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A Bioelectrochemical Approach for Brine Management in Water Reuse Plants: Pilot-Scale Evaluation of Microbial Fuel Cells for RO Concentrate Treatment and CEC and PFAS Removal

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Abstract

Reverse osmosis (RO) membranes are widely applied in reuse facilities, but the management of RO concentrate remains a major sustainability challenge. Conventional brine disposal methods, such as deep well injection or evaporation ponds, are costly, energy intensive, and often ineffective at addressing the accumulation of contaminants of emerging concern (CEC) and per- and polyfluoroalkyl substances (PFAS). Bioelectrochemical systems, such as microbial fuel cells (MFCs), offer a promising pathway for sustainable brine organic load management by simultaneously reducing organic load and recovering energy. In this study, a pilot-scale MFC system (Aquacycl BETT®, Escondido, CA, USA, unit, 12 modular reactors) was evaluated for treatment of RO concentrate produced by a combined ultrafiltration and closed-circuit reverse osmosis pilot train at the San Jacinto Valley Regional Water Reclamation Facility (San Jacinto, CA, USA). Operating with a 4-h hydraulic retention time, the MFC achieved an average chemical oxygen demand (COD) removal of 40% and biochemical oxygen demand (BOD_5) removal of 52%. Coulombic efficiency ranged from 2.8% to 15.5%, with an average energy recovery value of about 8.1 Wh per kg of COD removed. PFOS concentrations decreased by 36% across the MFC, and PFAS were not detected in the harvested anode biomass. The mechanism of PFOS attenuation (e.g., adsorption vs. transformation) was not directly evaluated. These findings highlight the potential of MFCs as a bioelectrochemical solution for sustainable water reuse RO brine management.

Keywords: water reuse; reverse osmosis brine; microbial fuel cells (MFC); bioelectrochemical systems (BESs); contaminants of emerging concern (CECs); PFAS removal; brine management; energy recovery

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1. Introduction

Global water scarcity is intensifying as a result of climate change, urban population growth, and the overexploitation of surface and groundwater resources [1]. In regions such as California, prolonged droughts and increasing demand have placed significant pressure on traditional freshwater supplies [2]. Water reuse, particularly indirect and direct potable

reuse (IPR and DPR), has therefore emerged as a critical strategy to supplement drinking water supplies while reducing reliance on imported water [3,4]. Numerous large-scale reuse projects in the United States and worldwide have already demonstrated that advanced treatment trains can reliably produce high-quality water that meets or exceeds regulatory standards [5–8].

The most common configuration for potable reuse includes secondary biological treatment, micro- or ultrafiltration, reverse osmosis (RO), and advanced oxidation processes (AOPs) [9,10]. Although these systems successfully produce safe and high-quality water, they generate a concentrated brine stream that remains an unresolved challenge [9,11].

The brine or concentrate generated by RO contains elevated levels of salts, nutrients, and contaminants of emerging concern (CEC), including pharmaceuticals, personal care products, endocrine-disrupting compounds, and industrial chemicals [9]. Among these, per- and polyfluoroalkyl substances (PFAS) are especially problematic due to their high persistence, strong carbon–fluorine bonds, and resistance to conventional treatment [12]. When discharged, RO brine can pose ecological risks to receiving waters or soils, while disposal options, such as deep well injection or evaporation ponds, are energy intensive and costly [11]. The growing attention to CEC and PFAS in water reuse has therefore elevated the need for alternative concentrate management strategies that are both technically feasible and environmentally sustainable [5].

Recent efforts have sought to reduce brine volumes through high-recovery RO configurations, such as closed-circuit reverse osmosis (CCRO), but these processes further increase the concentration of pollutants in the reject stream [9]. An alternative strategy to reducing pollutants in the reject stream is the application of bioelectrochemical systems, including microbial fuel cells (MFCs), which utilize electroactive microorganisms to oxidize organic matter while transferring electrons to an external circuit and generating electricity [13]. In addition to energy recovery, MFCs can degrade organics and attenuate selected CECs. Studies have demonstrated their potential for treating high-strength wastewaters, but literature for its application to RO brine is still limited [14,15].

A notable pilot-scale study by Shad et al. [16] evaluated bench-scale microbial fuel cells (MFCs) for RO concentrate treatment in a novel water reuse train and reported 75–100% removal for selected pharmaceuticals, personal care products, flame retardants, by-products, and PFAS, along with measurable power generation. Laboratory investigations have further indicated that bioelectrochemical systems may contribute to PFAS transformation under certain conditions. However, despite this progress, little is known about the performance of MFCs under real operating conditions in municipal reuse projects, where brine salinity, ionic strength, and contaminant mixtures are highly variable [14,17,18]. The fate of PFAS in MFCs also remains poorly characterized, with questions about adsorption versus degradation mechanisms [19].

This study addresses these gaps by evaluating a pilot-scale MFC system treating RO concentrate generated from a municipal reuse pilot train. The objectives were to (i) assess the removal of bulk organics, measured as chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5), (ii) evaluate energy recovery potential through coulombic efficiency (CE; equivalent to Faradaic efficiency "FE" in electrochemistry) and net energy recovery, and (iii) investigate the behavior of CEC and PFAS across the MFC unit. By focusing on the role of MFCs as a brine management strategy, this research contributes to the growing body of work exploring sustainable and energy-efficient alternatives for advanced water reuse. The findings provide new insights into the feasibility of bioelectrochemical treatment of RO brine, with implications for future design and integration into potable reuse schemes.

2. Materials and Methods

2.1. Pilot Site and Feedwater

The pilot study was conducted at the San Jacinto Valley Regional Water Reclamation Facility (SJVRWRF) owned and operated by the Eastern Municipal Water District (EMWD, Perris, CA, USA). The SJVRWRF treats municipal wastewater using conventional primary, secondary, and tertiary processes that utilize RO for reuse purposes. For this study, the feedwater to the microbial fuel cell (MFC) system (Aquacycl Inc., Escondido, CA, USA) was reverse osmosis (RO) concentrate generated by a pilot treatment train consisting of ultrafiltration (UF) unit (HFU-2020AN, Toray Membrane, Poway, CA, USA) for pretreatment of primary effluent and a closed-circuit reverse osmosis (CCRO) unit (FilmTecTM FortilifeTM CR100, DuPont, Wilmington, DE, USA). The RO concentrate, enriched in dissolved salts, organics, and contaminants of emerging concern (CEC), was collected in a dedicated tank and supplied continuously to the MFC system. The overall configuration of the integrated UF–CCRO–MFC pilot system is shown in Figure 1.

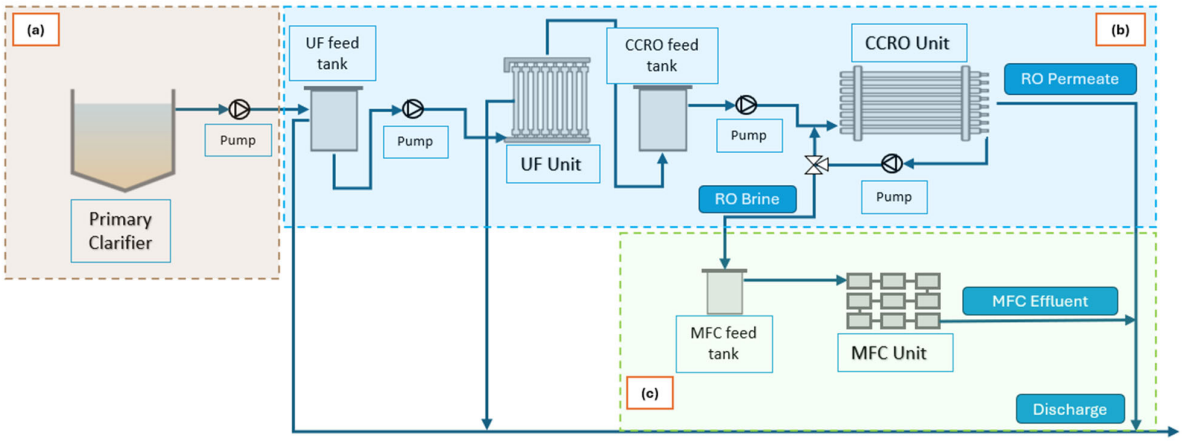

Figure 1. Process flow diagram of the pilot units including UF, CCRO, and MFC systems: (**a**) host WWTP, (**b**) water reuse pilot (UF, CCRO units), (**c**) brine treatment pilot (MFC unit).

2.2. Microbial Fuel Cell (MFC) System

MFCs are bioelectrochemical reactors that employ electroactive microorganisms to oxidize organic matter at the anode and transfer electrons to the cathode via an external circuit, simultaneously achieving wastewater treatment and electricity generation. Their performance is governed by electrode materials, biofilm development, and operating conditions such as hydraulic retention time (HRT), conductivity, and pH [20–22]. High-strength, high-conductivity waste streams are especially suitable for MFC feeds because elevated ionic strength lowers internal resistance and supports higher current densities; conversely, decreases in conductivity raise internal resistance and suppress power generation. Empirical studies and meta-analyses document these relationships and their impact on COD removal, CE, and energy yields [23–25].

Continuous-flow, modular MFCs have been demonstrated at liter- to pilot-scale with real wastewaters. A 20-L system treating brewery wastewater achieved long-term stable operation and high COD removal under controlled HRT and resistive loading [26]. A 12-module, 110-L system operated >200 days on swine wastewater reached up to 65% COD removal at 4 h HRT with a treatment rate of 5.0 kg-COD·m^{-3}·d^{-1} and reported net energy recovery (NER) competitive with conventional cogeneration benchmarks [27].

In this study, the microbial fuel cell platform was Aquacycl's BioElectrochemical Treatment Technology (BETT®), a single-chamber, modular, continuous-flow system designed for scalability and field deployment. The RO concentrate was directed to a skid-mounted

pilot unit configured for both batch and continuous-flow operation. The system consisted of a feed tank, an equalization tank, a supply tank, a feeder tank, and a collection tank, connected to an array of twelve modular microbial fuel cell reactors arranged hydraulically in series (Figure 2). Feed was delivered at an average flow rate of 0.15 gpm (≈0.57 L/min), corresponding to a hydraulic retention time of approximately 4 h across the reactor train. Flow mode (batch or continuous) was controlled by valves and recirculation lines built into the skid. Reactor startup involved seeding with natural lagoon sediment followed by batch recirculation to promote biofilm establishment prior to continuous flow operation.

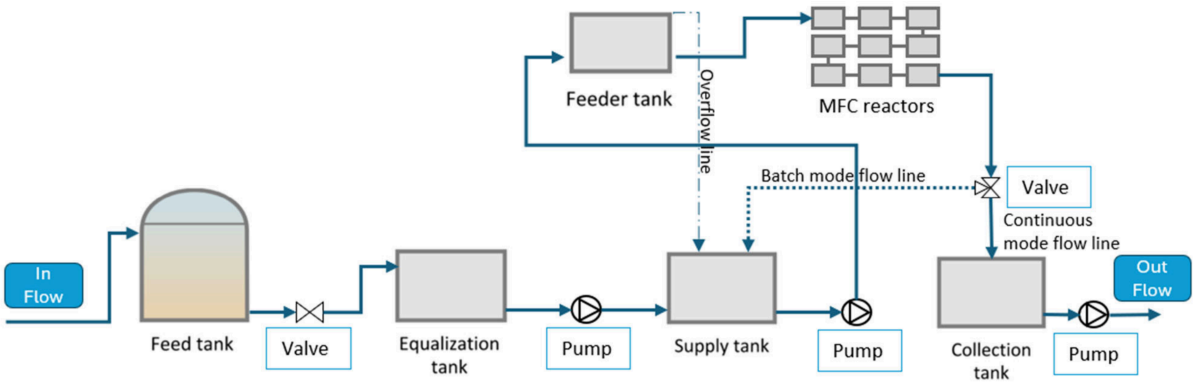

Figure 2. Hydraulic diagram of the BETT® MFC pilot unit.

The pilot-scale BETT® system used in this study is shown in Figure 3, consisting of 12 reactors hydraulically connected in series.

Figure 3. MFC Pilot Skid.

2.3. Operation and Monitoring

The MFC unit was supplied with RO concentrate collected from the CCRO unit and stored in a dedicated Equalization tank. Flow through the system was regulated using a peristaltic pump to maintain the target hydraulic retention time (HRT) of approximately 4 h. Although the system was intended for continuous operation, interruptions in influent supply resulted in periods of batch or idle mode, which likely contributed to some variabilities in the performance of the unit.

Field parameters, including pH, conductivity, and turbidity, were measured periodically at both influent and effluent sampling points using portable probes. Voltage across a pre-defined impedance of each of the 12 reactor modules was logged continuously using a measurement system specifically designed by Aquacycl. Generated voltage was used to support calculations of coulombic efficiency (CE) and net energy recovery (NER).

Influent and effluent grab samples were collected at predetermined intervals for laboratory analysis. At the conclusion of the pilot study, biomass was harvested from the anodes to evaluate the potential accumulation of per- and polyfluoroalkyl substances (PFAS) and other contaminants of emerging concern (CECs).

2.4. Analytical Methods

2.4.1. Field Monitoring

Daily operational monitoring was conducted on influent and effluent streams. Parameters measured included pH, oxidation–reduction potential (ORP), temperature, conductivity, and turbidity, using portable field probes. In addition, voltage and current generation across each of the 12 MFC reactors were logged by the BETT® unit's internal monitoring system. These data were used to evaluate reactor stability, track operational changes, and calculate electrochemical performance.

2.4.2. Laboratory Analyses

Comprehensive water quality analyses were performed by the Eastern Municipal Water District (EMWD) laboratory on grab samples collected periodically from the influent and effluent of the MFC system. Parameters included alkalinity, ammonia, biochemical oxygen demand (BOD_5), boron, calcium, chloride, chemical oxygen demand (COD), copper, iron, magnesium, manganese, ortho-phosphate, potassium, reactive silica, silica, sodium, sulfate, total organic carbon (TOC), total dissolved solids (TDS), total phosphorus, total suspended solids (TSS), and zinc.

CEC and PFAS analyses were conducted by a certified external laboratory using EPA-approved analytical methods (e.g., EPA Method 533 for PFAS). Target analytes included selected pharmaceuticals, personal care products, endocrine-disrupting compounds, and representative PFAS (e.g., PFOA, PFOS, PFHxA, PFNA).

2.4.3. Parameters for Electrochemical Performance

Electrochemical data recorded from the MFC unit were used to calculate Coulombic efficiency (CE) and net energy recovery (NER) following standard MFC methodologies [20]. CE represents the fraction of electrons from substrate oxidation that are captured as electrical current, and NER quantifies the recoverable electrical energy normalized to the mass of organic matter removed. Volumetric power density was calculated based on the electrical power output normalized to the effective reactor volume.

The CE (%) was determined using:

$$CE(\%) = \frac{M \times \int Idt}{F \times b \times \Delta COD \times V} \times 100$$

where:

M = molecular weight of oxygen (32 g mol^{-1})
$\int$ Idt = total current over time (coulombs)
I = current (amp)
F = Faraday's constant (96,485 C mol^{-1} e^-)
b = 4 mol e^-/mol O_2
ΔCOD = difference between influent and effluent COD (g L^{-1})
V = liquid volume in the anode chamber (L).

The net energy recovery (NER) was determined as:

$$NER = \frac{V \times I \times t}{\Delta COD \times V}$$

where:

V = measured cell voltage (V),
I = current (amp),
HRT = hydraulic retention time.

The volumetric power density (PD) was then calculated as:

$$PD = \frac{V^2}{R \times V_{reactor}}$$

where:

V = measured cell voltage (V),
R = external resistance (Ω),
$V_{reactor}$ = total effective liquid volume of the MFC reactors (m^3).

3. Results and Discussion

3.1. Water Quality of RO Concentrate

The RO pilot produced a concentrate stream characterized by elevated salinity, organic loading, and a wide range of contaminants (Tables 1 and 2). Conductivity averaged 3796 µS/cm, with total dissolved solids (TDS) of 1845 mg/L. Major ionic constituents included chloride, sodium, sulfate, calcium, magnesium, potassium, and silica. Bulk organic matter was reflected in COD (463 mg/L), BOD_5 (203 mg/L), and TOC (126 mg/L). Nutrient analyses showed ammonia (145 mg/L) and total phosphorus (19.7 mg/L), demonstrating that the concentrate retained significant nutrient loads consistent with the quality of the primary effluent source water.

Table 1. Brine Line Water Quality Parameters & Major Inorganic Constituents (average values, n = 15).

		CCRO Concentrate		
		Average	**Min**	**Max**
pH		6.0	5.7	6.4
ORP	mV	−159.1	−230	−42
Temp	C	27.6	17	33
Conductivity	µS/cm	3796	1849	6220
Turbidity	NTU	3.8	0.6	12.8
Alkalinity, Total as $CaCO_3$	mg/L	280	158	563
Ammonia as N	mg/L	145	62	274
BOD	mg/L	203	99	441
Boron	µg/L	417	199	701
Calcium	mg/L	143	70	313
Chloride	mg/L	408	188	873
COD	mg/L	463	160	1000
Copper	µg/L	6	5	7
Iron	µg/L	1954	275	5880
Magnesium	mg/L	25	11	53

Table 1. *Cont.*

		CCRO Concentrate		
		Average	**Min**	**Max**
Manganese	µg/L	113	54	208
Ortho Phosphate as P	mg/L	18	6	42
Potassium	mg/L	55	22	117
Reactive Silica	mg/L	79	35	166
Silica	mg/L	60	27	123
Sodium	mg/L	319	144	648
Sulfate	mg/L	739	303	1540
TOC	mg/L	126	41	256
TDS	mg/L	1845	1030	3820
Total Phosphorus	mg/L	20	7	48
TSS	mg/L	<6	<6	<6
Zinc	µg/L	17	6	35

Table 2. CECs Concentrations in RO concentrate (mean values, n = 4).

CEC Type	Compound	Unit	CCRO Concentrate (Average)	RL
By-products (BPs)	N-Nitrosodimethylamine (NDMA)	ng/L	44.7	2
	N-Nitrosomorpholine	ng/L	11	2
Per- and polyfluorinated alkyl substances (PFAS)	PFBS	ng/L	ND	3.3
	PFDA	ng/L	ND	3.3
	PFHpA	ng/L	ND	3.3
	PFHxA	ng/L	12.3	3.3
	PFNA	ng/L	ND	3.3
	PFOA	ng/L	4.6	3.3
	PFOS	ng/L	31.7	3.3
Analgesics/anti-inflammatories	Diclofenac	ng/L	1850	40
	Acetaminophen	ng/L	702,500	10,000
	Naproxen	ng/L	61,750	2000
	Salicylic Acid	ng/L	405,000	50,000
	Ibuprofen	ng/L	131,000	2000
Hormones	17-a-Ethynylestradiol	ng/L	ND	20
	17-b-Estradiol	ng/L	52	40
	Testosterone	ng/L	136	40
	Estrone	ng/L	121.5	40
	Progesterone	ng/L	126	40
Antibiotic	Trimethoprim	ng/L	1975	40
	Sulfamethoxazole	ng/L	10,875	2000
	Amoxicillin	ng/L	ND	200

Table 2. *Cont.*

CEC Type	Compound	Unit	CCRO Concentrate (Average)	RL
Beta-blockers	Atenolol	ng/L	5400	40
	Propranolol	ng/L	131	40
Lipid regulators	Gemfibrozil	ng/L	4775	40
Psychiatric drugs	Carbamazepine	ng/L	602.5	40
	Fluoxetine	ng/L	48	40
	Primidone	ng/L	ND	2000
	Phenytoin (Dilantin)	ng/L	255	40
Antianxiety	Diazepam	ng/L	76	40
	Meprobamate	ng/L	114.5	40
Drugs of abuse	Cotinine	ng/L	14,700	4000
Contrast media	Iopromide	ng/L	ND	40
Opioid	Methadone	ng/L	61	40
Psychostimulants	Caffeine	ng/L	292,500	8000
Antiseptics	Triclosan	ng/L	ND	80
Component of plastics	Bisphenol A	ng/L	380	100
Statins	Atorvastatin	ng/L	2500	40
Flame retardant	TCEP	ng/L	222.5	100
	TCPP	ng/L	3350	500
	TDCPP	ng/L	1775	500
Pesticides	DEET	ng/L	2262.5	40
Industrial Compound	1,4-Dioxane	µg/L	ND	5

ND: non-detectable, RL: reporting limit.

Analysis of CEC and PFAS confirmed the presence of multiple classes of organic micropollutants (Table 2). Detected PFAS included PFOS (31.7 ng/L), PFOA (4.6 ng/L), and PFHxA (12.3 ng/L), with other species below reporting limits. Similar PFAS enrichment has been reported in brines from full-scale advanced water reuse facilities, where membrane rejection concentrates perfluorinated compounds in the reject stream [16,28,29]. High concentrations of pharmaceuticals were also observed, notably acetaminophen (702,500 ng/L), caffeine (292,500 ng/L), salicylic acid (405,000 ng/L), and ibuprofen (131,000 ng/L). Hormones (estrone, progesterone, testosterone), antibiotics (sulfamethoxazole, trimethoprim), and lipid regulators (gemfibrozil) were detected at levels consistent with those reported in other municipal wastewaters [18,30,31].

3.2. Bulk Organic Removal

The MFC system achieved measurable attenuation of bulk organics in the RO concentrate given the short HRT. Average removals were COD 40%, BOD_5 52%, and TOC 48% (Figure 4). The BOD values are a mixture of actual results and calculated values based on the BOD/COD ratios. These values are consistent with prior field-scale demonstrations of continuous-flow MFCs, which often report COD reductions between 20–80% when operated on high-strength wastewaters [32,33].

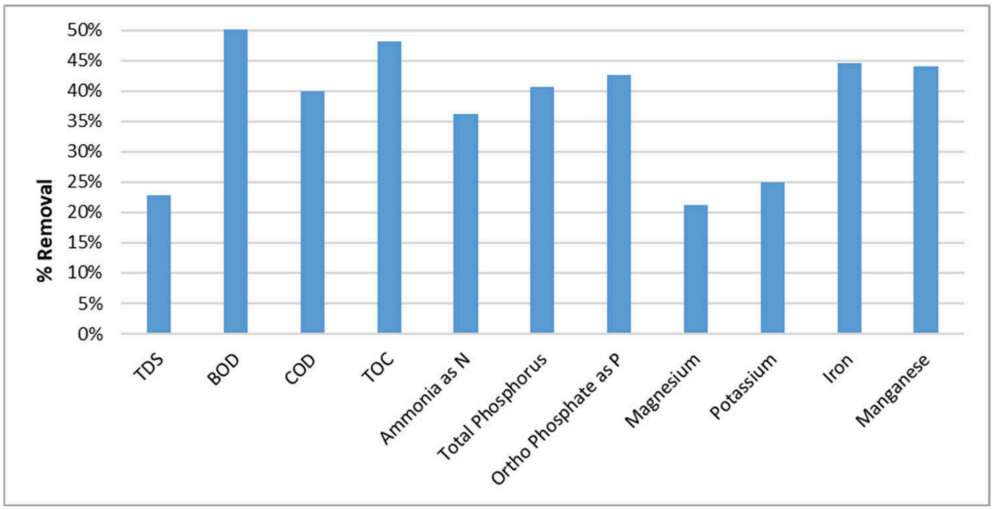

Figure 4. Removal efficiencies of bulk organics, nutrients, and selected inorganic constituents in the MFC system treating RO concentrate.

The COD removal efficiency compares reasonably with brewery and food-waste MFC pilots, which typically reach 40–99% removal under more favorable substrate conditions [34–36]. In contrast, Shad et al. (2019) reported higher COD attenuation (>70%) in bench-scale MFCs treating RO concentrate from a hybrid MF–RO train, though at significantly longer retention times (24 h) and under batch operation [16]. The performance in the present study is attributable to shorter HRT, continuous-flow operation, saline RO concentrate matrix, and interruptions during pilot runs.

Nutrient reductions were moderate, with ammonia decreased by 36%, orthophosphate by 43%, and total phosphorus by 41%. These values are comparable to those reported by Baby et al. [37], who found that nutrient removal in MFCs is generally limited under continuous flow. Higher removals reported by Tao et al. [38] (>60% for TN and TP) were achieved only in systems coupled with wetlands and adsorptive substrates. In contrast, the standalone MFC modules in this study, operated at relatively low HRTs and treating a complex water-reuse brine stream, provided meaningful reduction of N and P which can contribute significantly to overall nutrient control.

3.3. Electrochemical Performance

The BETT® system produced consistent current across the 12-module array during pilot operation. The net energy recovery (NER) varied between 3.7 and 19.5 Wh·kg^{-1} COD removed, with an average of approximately 8.2 Wh·kg^{-1} COD removed (Figure 5). The coulombic efficiency (CE) ranged from 2.8 to 15.5% (Figure 6). The highest CE (15.5%) was observed when COD removal was lowest (38 mg/L), indicating a possibility of trade-off between substrate availability and electron recovery efficiency.

Hiegemann et al. (2016) [38] observed a CE of 24.8% and NER of 0.36 kWh·kg^{-1} COD in a 45 L pilot treating municipal wastewater. Bird et al. (2022) [32] reported that most pilot MFCs achieve CE values below 20% and NER values in the range of 0.05–0.3 kWh·kg^{-1} COD. Heinrichmeier et al. (2023) documented CE values of 10–25% in a 1000 L on-site MFC system [39]. By comparison, the CE values observed in this study are similar, which is noteworthy given the complexity and salinity of RO concentrate. The NER values reported here are substantially lower than most pilot-scale systems. It is noteworthy that the MFC pilot skid design has been modified to have the highest organic removal in a hybrid continuous/batch mode and in a series configuration. Future improvements in NER could be achieved by adjusting external resistance and operating conditions, and by evaluating alternative electrode materials or configurations.

Additionally, advanced real-time electrochemical or ion-sensitive sensors could be used to monitor localized pH shifts and ionic variations within the MFC reactors. Incorporation of these tools in future studies would improve mechanistic understanding and support operational optimization.

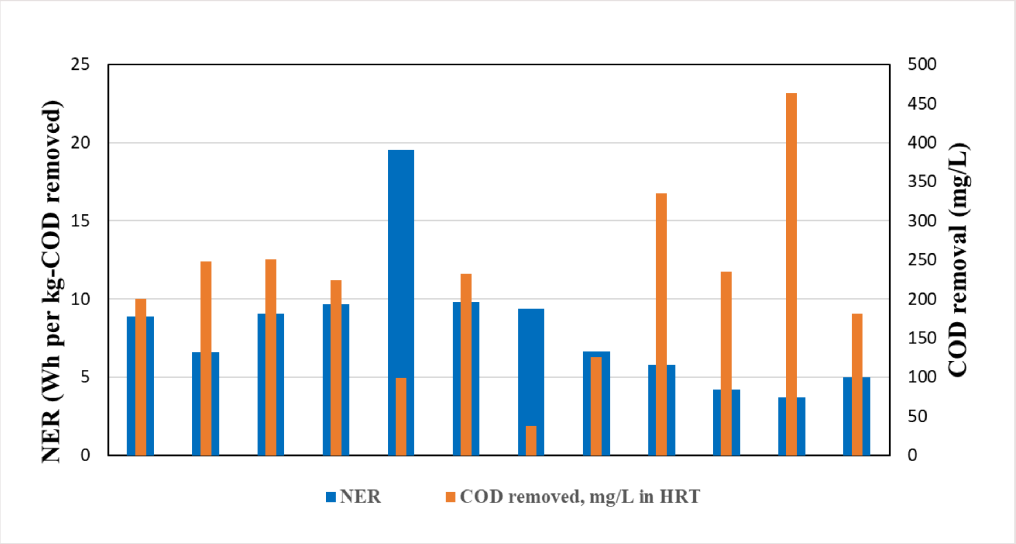

Figure 5. Net energy recovery (NER) and corresponding COD removal.

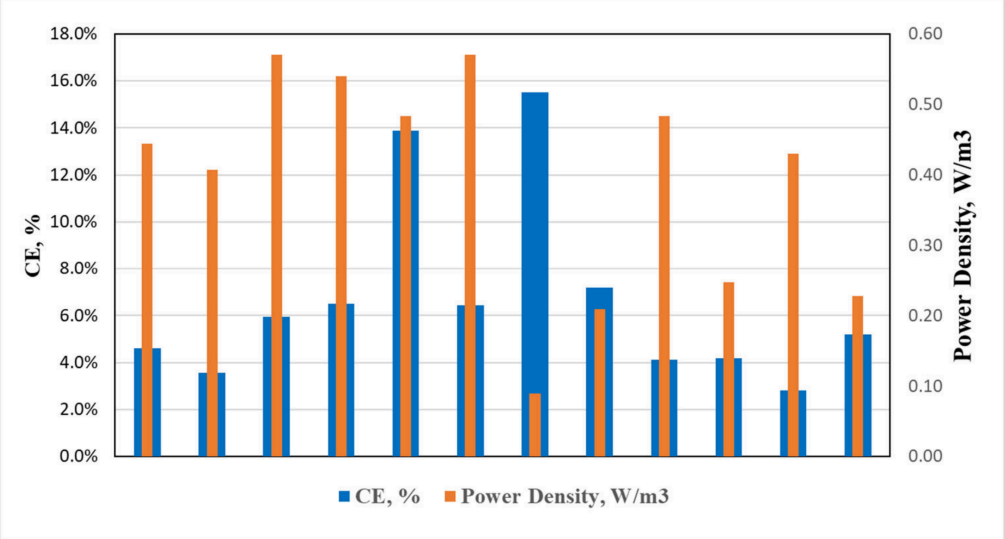

Figure 6. Coulombic efficiency (CE) and volumetric power density of the MFC system.

3.4. Contaminants of Emerging Concern (CEC) and PFAS Removal

The MFC system achieved partial but distinct removal of a wide range of contaminants of emerging concern (CEC) and select per- and polyfluoroalkyl substances (PFAS) from RO concentrate (Figure 7). The highest removals were observed for progesterone (79%), naproxen (58%), and 17-β-estradiol (100%), followed by carbamazepine (44%), estrone (44%), acetaminophen (43%), cotinine (42%), and amoxicillin (42%). Diazepam, atenolol, and PFOS exhibited moderate reductions (36–39%), while persistent compounds such as sulfamethoxazole (27%), propranolol (20%), TCEP (19%), and DEET (16%) showed limited removal.

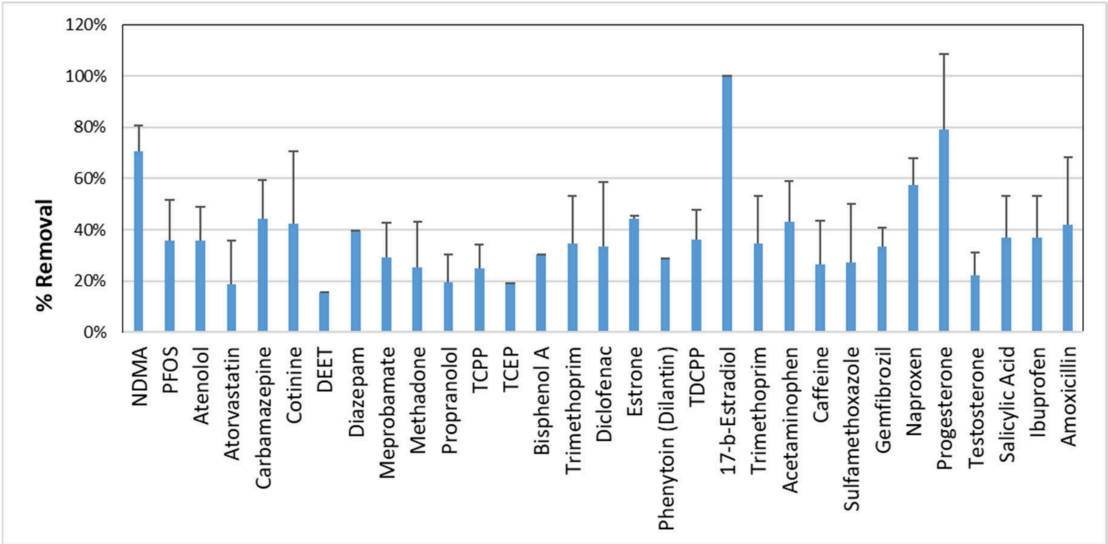

Figure 7. Removal efficiencies (±SD) of selected contaminants of emerging concern (CEC) and PFAS in the MFC effluent.

These results are comparable to those reported by Shad et al. [16], where MFCs treating RO brine from a similar hybrid water reuse train achieved 75–100% removal for anti-inflammatories and lipid regulators under batch conditions and longer retention times. Nevertheless, the MFC configuration achieved consistent attenuation of biodegradable and polar organics under saline, high-strength conditions, confirming its capability to function as a polishing step for water-reuse brine streams.

It should be noted that this study was conducted under field pilot conditions rather than controlled laboratory settings. Variability in removal efficiencies reflects fluctuations in CCRO recovery rates, which directly influenced RO concentrate composition and CEC/PFAS concentrations in the MFC feed. In addition, periodic interruptions in continuous operation and transitions to batch mode contributed to variability in MFC performance. These factors are inherent to pilot-scale deployments and are reflected in the error bars presented in Figure 7.

Among the PFAS analyzed, PFOS showed the highest removal (~36%), while PFOA and PFHxA showed increases within analytical variability. Higher attenuation of PFOS compared to carboxylic PFAS is consistent with previous studies, which report that sulfonated PFAS are generally more amenable to removal or transformation than carboxylates under biological and electrochemical conditions. In addition, transformation of precursor PFAS present in the feed stream may contribute to increases in terminal carboxylic acids such as PFOA, which can complicate interpretation of concentration trends.

Analysis of solids collected from the anodes did not indicate measurable PFAS accumulation within the biofilm. However, PFAS removal may still be associated with adsorption onto electrode surfaces, biofilm-coated materials, or other reactor components. Carbon-based electrodes, polymeric reactor materials, and incidental solids within the system can provide surfaces with affinity for PFAS, particularly PFOS, which is known to sorb more strongly than carboxylic PFAS. Accumulation of fine suspended solids or deposits within the reactors may therefore have contributed to partial PFOS retention. Minor transformation processes during extended operation cannot be excluded, although because no abiotic/open-circuit controls were conducted, adsorption versus transformation mechanisms cannot be distinguished in this pilot dataset.

Overall, the BETT® MFC provided partial yet meaningful removal of biodegradable CEC and moderate attenuation of PFOS, while other PFAS and highly persistent compounds remained largely unaffected.

4. Conclusions

This study evaluated the performance of a pilot-scale microbial fuel cell (MFC) system for treatment of reverse osmosis (RO) concentrate generated from a municipal water-reuse pilot. The BETT® unit achieved measurable removal of organics and nutrients and partial attenuation of contaminants of emerging concern (CECs) and per- and polyfluoroalkyl substances (PFAS) while producing recoverable electrical energy.

The system achieved average removals of approximately 40% for COD, 52% for BOD_5, and 48% for TOC under continuous-flow operation with a 4 h hydraulic retention time. Coulombic efficiency ranged from 2.8% to 15.5%, corresponding to an average net energy recovery of about 8.1 $Wh \cdot kg^{-1}$ COD removed. Nutrient reductions were moderate, but meaningful in the context of reducing environmental impacts, with 36% ammonia-N and 41% phosphorus removal. PFOS concentrations declined by 36% across the MFC, whereas PFOA and PFHxA remained largely unchanged. No PFAS were detected in the anode biomass, suggesting that the observed PFOS decrease may be associated with adsorption onto conductive surfaces or with limited compositional changes during extended operation.

These findings demonstrate that bioelectrochemical treatment can contribute to selective polishing of high-salinity water reuse RO concentrate streams, reducing organic and nutrient loads and partially attenuating persistent micropollutants while simultaneously recovering energy. Although overall removal efficiencies remain lower than those achieved under longer retention or batch conditions, the results confirm the feasibility of integrating modular MFC technology as a sustainable, low-energy component within advanced water-reuse and brine-management systems. Future research should focus on optimization of retention time, electrode potential, and microbial community structure, as well as long-term assessment of PFAS fate and transformation pathways in bioelectrochemical environments.

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