Upgrading fluidised bed bioreactors for treating brewery wastewater by using a fluid-like electrode

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Abstract

Anaerobic digestion has historically shown critical operational limitations for treating industrial wastewater. Our work aims to evaluate the resilience capacity of a novel concept so-called microbial electrochemical-fluidised bed reactor (ME-FBR) for treating real brewery wastewater under continuous operation mode over one year period. All assays were run in parallel using a conventional anaerobic fluidised bed reactor (AFBR). The resilience tests were designed attending to the most typical operational problems showed by the AFBR technology in real brewery wastewater treatment plants. Four different stress situations were tested: i) pollutants overloading (as high as 51.2 kgCOD/m^3 d), ii) presence of an active biocide in the fed stream (5% v/V), iii) operation of the reactors after long starvation periods (16 days) and iv) operation at low temperature (<25ºC). Our pre-pilot scale ME-FBR outperformed traditional AFBR for wastewater treatment capacity under all stress test regarding COD removal rate, total nitrogen (TN) removal rate and bioenergy recovery (bioelectrochemical-assisted hydrogen generation). Among all stress test, low temperatures and long starvation periods deeply decrease the robustness of both technologies.

Keywords: Microbial electrochemistry; anaerobic fluidised bed reactor; anaerobic digestion; electroactive bacteria; brewery wastewater

1. Introduction

Anaerobic digestion (AD) and Anaerobic Fluidised Bed Reactors (AFBR) are currently the most widely installed secondary treatments in industrial wastewater treatment plants (WWTP) for treating high-strength wastewaters due to its capacity to generate methane, providing a potential for energy generation while producing low surplus sludge respecting aerobic treatments [1–3]. In spite of being designed attending to the coarse experience gained during the last 100 years, AD has historically showed some critical operational limitations. Some of those well identified operational problems are i) high concentration of nutrients, specially nitrogen and phosphorous in the effluent [4–7], ii) low capacity to treat wastewater at low temperatures [8,9], iii) instability of the technology under high organic loads in the fed stream [10–12], iv) low COD removal rates after starving periods [13,14] and v) microorganism inhibition with the presence of biocides extensively used in the brewery industry as cleaning agents [15,16]. The increase of the matrix complexity in industrial wastewater during the last years demands to explore new strategies to increase the robustness of such treatment systems.

In that sense, Microbial electrochemical technologies (MET) represent a promising field to overcome the well-known limitations of conventional AD technologies [17–22]. These technologies are based on the capacity of electroactive bacteria to exchange electrons with electrically conductive materials [23,24]. In some MET, electroactive bacteria act as a natural catalyst for oxidizing the organic pollutants present in wastewater, then transferring electrons to the electrode so green bioenergy (eg. electrical power, hydrogen, methane) can be harvested [25–27]. The electrons accepted by the electroconductive material (anode) are then transferred i) to the cathode material by an external electric circuit for generating power in devices called microbial fuel cells (MFC) [23,28–30], or ii) to a counter electrode, under potentiostat control, in devices called microbial electrolysis cell (MEC) [31–34]. So, both MFC and MEC have been extensively tested during the last decades as promising industrial wastewater treatments at lab-scale [35–40]

Nevertheless, even if at laboratory scale results are promising, scaling-up this technology is a huge handicap due to a limited electrode surface area where redox reactions take place and, consequently, a mass transfer limitation between substrates and microorganisms [41]. Such problems associated to the use of static biofilm-based electrodes have proposed to be overcome by

a novel concept where the classical static electrode is replaced by a fluid-like electrode made of electroconductive carbon microparticles [42–44]. Indeed, the proof of concept raised a device so-called Microbial Electrochemical Fluidized Bed Reactor (ME-FBR) that was applied to treat industrial wastewater from the brewery sector. Actually, the advantage of using ME-FBR has been already reported regarding available electrode surface, decrease in cell wash-out, and enhancement of mass transfer [45,46]. The concept of using a fluidised anode serving as electron acceptor for electroactive bacteria achieved up to 87% removal of the total COD contained in the wastewater [42], and revealed a process of extremely high coulombic efficiency. In addition, polarization of the fluidized electrode favored the removal of total nitrogen and total phosphorus (46% and 50%, respectively), what implies a realistic operational advantage respecting the conventional biologic treatments [42]. Furthermore, a recent application has demonstrated that ME-FBR can operate with the fluidized bed acting as electron donor to promote reductive metabolism by electroactive bacteria in low COD medium (eg. denitrification) and, additionally, produce biohydrogen (Tejedor et al., 2020).

Electroactive bacteria commonly interact with electrodes directly by forming a biofilm. Actually, *Geobacter* species have been reported to dominate the microbial communities found in anodes composed of mixed populations [47–49] . This genus has also been identified in the granules of an upflow anaerobic sludge blanket (UASB) reactor treating brewery waste [50]. In spite of the absence of an electrode, *Geobacter* was found to perform direct extracellular electron transfer (DEET) by exchanging the electrons with methanogenic communities, through direct interspecies electron transfer (DIET). Specifically, *Methanosarcina barkeri* has been shown to be capable of performing DIET in co-cultures with *Geobacter* species [50,51]. DIET can also take place with a mineral as a mediator, a process in which different species use as conduits of electrons nano-mineral particles or conductive surfaces such as activated carbon granules or biochar [52,53]. This phenomena has also been described to stimulate methane production and Geobacter growth [45,50,54,55]. All these findings suggest that co-aggregation of *Geobacter* species and methanogens may be a common phenomenon in methanogenic environments and that might be relevant with respect to methane production in anaerobic digesters.

In this context, the goal of this work has been to evaluate the resilience capacity for AFBR and ME-FBR technologies for treating real brewery wastewater during one-year period. The stress

tests have simulated most typical operational problems for conventional operation of AD in industrial WWTPs; COD overloads, biocide dosing, starving periods and operation under low temperatures (<25ºC).

2. Materials and methods

2.1. Design of the Microbial electrochemical-fluidised bed reactor (ME-FBR) and the anaerobic fluidized bed reactor (AFBR).

The set-ups used in this work consisted of two membrane-less pre-pilot reactors, ME-FBR and AFBR. They were evaluated regarding the wastewater treatment capacity during several resilience tests.

The pre-pilot ME-FBR and AFBR units were designed and assembled in methacrylate with a tubular geometry. Both reactors were equipped by a flux distributor at the bottom zone in order to assure the fluidisation of the sewage sludge and the electro-conductive anode material though the column, such distributor was key to avoid dead zones, capable of affecting the efficiency in the wastewater treatment. The top zone of both reactors was sealed with a gas collector in order to periodically (every two days) monitor the biogas and hydrogen generation by a portable biogas-analyser (Dräger X-am® 5000, Germany). In addition, five sampling ports were installed at different heights over the tubular structure. The main structural difference between the ME-FBBR and the AFBR was the presence of two additional sampling ports on the ME-FBR to host the electrochemical probes, one on the bottom zone and the other on the top zone. The working volume of the ME-FBR and AFBR was 5.4 L, including the recirculation pipe and the bed volume.

Despite de similarity in geometrical design, the difference between the AFBR and ME-FBR was due the integration of electrodes (anode and cathode) in the last one. The anode material in ME-FBR was made of electroconductive activated carbon (20% v/V, Aquasorb®, Germany). This electroconductive activated carbon accepted the electron transfer from the microbial biofilm and, eventually transferred such electrons to the conductive anode collector. Additionally, this material showed a high porosity that highly favour the microorganism's growth on its surface. The anode collector was a graphite plate (4.5 cm x 4.5 cm) vertically immersed in the fluidising bed. A stainless-steel sponge was equipped as cathode material.

119 *2.2. Experimental procedure of resilience tests*

120 The resilience tests were conducted to simulate i) two high organic loading rates (27.2
121 kgCOD/m^3 d and 51.2 kgCOD/m^3 d), ii) a biocide dosing based on quaternary amines normally
122 used to clean the industrial equipment (didecyldimehtylammonium chloride – DDAC), iii) a
123 starving period and, finally, iv) operation under low temperature (25ºC) Table 1. The resilience
124 tests were performed independently and consecutively, always waiting for the systems to be
125 recovered and stabilized from the previous disruption test.

126

Table 1. Conventional AFBR and ME-FBR long-term operation. Resilience test descriptions and monitored parameters.

Resilience test	Operation time (d)	Monitored paramet
No resilience tests (Standard operation of AFBR and ME-FBR)	1 – 31 39 - 52	COD removal, biogas hydrogen generation, p generation, nutrients ren
COD overloads	32 -38 53 -59	COD consumption rate, b and hydrogen generati
Biocide dosing	73 -79	TN consumption rat
Starvation period	88 - 110	COD removal
Low temperature	306 -340	COD removal

127

128 *2.3 Electrochemical control and operation*

129 A potentiostat (NANOELECTRA NEV3, Spain) was connected to the electrodes to
130 polarize the anode material at 0.6 V (versus Ag/AgCl) during the operation of the ME-FBR. The

131 presence of two reference electrodes (Ag/AgCl 3 M KCl – HANNA Instruments, Germany)
132 allowed to monitor the cathode and cell potentials during the continuous operation of the reactor.
133 Nevertheless, the AFBR was not equipped with any potentiostat since such reactor was free of
134 electronductive material.

135 Both pre-pilot reactors were fed in continuous mode by a peristaltic pump (Watson Marlow
136 205S, United Kingdom); moreover, fluidization was achieved by using two additional peristaltic
137 pumps (Heidolph 5006, Germany), one for each reactor. They operated to favour a recirculation
138 flow from the top section to the flow distributor hosted in the bottom zone. Both reactors were
139 operated with a hydraulic retention time (HRT) of 9 h. Sampling and analysis were performed
140 daily.

141 *2.4. Inoculum and real wastewater*

142 Activated anaerobic granular sludge from an industrial wastewater treatment plant of a
143 brewery WWTP (Alovera, Guadalajara, Spain) was used as inoculum for both reactors. Both
144 bioreactors were fed by (1:1 v/v) activated sludge from chemical coagulated wastewater. This
145 start-up phase took seven days under both semi-continuous mode and anoxic conditions to favour
146 the formation of electroactive and anaerobic communities for ME-FBR, and just anaerobic ones
147 for the AD-FBR. After this period both reactors were fed in continuous mode with real wastewater
148 from the brewery plant using a peristaltic pump (Watson Marlow 205S) with a fixed flowrate of 1
149 L/h.

150 *2.5. Chemical and Physical-chemical analysis*

151 COD concentration and nutrient, total nitrogen and total phosphorous, concentrations were
152 determined using commercial colorimetric probe tests (HACH – LCK cuvette tests, Germany)
153 digested in a commercial HACH digester (HACH ref. DRB-201B, Germany) and measured on a
154 spectrophotometer analyser (HACH ref. DR1900, Germany). Finally, pH and conductivity were
155 measured by a multiparametric probe (HACH ref. HQ40D, Germany).

156

157 **3. Results and Discussion**

158 The most standard methodology for treating brewery wastewater is to conduct an anaerobic
159 biological treatment. In the current study such technology is represented by an Anaerobic
160 Fluidised-bed reactor that will be our reference system to explore the capacity of a new design so-
161 called microbial electrochemical fluidized-bed reactor.

162 3.1. The performance of a Microbial Electrochemical Fluidized Bed Reactor (ME-FBR)

163 An initial characterization of the ME-FBR was performed in order to validate the efficiency
164 of the new approach regarding COD removal, biogas generation and electrochemical-assisted
165 hydrogen production with real brewery wastewater. The strategy after the ME-FBR configuration
166 was based on enhancing the oxidative metabolism by using a fluid-like electroconductive material
167 acting as terminal electron acceptor in microbial respiration. The electrochemical nature of such
168 electron acceptor allowed a control of the redox potential of the bed. Indeed, the first parameter to
169 be evaluated was the impact of such polarization potential in the COD removal. Not surprisingly,
170 the COD removal increased from 60% COD removal at 0,15 V to 87% under a polarization of 0,7
171 V. Thus, the behavior of COD removal (see Fig.1.a) suggested that microbial oxidation of organic
172 matter is limited by mass transfer, and not by electron transfer, as COD removal is directly related
173 to oxidation current in the anode. So, by using ME-FBR is possible to overcome one of the main
174 problems related to MET devices as indicated previously, namely, low overall current for practical
175 treatment uses. Thus, anode potentials higher than 0.7 V would not reach better performance
176 despite investing more energy in polarizing. On top of that, it seems reasonable to avoid such a
177 high redox potential that could damage molecules from membrane bacteria.

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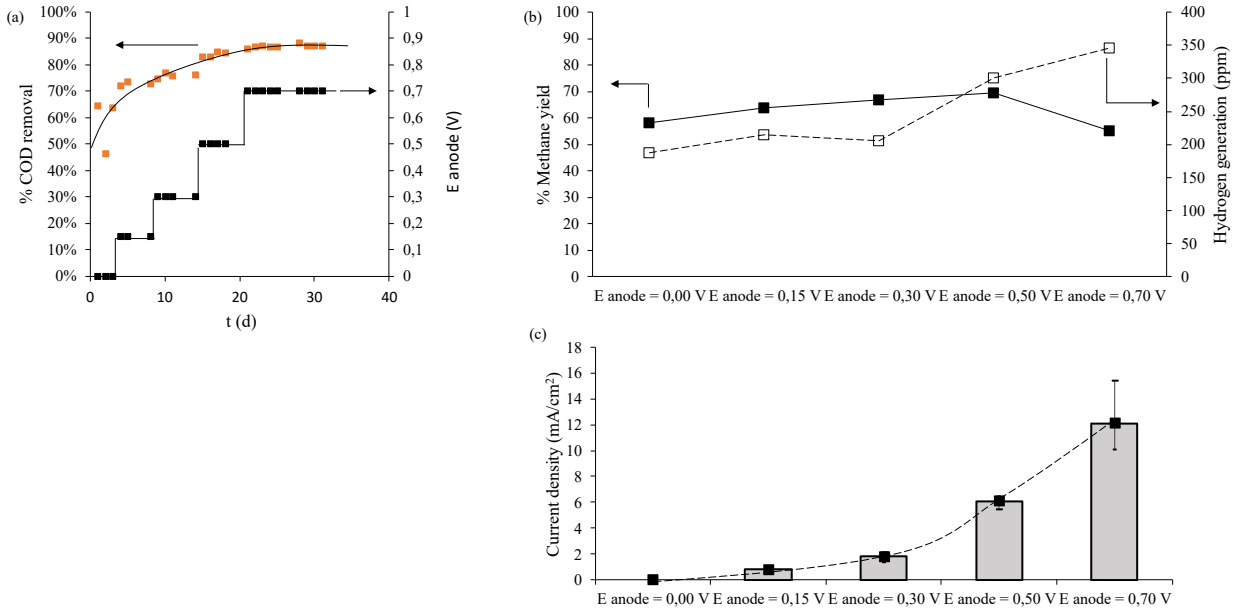

Fig.1. ME-FBR characterization. **(a)** Influence of the anode polarization (V) on the % COD removal. Symbols: (■) % COD removal, (■) Anode polarization, E (V vs Ag/AgCl). **(b)** Methane and hydrogen production in the ME-FBR reactor. Symbols: (■) Hydrogen concentration in the produced biogas (mg/L). **(c)** Current density obtained in the ME-FBR. Symbols: (■) Output current density (mA/cm^2).

On top of removing COD from wastewater, a ME-FBR constitutes by itself a device for generating biogas. In contrast with standard anaerobic bioreactors where organic matter is converted into CH_4 and CO_2, the electrochemical nature of ME-FBR allows the production of hydrogen at the counter electrode (cathode, water reduction reaction, $2\ H_2O + 2e^- \rightarrow H_2 + 2OH^-$, E^o= -0.83 V). Interestingly, all the electrons reducing water on the surface of the cathode were originally transferred to the anodic bed by electroactive microbial oxidation of COD (as anode potential is significantly lower than redox potential for water oxidation, $O_2 + 4H^+(aq) + 4e^- \rightarrow 2H_2O$, E^o= 1.23 V). Moreover, the methane concentration in the biogas did not varied substantially (Fig 1.B), while the hydrogen concentration rapidly increased when the anode potential was set in the range 0.5 – 0.7 V, achieving a maximum hydrogen generation at 0.7 V. This increase in the hydrogen generation at higher anode potentials was also correlated with the higher current density (Fig.1. c) harvested by the system (2.24 A/m^3, referred to anode fluidized bed volume).

3.2. ME-FBR versus AFBR: exploring the limits

Conventional anaerobic digesters for treating wastewater from the brewery industry must deal with a well-known set of operational problems (e.g. overload, biocide, starving, low temperature). Our first target was to perform a series of resilience tests in order to compare the robustness of both technological solutions, ME-FBR and AFBR, using chemically coagulated wastewater from a brewery plant. Interestingly, the analysis of such wastewater revealed a complex feeding stream marked by its variability, mainly high content of COD, total nitrogen (TN) and total phosphorous (TP). Furthermore, the comparative study was monitored for one year, evaluating the long-term operation of the conventional AFBR and ME-FBR (Figure 2).

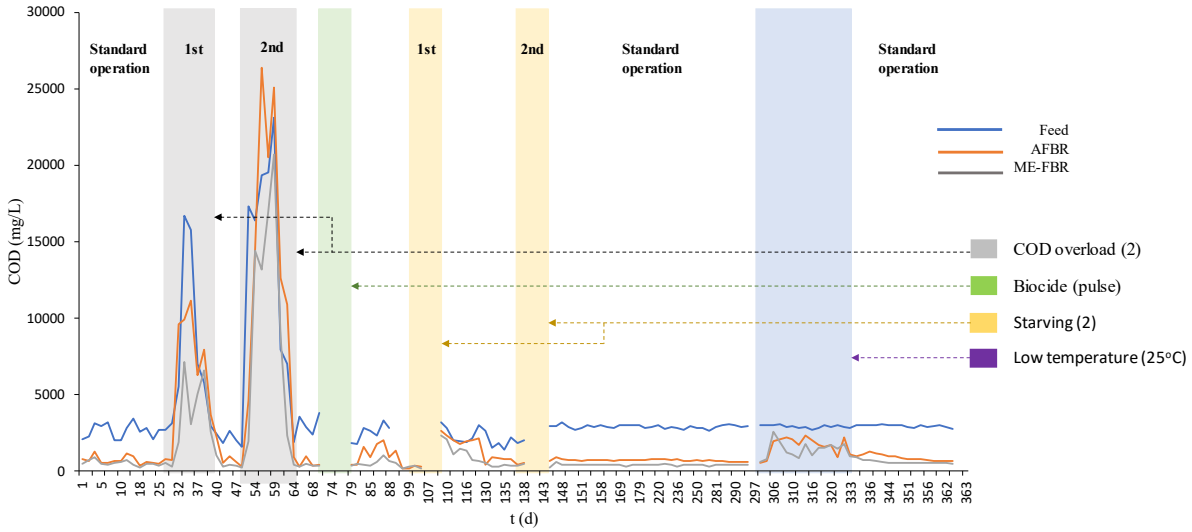

Fig.2. Long-term operation of the AFBR and ME-FBR for one year. Description of the resilience tests. (-) Influent COD concentration at influent (mg O_2/L), (-) COD concentration of the AFBR effluent (mg O_2/L), (-) COD concentration of the ME-FBR effluent (mg O_2/L).

Our first attempt was to explore the robustness of ME-FBR and AFBR for treating real brewery wastewater as a key baseline for further disruption effects. The operation of both technologies in terms of %COD removal, biogas generation and power production were performed using the same feeding stream (Figure 3).

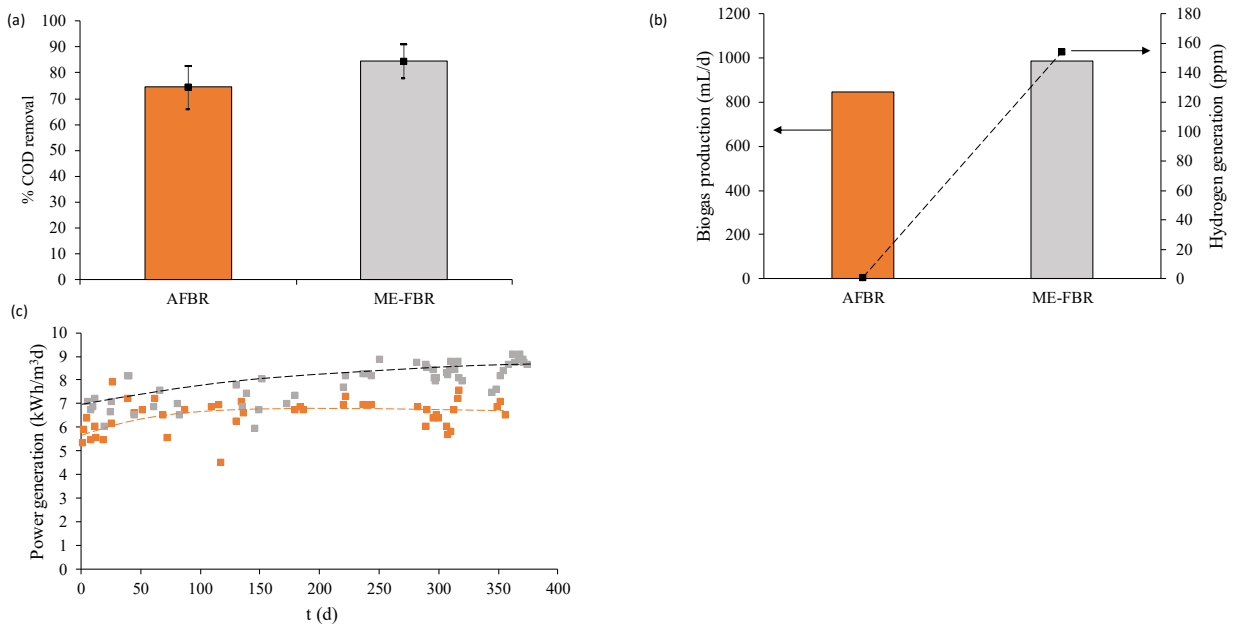

Fig.3. ME-FBR and AFBR operation during standard operation. **(a)** AFBR (orange bar) and COD removal for ME-FBR (grey bar). **(b)** Biogas generation and hydrogen concentration. Symbols: (■) Hydrogen concentration on the enriched biogas (mg/L). **(c)** Energy generation of the ME-FBR and AFBRD reactor during standard operation associated to biogas production. Symbols: (■) ME-FBR (kWh/m^3 d), (■) AFBR (kWh/m^3 d).

During the standard operation, ME-FBR outperformed AFBR for COD removal by up to 10%. The higher efficiency of ME-FBR for treating wastewater was directly related to the anode polarization and indeed to the activity of electroactive bacteria. Such an increase in COD oxidation favored biogas generation (984 mL/d) including a high hydrogen concentration (154 mg H_2/L), that notably increased the net power generation in respect to the conventional AFBR (Fig.2. c). Moreover, the net energy applied to the electroconductive bed was negligible in comparison with the high net energy produced by the reactor.

Once the standard operation was tested for AFBR and ME-FBR reactors, the resilience capacity of both technologies under COD overload was performed. Two different COD overloads (27.20 and 51.20 kgCOD/m^3 d) were evaluated for one week period each (Table 2).

Table 2. OLR (kgCOD/m^3 d) and HRT (h) during the two COD overloads applied to the conventional AFBR and ME-FBR reactors

	Operation time (d)	OLR (kgCOD/m^3 d)	HRT (h)
Standard operation	1 -31	7.10	9
	39 – 52	6.00	9
COD overload 1	32 -38	27.20	9
COD overload 2	53 – 59	51.20	9

234

235 The wastewater treatment capacity under this first disruptive test was measured in terms of
236 COD removal rate. AFBR was severely affected by high concentrations of COD, actually reducing
237 the treatment capacity of the system from 71.9 kgCOD/m^3 d to 0.23 kgCOD/m^3 d during the first
238 COD overload (Fig. 4). Such decrease was observed not just as accumulation of organics in
239 effluent but also as an increase in values from error bars (Fig.4.a). This negative effect was greatly
240 intensified with the second COD overload when the conventional AFBR was not able to consume
241 COD, mainly due to VFA accumulation, which eventually inhibited the hydrolytic bacteria
242 responsible for the first step of conventional anaerobic digestion. In contrast, ME-FBR validation
243 for COD removal outperformed AFBR by 30-fold after the first overload and 55-fold after second
244 overload. The higher stability of ME-FBR could be observed in low values for error bars (Fig 4.a).
245 So, the anode polarization in ME-FBR favored the oxidation of organic pollutants, even supporting
246 high VFA removal rates avoiding critical operational problems as pH depletion normally observed
247 in AFBR technology.

248 The biogas production after first COD overloading resulted in an increase of flow rate by 2-fold
249 as a general trend for both AFBR and ME-FBR. Such situation was not kept after a more severe
250 COD overloading resulting in a flow rate for AFBR even lower than shown in the pre-overloading
251 situation. In contrast, ME-FBR flow rate was not affected after overloading COD by 8-fold. VFA
252 accumulation in AFBR is a typical situation of destabilization, due to hydrolytic bacteria
253 inhibition, leading to a critical decrease on the biogas generation. Actually, very little
254 concentration of hydrogen was detected in AFBR (14 mg H_2/L), suggesting an increase in the

partial fermentation of the accumulated organic compounds. In contrast, the cathode-based generation of hydrogen increased resulted in biogas hydrogen percentage as high as 500ppm.

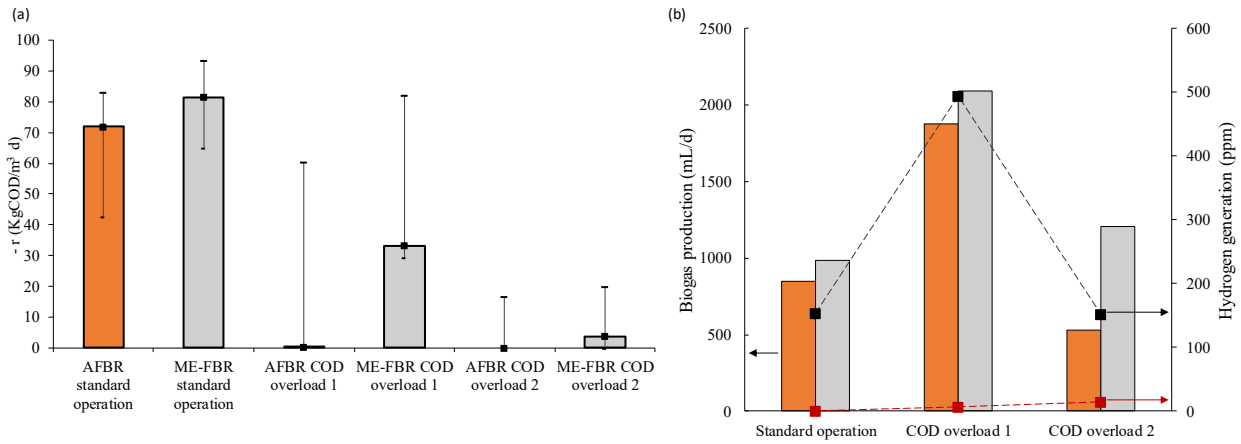

Fig.4. COD removal rate under COD overloads of the AFBR and ME-FBR technologies. **(a)** COD removal rates of AFBR and ME-FBR reactors. **(b)** Biogas generation and hydrogen production. Symbols: (■) Hydrogen production during the ME-FBR operation (mg/L), (■) Hydrogen production during the AFBR operation (mg/L).

The presence of very high-effective biocides for cleaning purposes is frequent in the food and brewery industry. The main problems associated to these active molecules are related to their complex structure and their recalcitrant nature. Both inherent characteristics exacerbates the difficulty for removing their traces after use in conventional primary and secondary treatments from common industrial WWTP. Attending to this problem, the capacity of the AFBR and ME-FBR to remove the most typical biocide used in the food and brewery industry was evaluated. The resilience capacity of the systems to remove this product was monitored attending to the total nitrogen removal rates associated to both systems when a biocide was dosed in continuous mode for six days as observed (Fig.5).

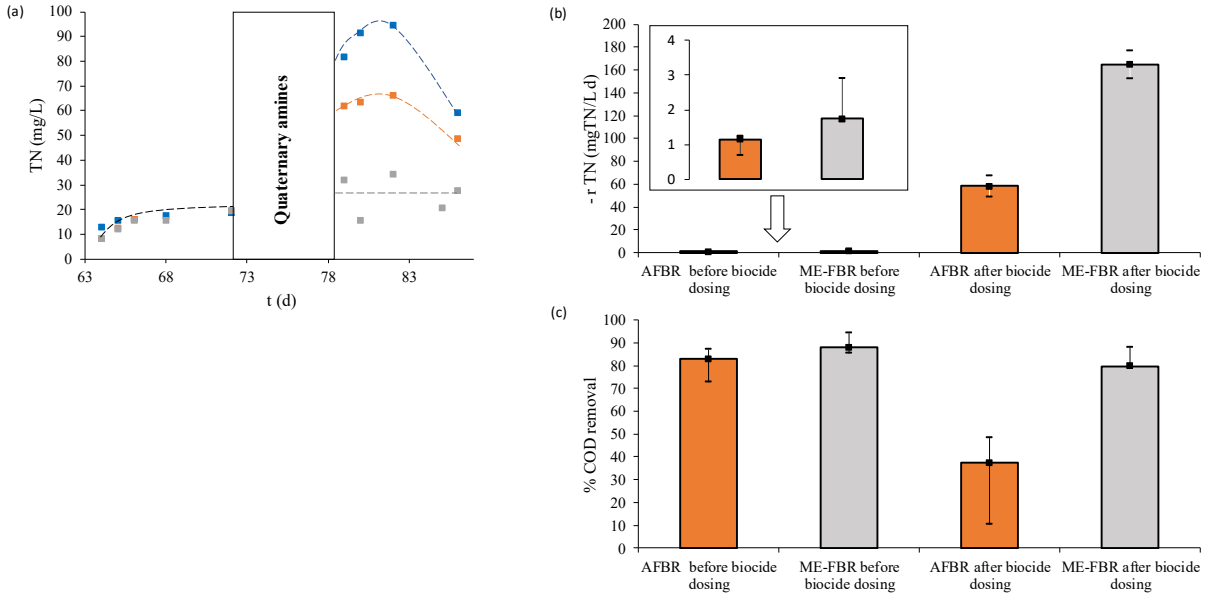

Fig.5. TN concentration, TN removal rates, and COD removal for AFBR and ME-FBR reactors during a biocide resilience test. (a) TN concentration. Symbols: (■) TN concentration in the feed stream (mg/L), (■) TN concentration in AFBR effluent (mg/L), (■) TN concentration in ME-FBR effluent (mg/L). (b) TN removal rate for AFBR and ME-FBR reactors before and after the biocide dosing. (c) COD removal for AFBR and ME-FBR reactors before and after the biocide dosing.

The resilience test for ME-FBR revealed a lack of inhibition in terms of nitrogen removal after the biocide dosing (Fig.5.a). In contrast, AFBR was severely affected and TN concentration in the effluent increased from 20 mg/L to 66 mg/L, while TN removal rate was ca. 30% of the one shown by ME-FBR. In addition, a marked decrease on COD removal was shown by the AFBR after the biocide dosing, from 83% to 37%, while biocide did not have major impact in COD removal for ME-FBR (Fig 5.c). Despite the anoxic conditions, the ME-FBR revealed an unexpected high nitrogen removal (70%); the rationale after such finding could be the microbial electrochemical oxidation of nitrogen compounds to nitrate in the anodic particles, and subsequent nitrate reduction by anaerobic suspended microorganisms using organic matter as electron donor.

Finally, the stress response after a starvation period of 16 days and low temperature (25ºC) was evaluated. The resilience tests attending to the % COD removal revealed a severe decrease (ca.

70%) for both systems just after the starvation period (Fig.6). Nevertheless, the recovery period in the case of the ME-FBR was just 20 days of operation, in contrast with the 40 days necessary to recover the standard capacity for AFBR. In a similar way, a temperature drop, from 35ºC to 25ºC had a dramatically reduction of in COD removal (ca. 40-50%) for both systems. However, ME-FBR microbial community readapted to low temperature after one month of operation to reach 70% COD removal in contrast with AFBR that unable to remove more than 30% of the COD. The buffer capacity of the ME-FBR in respect to AFBR during starvation and low temperatures was due to the selective advantage achieved by applying a constant anode potential to stimulate electroactive bacteria.

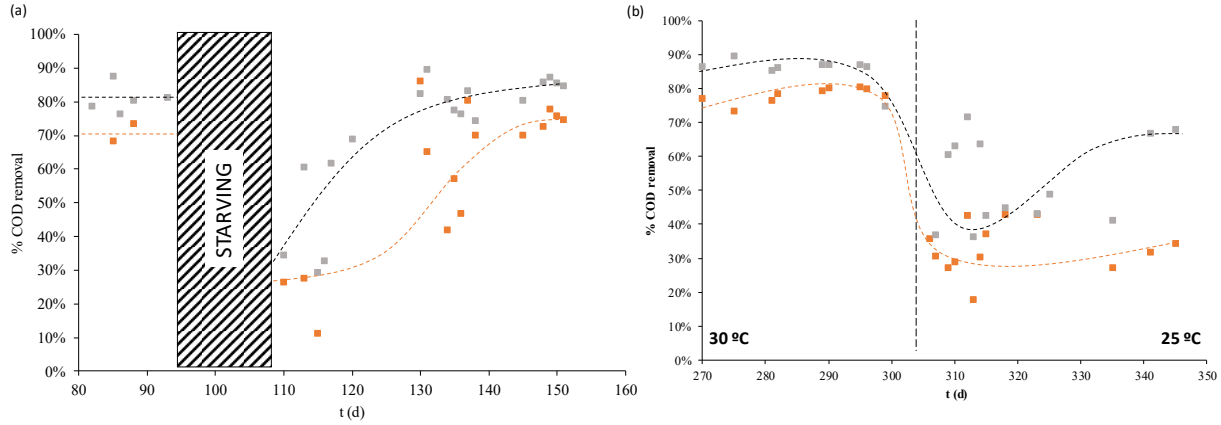

Fig.6. Resilience capacity of the AFBR and ME-FBR reactors during starving step and under low operational temperatures (25ºC). **(a)** % COD removal after staving. Symbols: (■) AFBR, (■) ME-FBR. **(b)** % COD removal under the operation of the systems at low operational temperatures (25ºC). Symbols: (■) AFBR, (■) ME-FBR

The basic microbial electrochemical parameters of the ME-FBR reactor were monitored during the long-term operation to obtain physiological information on real time that complement the standard data based on COD removal. The complete inhibition of electroactive bacteria was observed at low temperatures and after long starvation periods (Fig.7). This inhibition was checked attending to the very low current densities during those disruptive periods, 2.5 x 10^{-3} mA after the starvation period and 1.1 mA at low temperatures. Those low current densities were directly related to the low coulombic efficiencies (CE) achieved during those periods, being 0.04% after the

starvation time and 0.97% during the operation at 25ºC, revealing a severe inhibition of electroactive bacteria. CE referred to the rate of total organic matter in the wastewater that is converted into electricity by electrogenic microorganisms, and eventually harvested as current flow, over the total amount of electrons obtained from the organic matter oxidation. Furthermore, ME-FBR technology resulted highly capable of treating biocide-supplemented wastewaters attending to the bioelectrochemical parameters, current density and CE, which were quite similar in respect to the conventional operation of the reactor (3.0 A/m^3 and 5.7%, approximately).

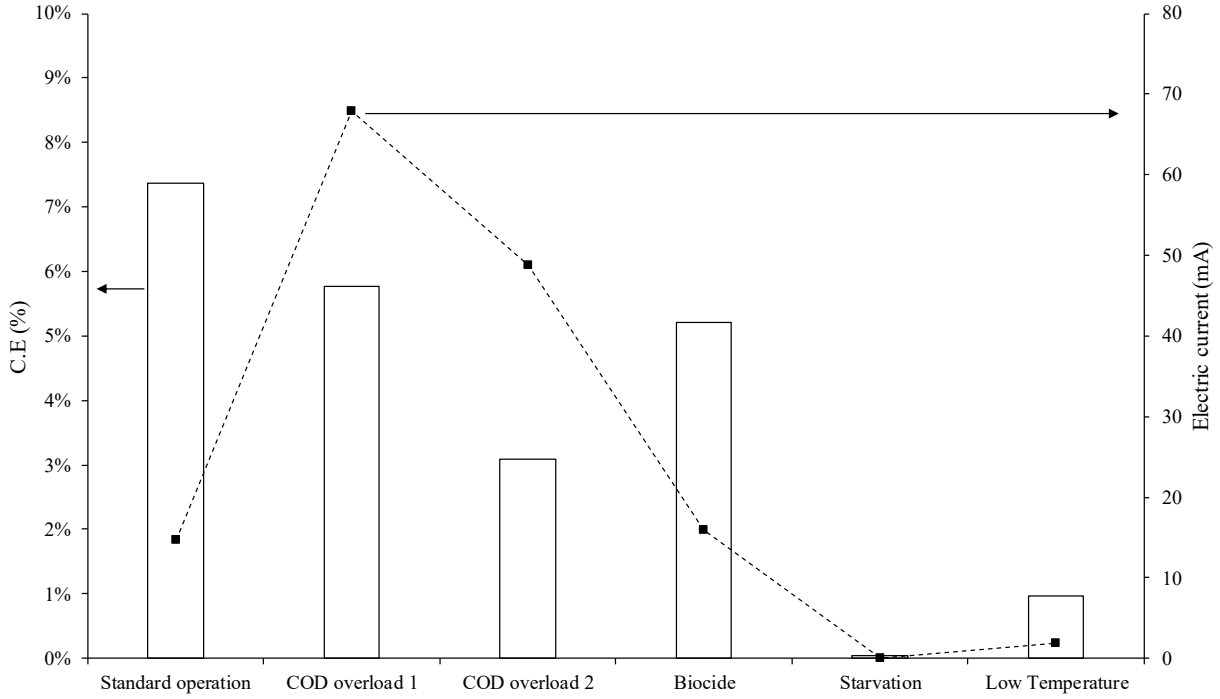

Fig.7. Basic electrochemical parameters of the ME-FBR. Average electric current of the ME-FBR technology during the different resilience tests and related CE (%). Symbols: ■ Electric current (mA)

The increase of COD in the influent has a direct influence on both the current density and CE (Fig.7). During the first COD overload (27.2 kgCOD/m^3 d) the current density was increased by 6-fold. Such results indicated the fast adaptability of electroactive bacteria at high COD overloads. Nevertheless, very high COD concentrations in the feeding stream (51.2 kgCOD/m^3 d) led to a smooth current efficiency drop in respect to the first COD overload. Nevertheless, the high

increase on the inlet COD did not really affect the electroactive bacteria according to the high current densities achieved (9.19 A/m^3). Nevertheless, it should be considered that the experimental work has been performed in an industrial environment with real wastewater. However, since our research has been conducted at pre- pilot scale, additional activities should be performed in order to scale-up ME-FBR technology for treating industrial wastewater.

4. Conclusions

This study demonstrates that ME-FBR outperforms AFBR either under standard operational conditions or under stress operational tests (COD overload, biocide dosing, long starvation periods and operation at low operational temperatures). In steady state, ME-FBR increases the wastewater treatment capacity in 10% compared to AFBR with an organic loading rate (OLR) of 6.0-7.1 kg COD/m^3 d, as well as an increase of 30% related to the energy production associated to generated biogas. Our results clearly revealed why polarizing a fluidized-electrode shows a direct impact on COD and TN removal, avoiding inhibition phenomena typically observed in standards systems like AFBR. Moreover, the use of ME-FBR could be a convenient strategy for implementing of MET for wastewater applications, as it is possible to overcome one of the main problems related to these MET devices: low overall electric current for practical treatment uses due to electron transfer limitations. Finally, the bioelectrochemical hydrogen generation by ME-FBR increases the power capacity of biogas, making the technology more attractive to be implemented at higher scale.

Acknowledgement

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