real MBR systems with cathodes separate from a non-conductive filtration medium.

Table 5 | Fouling in the E_2BCR and CBCR systems during the 180 days running test

Day	E_2BCR	CBCR
69	67.4%	97.6%
107	88.3%	61.5%
155	54.3%	98.6%
180	75.2%	56.8%

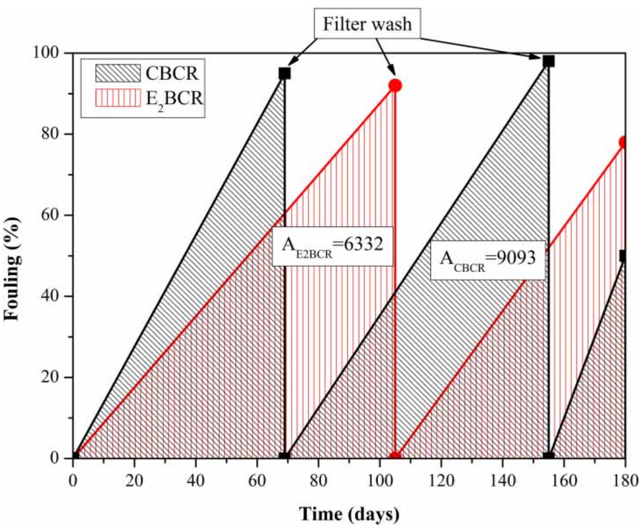

Figure 4 | Simplified scheme for comparing overall fouling tendency of E_2BCR and CBCR.

Table 6 | Fouling decrease in electrically assisted MBR and BCR systems in comparison with control systems.

Reference	Anode material	Cathode material	Fouling decrease
This work	Iron	Stainless steel	30.4%
Cecconet *et al.* (2017b)	Aluminum/ iron	Stainless steel	24%
Bani-Melhem & Elektorowicz (2010)	Iron	Iron	16.3%
Keerthi *et al.* (2013)	Aluminium	Stainless steel	~12%
Vijayakumar *et al.* (2015)	Aluminium	Stainless steel	~12%

Future applications and perspectives

Due to the reliability of the system in the long-term proven in this study, and its simplicity of operation, the E_2BCR

could be applied in the treatment of a wide range of different wastewater types. An application of the E_2BCR could be envisioned in small communities' decentralized wastewater treatment, as postulated in Capodaglio *et al.* (2017), since it would limit operational interventions needed on systems based on MBRs or non-enhanced BCRs, due to lower fouling problems, good COD removal performance at variable organic loads, and ample capacity to sustain elevated hydraulic loads. Modified voltage cycles and intensity could further improve electrocoagulation and the sludge separation efficiency of the system. Further investigation on higher, varying hydraulic loads is planned to define this effect on system performance: better definition of the maximum applicable hydraulic load is deemed necessary for cost-effective real life application of an E_2BCR system.

A possible application of these systems is the treatment of greywater in separated flow sanitation, due to the fact that the COD values in the influent adopted during this test fell in the typical upper range of greywater (Eriksson *et al.* 2002) or small domestic treatment facilities (Almeida *et al.* 1999). Electrically-assisted MBRs haVE shown to be a good option for the treatment of greywater, obtaining 89% COD removal (Bani-Melhem & Smith 2012), and this system modification could constitute a further technological breakthrough.

The stainless steel (SS316), industrial wedge-wire filter (slots = 25 μm) used for this application, compared with the common HDMWPE filters previously used, has a much higher structural strength and a potentially much longer duration. The filter (Figure 5) is the product of a state-of-the-art fabrication method and has been around with these characteristics for a very brief time, finding its main application (at higher slot sizes) in primary sludge filtration. In the authors' opinion, and based on this specific application, this type of filter has several other potential applications that could be imagined in the near future.

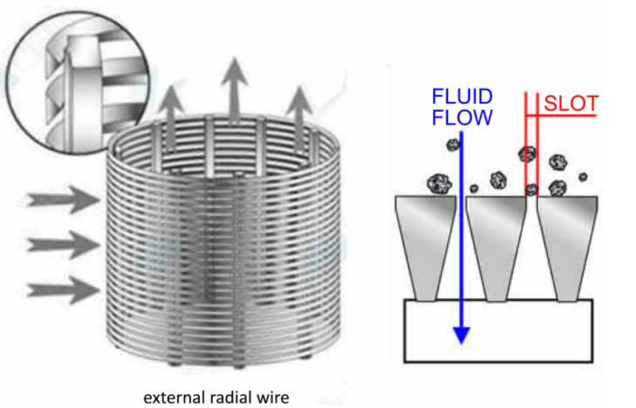

Figure 5 | Wound wedge wire filter. The shape of the wound wire helps improve filtration and backwash efficiency.

A particular application of the metallic filter used in the E_2BCR could be found in coupling it with bioelectrochemical systems (BES), such as microbial fuel cells (MFCs) (Capodaglio *et al.* 2013; Molognoni *et al.* 2014, 2016), to enhance performance and sustainability of BESs, as recently proposed (Li *et al.* 2016). Practicable applications could be the use of the E_2BCR's filter as a cathode for the enhancement of the hybrid system's performance; an anoxic step would work as anodic chamber. The coupling of the system with MFC could enhance denitrification of wastewater. BES have proven to be able to achieve removal of nitrate, both from wastewater (Kelly & He 2014) and groundwater (Molognoni *et al.* 2017; Cecconet *et al.* 2018); a hybrid MFC-MBR system proved to be able to successfully remove ammonia from wastewater (Wang *et al.* 2011).

CONCLUSIONS

An electrically-enhanced biomass concentrator reactor (E_2BCR) obtained from a stainless steel, wound wedge wire filter was assembled and operated at long term for wastewater treatment at different organic loads, enhanced with an external electric field application. The system was tested against an identical control reactor without electric enhancement. The electrically-enhanced reactor showed better COD removal performances (+8.1%) and a lower fouling tendency (−30%) than the non-enhanced control reactor. Several factors concur to these performance improvements, and confirm the findings of other researchers on both BCR and MBR-type systems: better electrocoagulation of sludge flocs due to the iron anode ion release, enhanced charge-related sludge rejection by the filter itself, and increase in the biodegradable fraction of COD due to electrolysis effects.

Better COD removal achieved by the E_2BCR in comparison with the control system is consistent with values presented in literature, while the decrease in fouling tendency is higher. In terms of organic matter removal, the E_2BCR obtained 92.4% COD removal; best results were obtained at higher influent COD concentration. The system proved to be reliable, and appears to be a feasible option for wastewater treatment, in particular, in decentralized and small wastewater treatment plants where it could be a good alternative to currently adopted treatment technologies.

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