



Review

A Review of Stand-Alone and Hybrid Microbial Electrochemical Systems for Antibiotics Removal from Wastewater

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Abstract: The growing concern about residual antibiotics in the water environment pushes for innovative and cost-effective technologies for antibiotics removal from wastewater. In this context, various microbial electrochemical systems have been investigated as an alternative to conventional wastewater technologies that are usually ineffective for the adequate removal of antibiotics. This review article details the development of stand-alone and hybrid or integrated microbial electrochemical systems for antibiotics removal from wastewater. First, technical features, antibiotics removal efficiencies, process optimization, and technological bottlenecks of these systems are discussed. Second, a comparative summary based on the existing reports was established to provide insights into the selection between stand-alone and hybrid systems. Finally, research gaps, the relevance of recent progress in complementary areas, and future research needs have been discussed.

Keywords: antibiotics; microbial electrochemical technologies; microbial fuel cells; wastewater treatment



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1. Introduction

Antibiotics are widely used in humans and livestock due to their effectiveness in inhibiting bacterial infection [1,2]. However, only a small portion of consumed antibiotics can be metabolized by the human or animal body [3,4]. The rest is discharged to the environment via domestic and animal wastewater [3,4]. Several studies reported mg/L levels of antibiotics in different wastewater streams, including domestic sewage, livestock wastewater, pharmaceutical industry wastewater, hospital effluents, and so on [3,5]. Such unprecedented levels of antibiotics in wastewater have raised significant public health concerns [1]. In particular, residual antibiotics in the aquatic environment exert selective pressure to propagate antibiotic resistance genes and spread antibiotic-resistant bacteria [1,3]. The overuse and discharge of antibiotics in wastewater have increased the emergence of antibiotic-resistant bacteria at an alarming rate and have caused the death of humans infected with antibiotic-resistant bacteria [6]. Therefore, antibiotic resistance is currently considered the most critical public health threat [7]. As a result, understanding the fate and removal of antibiotics during wastewater treatment, which is regarded as a hotspot for disseminating antibiotic-resistant bacteria, has received significant attention [3,5,8].

To minimize the dissemination and risks of antimicrobial resistance, it is critical to remove antibiotics before discharging treated wastewater to the environment. However, traditional wastewater treatment processes, such as the aerobic activated sludge process, cannot effectively remove antibiotics [9]. To date, different biological and physicochemical treatment processes have been investigated for removing antibiotics from wastewater [2,9–14]. Despite the effective removal of a broad spectrum of antibiotics, most of these methods require external energy input and/or extensive chemical usage or replenishment for their implementation [15]. For instance, advanced oxidation processes (AOPs) are highly effective for antibiotics removal via oxidation to simple molecules or mineralization; however, they require expensive chemicals or catalysts [8,9]. Therefore, there is a growing need for

innovative and low-cost wastewater technologies to effectively remove antibiotics. In this context, microbial electrochemical systems have shown great potential.

Despite different design configurations that have evolved over the years, microbial electrochemical systems usually consist of anode and cathode electrodes, often physically separated by a membrane [16]. Electroactive bacteria on the anode biofilm can capture electrons from the organic substrates in wastewater and transfer them to the electrode surface via a unique extracellular electron transfer (EET) process [17,18]. The transferred electron flows through the external circuit to the cathode, which can be abiotic or biotic depending on the target application. By manipulating the terminal electron acceptors in the cathode, the system can be engineered for high value-added applications, such as bioenergy (e.g., bioelectricity, hydrogen, methane) production or the synthesis of industrial chemicals (e.g., hydrogen peroxide) [19,20]. Thus, microbial electrochemical systems provide simultaneous wastewater treatment and resource recovery. Furthermore, microbial electrochemical systems have been investigated for nutrient recovery [21,22], water desalination [23,24], and biosensing applications [25,26].

Several studies have recently investigated antibiotics removal in microbial electrochemical systems as a stand-alone process [27–31] as well as their integration with constructed wetlands [32–34] and other physicochemical processes, such as advanced oxidation processes [35–37], membrane bioreactors [38], and electrosorption [39]. However, a critical appraisal of these processes is vital to guide their selection to meet target antibiotics removal efficiencies and future development needs. Therefore, this article presents a systematic critical overview of stand-alone and hybrid microbial electrochemical systems for antibiotics removal. Furthermore, the research gaps and future outlook are discussed.

2. Stand-Alone Microbial Electrochemical Systems for Antibiotics Removal

2.1. Process Schemes and Antibiotics Removal Efficiencies

To date, several studies have investigated microbial electrochemical systems as a stand-alone process for antibiotics removal from synthetic wastewater containing acetate, glucose, sucrose, and lactate as carbon sources (Table 1). Most studies used microbial fuel cells (MFCs) (without an external power supply), except for Liang et al. [30], who used a microbial electrolysis cell (MEC) with an external power supply of 0.5 V. Several studies considered comparing their results with open-circuit biotic and/or abiotic reactor having electrodes as control [27–31]. For instance, Wu et al. [29] reported an almost doubled sulfamethoxazole removal in an MFC compared to an open-circuit MFC (i.e., control). Moreover, Yan et al. [27] found negligible removal of oxytetracycline in an abiotic control reactor having electrodes. Thus, these findings highlighted that bio-electrochemical degradation played a major role in removing antibiotics in stand-alone microbial electrochemical systems. Furthermore, previous studies have revealed that syntrophic interactions between electroactive bacteria and antibiotic-degrading bacteria would play a critical role in effective antibiotics removal in microbial electrochemical systems [40,41].

Figure 1 summarizes different process schemes studied for antibiotics removal with stand-alone MFCs. Both single- and dual-chamber MFCs have been used in previous studies (Table 1), while most were dual-chamber configurations. The maximum removal efficiencies for different antibiotic compounds ranged from 59.4% to 100%. To the best of the authors' knowledge, no studies systematically compared single- and dual-chamber designs to date. However, depending on the type of antibiotics, both single- and dual-chamber configurations could provide up to 99–100% removal (see Table 1), suggesting that MFCs as a stand-alone process could effectively remove certain antibiotics from wastewater. Single-chamber configuration would reduce the reactor fabrication cost and maintenance requirement due to the exclusion of membrane [42,43]; thus, it would be preferred over the dual-chamber design. However, further confirmation of the effectiveness of single-chamber configuration for removing a broad spectrum of antibiotics is still warranted due to a limited number of studies.

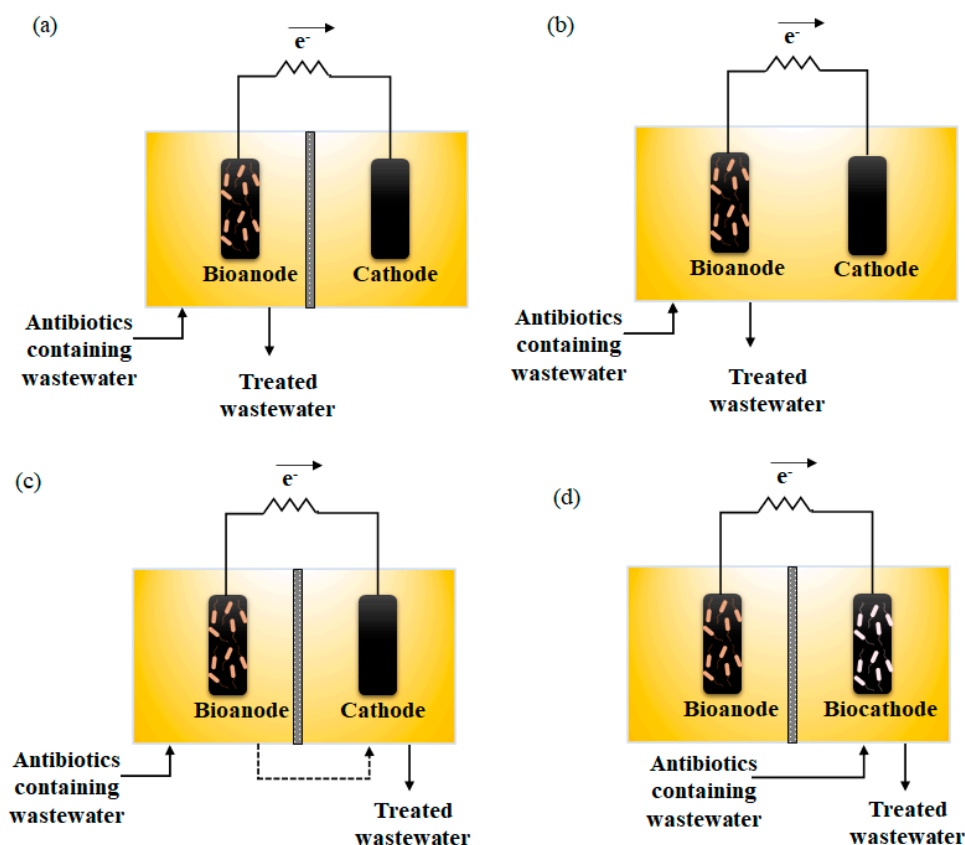


Figure 1. Different process schemes studied for antibiotics removal in MFCs: (a) dual-chamber MFC, (b) single-chamber MFC, (c) sequential anode–cathode operation in a dual-chamber MFC, and (d) biocathode operation in a dual-chamber MFC.

In dual-chamber configurations, antibiotics removal primarily occurs in the bioanode, while a few studies investigated treatment options with a biocathode or a sequential anode–cathode operation [15,30,31,41,44]. The major benefit of biocathode-based treatment is faster antibiotic degradation than bioanode or abiotic cathode-based treatment [15,30,41]. For instance, Sun et al. [15] found that biocathode-based treatment could provide 3.2 times faster degradation of chloramphenicol than the abiotic cathode. Chen et al. [44] found that a biocathode could provide a slightly higher removal of oxytetracycline than a bioanode (95% vs. 91.8%). Furthermore, Cheng et al. [31] recently reported that the sequential anode–cathode mode (see Figure 1c) could effectively remove residual antibiotics from anodic effluent. Therefore, future studies should systematically compare different process schemes to select an optimum approach for antibiotics removal.

2.2. Process Parameters

Previous studies have primarily focused on investigating the removal efficiencies of different antibiotic compounds and the effects of their initial concentrations (Table 1). However, a few studies have also focused on other process parameters, such as pH, temperature, and biofilm acclimatization [27,28,40]. Among 10+ antibiotic compounds researched in different studies (see Table 1), only a few of them (e.g., sulfamethoxazole, oxytetracycline, chlortetracycline, chloramphenicol, sulfadiazine, and tetracycline) have been studied multiple times. While most investigated removal of a single antibiotic compound, a few studies compared removal efficiencies of multiple antibiotics [31,45–47].

Previous studies have suggested that removal efficiencies would be different depending on the type of antibiotics. Zhou et al. [47] studied the removal efficiencies of four antibiotics (aureomycin, sulfadimidine, roxithromycin, and norfloxacin) belonging to dif-

ferent chemical classes in a single-chamber MFC. The authors found that all antibiotics could be effectively degraded (99.9–100% removal). Cheng et al. [31] studied the removal efficiencies of three antibiotics (sulfamethoxazole, sulfamethazine, and sulfadiazine) that belong to the same class (sulfonamide). Their results suggested that sulfamethoxazole could be degraded more easily than sulfamethazine and sulfadiazine. The removal efficiency of sulfamethoxazole was as high as 59.4%, while the maximum removal efficiencies of sulfamethazine and sulfadiazine were <20%. Thus, antibiotics under the same classes could exhibit different removal efficiencies. Wang et al. [48] also suggested slight differences in removal efficiencies for two tetracycline antibiotics (chlortetracycline and oxytetracycline).

The initial concentrations of antibiotics in wastewater have shown considerable impact in several studies [27,41,49–51]. In general, removal efficiencies decreased after increasing initial concentrations of antibiotics to certain levels. For instance, Catal et al. [49] reported 88% removal of neomycin sulfate for an initial concentration of 20 mg/L, while removal efficiency considerably decreased after increasing the initial concentration to 75 mg/L. Furthermore, several studies reported a negative impact of higher initial antibiotics concentrations on MFC performance (i.e., energy output in terms of voltage or current) [46,52]. Thus, high antibiotic concentrations in wastewater may impede MFC performance in terms of antibiotics removal and energy output.

However, Yan et al. [27] suggested that long-term acclimation with gradually increasing antibiotic concentration could establish a more resilient and kinetically efficient anode biofilm in MFCs for antibiotics removal. The authors slowly increased oxytetracycline concentrations in the influent from 0.5 to 10 mg/L over ten months, achieving up to 99% removal at an initial oxytetracycline concentration of 10 mg/L. Notably, such long-term acclimation enriched *Eubacterium* species, a functional bacterial genus responsible for oxytetracycline degradation. Miran et al. [28] also found that acclimatized cultures in MFC could provide higher sulfamethoxazole removal than unacclimatized cultures. Furthermore, voltage generation was unaffected despite increasing sulfamethoxazole concentration from 0.04 to 0.20 mM. MFC inoculated with acclimatized cultures showed a higher abundance of *Thauera* species that have been reported to be capable of antibiotic degradation and adaptive to the antibiotic pressure in the literature [3,53].

Table 1. Summary of studies using microbial electrochemical systems as a stand-alone process for antibiotics removal from wastewater.

Antibiotic (Initial Concentration)	Wastewater (WW)	System Design	Maximum Removal Efficiency	Remarks/Key Findings	Ref.
Sulfamethoxazole (100 µg/L), Sulfamethazine (100 µg/L), and Sulfadiazine (100 µg/L)	Synthetic swine wastewater (glucose)	Dual chamber MFC	59.4% (Sulfamethoxazole)	The removal efficiencies of sulfadiazine (16.8–19.5%) and sulfamethazine (14.0–16.3%) were relatively lower than sulfamethoxazole. Moreover, the sequential anode–cathode operation was more efficient than the single (anode) continuous mode.	[31]
Oxytetracycline (12.5–16.5 mg/L)	Synthetic WW (glucose)	Dual chamber MFC	95%	Dual graphene-modified bioelectrode was developed for more efficient oxytetracycline removal.	[44]
Sulfamethoxazole (100 µg/L), Sulfamethazine (200 µg/L), and Sulfadiazine (300 µg/L)	Synthetic swine wastewater	Dual chamber MFC	99% (Sulfamethoxazole)	The removal efficiencies of sulfadiazine (13.39–66.91%) and sulfamethazine (32.84–67.21%) were relatively low.	[45]

Table 1. Cont.

Antibiotic (Initial Concentration)	Wastewater (WW)	System Design	Maximum Removal Efficiency	Remarks/Key Findings	Ref.
Tobramycin (0.1–1.9 g/L)	Synthetic WW (acetate)	Single chamber MFC	-	Anode biofilm was resilient against antibiotics in µg/L level but was sensitive to g/L level (inhibition ratio increased with increasing concentrations).	[52]
Neomycin sulfate (20–100 mg/L)	Synthetic WW (glucose)	Single chamber MFC	88% (20 mg/L)	Antibiotic degradation efficiency decreased with increasing initial concentration.	[49]
Sulfamethoxazole (0.04–0.79 mM)	Synthetic WW (lactate)	Dual chamber MFC	83.3%	Acclimatized biofilm showed better removal efficiency than unacclimatized one (70.1% vs. 83.3%).	[28]
Sulfamethoxazole (10–30 mg/L)	Synthetic WW (acetate)	Single chamber MFC	96.1%	>85.1% removal efficiency achieved within 60 h.	[54]
Norfloxacin (4–128 mg/L)	Synthetic WW (acetate)	Single chamber MFC	65.5% (4 mg/L)	Removal efficiencies decreased with increasing initial concentration (e.g., 48.4% removal with 128 mg/L).	[50]
Chlortetracycline and Oxytetracycline (10–60 mg/L)	Synthetic WW (glucose)	Dual chamber MFC	78%	Higher degradability was observed for oxytetracycline (78% vs. 74.2%).	[48]
Sulfamethoxazole (20 mg/L)	Synthetic WW (acetate)	Dual chamber MFC	98%	Compared to an open circuit control, removal efficiency almost doubled (47% vs. 98%). Moreover, sulfamethoxazole increased power density by 18.09%.	[29]
Ampicillin (10–25 mg/L)	Synthetic WW (sucrose)	Dual chamber MFC	86% (10 mg/L)	Here, 25 mg/L negatively affected MFC performance and decreased removal efficiency of ampicillin.	[51]
Tetracycline, Chlortetracycline, and Oxytetracycline (0.25–50 mg/L)	Synthetic WW (acetate)	Dual chamber MFC	-	Increasing concentrations negatively affected MFC performance; chlortetracycline showed the highest toxicity among the three antibiotics tested.	[46]
Aureomycin (3–45 µg/L), Sulfadimidine (2–30 µg/L), Roxithromycin (1.2–18 µg/L), and Norfloxacin (1.2–18 µg/L)	Synthetic animal wastewater (glucose)	Single chamber MFC	99.9–100%	After adding antibiotics, MFC voltage dropped from 0.51 V to 0.41 V. Inhibition intensity was ordered as sulfadimidine > aureomycin > roxithromycin > norfloxacin	[47]
Oxytetracycline (0.5–10 mg/L)	Synthetic WW (acetate)	Dual chamber MFC	99% (10 mg/L)	Long-term (10 months) acclimation improved antibiotics removal efficiency.	[27]
Tetracycline (2–30 mg/L)	Synthetic WW (acetate)	Dual chamber MFC	90% (10 mg/L)	Biocathode operation provided effective degradation of tetracycline than aerobic treatment.	[41]

Table 1. Cont.

Antibiotic (Initial Concentration)	Wastewater (WW)	System Design	Maximum Removal Efficiency	Remarks/Key Findings	Ref.
Chloramphenicol (100–200 mg/L)	Synthetic WW (acetate)	Dual chamber MFC	96.53%	pH, temperature, and initial antibiotic concentration had a significant impact; pH of 7.12, the temperature of 31.48 °C, and the initial chloramphenicol concentration of 106.37 mg/L were optimum.	[40]
Chloramphenicol (32 mg/L)	Synthetic WW (glucose)	Dual chamber MEC (0.5 V)	96%	Biocathode could provide higher removal efficiencies than abiotic cathode (96% vs. 73%).	[30]
Chloramphenicol (30 mg/L)	Synthetic WW (glucose)	Dual chamber MFC	-	Biocathode could provide 3.2 times higher antibiotics removal rate than abiotic cathode.	[15]
Tetracycline (10–50 mg/L)	Synthetic WW (glucose)	Dual chamber MFC	79.1%	Compared to traditional anaerobic treatment, MFC was more effective in tetracycline removal.	[55]
Sulfadiazine (10 mg/L)	-	Dual chamber MFC	100%	After acclimation of biofilms, >80% of sulfadiazine could be removed in 24 h.	[56]

3. Hybrid Microbial Electrochemical Systems for Antibiotics Removal

3.1. Constructed Wetland–Microbial Fuel Cell (CW-MFC)

Constructed wetlands (CWs) are nature-based wastewater treatment processes that can provide cost-effective and adequate removal of various environmental pollutants [57–59]. CWs simultaneously combine multiple mechanisms for pollutants removal, including photodegradation, biodegradation, plant uptake, filtration, sorption, and phytoremediation [57]. CWs are often considered as a low-cost stand-alone alternative to conventional treatment processes, particularly in areas not limited by land availability [57,59]. For instance, CWs can be a feasible option for wastewater generated from livestock farms as well as agro-industrial sources in remote locations [59]. Both lab and field-scale studies demonstrated effective antibiotics removal using conventional CWs [10,57,60]. Notably, the literature has highlighted that CWs can provide more effective removal of antibiotics than conventional wastewater treatment processes [57]. Several studies have demonstrated that MFCs could be coupled with CWs to further improve their effectiveness for pollutants removal along with energy recovery opportunities [61,62]. Design-wise, CWs consist of upper aerobic and lower anaerobic zones, similar to typical aerobic and anaerobic chambers of MFCs [61]. Systems combining CWs and MFCs are called constructed wetland-microbial fuel cell (CW-MFC), where anode and cathode electrodes of an MFC are embedded within CW [61]. Many studies demonstrated the effectiveness of CW-MFCs for removing various recalcitrant and hazardous pollutants from wastewater, such as dyes, salts, antibiotics, personal care products, pesticides, etc. [61,62]. Furthermore, the integration of MFCs with CWs was reported as a promising approach for mitigating methane emissions from CWs [63,64].

Despite that only limited studies have focused on the application CW-MFCs from antibiotics removal from wastewater (see Table 2), it has still been the most examined hybrid microbial electrochemical system studied for antibiotics removal. In addition to demonstrating the superior removal efficiencies for various antibiotics with hybrid CW-MFC systems over conventional CWs, previous studies investigated the effective electrode materials [65], and the significance of various process parameters [32–34]. To date, CW-MFCs have been assessed to remove sulfamethoxazole, sulfadiazine, ciprofloxacin, and tetracycline from synthetic wastewater (see Table 2). Most studies used vertical up-flow

CW-MFCs (Figure 2). To the best of our knowledge, Zhang et al. [66] first demonstrated the feasibility of using a CW-MFC system for tetracycline and sulfamethoxazole removal from synthetic wastewater over a period of 6 months. Their results demonstrated that tetracycline could be more effectively degraded than sulfamethoxazole; however, effluent antibiotic concentrations remained below $<2.5 \mu\text{g/L}$ for a wide range of influent antibiotic concentrations (400–1600 $\mu\text{g/L}$). Granular activated carbon (GAC) particles were used as electrode materials in their study, while antibiotic adsorption onto GAC has been reported in the literature [67]. However, their study did not provide any control test results for systematic comparison between CW and CW-MFC systems. Recently, Dai et al. [68] compared the performance of CW and CW-MFCs for sulfamethoxazole (4 mg/L) removal from synthetic wastewater. Based on their results, CW-MFC could provide higher removal of sulfamethoxazole (82.37 vs. 71.32%) than a control CW. Furthermore, Song et al. [34] compared sulfadiazine removal efficiencies of CW-MFCs under open and closed circuit operation. Their results showed that sulfadiazine concentrations in the effluent of CW-MFCs operating under an open-circuit condition were relatively higher than the closed-circuit operation, demonstrating the significant contribution of anodic microbial oxidation in antibiotics removal. However, some antibiotics could still be adsorbed by the electrodes under an open-circuit condition [67]. Notably, understanding the relative contribution of anodic microbial oxidation, adsorption by electrodes, and other mechanisms associated with CWs would be necessary for further system optimization from an energy recovery perspective. Furthermore, antibiotics adsorbed onto the electrodes may contribute to selective pressure for ARG proliferation and eventually increase ARG transmission risks [69].

Table 2. Summary of studies related to constructed wetland coupled with microbial fuel cell (CW-MFC) for antibiotics removal from wastewater.

Antibiotic (Initial Concentration)	Carbon Source	Key Findings	Ref.
Sulfadiazine (4 mg/L)	Glucose	<ul style="list-style-type: none"> - Up-flow CW-MFCs were assessed under two HRT (1.5 and 3 days) and two circuit operation modes (open and closed). - Closed-circuit mode and a high HRT provided relatively higher antibiotics removal. - Both adsorption and biodegradation contributed to antibiotics removal in CW-MFCs. 	[34]
Tetracycline and Sulfamethoxazole (400–1600 $\mu\text{g/L}$)	Glucose	<ul style="list-style-type: none"> - Effluent antibiotics concentrations were $<2.5 \mu\text{g/L}$ under all conditions. - Power density decreased when antibiotic concentration increased from 400 to 1600 $\mu\text{g/L}$. 	[66]
Sulfadiazine (2 mg/L) and Ciprofloxacin (2 mg/L)	Glucose	<ul style="list-style-type: none"> - The average sulfadiazine and ciprofloxacin removal efficiencies were 80% and 90%, respectively. 	[63]
Sulfadiazine (2 mg/L) and Ciprofloxacin (2 mg/L)	Glucose	<ul style="list-style-type: none"> - Exposure of antibiotics and Zn on antibiotic resistance genes (ARGs) profiles was assessed. - A low level of Zn could enrich ARGs, while excessive Zn could inhibit ARG proliferation. 	[33]

Table 2. Cont.

Antibiotic (Initial Concentration)	Carbon Source	Key Findings	Ref.
Sulfamethoxazole (5–100 µg/L), Tetracycline (5–50 µg/L)	Glucose	- Almost complete removal of antibiotics was achieved at an HRT of 1 day. CW-MFCs with plant and circuit-circuit operation showed the highest antibiotics removal.	[32]
Sulfamethoxazole (4 mg/L)	Glucose	- CW-MFC could provide higher removal of antibiotics than a control CW (82.37 vs. 71.32%). - Sulfamethoxazole resistance gene copy number was much lower for CW-MFC, indicating a lower risk of ARG transmission due to the integration of an MFC.	[68]
Sulfamethoxazole (100 µg/L), Tetracycline (50 µg/L)	Glucose	- The addition of sponge iron (s-Fe ⁰) and calcium peroxide could improve antibiotics removal in CW-MFC. - Furthermore, s-Fe ⁰ could improve ARGs removal.	[69]
Sulfamethoxazole (60 µg/L), Tetracycline (25 µg/L)	Glucose, Sucrose, Starch, Acetate	- Glucose as a carbon source provided the highest antibiotics removal. - Providing external aeration on the cathode enhanced the performance of CW-MFCs.	[70]

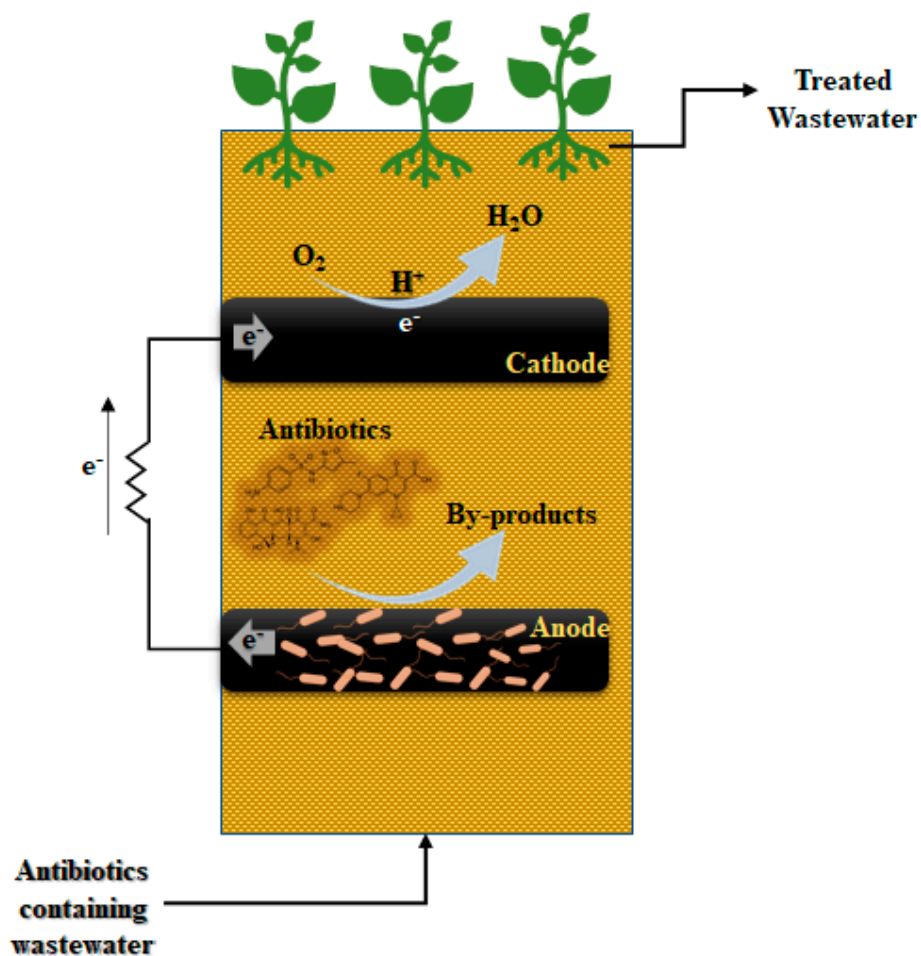


Figure 2. Schematic of an up-flow CW-MFC for removal of antibiotics from wastewater.

Furthermore, Wen et al. [32] examined the roles of plants and open vs. closed circuit operation on antibiotics removal in CW-MFCs. Their results demonstrated that both plant

and closed-circuit operation contributed to removing sulfamethoxazole (5–100 µg/L), tetracycline (5–50 µg/L). At an HRT of 1 day, removal efficiencies were >99% for both antibiotics. However, the closed-circuit operation had a more significant impact on antibiotics removal than the plants. The authors suggested that the plant might increase oxygen levels on the cathode, thereby improving performance. Wen et al. [70] also found that external aeration in the cathode can enhance antibiotics removal in CW-MFCs. However, providing external aeration can be expensive. Therefore, Wen et al. [69] proposed adding calcium peroxide in the cathode of CW-MFCs for improving dissolved oxygen (DO) levels to enhance antibiotics removal. Calcium peroxide is known for oxygen releasing capacity and has been widely used in recalcitrant pollutants removal in water and soil [71]. Therefore, such an approach could serve as an alternative to the conventional energy-intensive aeration method.

A few studies have also focused on developing or modifying electrodes to improve antibiotics removal in CW-MFCs [65,69]. Wen et al. [65] found that the amendment of a GAC-based anode electrode with sponge iron (s-Fe⁰) can further intensify the antibiotics removal efficiencies of CW-MFCs. Based on the literature, sponge iron (also known as direct reduced iron) can facilitate the electrochemical synthesis of ferrate(VI), which can oxidize antibiotics [72]. Wen et al. [65] also found that adding sponge iron could reduce antibiotics (sulfamethoxazole and tetracycline) accumulation on the cathode, consequently decreasing ARG abundance. Sponge iron is a cheap by-product found in steel plants [72]; thus, such an approach can provide an affordable solution to enhance CW-MFC performance for antibiotics removal.

Li et al. [65] compared graphite and manganese (Mn) ore media as electrodes for CW-MFCs for antibiotics removal. As Mn ores are composed of manganite and ferric oxides [73], the authors hypothesized that such electrode material could enhance anodic oxidation by electroactive bacteria. Furthermore, manganese oxide (MnO₂), a powerful oxidant with adsorptive capability [74], can contribute to antibiotics removal. Conversely, graphite was selected for its high adsorptive capacities and electrical conductivity. The authors found that a graphite-based electrode could provide superior sulfadiazine removal due to its high adsorption capacity, while both systems efficiently removed ciprofloxacin. In contrast, Mn ore electrode exhibited higher voltage generation than graphite. Moreover, the estimated cost of Mn ore electrode was ~18 times lower than graphite (based on per m³ anodic chamber). Thus, the type of antibiotics in incoming wastewater should be carefully considered in selecting optimum electrode materials for CW-MFCs.

3.2. Microbial Electrochemical Systems Coupled with Other Physicochemical Processes

In addition to slow biodegradation kinetics, some antibiotics may be highly recalcitrant to biodegradation. Furthermore, biodegradation may often lead to the formation of refractory intermediates. As shown in Table 3, several studies proposed the integration of microbial electrochemical technologies with advanced physicochemical processes, such as advanced oxidation process (AOP), membrane, and electrosorption, to achieve high antibiotics removal efficiencies (88.73–98.8%).

Particularly, integrating the electro-Fenton process as an AOP with microbial electrochemical systems has been investigated by multiple studies for the degradation and mineralization of antibiotics [35–37]. Briefly, the Fenton process uses a mixture of hydrogen peroxide (H₂O₂) and ferrous iron (Fe²⁺) to produce hydroxyl radicals (·OH) that can oxidize recalcitrant environmental pollutants, including antibiotics [75]. However, storage and transportation of H₂O₂ can often be challenging. The electro-Fenton process can be used for the on-site synthesis of H₂O₂ from the cathodic two-electrode reduction of dissolved oxygen in electrochemical cells [20,76]. Combining microbial electrochemical systems can provide a sustainable option for powering the electro-Fenton process. Such hybrid systems are called the bio-electro-Fenton (BEF) process (see Figure 3) [20,35]. Wang et al. [35] demonstrated a BEF process with a γ-FeOOH graphene polyacrylamide carbonized aerogel cathode for in situ removal of sulfamethoxazole and norfloxacin in wastewater sludge. Their study showed that both antibiotics could be effectively removed under neutral pH

from both aqueous and solid phases, despite differences in their different absorbability. Sulfamethoxazole has moderate sorption ability to sludge, while norfloxacin can be highly adsorbed to sludge. The authors found that the BEF process could accelerate the desorption of antibiotics from sludge to the aqueous phase; thus, most antibiotics (79.9–86.6%) could be removed primarily by $\cdot\text{OH}$ radicals. Li et al. [36] reported that the BEF process could provide effective removal of a low concentration of erythromycin (50 $\mu\text{g}/\text{L}$), and associated resistance genes (*erm*).

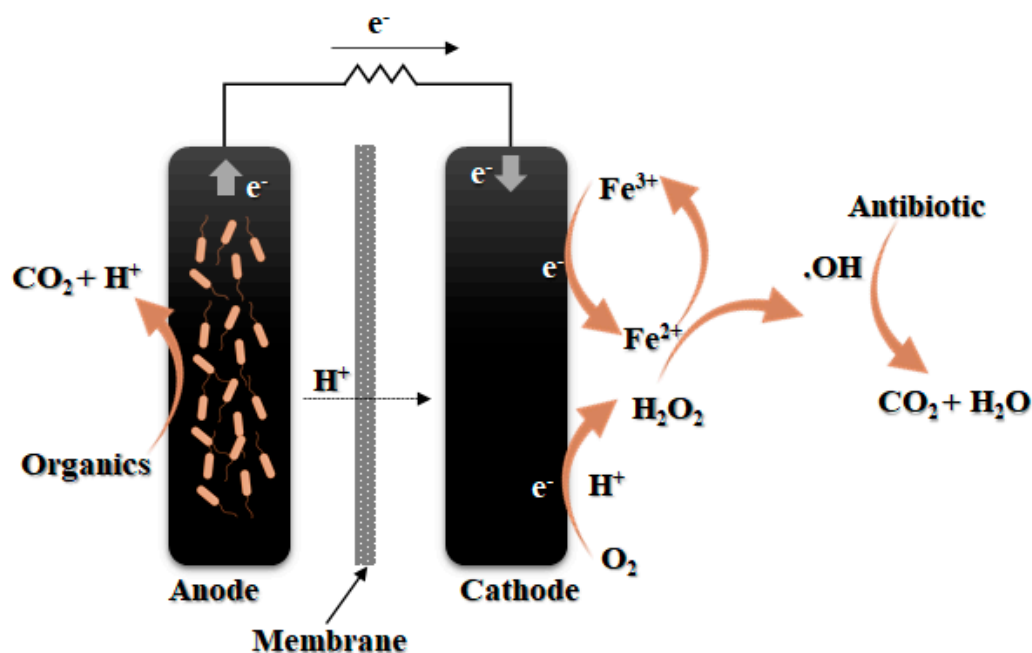


Figure 3. Schematic of a bio-electro-Fenton (BEF) process for antibiotics removal.

Li et al. [38] developed a hybrid membrane bioreactor (MBR) integrated with MFC having a conductive membrane cathode, and demonstrating up to 90% removal of tetracycline. The membrane cathode was fabricated with polyvinylidene fluoride (PVDF) coated carbon fiber cloth and was further expanded with a dynamic granular activated carbon (GAC) cathode doped with $\text{FeOOH}/\text{TiO}_2$, which could catalyze in situ electro-generation of H_2O_2 for Fenton-like oxidation. The vertical design of their reactor (anode at the top and cathode at the bottom) enabled permeate generation through the conductive cathode membrane by gravity, indicating an attractive energy-saving option (i.e., no requirement of pumping). Furthermore, over 60 days of operation membrane showed negligible fouling, possibly due to the generation of H_2O_2 [77] as well as electric field [78]. However, the authors operated the system with synthetic wastewater (glucose) containing tetracycline. Therefore, further investigation with real wastewater containing antibiotics is warranted for such promising designs.

In addition to the direct removal of antibiotics, MFCs can also be used to serve as energy suppliers for the electrosorption (ES) process for antibiotics removal (see Figure 4). Electrosorption is considered as an efficient adsorption method for removing heavy metals, salinity, organic pollutants, pharmaceuticals, personal care products, and (nano)microplastics [79–81]. The major benefits of electrosorption include a lack of secondary pollutants generation and flexible electrode regeneration by applying reverse voltage or removing voltage [39,82]. Due to the application of a low voltage between the anode and the cathode, charged ions or polar molecules (i.e., target pollutants) can migrate to the counter-charged electrode, accumulating an electric double layer on the electrode surface [80,82]. However, the operation of electrosorption requires electrical energy input for its operation. To the best of the authors' knowledge, Yang et al. [39] first demonstrated that MFCs could generate adequate energy output to enable the operation of

continuous-flow electrosorption for tetracycline removal. The authors found that connecting multiple MFCs would be necessary to attain high adsorption capacity. For instance, compared to a single MFC, connecting three MFCs in series could considerably increase tetracycline adsorption capacity from 14.16 to 23.12 mg/g. However, adsorption capacity did not increase linearly with an increasing number of MFCs, which could be attributed to voltage reversal during the operation of MFCs in series. Zhao et al. [82] also demonstrated that electrical energy generated by MFCs could be utilized for running continuous-flow electrosorption for oxytetracycline removal. Furthermore, effluent from the electrosorption process could be further treated with MFCs to remove residual oxytetracycline (see Figure 4), providing up to 98.8% removal for an initial antibiotic concentration of 2 mg/L. However, at a higher initial antibiotic concentration of 10 mg/L, removal efficiency decreased to 76.3%, which was primarily caused by the decline in removal efficiency in the electrosorption unit due to enhanced competition between antibiotics molecules for active sites at higher concentrations. In contrast, the performance of MFCs was unaffected by the increase in oxytetracycline concentration from 2 to 10 mg/L. Thus, in addition to being an energy supplier, MFCs could provide additional benefits by treating electrosorption effluent. Nonetheless, Yang et al. [39] emphasized that pH would be a critical factor for the electrosorption process, which could pose concerns for the operation of MFCs. Depending on the pK_a values of the target antibiotic, acidic pH may be necessary to achieve efficient electrosorption. For instance, for $pH < 3.3$, tetracycline would exist in the form of protonated tetracycline (TCH_3^+), which can easily be combined with the negative charge on the electrode surface, facilitating cation exchange for adsorption [39]. In contrast, neutral or alkaline pH may decrease the electrosorption of tetracycline. Therefore, adjusting pH to the acidic condition may be required for effective electrosorption. However, treating acidic effluent from the electrosorption process using MFC would be challenging, as acidic pH may inhibit the activity of electroactive bacteria in an anode biofilm [83].

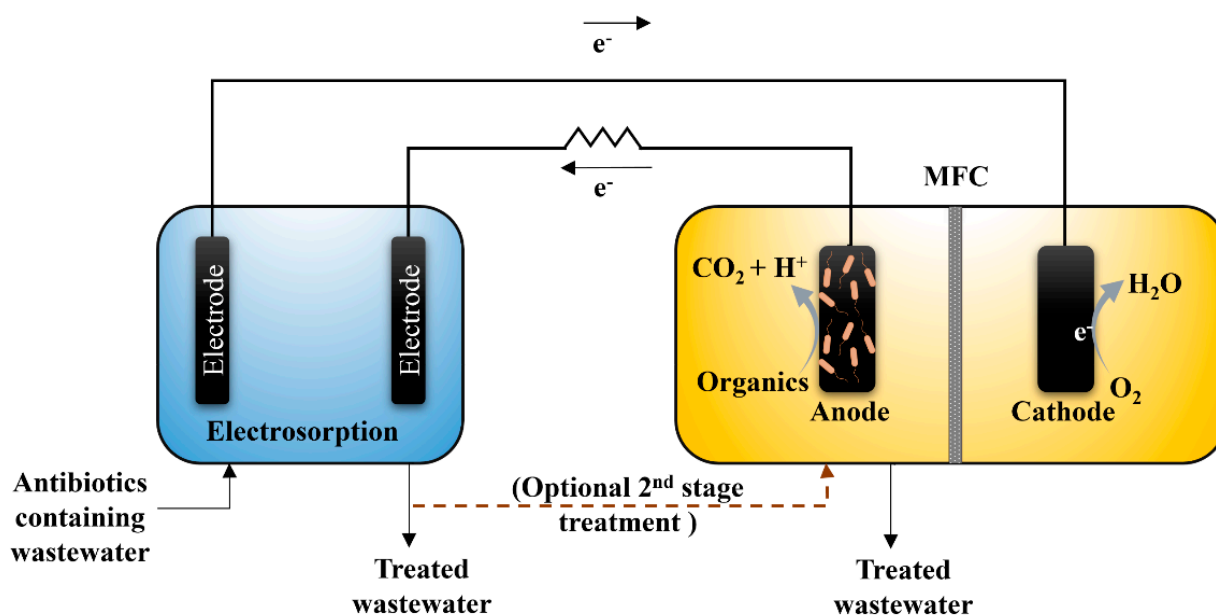


Figure 4. Schematic of hybrid process coupling electrosorption and MFCs.

Table 3. Hybrid MFCs coupled with advanced physicochemical processes.

Physicochemical Processes	Antibiotic (Initial Concentration)	Wastewater (WW)	Maximum Removal Efficiency	System Description	Ref.
AOP	Sulfamethoxazole and Norfloxacin	Sludge	97.4% (Sulfamethoxazole), 96.1% (Norfloxacin)	A sediment-type BEF process was developed using γ -FeOOH graphene polyacrylamide carbonized aerogel (γ -FeOOH GPCA) cathode.	[35]
AOP	Erythromycin (50 μ g/L)	Synthetic WW (acetate)	88.73%	A BEF system was developed using a carbon nanotube (CNT)/ γ -FeOOH cathode.	[36]
AOP	Metronidazole (80 mg/L)	Synthetic WW (acetate)	94.5%	A photo-assisted BEF process was developed with Mo-W catalytic cathodes to intensify cathodic reduction under anaerobic conditions and oxidation under aerobic conditions.	[37]
Membrane	Tetracycline hydrochloride	Synthetic WW (Glucose)	90%	An integrated MBR/MFC was developed with membrane cathode expanded with TiO ₂ /FeOOH doped GAC.	[38]
Electrosorption	Tetracycline (20–100 mg/L)	Synthetic WW (Glucose)	93.16%	Electricity generated by MFCs was used to operate an electro-sorption (ES) system.	[39]
Electrosorption	Oxytetracycline (2–10 mg/L)	Synthetic WW (acetate)	98.8% (2 mg/L)	An electro-sorption (ES) system followed by MFCs was proposed for a two-stage treatment scheme, where MFCs powered the ES system and treated the ES effluent.	[82]

4. Summary and Outlook

To date, microbial electrochemical systems have been studied to remove around 17 antibiotic compounds (Figure 5). The most widely investigated compounds were sulfamethoxazole, tetracycline, sulfadiazine, and oxytetracycline. About half of the compounds were only studied in stand-alone single or dual-chamber MFCs. In contrast, a few compounds (sulfadiazine, ciprofloxacin, erythromycin, and metronidazole) were examined in hybrid systems. Previous research has studied only a handful of these compounds (sulfamethoxazole, tetracycline, oxytetracycline, and norfloxacin) in both stand-alone and hybrid systems. Thus, limited information is available in the literature to establish a systematic comparison between stand-alone and hybrid microbial electrochemical systems for antibiotics removal. It was apparent that most of the antibiotic compounds could be efficiently degraded in stand-alone MFCs (Figure 6). Some antibiotics (ciprofloxacin, erythromycin, and metronidazole) were effectively degraded in hybrid systems (e.g., CW-MFCs, BEF), while they have not been studied in stand-alone MFCs (Figure 5). Thus, further studies will clearly be needed to identify if these antibiotics can be adequately degraded in stand-alone MFCs. Moreover, among stand-alone MFCs, systematic studies to compare single- and dual-chamber MFCs are also required.

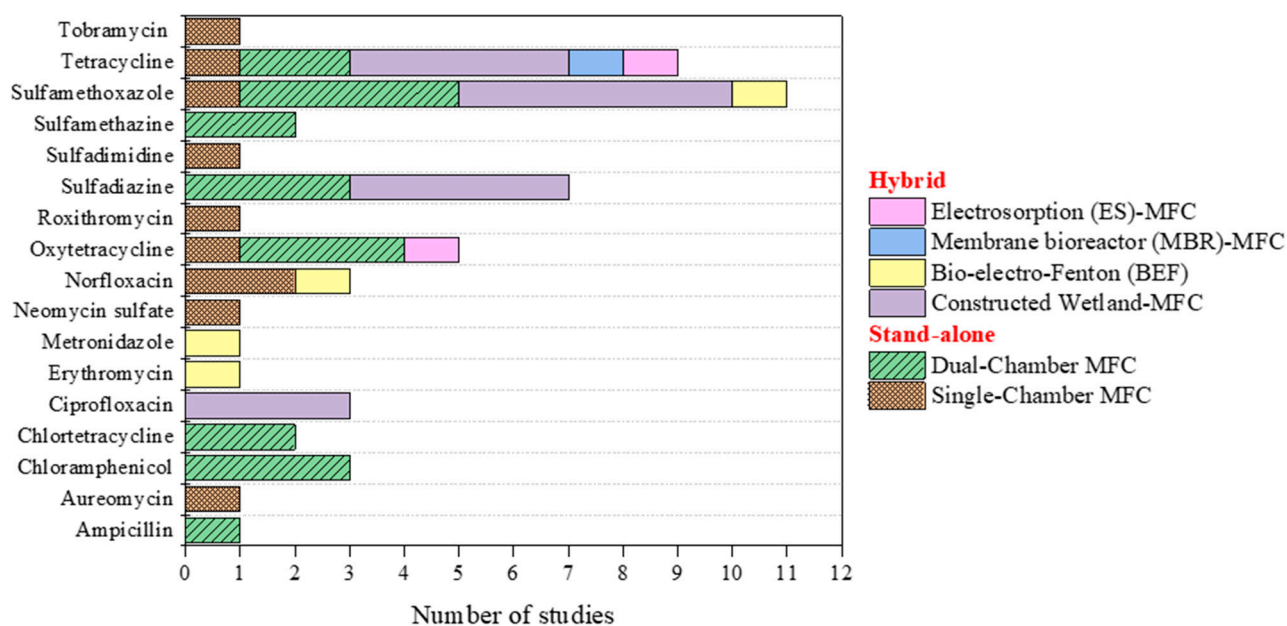


Figure 5. Different antibiotics studied in stand-alone and hybrid microbial electrochemical systems (based on the references shown in Tables 1–3).

Initial antibiotics concentrations widely varied in previous studies (see Tables 1–3), which would be a critical factor influencing their removal efficiencies [27,41,49–51]. Higher initial antibiotics concentrations could evidently deteriorate the performance of microbial electrochemical systems and antibiotics removal efficiencies [46,49,52]. Nonetheless, most antibiotics were efficiently degraded ($\geq 90\%$) in microbial electrochemical systems except for chlortetracycline and sulfamethazine (Figure 6). Chlortetracycline and sulfamethazine were only studied in dual-chamber MFCs [31,45,46,48]. It has been previously reported that these antibiotic compounds are highly persistent and difficult to biodegrade [84–86]. Among various tetracycline derivatives, chlortetracycline has been identified to be the most toxic [84]. Notably, its toxicity can be 100 times higher than sulfamethazine [87]. Topcu et al. [46] also reported that chlortetracycline showed the highest toxicity to anode biofilms among the three antibiotics (tetracycline, chlortetracycline, and oxytetracycline) tested in their study. Thus, stand-alone MFCs may not be highly effective for removing persistent and toxic antibiotics. Previous studies have suggested that Fenton-based AOPs might be required to effectively remove persistent antibiotics such as chlortetracycline and sulfamethazine [86,88,89]. Therefore, hybrid microbial electrochemical systems such as BEF should be investigated to remove such persistent antibiotics (e.g., chlortetracycline, sulfamethazine, etc.). Overall, it can be summarized that both stand-alone and hybrid microbial electrochemical systems can be technically viable for removing antibiotics from wastewater. However, the selection between stand-alone and hybrid processes should be between the type of antibiotics present in the wastewater.

The key features highlighted for microbial electrochemical systems often lie in energy and resource recovery. Despite demonstrating the technical feasibility of various microbial electrochemical systems, results from lab-scale studies may not provide a clear picture of the energy/resource recovery potential [90]. Until now, almost all studies have used synthetic wastewater containing antibiotics (see Tables 1–3), while future research should focus on testing antibiotics removal from real wastewater followed by in-depth techno-economic analysis. Moreover, scale-up remains an ongoing challenge towards the commercialization of microbial electrochemical technologies [91–94]. The field-pilot of different microbial electrochemical technologies has been limited [90,94]. However, there have been some encouraging reports. A report was recently published on the successful demonstration of a pilot-scale (1400 L) single-chamber MFC [94]. The integration of MFC with a biofilter

could reduce energy consumption by more than 50% compared to conventional wastewater treatment [94]. Another study demonstrated a pilot-scale (100 L) microbial electrochemical system for cathodic H_2O_2 generation [95]. Although the system could not generate concentrated H_2O_2 , the results suggested that the concentration should be adequate for in situ oxidation of pollutants, such as applications as the cathodic Fenton process (i.e., BEF). A process quite similar to CW-MFCs (called METland[®]) has recently been demonstrated in Spain and Denmark to treat wastewater generated from small communities [96,97]. METland[®] could effectively remove (>90%) sulfamethoxazole from wastewater [98]. Given these promising developments, the possible implementation of microbial electrochemical systems for antibiotics removal is likely for years to come.

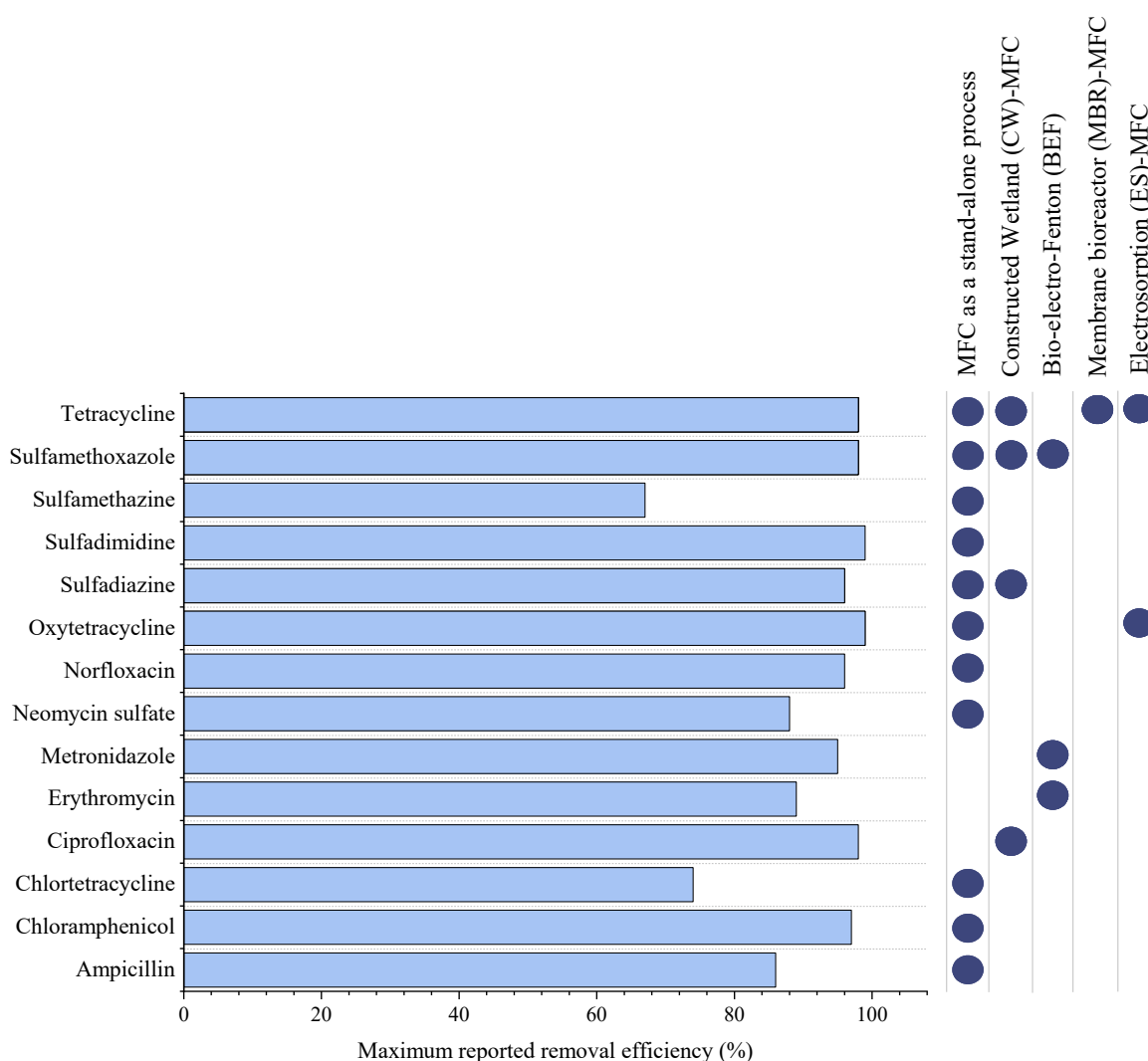


Figure 6. Maximum reported removal efficiencies of different antibiotics and corresponding microbial electrochemical systems used for treatment (based on the references shown in Tables 1–3).

5. Conclusions

This review summarized the application of microbial electrochemical systems for antibiotics removal from wastewater. Both stand-alone and hybrid microbial electrochemical systems hold great potential for antibiotics removal; however, significant research gaps appear as the unavailability of their systematic comparison. Nonetheless, it seemed that most antibiotics could be effectively removed in stand-alone MFCs, while persistent and toxic antibiotics may require hybrid or integrated systems. However, only a limited number of antibiotic compounds have been investigated thus far; therefore, further investigation needs to be expanded to more persistent and toxic antibiotics. In addition, the studies primarily

used synthetic wastewater, while a complex matrix of actual wastewater may influence removal efficiencies and energy output. Therefore, comprehensive environmental and cost-benefit analysis and efficient system design are needed before field implementation of microbial electrochemical systems for antibiotics removal from wastewater.

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References

1. Michael, I.; Rizzo, L.; McArdell, C.S.; Maniaia, C.M.; Merlin, C.; Schwartz, T.; Dagot, C.; Fatta-Kassinos, D. Urban wastewater treatment plants as hotspots for the release of antibiotics in the environment: A review. *Water Res.* **2013**, *47*, 957–995. [[CrossRef](#)]
2. Cheng, D.; Ngo, H.H.; Guo, W.; Chang, S.W.; Nguyen, D.D.; Liu, Y.; Zhang, X.; Shan, X.; Liu, Y. Contribution of antibiotics to the fate of antibiotic resistance genes in anaerobic treatment processes of swine wastewater: A review. *Bioresour. Technol.* **2020**, *299*, 122654. [[CrossRef](#)]
3. Zhao, R.; Feng, J.; Liu, J.; Fu, W.; Li, X.; Li, B. Deciphering of microbial community and antibiotic resistance genes in activated sludge reactors under high selective pressure of different antibiotics. *Water Res.* **2019**, *151*, 388–402. [[CrossRef](#)]
4. Qiao, M.; Ying, G.-G.; Singer, A.; Zhu, Y.-G. Review of antibiotic resistance in China and its environment. *Environ. Int.* **2018**, *110*, 160–172. [[CrossRef](#)]
5. Guo, X.; Yan, Z.; Zhang, Y.; Xu, W.; Kong, D.; Shan, Z.; Wang, N. Behavior of antibiotic resistance genes under extremely high-level antibiotic selection pressures in pharmaceutical wastewater treatment plants. *Sci. Total Environ.* **2018**, *612*, 119–128. [[CrossRef](#)]
6. Zhang, X.; Yan, S.; Chen, J.; Tyagi, R.; Li, J. Physical, chemical, and biological impact (hazard) of hospital wastewater on environment: Presence of pharmaceuticals, pathogens, and antibiotic-resistance genes. In *Environmental and Health Impact of Hospital Wastewater, Current Developments in Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 79–102. [[CrossRef](#)]
7. Abadi, A.T.B.; Rizvanov, A.A.; Haertlé, T.; Blatt, N.L. World Health Organization Report: Current Crisis of Antibiotic Resistance. *BioNanoScience* **2019**, *9*, 778–788. [[CrossRef](#)]
8. Ahmed, M.B.; Zhou, J.L.; Ngo, H.H.; Guo, W. Adsorptive removal of antibiotics from water and wastewater: Progress and challenges. *Sci. Total Environ.* **2015**, *532*, 112–126. [[CrossRef](#)]
9. Leng, L.; Wei, L.; Xiong, Q.; Xu, S.; Li, W.; Lv, S.; Lu, Q.; Wan, L.; Wen, Z.; Zhou, W. Use of microalgae based technology for the removal of antibiotics from wastewater: A review. *Chemosphere* **2020**, *238*, 124680. [[CrossRef](#)]
10. Liu, X.-H.; Guo, X.; Liu, Y.; Lu, S.; Xi, B.; Zhang, J.; Wang, Z.; Bi, B. A review on removing antibiotics and antibiotic resistance genes from wastewater by constructed wetlands: Performance and microbial response. *Environ. Pollut.* **2019**, *254*, 112996. [[CrossRef](#)]
11. Chen, G.; Yu, Y.; Liang, L.; Duan, X.; Li, R.; Lu, X.; Yan, B.; Li, N.; Wang, S. Remediation of antibiotic wastewater by coupled photocatalytic and persulfate oxidation system: A critical review. *J. Hazard. Mater.* **2021**, *408*, 124461. [[CrossRef](#)]
12. Oberoi, A.S.; Jia, Y.; Zhang, H.; Khanal, S.K.; Lu, H. Insights into the Fate and Removal of Antibiotics in Engineered Biological Treatment Systems: A Critical Review. *Environ. Sci. Technol.* **2019**, *53*, 7234–7264. [[CrossRef](#)]
13. Shi, H.; Ni, J.; Zheng, T.; Wang, X.; Wu, C.; Wang, Q. Remediation of wastewater contaminated by antibiotics. A review. *Environ. Chem. Lett.* **2020**, *18*, 345–360. [[CrossRef](#)]
14. Wen, X.-J.; Niu, C.-G.; Zhang, L.; Liang, C.; Zeng, G.-M. A novel Ag₂O/CeO₂ heterojunction photocatalysts for photocatalytic degradation of enrofloxacin: Possible degradation pathways, mineralization activity and an in depth mechanism insight. *Appl. Catal. B Environ.* **2018**, *221*, 701–714. [[CrossRef](#)]
15. Sun, F.; Liu, H.; Liang, B.; Song, R.; Yan, Q.; Wang, A. Reductive degradation of chloramphenicol using bioelectrochemical system (BES): A comparative study of abiotic cathode and biocathode. *Bioresour. Technol.* **2013**, *143*, 699–702. [[CrossRef](#)]

16. Chung, T.H.; Dhar, B.R. A multi-perspective review on microbial electrochemical technologies for food waste valorization. *Bioresour. Technol.* **2021**, *342*, 125950. [[CrossRef](#)]
17. Dhar, B.R.; Ryu, H.; Ren, H.; Domingo, J.W.S.; Chae, J.; Lee, H.-S. High Biofilm Conductivity Maintained Despite Anode Potential Changes in a Geobacter -Enriched Biofilm. *ChemSusChem* **2016**, *9*, 3485–3491. [[CrossRef](#)]
18. Lee, H.-S.; Dhar, B.R.; Ranjan, D.B.; Rittmann, B.E.; Ryu, H.; Domingo, J.W.S.; Ren, H.; Chae, J. The Roles of Biofilm Conductivity and Donor Substrate Kinetics in a Mixed-Culture Biofilm Anode. *Environ. Sci. Technol.* **2016**, *50*, 12799–12807. [[CrossRef](#)]
19. Zakaria, B.S.; Dhar, B.R. Progress towards catalyzing electro-methanogenesis in anaerobic digestion process: Fundamentals, process optimization, design and scale-up considerations. *Bioresour. Technol.* **2019**, *289*, 121738. [[CrossRef](#)]
20. Chung, T.H.; Meshref, M.N.; Hai, F.I.; Al-Mamun, A.; Dhar, B.R. Microbial electrochemical systems for hydrogen peroxide synthesis: Critical review of process optimization, prospective environmental applications, and challenges. *Bioresour. Technol.* **2020**, *313*, 123727. [[CrossRef](#)]
21. Barua, S.; Zakaria, B.S.; Chung, T.; Hai, F.; Haile, T.; Al-Mamun, A.; Dhar, B.R. Microbial electrolysis followed by chemical precipitation for effective nutrients recovery from digested sludge centrate in WWTPs. *Chem. Eng. J.* **2019**, *361*, 256–265. [[CrossRef](#)]
22. Ye, Y.; Ngo, H.H.; Guo, W.; Chang, S.W.; Nguyen, D.D.; Liu, Y.; Ni, B.-J.; Zhang, X. Microbial fuel cell for nutrient recovery and electricity generation from municipal wastewater under different ammonium concentrations. *Bioresour. Technol.* **2019**, *292*, 121992. [[CrossRef](#)]
23. Al-Mamun, A.; Ahmad, W.; Baawain, M.S.; Khadem, M.; Dhar, B.R. A review of microbial desalination cell technology: Configurations, optimization and applications. *J. Clean. Prod.* **2018**, *183*, 458–480. [[CrossRef](#)]
24. Rahman, S.; Jafary, T.; Al-Mamun, A.; Baawain, M.S.; Choudhury, M.R.; Alhaimali, H.; Siddiqi, S.A.; Dhar, B.R.; Sana, A.; Lam, S.S.; et al. Towards upscaling microbial desalination cell technology: A comprehensive review on current challenges and future prospects. *J. Clean. Prod.* **2021**, *288*, 125597. [[CrossRef](#)]
25. Chung, T.H.; Dhar, B.R. Biosensors and Bioelectronics Paper-based platforms for microbial electrochemical cell-based biosensors: A review. *Biosens. Bioelectron.* **2021**, *192*, 113485. [[CrossRef](#)]
26. Chung, T.H.; Meshref, M.N.; Dhar, B.R. A review and roadmap for developing microbial electrochemical cell-based biosensors for recalcitrant environmental contaminants, emphasis on aromatic compounds. *Chem. Eng. J.* **2021**, *424*, 130245. [[CrossRef](#)]
27. Yan, W.; Guo, Y.; Xiao, Y.; Wang, S.; Ding, R.; Jiang, J.; Gang, H.; Wang, H.; Yang, J.; Zhao, F. The changes of bacterial communities and antibiotic resistance genes in microbial fuel cells during long-term oxytetracycline processing. *Water Res.* **2018**, *142*, 105–114. [[CrossRef](#)]
28. Miran, W.; Jang, J.; Nawaz, M.; Shahzad, A.; Lee, D.S. Biodegradation of the sulfonamide antibiotic sulfamethoxazole by sulfamethoxazole acclimatized cultures in microbial fuel cells. *Sci. Total Environ.* **2018**, *627*, 1058–1065. [[CrossRef](#)]
29. Wu, D.; Sun, F.; Chua, F.J.D.; Zhou, Y. Enhanced power generation in microbial fuel cell by an agonist of electroactive biofilm–Sulfamethoxazole. *Chem. Eng. J.* **2020**, *384*, 123238. [[CrossRef](#)]
30. Liang, B.; Cheng, H.-Y.; Kong, D.-Y.; Gao, S.-H.; Sun, F.; Cui, D.; Kong, F.-Y.; Zhou, A.-J.; Liu, W.-Z.; Ren, N.-Q.; et al. Accelerated Reduction of Chlorinated Nitroaromatic Antibiotic Chloramphenicol by Biocathode. *Environ. Sci. Technol.* **2013**, *47*, 5353–5361. [[CrossRef](#)]
31. Cheng, D.; Ngo, H.H.; Guo, W.; Chang, S.W.; Nguyen, D.D.; Liu, Y.; Liu, Y.; Deng, L.; Chen, Z. Evaluation of a continuous flow microbial fuel cell for treating synthetic swine wastewater containing antibiotics. *Sci. Total Environ.* **2021**, *756*, 144133. [[CrossRef](#)]
32. Wen, H.; Zhu, H.; Yan, B.; Xu, Y.; Shutes, B. Treatment of typical antibiotics in constructed wetlands integrated with microbial fuel cells: Roles of plant and circuit operation mode. *Chemosphere* **2020**, *250*, 126252. [[CrossRef](#)]
33. Li, H.; Xu, H.; Song, H.-L.; Lu, Y.; Yang, X.-L. Antibiotic resistance genes, bacterial communities, and functions in constructed wetland-microbial fuel cells: Responses to the co-stresses of antibiotics and zinc. *Environ. Pollut.* **2020**, *265*, 115084. [[CrossRef](#)]
34. Song, H.-L.; Li, H.; Zhang, S.; Yang, Y.-L.; Zhang, L.-M.; Xu, H.; Yang, X.-L. Fate of sulfadiazine and its corresponding resistance genes in up-flow microbial fuel cell coupled constructed wetlands: Effects of circuit operation mode and hydraulic retention time. *Chem. Eng. J.* **2018**, *350*, 920–929. [[CrossRef](#)]
35. Wang, Y.; Zhang, H.; Feng, Y.; Li, B.; Yu, M.; Xu, X.; Cai, L. Bio-Electron-Fenton (BEF) process driven by sediment microbial fuel cells (SMFCs) for antibiotics desorption and degradation. *Biosens. Bioelectron.* **2019**, *136*, 8–15. [[CrossRef](#)]
36. Li, S.; Liu, Y.; Ge, R.; Yang, S.; Zhai, Y.; Hua, T.; Ondon, B.S.; Zhou, Q.; Li, F. Microbial electro-Fenton: A promising system for antibiotics resistance genes degradation and energy generation. *Sci. Total Environ.* **2020**, *699*, 134160. [[CrossRef](#)]
37. Wang, Q.; Cai, Z.; Huang, L.; Pan, Y.; Quan, X.; Puma, G.L. Intensified degradation and mineralization of antibiotic metronidazole in photo-assisted microbial fuel cells with Mo-W catalytic cathodes under anaerobic or aerobic conditions in the presence of Fe(III). *Chem. Eng. J.* **2019**, *376*, 119566. [[CrossRef](#)]
38. Li, Y.; Liu, L.; Yang, F. Destruction of tetracycline hydrochloride antibiotics by FeOOH/TiO₂ granular activated carbon as expanded cathode in low-cost MBR/MFC coupled system. *J. Membr. Sci.* **2017**, *525*, 202–209. [[CrossRef](#)]
39. Yang, W.; Han, H.; Zhou, M.; Yang, J. Simultaneous electricity generation and tetracycline removal in continuous flow electrosorption driven by microbial fuel cells. *RSC Adv.* **2015**, *5*, 49513–49520. [[CrossRef](#)]
40. Zhang, Q.; Zhang, Y.; Li, D. Cometabolic degradation of chloramphenicol via a meta-cleavage pathway in a microbial fuel cell and its microbial community. *Bioresour. Technol.* **2017**, *229*, 104–110. [[CrossRef](#)]
41. Wang, L.; Liang, D.; Shi, Y. Profiling of co-metabolic degradation of tetracycline by the bio-cathode in microbial fuel cells. *RSC Adv.* **2021**, *12*, 509–516. [[CrossRef](#)]

42. Chung, T.H.; Dhar, B.R. A Mini-Review on Applications of 3D Printing for Microbial Electrochemical Technologies. *Front. Energy Res.* **2021**, *9*. [[CrossRef](#)]
43. Dhar, B.R.; Lee, H.-S. Membranes for bioelectrochemical systems: Challenges and research advances. *Environ. Technol.* **2013**, *34*, 1751–1764. [[CrossRef](#)]
44. Chen, J.; Hu, Y.; Huang, W.; Liu, Y.; Tang, M.; Zhang, L.; Sun, J. Biodegradation of oxytetracycline and electricity generation in microbial fuel cell with in situ dual graphene modified bioelectrode. *Bioresour. Technol.* **2018**, *270*, 482–488. [[CrossRef](#)]
45. Cheng, D.; Ngo, H.H.; Guo, W.; Lee, D.; Nghiem, D.L.; Zhang, J.; Liang, S.; Varjani, S.; Wang, J. Performance of microbial fuel cell for treating swine wastewater containing sulfonamide antibiotics. *Bioresour. Technol.* **2020**, *311*, 123588. [[CrossRef](#)]
46. Topcu, Ş.; Taşkan, E. Effect of the tetracycline antibiotics on performance and microbial community of microbial fuel cell. *Bioprocess Biosyst. Eng.* **2021**, *44*, 595–605. [[CrossRef](#)]
47. Zhou, Y.; Zhu, N.; Guo, W.; Wang, Y.; Huang, X.; Wu, P.; Dang, Z.; Zhang, X.; Xian, J. Simultaneous electricity production and antibiotics removal by microbial fuel cells. *J. Environ. Manag.* **2018**, *217*, 565–572. [[CrossRef](#)]
48. Wang, J.; Zhou, B.; Ge, R.; Song, T.-S.; Yu, J.; Xie, J. Degradation characterization and pathway analysis of chlortetracycline and oxytetracycline in a microbial fuel cell. *RSC Adv.* **2018**, *8*, 28613–28624. [[CrossRef](#)]
49. Catal, T.; Yavaser, S.; Enisoglu-Atalay, V.; Bermek, H.; Ozilhan, S. Monitoring of neomycin sulfate antibiotic in microbial fuel cells. *Bioresour. Technol.* **2018**, *268*, 116–120. [[CrossRef](#)]
50. Ondon, B.S.; Li, S.; Zhou, Q.; Li, F. Simultaneous removal and high tolerance of norfloxacin with electricity generation in microbial fuel cell and its antibiotic resistance genes quantification. *Bioresour. Technol.* **2020**, *304*, 122984. [[CrossRef](#)]
51. Bagchi, S.; Behera, M. Evaluating the Effect of the Antibiotic Ampicillin on Performance of a Low-Cost Microbial Fuel Cell. *J. Hazard. Toxic Radioact. Waste* **2020**, *24*, 04020011. [[CrossRef](#)]
52. Wu, W.; Lesnik, K.L.; Xu, S.; Wang, L.; Liu, H. Impact of tobramycin on the performance of microbial fuel cell. *Microb. Cell Factories* **2014**, *13*, 91. [[CrossRef](#)]
53. Zhu, Y.; Wang, Y.; Jiang, X.; Zhou, S.; Wu, M.; Pan, M.; Chen, H. Microbial community compositional analysis for membrane bioreactor treating antibiotics containing wastewater. *Chem. Eng. J.* **2017**, *325*, 300–309. [[CrossRef](#)]
54. Xue, W.; Li, F.; Zhou, Q. Degradation mechanisms of sulfamethoxazole and its induction of bacterial community changes and antibiotic resistance genes in a microbial fuel cell. *Bioresour. Technol.* **2019**, *289*, 121632. [[CrossRef](#)]
55. Wang, J.; He, M.-F.; Zhang, D.; Ren, Z.; Song, T.-S.; Xie, J. Simultaneous degradation of tetracycline by a microbial fuel cell and its toxicity evaluation by zebrafish. *RSC Adv.* **2017**, *7*, 44226–44233. [[CrossRef](#)]
56. Wang, L.; You, L.; Zhang, J.; Yang, T.; Zhang, W.; Zhang, Z.; Liu, P.; Wu, S.; Zhao, F.; Ma, J. Biodegradation of sulfadiazine in microbial fuel cells: Reaction mechanism, biotoxicity removal and the correlation with reactor microbes. *J. Hazard. Mater.* **2018**, *360*, 402–411. [[CrossRef](#)]
57. He, Y.; Zhang, L.; Jiang, L.; Wagner, T.; Sutton, N.B.; Ji, R.; Langenhoff, A.A. Improving removal of antibiotics in constructed wetland treatment systems based on key design and operational parameters: A review. *J. Hazard. Mater.* **2021**, *407*, 124386. [[CrossRef](#)]
58. Hijosa-Valsero, M.; Fink, G.; Schlüsener, M.P.; Sidrach-Cardona, R.; Martín-Villacorta, J.; Ternes, T.; Becares, E. Removal of antibiotics from urban wastewater by constructed wetland optimization. *Chemosphere* **2011**, *83*, 713–719. [[CrossRef](#)]
59. Katakai, S.; Chatterjee, S.; Vairale, M.G.; Dwivedi, S.K.; Gupta, D.K. Constructed wetland, an eco-technology for wastewater treatment: A review on types of wastewater treated and components of the technology (macrophyte, biofilm and substrate). *J. Environ. Manag.* **2021**, *283*, 111986. [[CrossRef](#)]
60. Rühmland, S.; Wick, A.; Ternes, T.; Barjenbruch, M. Fate of pharmaceuticals in a subsurface flow constructed wetland and two ponds. *Ecol. Eng.* **2015**, *80*, 125–139. [[CrossRef](#)]
61. Gupta, S.; Srivastava, P.; Patil, S.A.; Yadav, A.K. A comprehensive review on emerging constructed wetland coupled microbial fuel cell technology: Potential applications and challenges. *Bioresour. Technol.* **2021**, *320*, 124376. [[CrossRef](#)]
62. Guadarrama-Pérez, O.; Gutiérrez-Macías, T.; García-Sánchez, L.; Guadarrama-Pérez, V.H.; Estrada-Arriaga, E.B. Recent advances in constructed wetland-microbial fuel cells for simultaneous bioelectricity production and wastewater treatment: A review. *Int. J. Energy Res.* **2019**, *43*, 5106–5127. [[CrossRef](#)]
63. Xu, H.; Song, H.-L.; Singh, R.P.; Yang, Y.-L.; Xu, J.-Y.; Yang, X.-L. Simultaneous reduction of antibiotics leakage and methane emission from constructed wetland by integrating microbial fuel cell. *Bioresour. Technol.* **2021**, *320*, 124285. [[CrossRef](#)]
64. Liu, S.; Feng, X.; Li, X. Bioelectrochemical approach for control of methane emission from wetlands. *Bioresour. Technol.* **2017**, *241*, 812–820. [[CrossRef](#)]
65. Li, H.; Xu, H.; Yang, Y.-L.; Yang, X.-L.; Wu, Y.; Zhang, S.; Song, H.-L. Effects of graphite and Mn ore media on electro-active bacteria enrichment and fate of antibiotic and corresponding resistance gene in up flow microbial fuel cell constructed wetland. *Water Res.* **2019**, *165*, 114988. [[CrossRef](#)]
66. Zhang, S.; Song, H.-L.; Yang, X.-L.; Yang, Y.-L.; Yang, K.-Y.; Wang, X.-Y. Fate of tetracycline and sulfamethoxazole and their corresponding resistance genes in microbial fuel cell coupled constructed wetlands. *RSC Adv.* **2016**, *6*, 95999–96005. [[CrossRef](#)]
67. Nielsen, L.; Biggs, M.J.; Skinner, W.; Bandosz, T.J. The effects of activated carbon surface features on the reactive adsorption of carbamazepine and sulfamethoxazole. *Carbon* **2014**, *80*, 419–432. [[CrossRef](#)]
68. Dai, M.; Zhang, Y.; Wu, Y.; Sun, R.; Zong, W.; Kong, Q. Mechanism involved in the treatment of sulfamethoxazole in wastewater using a constructed wetland microbial fuel cell system. *J. Environ. Chem. Eng.* **2021**, *9*, 106193. [[CrossRef](#)]

69. Wen, H.; Zhu, H.; Yan, B.; Bañuelos, G.; Shutes, B.; Wang, X.; Cao, S.; Cheng, R.; Tian, L. High removal efficiencies of antibiotics and low accumulation of antibiotic resistant genes obtained in microbial fuel cell-constructed wetlands intensified by sponge iron. *Sci. Total Environ.* **2021**, *806*, 150220. [[CrossRef](#)]
70. Wen, H.; Zhu, H.; Xu, Y.; Yan, B.; Shutes, B.; Bañuelos, G.; Wang, X. Removal of sulfamethoxazole and tetracycline in constructed wetlands integrated with microbial fuel cells influenced by influent and operational conditions. *Environ. Pollut.* **2021**, *272*, 115988. [[CrossRef](#)]
71. Lu, S.; Zhang, X.; Xue, Y. Application of calcium peroxide in water and soil treatment: A review. *J. Hazard. Mater.* **2017**, *337*, 163–177. [[CrossRef](#)]
72. Sun, X.; Zu, K.; Liang, H.; Sun, L.; Zhang, L.; Wang, C.; Sharma, V.K. Electrochemical synthesis of ferrate(VI) using sponge iron anode and oxidative transformations of antibiotic and pesticide. *J. Hazard. Mater.* **2018**, *344*, 1155–1164. [[CrossRef](#)]
73. Ding, J.; Su, M.; Wu, C.; Lin, K. Transformation of triclosan to 2,8-dichlorodibenzo-p-dioxin by iron and manganese oxides under near dry conditions. *Chemosphere* **2015**, *133*, 41–46. [[CrossRef](#)]
74. Xie, H.; Yang, Y.; Liu, J.; Kang, Y.; Zhang, J.; Hu, Z.; Liang, S. Enhanced triclosan and nutrient removal performance in vertical up-flow constructed wetlands with manganese oxides. *Water Res.* **2018**, *143*, 457–466. [[CrossRef](#)]
75. Neyens, E.; Baeyens, J. A review of classic Fenton's peroxidation as an advanced oxidation technique. *J. Hazard. Mater.* **2003**, *98*, 33–50. [[CrossRef](#)]
76. Sopaj, F.; Oturan, N.; Pinson, J.; Podvorica, F.I.; Oturan, M.A. Effect of cathode material on electro-Fenton process efficiency for electrocatalytic mineralization of the antibiotic sulfamethazine. *Chem. Eng. J.* **2020**, *384*, 123249. [[CrossRef](#)]
77. Xu, L.; Zhang, G.-Q.; Yuan, G.-E.; Liu, H.-Y.; Liu, J.-D.; Yang, F.-L. Anti-fouling performance and mechanism of anthraquinone/polypyrrole composite modified membrane cathode in a novel MFC-aerobic MBR coupled system. *RSC Adv.* **2015**, *5*, 22533–22543. [[CrossRef](#)]
78. Li, Y.; Liu, L.; Liu, J.; Yang, F.; Ren, N. PPy/AQS (9, 10-anthraquinone-2-sulfonic acid) and PPy/ARS (Alizarin Red's) modified stainless steel mesh as cathode membrane in an integrated MBR/MFC system. *Desalination* **2014**, *349*, 94–101. [[CrossRef](#)]
79. Xiong, Y.; Zhao, J.; Li, L.; Wang, Y.; Dai, X.; Yu, F.; Ma, J. Interfacial interaction between micro/nanoplastics and typical PPCPs and nanoplastics removal via electrosorption from an aqueous solution. *Water Res.* **2020**, *184*, 116100. [[CrossRef](#)]
80. Yang, J.; Zhao, Y.; Zhang, C.; Hu, Y.; Zhou, M. Electrosorption driven by microbial fuel cells without electric grid energy consumption for simultaneous phenol removal and wastewater treatment. *Electrochem. Commun.* **2013**, *34*, 121–124. [[CrossRef](#)]
81. Chen, R.; Sheehan, T.; Ng, J.L.; Brucks, M.; Su, X. Capacitive deionization and electrosorption for heavy metal removal. *Environ. Sci. Water Res. Technol.* **2020**, *6*, 258–282. [[CrossRef](#)]
82. Zhao, W.; Qu, J.; Zhou, Y.; Zhao, J.; Feng, Y.; Guo, C.; Lu, Y.; Zhao, Y.; Peijnenburg, W.J.; Zhang, Y.-N. Continuous flow electrosorption-microbial fuel cell system for efficient removal of oxytetracycline without external electrical supply. *Bioresour. Technol.* **2019**, *290*, 121751. [[CrossRef](#)]
83. Dhar, B.R.; Sim, J.; Ryu, H.; Ren, H.; Domingo, J.W.S.; Chae, J.; Lee, H.-S. Microbial activity influences electrical conductivity of biofilm anode. *Water Res.* **2017**, *127*, 230–238. [[CrossRef](#)]
84. Saidi, M.; Fourcade, F.; Bellakhal, N.; Amrane, A.; Geneste, F. Nickel foam as a new material for chlortetracycline electrochemical oxidation: Biodegradability improvement and biological treatment. *J. Electroanal. Chem.* **2020**, *878*, 114543. [[CrossRef](#)]
85. Yu, M.; Sun, C.; Wang, L.; Zang, K.; Li, M.; Zhou, L.; Zheng, Y. Semi-coke activated persulfate promotes simultaneous degradation of sulfadiazine and tetracycline in a binary mixture. *Chem. Eng. J.* **2021**, *416*, 129122. [[CrossRef](#)]
86. Pérez-Moya, M.; Mansilla, H.D.; Graells, M. A practical parametrical characterization of the Fenton and the photo-Fenton sulfamethazine treatment using semi-empirical modeling. *J. Chem. Technol. Biotechnol.* **2011**, *86*, 826–831. [[CrossRef](#)]
87. Kümmerer, K. Pharmaceuticals in the Environment. *Annu. Rev. Environ. Resour.* **2010**, *35*, 57–75. [[CrossRef](#)]
88. Pulicharla, R.; Brar, S.K.; Rouissi, T.; Auger, S.; Drogui, P.; Verma, M.; Surampalli, R.Y. Degradation of chlortetracycline in wastewater sludge by ultrasonication, Fenton oxidation, and ferro-sonication. *Ultrason. Sonochem.* **2017**, *34*, 332–342. [[CrossRef](#)]
89. Qiao, X.; Liu, X.; Zhang, W.; Cai, Y.; Zhong, Z.; Li, Y.; Lü, J. Superior photo-Fenton activity towards chlortetracycline degradation over novel g-C₃N₄ nanosheets/schwertmannite nanocomposites with accelerated Fe(III)/Fe(II) cycling. *Sep. Purif. Technol.* **2021**, *279*, 119760. [[CrossRef](#)]
90. Jain, A.; He, Z. "NEW" resource recovery from wastewater using bioelectrochemical systems: Moving forward with functions. *Front. Environ. Sci. Eng.* **2018**, *12*, 1. [[CrossRef](#)]
91. Tan, W.; Chong, S.; Fang, H.-W.; Pan, K.-L.; Mohamad, M.; Lim, J.; Tiong, T.; Chan, Y.; Huang, C.-M.; Yang, T. Microbial Fuel Cell Technology—A Critical Review on Scale-Up Issues. *Processes* **2021**, *9*, 985. [[CrossRef](#)]
92. Jafary, T.; Al-Mamun, A.; Alhimali, H.; Baawain, M.S.; Rahman, M.S.; Rahman, S.; Dhar, B.R.; Aghbashlo, M.; Tabatabaei, M. Enhanced power generation and desalination rate in a novel quadruple microbial desalination cell with a single desalination chamber. *Renew. Sustain. Energy Rev.* **2020**, *127*, 109855. [[CrossRef](#)]
93. Dhar, B.R.; Ryu, H.; Domingo, J.W.S.; Lee, H.-S. Ohmic resistance affects microbial community and electrochemical kinetics in a multi-anode microbial electrochemical cell. *J. Power Sources* **2016**, *331*, 315–321. [[CrossRef](#)]
94. Rossi, R.; Hur, A.Y.; Page, M.A.; Thomas, A.O.; Butkiewicz, J.J.; Jones, D.W.; Baek, G.; Saikaly, P.E.; Cropek, D.M.; Logan, B.E. Pilot scale microbial fuel cells using air cathodes for producing electricity while treating wastewater. *Water Res.* **2022**, *215*, 118208. [[CrossRef](#)]

95. Sim, J.; Reid, R.; Hussain, A.; An, J.; Lee, H.-S. Hydrogen peroxide production in a pilot-scale microbial electrolysis cell. *Biotechnol. Rep.* **2018**, *19*, e00276. [[CrossRef](#)]
96. Peñacoba-Antona, L.; Senán-Salinas, J.; Aguirre-Sierra, A.; Letón, P.; Salas, J.J.; García-Calvo, E.; Esteve-Núñez, A. Assessing METland[®] Design and Performance Through LCA: Techno-Environmental Study With Multifunctional Unit Perspective. *Front. Microbiol.* **2021**, *12*, 652173. [[CrossRef](#)]
97. Prado, A.; Ramírez-Vargas, C.A.; Arias, C.A.; Esteve-Núñez, A. Novel bioelectrochemical strategies for domesticating the electron flow in constructed wetlands. *Sci. Total Environ.* **2020**, *735*, 139522. [[CrossRef](#)]
98. Pun, Á.; Boltes, K.; Letón, P.; Esteve-Núñez, A. Detoxification of wastewater containing pharmaceuticals using horizontal flow bioelectrochemical filter. *Bioresour. Technol. Rep.* **2019**, *7*, 100296. [[CrossRef](#)]