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Review

Application of Microbial Fuel Cell (MFC) for Pharmaceutical Wastewater Treatment: An Overview and Future Perspectives

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Abstract: Pharmaceutical wastewater (PWW) is rapidly growing into one of the world's most serious environmental and public health issues. Existing wastewater treatment systems carry numerous loopholes in supplying the ever-increasing need for potable water resulting from rises in population, urbanization, and industrial growth, and the volume of wastewater produced is growing each day. At present, conventional treatment methods, such as coagulation, sedimentation, oxidation, membrane filtration, flocculation, etc., are used to treat PWW. In contrast to these, the application of microbial fuel cells (MFCs) for decontaminating PWW can be a promising technology to replace these methods. MFC technologies have become a trending research topic in recent times. MFCs have also garnered the interest of researchers worldwide as a promising environmental remediation technique. This review extensively discusses the flaws in standalone conventional processes and the integration of MFCs to enhance electricity production and contaminant removal rates, especially with respect to PWW. This article also summarizes the studies reported on various antibiotics and wastes from pharmaceutical industries treated by MFCs, and their efficiencies. Furthermore, the review explains why further research is needed to establish the actual efficiency of MFCs to achieve sustainable, environmentally friendly, and cost-effective wastewater treatment. A brief on technoeconomic impacts has also been made to provide a glimpse of the way these technologies might replace present-day conventional methods.

Keywords: microbial fuel cell; pharmaceuticals; energy production; antibiotics; biofilm; electroactive bacteria

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1. Introduction

The pharmaceutical industry has been growing rapidly in recent decades, and drugs are now widely used in various industries, including agriculture, poultry farming, fisheries, and human health [1]. Thousands of anthropogenic and natural trace organic pollutants (e.g., pharmaceutically active compounds (PhACs), hormones, chemical products, biocides, polyaromatic hydrocarbons (PAH), illicit drugs, herbicides, pesticides, and surfactants) are contaminating aquatic environments worldwide [2]. While providing many benefits to

individuals, pharmaceuticals have also caused significant environmental harm due to their structural rigidity and nonbiodegradability [3]. Pharmaceuticals have been found in several environmental compartments, including soil, surface waterways, and drinking water. They are considered to be an emerging pollutant [4] that could have harmful consequences on the environment and human health [5]. For example, antibiotics in the environment are becoming a major source of concern due to the spread of antibiotic-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs) [6]. Furthermore, diclofenac (DCF) is a chemical with maximum toxicity among the nonsteroidal anti-inflammatory medications (NSAIDs), which can have chronic and acute toxicity effects on fish livers, kidneys, and gills [7].

The discharge of organic contaminants and drug components, such as antibiotics, antiepileptics, vitamins, and cosmetic components, distinguishes pharmaceutical effluents from conventional sewages; their negative environmental impacts are not well understood and are becoming a critical environmental problem [8]. To tackle this, microbial fuel cells (MFCs) are emerging as potent technologies in treating pharmaceutical waste. MFC technology has been extensively explored in the last decade due to its potential for producing electricity in an ecologically acceptable manner. MFCs are preferable to conventional methods for wastewater treatment because, instead of consuming energy, they use microbial metabolic activities for energy generation during wastewater treatment [9,10]. A typical two-chamber MFC contains an anode chamber, a cathode setup, and a separator or membrane, isolating both anode and cathode, whereas MFCs generate electricity by oxidizing biodegradable waste in the anodic compartment [9]. MFCs have sparked much interest in cleaning polluted water in recent years, even though most of them are only employed in the lab [11]. The present review discusses various techniques for treating pharmaceutical wastewater (PWW), emphasizing MFCs and their associations.

2. Basics of Microbial Fuel Cells (MFCs)

MFCs are a bio-electrochemical system that converts the chemical energy present in organic compounds into electrical energy using the catalytic action of microorganisms [12]. In MFCs, under anaerobic conditions, free electrons and protons produced from the oxidation of organic molecules are harvested from a cathode through the electric circuit and the selective proton exchange membrane, respectively. MFCs can treat various types of wastes, including industrial, agricultural, and municipal wastewaters [13]. Hence, to favor the growth of microbes, the anode materials mostly used are carbon-based. In cathode compartment, an oxygen reduction reaction (ORR) for a paired redox reaction is conducted on the cathode side with the production of water. To improve the performance of the cathode and MFCs overall, different electrode materials with superior conductivities are employed. The principal components of MFCs include: (i) anode—oxidation of organic matter takes place, catalyzed by electroactive bacteria; (ii) cathode—reduction of oxygen or carbon dioxide, a thermodynamically favorable reaction catalyzed in the presence or absence of catalysts; (iii) ion exchange membrane—a proton exchange membrane that favors the passage of protons from anode to cathode through simple diffusion; (iv) electroactive microorganisms—microorganisms with the ability to respire electrodes under anoxic conditions; (v) biofilm—the colonization of bacteria on the surface of the material; (vi) electric circuit—an external load where the electrons are passed through a fixed resistor to regulate the flow of electrons. MFCs can be either single-chamber or dual-chamber, whereas the former one consists of an open cathode system where the cathode is exposed to air for reduction reaction and the latter one consists of separate compartments for the anode and cathode [13,14]. Besides its basic components and reactor configuration, the efficiency of MFCs also relies on wastewater characteristics and operating parameters, e.g., pH, temperature, flow, hydraulic retention time (HRT), etc. [14].

3. Treatment of PWW Using Conventional and Advanced Oxidation Processes

PWW usually has a complicated composition that includes a high level of organic material, salt content, and microbial toxicity, the treatment of which is compulsory [1].

Pharmaceutical industries operate in batch mode, with diverse raw ingredients and manufacturing processes resulting in a wide range of contaminants. Organic matter is the primary contaminant in PWW, and biological treatment is considered the most cost-effective and promising approach for eliminating organic contaminants from PWW. Aerobic, anaerobic, and combined anaerobic–aerobic processes are the three types of biological treatment methods usually adopted for the treatment of PWW, and they are reported to reduce the concentration of contaminants. The focus of scientific studies and technical applications has turned recently to enhance the treatment of PWW using physicochemical technology as the primary technique, including both conventional (e.g., coagulation, adsorption, ozonation, and flotation) and advanced oxidation processes [15]. Table 1 summarizes different methods used for treating PWW.

3.1. Coagulation

Chemical agents are added to wastewater, rapidly mixing in to disperse them and then converting stable contaminants into unstable and precipitable particles. Compressing and removing bound water around a hydrophilic colloid is critical for enhanced PWW treatments. As a result, the nature of flocculent is crucial in determining the coagulation effect. As flocculants, inorganic metal salts and polymers are often utilized. Chromaticity and harmful organic particles can be removed with this method [16]. After coagulation, the most frequent procedure is sedimentation. Pollutants, which have a higher density than wastewater, can be separated using gravity. Coagulation and sedimentation offer numerous benefits, such as ease of use and being proven technologies, but removing dissolved organic debris is difficult.

A hybrid sequential treatment approach comprising coagulation, E-beam irradiation, and biological treatment was investigated to treat genuine PWW [17], while the influence of the combined treatment on the treated wastewater's physicochemical properties, biodegradability, and toxicity was studied. The PWW streams undergo a sequential treatment pathway that includes electron-beam irradiation, biological degradation, and coagulation, resulting in synergistic degradation and detoxification with enhanced COD and TOC degradation potential, with eliminations of 89% and 94% for high (H_{OSW}) and low (L_{OSW}) organic-strength wastewater, respectively. Tested against the specific microorganisms, cytotoxicity evaluation has indicated that combined wastewater treatment efficiently reduces toxicity. For L_{OSW}, the treatment costs of electron-beam radiolysis, biological, and E-beam biological treatments were 0.50, 2.35, and 2.85 USD m^{-3}, respectively; for H_{OSW}, they were 0.67, 0.7, and 1.37 USD m^{-3}.

3.2. Adsorption

Activated carbon has a large specific surface area, a multilayer porous structure, adsorption capacity, and stable chemical characteristics. It is used to treat industrial effluents that are hazardous and have difficult-to-discharge standards. Physical adsorption and chemical adsorption are two types of activated carbon adsorption. Adsorption by physical means is reversible and has no adsorbate selectivity. It is simple to desorb activated carbon that has been saturated with adsorbates. Chemical adsorption, on the other hand, adsorbs just one or a few distinct adsorbates; it is irreversible and difficult to desorb. Through rejuvenation, activated carbon regains its adsorption capability for cyclic usage. This technology is extensively employed for advanced therapy because of its capacity to be recycled, higher therapeutic effect, and wide applicability [18]. However, numerous drawbacks restrict its use, including high relative prices, limited regeneration efficiency, and complicated operation.

3.3. Ozonation

Ozone has long been used as a highly powerful oxidant and disinfectant. Ozone is predominantly an oxidant in acidic environments. However, it mostly relies on free radical reactions in neutral and alkaline pH environments. As a result, ozone can swiftly oxidize

and break down most organic substances in water, effectively removing contaminants. Using the oxidation process of hydroxyl radicals, several chemical treatment techniques have been used to remove refractory organic molecules from water and wastewater. The application of catalysts in advanced catalytic ozonation is anticipated to improve molecular ozone decomposition, resulting in highly active free radicals and helping mineralize and degrade a variety of organics. The sophisticated catalytic ozonation technique has been widely used to degrade harmful organic contaminants in wastewater. Advanced catalytic ozonation can correct low ozone utilization efficiency and the ineffective ozone mineralization of organic pollutants [19]. Direct mineralization is difficult, so a readily biodegradable substance must be created. It can also successfully remove turbidity and germs from wastewater simultaneously. Ozone-advanced oxidation technology is formed when ozone is mixed with other wastewater treatment technologies. This approach has a higher oxidation ability but a worse reactant selectivity for O_3/H_2O_2, O_3/UV, and so forth [20].

3.4. Flotation

Flotation can remove suspended particles from secondary effluents in addition to sedimentation. This method produces many tiny bubbles by injecting air into wastewater, generating floating floc with a lower density than the wastewater. It may also separate wastewater by floating to the surface. As a result, it is commonly used to remove pollutants as an adsorbent or catalyst carrier [21]. One of the most significant environmental issues is the presence of pharmaceutical micropollutants in aquatic ecosystems. Mojiri et al. [22] built two reactors to treat synthetic wastewater: a sequencing batch reactor (SBR) with a powdered composite adsorbent (CA) and a sequencing batch reactor. Synthetic wastewater was created by mixing ammonia with three pharmaceuticals: atenolol (ATN), diazepam (DIA), and ciprofloxacin (CIP). During optimization using the response surface method (RSM), it was observed that the SBR+CA eliminated up to 90.2% (2.26 mg L^{-1}), 94.0% (2.35 mg L^{-1}), and 95.5% (2.39 mg L^{-1}) of ATN, CIP, and DIA at the optimum independent variables [22]. Ferrer-Polonio et al. [23] employed SBR to remove ACT, CAF, and IBU in a concentration of 2 mg L^{-1} via five different pathways during biological treatment using an activated sludge system. A biological treatment technique with activated sludge and carbon adsorption has been devised to treat wastewaters containing the three target pharmaceuticals. According to 35-day testing, PhCs increased organic matter removal efficacy by 46.2% in effluent COD levels, while the combined system lowered it by 32.5%. In terms of PhC removal, the combined system yielded effluents in target pharmaceuticals, whereas biological treatment without activated carbon yielded modest amounts of CAF and IBU. The combination method proposed in this study provided an effluent free of PhCs and of greater quality than a normal activated sludge treatment [23].

Chu et al. [24] investigated the use of gamma irradiation to treat genuine PWW from an erythromycin (ERY) manufacturing plant. Antibiotics found in raw wastewater were directly connected to the location and quantity of the ARGs identified. Tetracycline (TC) and sulfamethoxazole (SMX) were also detected, with concentrations three orders of magnitude lower than ERY. It was also observed that the reduction of ARGs and antibiotics was considerably reduced more than that of antimicrobial activities and COD. The elimination percentages of ARGs, ERY, antibacterial activity, and COD were 96.5%, 99.8%, 90%, 47.8%, and 10.3%, respectively, with a 50 kGy absorbed dosage. At the same time, Tormo-Budowski et al. [25] demonstrated the capacity of *Trametes versicolor* in a stirred tank bioreactor (STB) and a trickle-bed bioreactor (TBB) to extract PhACs from sterile synthetic and nonsterile hospital wastewater. In this study, *T. versicolor* was employed in two bioreactor designs to treat manmade and hospital wastewater. The STB recovered 95.7% of 16 pharmaceuticals injected in synthetic wastewater, as well as those naturally occurring in hospital wastewater 85.0%. A TBB based on fungal biomass immobilized on rice bran removed 88.6% of synthetic wastewater and 89.8% of actual wastewater. However, adsorption of the bed's biomass was responsible for 73.3% of the removal. Toxicological

research has revealed that the toxicity of hospital wastewater decreases after treatment in a TBB. These results indicate that the fungal fixed-bed reactors may be a better alternative than the stirred tank reactor for eliminating pharma-molecules from polluted water, as they can eradicate PhACs on a wide scale while also purifying real wastewater [24].

3.5. Advanced Oxidation Processes (AOPs)

AOPs use free radicals to oxidize contaminants. These contaminants are incapable of being decomposed by a standard oxidizing agent. AOPs include wet air oxidation, photocatalytic oxidation, ultrasonic oxidation, supercritical water oxidation, and electrochemical oxidation [26]. Klavarioti et al. [27] made an extensive review on AOP-based PWW treatment. Supercritical water oxidation (SCWO) has a high oxidation efficiency, produces no secondary pollutants, and oxidizes organics. This approach, however, has numerous disadvantages, including the need for extreme working temperatures and its expensive nature [28]. Metal–organic framework (MOF)-based materials have recently emerged as promising catalysts for sulfate radical-based AOP (SR-AOP) applications. Most importantly, the use of MOF-based materials in SR-AOPs for wastewater treatment has received considerable attention [29]. Pandis et al. [30] discussed the key points and significance of AOPs in treating pharmaceutical wastewater.

Fenton's reagent is a kind of reagent used in the Fenton system that was primarily employed in organic synthesis, but as individuals gained a better knowledge of the system, it was progressively used to treat the wastewater in industries. The Fenton reaction may be operated at room temperature and pressure with no environmental impact [31]. It is a sophisticated oxidation technology with simple reaction conditions and excellent oxidation efficacy. Fenton oxidation is a useful AOP that works by employing Fe as a catalyst to catalyze the formation of OH^{-}. A higher than 80% degradation of emerging contaminants (ECs) has been obtained with effective mineralization efficiency using Fe-based catalysts, such as Fe oxide, zero-valent Fe, and multi-metallic composites. The bio-electro-Fenton (BEF), a newer form of Fenton oxidation, costs less. The BEF is a bio-electrochemical system combined with electro-Fenton oxidation, which has been extensively studied to degrade wastewater containing pharmaceutical contents. The popularity of BEF originates from the fact that the H^{+} ions, necessary at the cathode for the generation of H_2O_2, are created at the anode by electroactive microorganisms oxidizing organic substrates, releasing H^{+}, electrons, and CO_2 [32]. The flaws in the Fenton reaction, on the other hand, cannot be overlooked. One is oxidant loss due to scavenging free radicals and H_2O_2 breakdown.

AOPs are commonly regarded as a viable alternative for treating low-biodegradability effluents. Martínez et al. [33] utilized an effluent from organic chemical synthesis pharmaceutical plant with ca. 1.4 g L^{-1} of TOC and limited biodegradability, which were treated using a combination of advanced Fenton oxidation and conventional biological treatment. A decrease in temperature from 120 to 70 °C, combined with H_2O_2 uptake 65% lower than that used in the Fenton procedure at the PWW treatment plant, resulted in an easily degradable discharge that was effectively removed by a sequenced biological treatment, with TOC elimination exceeding 90% [33].

UV photocatalytic oxidation, also known as photochemical oxidation, is a process that combines UV light with an oxidant. The oxidative breakdown of oxidants during UV light stimulation produces free radicals with more oxidative power, allowing them to oxidize tougher organic pollutants with oxidants alone. Chlorinated cyanurates, prepared by adding hypochlorite to cyanuric acid in various ratios, have long been used for disinfection. Cl-cyanurates structurally resemble chlorinated amides, which have low reactivity with radicals, and Cl-cyanurates bearing multiple –Cl may have high molar absorptivity at 254 nm due to red-shifting absorption; thus, combining UV with chlorinated cyanurates (UV/Cl-cyanurates) can be a novel and effective AOP [34].

3.6. Membrane Separation

Membrane separation is a convenient technology when a constituent in water preferentially penetrates the membrane by putting a permselective membrane, separating the medium across the membrane at a specific driving force. As a result, the target material can be separated, purified, and concentrated from the mixture. In wastewater treatment, membrane separation approaches such as microfiltration, reverse osmosis, ultrafiltration, and electrodialysis are commonly employed. Because of their least biodegradability, PWW cannot be treated with biological treatment methods after secondary treatment methods. However, we cannot disregard the benefits of biological treatment, which include low prices and reliable therapeutic results. They can be utilized as an advanced therapeutic preparation [35].

Table 1. Conventional processes used to remove pollutants from PWW.

SL No.	Conventional Methods	Advantages	Disadvantages	References
1.	Coagulation/sedimentation	Economical	Sludge is produced in large quantities	[16]
2.	Adsorption	A process that is simple, consistent, and straightforward	Adsorbents must be replenished	[21]
3.	Oxidation process	Pollutants are removed quickly	An expensive procedure	[26]
4.	Ozonation process	Variation in volume	The half-life is extremely brief	[20]
5.	Membrane filtration	Metals from pharmaceuticals can be easily removed	Production with concentrated sludge	[36]
6.	Biological treatment	Feasible for eliminating a wide range of pharmaceutical contaminants	Not yet commercialized	[35]
7.	Flocculation	Less sludge settling, dewatering	Costly and high consumption of chemicals	[37]
8.	Membrane distillation	The thermally driven purifying process is cost-effective, especially with respect to waste heat or solar thermal energy	Pore-wetting in membranes	[38]
9.	Microbial electrochemical technology	Electricity production and other important commodities are among the many applications	Upscaling is difficult and expensive	[39]
10.	Nanomaterials	Highly efficient with higher adsorption efficiency, friendly with other techniques	Less ecofriendly, more expensive and hazardous	[40,41]

4. Treatment of PWW Using MFC

Although several traditional approaches, including coagulation, filtration, biological membranes, and advanced oxidations, have been utilized for the treatment of PWW, all of these treatments have limitations in terms of applicability and results. Because of their tolerance to microbial respiration and their natural habitat, the anaerobic breakdown of recalcitrant organic pharmaceutical pollutants poses a challenge to current water treatment technologies. Microorganisms may decompose various organic molecules into CO_2, H_2O, and energy in the anode of an MFC. Microbes react with an electrode through a variety of processes. In anaerobic respiration, the electrode serves as an electron sink. Many studies have shown that adopting MFCs as a remediation method can speed up the deterioration of pharmaceutical pollutants and reduce reaction time due to the driving power of cathode processes [42].

4.1. Removal of Antibiotics

Antibiotics are discharged in enormous quantities by pharmaceutical industries, healthcare centers, the animal breeding business, and patients, but only a few water treatment plants adhere to current regulations, causing the release of leftover antibiotics into the environment. Antibiotic abuse and leftover antibiotics in natural systems have

increased environmental degradation. Traditional physicochemical and biochemical methods for removing antibiotics from sewage water require a lot of energy and chemicals, while biological processes are inefficient at degrading antibiotics. Additionally, it is challenging to treat PWW using traditional technologies due to its complex composition and high toxicity. Recently, MFCs have been used to breakdown refractory organic molecules (Table 2). With glucose as fuel, the efficacy of a single-chamber MFC with an air cathode was successfully demonstrated for degrading penicillin combinations or penicillin. According to some studies, penicillin may be degraded while producing power. Surprisingly, these glucose–penicillin combinations were involved in generating power. When used as a single-chamber MFC, 1 g L^{-1} glucose (14.7 W m^{-3}) and 50 mg L^{-1} penicillin (2.1 W m^{-3}) had a power density that was six times lower than the combination of 1 g L^{-1} glucose + 50 mg L^{-1} penicillin (101.2 W m^{-3}). When 50 mg L^{-1} penicillin was used, the peak current density was 3.5 times higher (10.73 A m^{-2}) than when no penicillin was used (3.03 A m^{-2}). Penicillin appears to improve the permeability of the bacterial cell membranes, facilitating electron transport from the microbe to the anode via cell membranes while lowering the MFC's internal resistance and increasing power density. These outcomes specified that some hazardous and bio-refractory organic compounds, such as antibiotic effluents, could be a valuable resource for MFC-based energy generation [43].

Table 2. Degradation of antibiotics and power densities produced in MFCs.

SL No.	Antibiotics	Initial Wastewater Concentration	Time	Rate of Antibiotic Elimination	Power Density Produced	References
1.	Penicillin	50 mg L^{-1}	24 h	98%	101.7 W m^{-3}	[43]
2.	Tetracycline	50 mg L^{-1}	168 h	80%	2.5 W m^{-3}	[44]
3.	Cefazolin sodium	50 mg L^{-1}	30 h	~70%	30.4 W m^{-3}	[45]
4.	Chloramphenicol	80 mg L^{-1}	48 h	61%	0.86 W m^{-3}	[46]
5.	Sulfamethoxazole	200 mg L^{-1}	24 h	70%	-	[43]
6.	Ceftriaxone	50 mg L^{-1}	24 h	91%	113 W m^{-3}	[43]
7.	Sulfanilamide	30 mg L^{-1}	96 h	90%	-	[47]
8	Sulfamethoxazole	10 mg L^{-1}	240 d	80.3%	524.5 mv	[48]
9.	Carbamazepine	10 mg L^{-1}	10 d	99%	0.330 W m^{-2}	[49]
10.	p-nitrophenol	50 mg L^{-1}	24 h	81%	-	[50]
11.	Paracetamol	5 mg L^{-1}	9 h	71%	-	[51]
12.	Glucose–ceftriaxone sodium	50 mg L^{-1}	24 h	91%	11 W m^{-3}	[43]

One experiment employed two-chambered MFCs to study metronidazole degradation and evaluated the impact of antibiotics on energy production efficiency. The equivalent power densities for glucose (1000 mg L^{-1}) with varied concentrations of metronidazole (0, 10, 30, 50 mg L^{-1}), as the fuels were 141.94, 99.23, 25.44, and 16.26 mW m^{-2}, respectively. The MFCs' efficiency was impaired, but this was reversible. In the MFCs, metronidazole degradation was 85.4% within 24 h, compared to only 35.2% in open circuits. It was concluded that antibiotics such as metronidazole were degraded using the MFCs, which has applications for treating contaminated water [52].

Despite its high toxicity and persistence, tetracycline (TC) is the second most commonly used antibiotic. One study examined the anaerobic breakdown of TC in an MFC utilizing glucose–TC composites as substrates under gradient-acclimated procedures. The MFC treated almost 79.1% of the TC in just 7 d. This result was higher than those produced using a conventional anaerobic approach (14.9%). MFCs with a closed circuit had 31.6% greater TC removal efficiency than MFCs with an open circuit. Additionally, zebrafish testing revealed that MFC treatment caused no toxicity. Under gradient acclimation procedures, a microbiota evaluation was performed on the anode of the MFC, and the consequences demonstrated that TC was successfully eradicated via the integration of fermentative bacteria, electrogenic bacteria, and acid-synthesizing bacteria [44].

MFCs were used to examine the reductive breakdown of chloramphenicol (CAP), utilizing both abiotic cathodes and biocathodes. CAP reduction efficiency was 86.3% in the biocathode group within the first 24 h, but only 62.9% in the abiotic cathode group. Apart from cathode potential, biocathode performance metrics, such as cathode current, cyclic voltammetry current response, ohm resistance, and polarization resistance, were all superior to those of the abiotic group. Furthermore, the biocathode's specific CAP reductive rate using sludge-fermented liquid 0.199 h^{-1} as a source of carbon was similar to that of glucose, 0.215 h^{-1}, but was 3.2 times that of the abiotic cathode group, 0.062 h^{-1}. It was claimed that adding a biocathode might improve cathode efficiency, resulting in a greater degradation in CAP [52].

A performance analysis of an MFC for CAP breakdown was examined by Zhang et al. [46]. Almost 84% of 50 mg L^{-1} of CAP in the MFC was degraded within 12 h. Upon the elimination of CAP, an important interaction between the temperature, pH, and beginning CAP concentration was identified, with the best-predicted removal efficiency of 96.53% achieved at 31.48 °C, pH 7.12 and an initial CAP concentration of 106.37 mg L^{-1}. Furthermore, CAP was broken down using a ring-cleavage method. The antibacterial activity of CAP against *Escherichia coli ATCC 25922* and *Shewanella oneidensis MR1* was considerably lowered by the MFC treatment. The dominating species in the MFC anodic biofilm were *Rhodococcus*, *Chryseobacterium*, *Comamonas*, *Nitrososphaera*, *Azoarcus*, *Azonexus*, and *Dysgonomonas*, according to a high-throughput sequencing study. Finally, given its high CAP degradation and power production, the MFC was found to remediate antibiotic residue-containing wastewater [46].

Another study evaluated the effectiveness of vertical up-flow constructed wetlands (VUF-CWs) on swine wastewater TC compounds (TCs) and *tet* genes using three criteria: TC and *tet* gene elimination potential, residual TCs and *tet* genes in soils and plants, and the impact of TC deposition on nutrient degradation and *tet* gene development. With or without OTC spiked in the wastewater, high degradation performances (69.0–99.9%) were attained for TC, oxytetracycline (OTC), and chlortetracycline (CTC). After plant harvest, TC concentrations in surface soils rose for the first two monitoring periods, then reduced. There were also reasonable nutrient degradation capacities, but TN and NH_4–N degradation potentials were negatively linked with total TCs in the soils ($p < 0.01$). All of the target genes (*tetO*, *tetW*, *tetM*, *tetA*, *intI1*, and *tetX*) had their absolute abundances drastically decreased, with log units varying from 0.26 to 3.3. Conversely, in several effluent samples, the proportions of the abundance of *tetO*, *tetM*, and *tetX* were considerably more developed than in the wastewater. Except for *tetO*, the relative abundances of *tet* genes were substantially linked with TCs in soils. In conclusion, the projected VUF-CWs were found to be viable for removing TCs and *tet* genes. However, preventing high amounts of TCs from accumulating in soils is critical [53].

Zhou et al. [20] examined the potential of using MFCs for antibiotic biodegradation. Sludge supernatant mixes and synthetic wastewater containing animal waste were used to inoculate MFCs. Furthermore, adding norfloxacin, roxithromycin, sulfadimidine, and aureomycin to the reactors reduced MFC efficiency (0.51–0.41 V), but decreasing the antibiotic concentration increased the output voltage. According to LC-MS analysis, the degradation efficacy of norfloxacin, roxithromycin, and aureomycin was 100%, while the degradation efficiency of sulfadimidine was about 99.9%. According to these findings, antibiotics dramatically inhibited electrical performance while simultaneously improving water quality [20]. Cheng et al. [47] examined the viability of removing sulfanilamide from the anode of two-chambered MFCs and the impact of sulfanilamide on MFC power production. At the investigated concentration range (10–30 mg L^{-1}), the results revealed that sulfanilamide may be effectively degraded in the anode of MFC and has a beneficial impact on power production. Compared to MFCs utilizing glucose as the precursor, the highest voltage output of MFCs with 10, 20, and 30 mg L^{-1} improved sulfanilamide degradation by 8.5, 13.9, and 15.7%, respectively. According to the anode and cathode potentiodynamic polarization, the higher electricity output of MFCs is due to the lower anode overpotential generated by the addition of sulfanilamide. The sulfanilamide removal rate in typical MFCs

approaches 90% after 96 h, while no co-substrate, open-circuit, and abiotic MFCs exhibited removal efficiencies of 10.8, 58, and 7.5%, respectively. The outcomes of comparative tests show that sulfanilamide removal in MFCs is primarily due to biocatalytic co-metabolism degeneration rather than adsorption, indicating the electricity produced in MFCs plays an important role in speeding up the pollutant elimination rate [47].

In another study by Cheng et al. [54], pomelo peel-derived biochar was used in the anode compartment to enhance the degradation of sulfonamide antibiotics in the continuous operation of MFC via pore-filling and EDA interaction; sulfonamide antibiotics were absorbed into the diverse interfaces of the biochar. As a result, SMX, sulfadiazine, and sulfamethazine removal efficiency may be increased by 82.44–88.15%, 53.40–77.53%, and 61.12–80.68%, respectively, by introducing biochar to a particular concentration (500 mg L^{-1}). Furthermore, raising the concentration of biochar enhanced energy production, COD removal, and nutrient metabolism. Consequently, it has been shown that including biochar in MFC substantially improves the capacity of MFCs to handle pharmaceutical swine effluent containing sulfonamide antibiotics [54]. Antibiotic degradation by utilizing constructed wetlands (CWs) with MFC-CWs has also proven effective (as shown in Figure 1). Wen et al. [43] tested the effects of carbon sources and external resistance, concentrations, and aeration periods on SMX and TC removal and bioelectricity production in four studies with MFC-CW microcosms. MFC-CWs given glucose excelled compared to those fed with other carbon sources, and a low permeate glucose concentration of 200 mg L^{-1} resulted in the best SMX and TC removal. Compared to other external resistance treatments, MFC-CWs with an external resistance of 700 exhibited the greatest SMX (99.4%) and TC removal (97.8%). An aeration duration of 12 h increased SMX and TC removal in MFC-CWs by 4.98 and 4.34%, respectively, compared to no aeration [43].

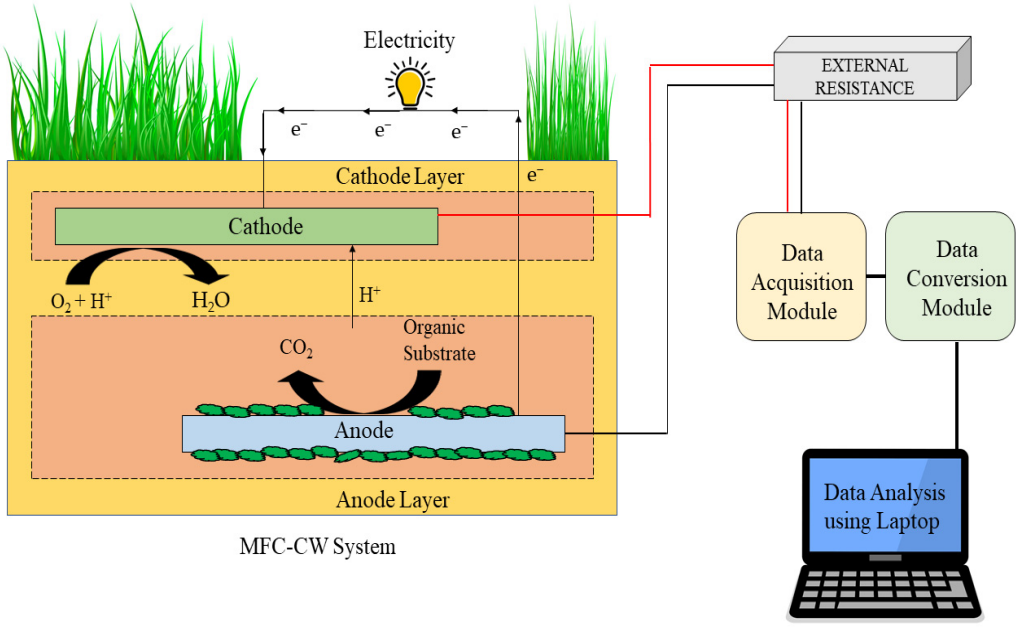

Figure 1. Schematic of an MFC–constructed wetland system for the degradation of antibiotics.

Single-chamber MFCs have proven to be an excellent solution for cefazolin sodium (CFZS)-polluted wastewater treatment in power generation. Despite a longer acclimatization MFC activation, MFCs subjected to CFZS loadings up to 100 mg L^{-1} generated steady power of 30.4 ± 2.1 W m^{-3} and a minimum power of 18.2 ± 1.1 W m^{-3} equivalent to CFZS-free MFCs (static power 19.4 ± 0.8 W m^{-3} and highest power 32.5 ± 1.6 W m^{-3}). In CFZS-acclimatized anodes, more androphilic genera (e.g., *Acinetobacter*, *Lysinibacillus*, *Stenotrophomonas*) and antibiotic-resistant genera (e.g., *Dysgonomonas*) were found. The establishment of high CFZS resistance (e.g., 450 mg L^{-1}) depended on both the thickness of biofilms and the time of CFZS acclimatization. CFZS reversibly inhibited MFCs. The

current MFCs removed CFZS at a rate of 1.2–6.8 mg L^{-1} h^{-1} without causing any noticeable reduction in electric power output [51].

In the MFCs, the antibiotic neomycin sulfate was detected and quantified indirectly. Voltage production, power density, current density, and coulombic efficiency were all used to evaluate the efficiency of the MFCs. In addition, LC-MS/MS was used to track neomycin sulfate degradation with COD and the total carbohydrate clearance. While neomycin sulfate was partly decomposed, neomycin sulfate appeared to impact and eventually limit MFC performance in a concentration-dependent manner. To understand more about the MFCs' neomycin sulfate bio-sensing function, researchers employed a computational chemistry approach to collect data on the maximum occupied orbital–lowest unoccupied molecular orbital energy value distribution and ionization potentials. The findings demonstrated that electroactive biofilm-based MFCs might be used to detect neomycin sulfate in wastewaters with high sensitivity [55]. Wu et al. [56] examined the efficiency of copper and nickel metal foam cathodes in degrading CAP. Under 0.5 V, the copper foam electrode completely removed and mineralized the antibiotic in 12 h, significantly faster than the nickel foam electrode. The experiment determined that raising the applied voltage from 0.3 to 0.5 V aided CAP breakdown and mineralization [56].

The antibiotic norfloxacin is a synthetic antibiotic used to treat infections. The efficacy of MFC for norfloxacin biodegradation, electricity production, and the creation of ARGs was studied in the literature by Ondon et al. [57]. Norfloxacin degradation and COD removal effectiveness were 65.5 and 94.5%, respectively. While electricity was effectively produced, a rise in norfloxacin concentration (128 mg L^{-1}) did not affect norfloxacin biodegradation efficacy, COD elimination, or MFC voltage output.

4.2. Removal of Aromatic Compounds

Aromatic compounds and their compounds are a class of hazardous or difficult-to-degrade organic chemicals. Benzene, nitrobenzene, phenol, and their derivatives have been designated major contaminants by the US Environmental Protection Agency (USEPA), while various phenols have been designated as dominant pollutants by the European Union. Aromatic compounds are common contaminants released by pharmaceutical industries. As a result, before being discharged into the environment, PWW that includes various harmful recalcitrant compounds and excessive salinity needs a unique treatment technology. One study examined the process for the decontamination of PWW and energy production in an air cathode (ACMFC) in saline conditions using the bioaugmentation of halophilic consortia. The ACMFC was operated with organic loads ranging from 1.04 to 3.51 g COD L^{-1}, and it showed a TCOD removal of 65–89%. Significant removals of SCOD (90%), TSS (total suspended solids) (73%), and TCOD (92%) were achieved with an energy generation of 896 mV, and complete phenol removal was obtained. At various organic loads, *Rhodococcus*, *Bacillus*, *Marinobacter*, and *Ochrobactrum* were the most common halophilic electrogenic strains in ACMFC [58]. In another experiment, a two-chamber MFC was used to treat PWW containing phenol or acetone and produce electricity simultaneously. If the phenol concentration was less than 50 mg L^{-1} and the acetone level was less than 100 mg L^{-1}, the MFC showed an excellent pollutant removal rate with no phenol or acetone found [59].

In one study, an MFC was used to decompose p-nitrophenol (PNP). At 28 °C and pH 7.0, the anode decomposed almost 81% of 50 mg L^{-1} PNP after 24 h. After a three-day incubation, a substantial communication between temperature, pH, and baseline PNP concentration for PNP degradation was identified, with a maximum theoretical degradation rate of 95% was attained at 34.63 °C, pH 7.4, and an acute PNP concentration of 126.96 mg L^{-1}. Furthermore, the anodic biofilm demonstrated the capacity to break down aromatic chemicals such as CAP, benzofluorfen, fluoxastrobin, and flubendiamide during a sufficient period. Beneficial bacteria from the genera *Comamonas*, *Chryseobacterium*, *Corynebacterium*, and *Rhodococcus* predominated in the MFC anode biofilm, according to high-throughput sequencing analysis. The complicated syntrophic relationships among bacteria were necessary for effective organic material removal. Hence, the MFC can re-

mediate aromatic contaminants from PWW due to its energy recovery and the catabolic flexibility of the anodic biofilm [50].

Because of its widespread use, paracetamol (PAM) has become a significant wastewater pollutant. Fenton reactions were familiarized with MFCs in an experiment by Zhang et al. [51] for the bio-electrochemical breakdown of PAM without external power. Electrons were released in the anode chambers by oxidizing biodegradable pollutants in the PWW; the input fluxes of electrons from the anode could encourage the synthesis of free radical OH by aiding the rehabilitation of the iron source in the cathode compartments. Within 9 h, the highest PAM biodegradation efficiency, 70%, was achieved at a total iron content of 5 mg L^{-1}, an initial pH of 2.0, and an external resistance of 20 ohms. Furthermore, a quarter of a percent of PAM could be mineralized entirely, while the rest was mostly transformed into PNP intermediate metabolites via p-aminophenol and less dangerous dicarboxylic or carboxylic acids. These results showed that MFC-Fenton might be used as an energy-efficient and productive method for treating PAM-containing wastewater and non-biocompatible pharmaceutical decomposition in the aquatic environment [51].

In one study, a unique photocatalytic-MFC with a bioanode and a photocatalytic cathode was employed to eliminate ibuprofen (IBF) and produce power. The kinetic data further verified that the breakdown of IBF follows the pseudo-first-order kinetic model under various starting concentrations and pH conditions. Under ideal conditions, the highest power density was 0.119 W m^{-2}, the current density was 0.75 A m^{-2}, and the voltage was 950 mV. Furthermore, the experiments showed that O_2 and OH were the most reactive oxidative species, implying that the system's electron transport mechanism and IBF degradation route are hypothesized. In conclusion, it was confirmed that the novel photocatalytic-MFC could optimize semiconductor photocarrier separation and the reduction of cathode pollution, indicating that it is a new, sustainable, and eco-friendly treatment for refractory pharmaceutical contaminants that delivers an experimental base for future applications [60].

In another study, MFC was used to treat glucose–ceftriaxone sodium combinations or ceftriaxone sodium. The findings revealed that ceftriaxone sodium can be degraded while also producing electrical power. Surprisingly, these ceftriaxone sodium–glucose combinations were involved in generating electricity. In contrast to 1000 mg L^{-1} glucose (19 W m^{-3}), the efficiency for 50 mg L^{-1} ceftriaxone sodium + 1000 mg L^{-1} glucose (113 W m^{-3}) was found to be 495% higher, while the highest energy output for 50 mg L^{-1} ceftriaxone sodium, as the single fuel, was 11 W m^{-3}. Furthermore, the MFC biodegraded the ceftriaxone sodium at a rate of 91% in 24 h, as compared to 51% in a typical anaerobic reactor. These findings suggested that some toxic and bio-recalcitrant organics, such as antibiotic effluents, could be used to generate energy by utilizing MFC technology [43]. In one of the experiments, an MFC was used to eliminate ciprofloxacin from contaminated PWW [61]. In 88 h, the elimination potential of 10 mg L^{-1} ciprofloxacin in the MFC improved to 99.0%. These findings were consistent with increased biofilm development and MFC voltage output. The antishock powers of biofilms in MFCs were also tested by treating them with ofloxacin and enrofloxacin and functioning them at varying temperatures and salinities. In 72 h, these MFCs eradicated 87.31% of ofloxacin and 40.81% of enrofloxacin. Furthermore, the MFCs attained more than 50% and approximately 80% ciprofloxacin elimination efficacy even when subjected to a low temperature of 10 °C and salinity of 3%, respectively. The elimination of quinolone antibiotics was mostly due to the enrichment of *Alcaligenes* and *Chryseobacterium*. This research presents scientific support for employing MFCs to treat quinolone antibiotic wastewater [61].

4.3. Other Pharmaceutical Pollutants

Velvizhi and Mohan [62] investigated the functional properties of anaerobic culture as a biocatalyst in the treatment of complex PWW, utilizing both classic anaerobic treatment (AnT) and self-induced electrogenic microenvironments (BET). A self-induced electrogenic microenvironment outperformed a typical anaerobic treatment process in treating low-

biodegradable PWW. BET (COD elimination, 78.70%) outperformed AnT (32%) in terms of treatment efficiency and power output. Adding an electrode to the BET resulted in increased electrogenesis, which improved the substrate degradation and the elimination of several pollutants, leading to a considerable reduction in wastewater toxicity levels. In addition, BET demonstrated good treatment efficiency even at larger organic loads without process hindrance [62].

In another study, a unique paraboloid of graphite-based MFC structure was created for bio-electrogenesis and PWW treatment by removing various casings and membranes. The biofilm in the paraboloid graphite-based MFC was developed on a substrate of municipal solid wastewater (MSW). According to the findings, MFC significantly reduced COD and TDS by 80.55% (5460 to 1060 mg L^{-1}) and 35.62% (800 to 515 mg L^{-1}), respectively. The decrease in COD removal efficiency (80.55%) showed that eliminating organic compounds from PWW occurs in tandem with electrogenesis [8].

In MFCs, anodes altered with Pd, Fe_3O_4, and MnO_2 nanoparticles were utilized, and their implications on the elimination of pharmaceutically active chemicals (PhACs) and electricity production were studied. According to the findings, anode decoration with Pd, Fe_3O_4, and MnO_2 resulted in varying efficacy in eradicating PhACs from MFCs. DCF, carbamazepine (CBZ) and IBF were eliminated more efficiently in MFCs with the MnO_2, Fe_3O, or Pd anode than with the carbon black (CB)-altered control anode, with elimination rates of 81.5–84.0% for CBZ, 48.7–52.6% for DCF, and 18.8–20.1% for IBF. While the CB anode obtained 28.8% for DCF, 71.0–78.5% for CBZ, and 14.6% for IBF, the corresponding portions using the CB anode achieved 71.0–78.5% for CBZ, 14.6% for IBF, and 28.8% for DCF. PhACs were removed at a reduced rate when a commonly used noncarrier (nonwoven) was employed as the anode of the MFC, showing that MFCs had distinct benefits in the removal of PhACs. Enhanced electron transport, a particularly rich microbial community, and the exclusive catalytic activities of the intermetallic oxides deposited on the anodes might improve MFC power generation and PhAC-removal effectiveness [63].

Birjandi et al. [64] proposed a microbial propulsion system with anodic bio-oxidation injected with seed sludge as an efficient biocatalyst combined with cathodic electro-Fenton integrated with a Fe_2O_3/graphite composite electrode for enhanced medicinal herb sewage treatment. The effect of HRT and industrial effluent organic loading rate (OLR) on the treatment efficiency and power balance of the BEF system were explored. With an HRT of 83.33 h and OLR of 0.58 g L^{-1} d^{-1}, the constant BEF system removed 93% of COD and had a BOD_5/COD ratio of 0.89. With an OLR 5.77 g L^{-1} d^{-1} and HRT 5.21 h, a highest current productivity of 603.86 mA m^2, a power density of 183.06 mW m^{-2} a, and a voltage of 892 mV were attained. The coulombic and energy densities were 5.36 and 65.33%, respectively. For simultaneous energy generation and COD extraction from PWW, the optimal HRT was found to be around 11–21 h [64]. The discharge of ECs into the atmosphere has created a great concern due to their negative impacts on the environment. Several kinds of research have been conducted to identify efficient techniques to remove these substances. The elimination of four ECs (sulfamethazine, bisphenol A (BPA), triclocarban (TCC), and estrone) from the MFC–Fenton system (Figure 2) was explored in an experiment [65]. MFCs were compared in batch and continuous flow modes, whereas the operational factors were investigated for increased H_2O_2 yield. The production of OH radicals was demonstrated through salicylic acid breakdown and the creation of its OH products by combining in situ H_2O_2 synthesis with an Fe^{2+} addition in the cathodic compartment. Estrone, BPA, TCC, and sulfamethazine could all be removed using the MFC–Fenton technique. The oxidation by the OH radical and permeation on graphite materials were responsible for eliminating ECs [65].

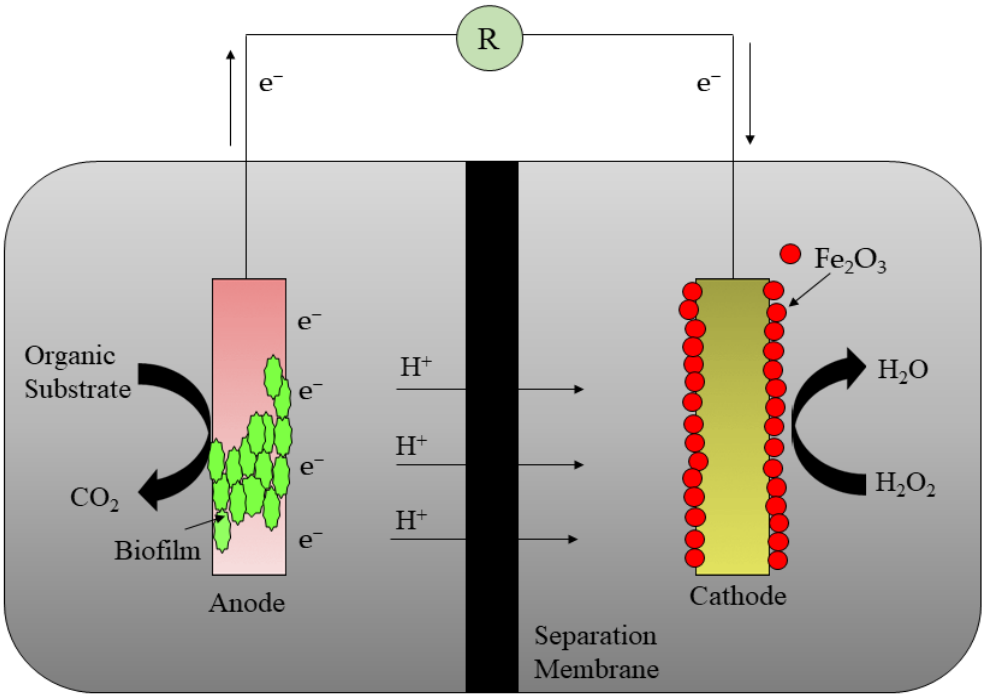

Figure 2. Schematic representation of the MFC–Fenton system.

The recovery of nutrients from source-separated human urine has caught the interest of researchers since it is abundant in nitrogen and phosphorus, both of which may be utilized as fertilizers. Medicines, steroid hormones, and other compounds discovered in urine, on the other hand, must be eliminated since they wreak havoc on the environment and human health. Sharma et al. [66] reported how a double-chamber MFC can degrade medicines. Four medications were added to urine at a concentration of 2 mg L^{-1} (trimethoprim, lamivudine, levofloxacin, and estrone); the greatest removal rate attained was approximately 96%. Sorption and anoxic biodegradation were part of the degradation mechanisms. The voltage curve showed that the availability of medicines, together with growing organic content, initially had a detrimental impact on power generation; however, after reactor acclimation, a higher power output was attained, with maximal organics extraction after 30 h of retention time [66]. Table 3 provides the information about various pharmaceutical drugs and molecules degraded using MFCs.

Sogani et al. [67] used an MFC to examine the biodegradation capacity of ethinylestradiol (EE2) in anaerobic conditions, exploiting the exoelectrogenic behavior of *Rhodopseudomonas palustris*. EE2, a common element in oral contraceptives, is a major estrogenic micropollutant found in several kinds of PWW and is believed to be refractory. When EE2 was employed with glycerol as the major carbon source in the culture medium, an initial EE2 concentration of 1 mg L^{-1} resulted in a 70% EE2 breakdown over 16 d and a 63% rise in H_2 generation when employed in an anaerobic photobioreactor. EE2 degradation increased to 89.82% with a maximum power density of 0.633. The hybrid MFC used in this study could digest EE2 and maintain biohydrogen production for 14 d, allowing the MFC to run longer than it could with glycerol alone, increasing overall energy output [67].

Single-chamber MFCs were utilized to treat steroidal drug production wastewater (SPW) and generate electricity. The highest COD elimination potential was 82%, while the total sulfate and nitrogen removal rates were found to be 26.46 and 62.47%, respectively. The greatest power density and coulombic efficiencies were 22.3 W m^{-3} and 30%, respectively. The SEM revealed that the dominating microbial communities on the surface of the SPW and acetate-fed anodes had noticeably different shapes. This study revealed that MFCs fed with SPW have a high power density and the ability to remove nutrients simultaneously [68].

Table 3. Degradation of different Pharmaceutical wastes in MFCs.

SL No.	Other Pharmaceutical Compounds	Initial Wastewater Concentration	Time	Rate of Antibiotic Elimination	Power Produced	References
1.	Trimethoprim, lamivudine, levofloxacin, and estrone	2 g mL^{-1}	30 h	~97%	High energy production	[66]
2.	COD	-	5.21 h	93%	183.06 mW m^{-2}	[64]
3.	TDS and COD	800 to 515 mg L^{-1} (TDS); 5460 to 1060 mg L^{-1} (COD)	-	35.2% (TDS) and 80.55% (COD)	High energy production	[8]
4.	Nitrate, phosphate and COD	-	-	97.12% (nitrate); 93.7% (phosphate); 77.3% (COD)	838.68 mW m^{-2}	[69]
5.	COD and NH_4^+-N	0.01 g L^{-1}	-	39.68% (NH_4^+-N); 93.68% (COD)	18.67 W m^{-3}	[70]
6.	Ciprofloxacin	10 mg L^{-1}	88 h	99%	-	[61]
7.	Recalcitrant pollutants	2.52 g COD L^{-1}	8 d	90% (SCOD); 92% (TCOD); 73% (TSS); 82% (COD)	High energy production	[58]
8.	Triclosan	5.8 mg L^{-1}	96 h	50 to 80%	Intra particle diffusion	[71]

5. Advantages of MFC over Traditional Processes

The advantages of MFCs advantages include direct power production, energy-efficient processes, anaerobic treatment due to minimal sludge output, centralized and decentralized applications, and a lack of expensive aeration (Figure 3). These advantages also include environmental factors, such as water reuse, low carbon emissions, and a relatively small carbon footprint; economic factors, such as money from energy, less expense, and the elimination of downstream methods; and operational advantages, such as self-generation of microbes, strong resilience to environmental stresses, and real-time monitoring. Some of the other key advantages of MFC technology are increased conversion efficacy from substrates to energy, reduced sludge volume, and recovery of elevated products [72]. MFCs generate clean power directly from organic matter in contaminated water, eliminating the need for energy product separation, purification, and conversion. On the other hand, methane and hydrogen may be generated by anaerobic digestion, and they must be separated and purified before being used. MFCs are ecologically beneficial technologies because they may directly create clean power and operate at low temperatures, especially at ambient temperatures [73].

Using the biological decomposition of organic material to create energy, the treatment of polluted water using MFCs has also been explored for the elimination and recovery of pollutants such as heavy metals, ammonia (NH_3), and COD [74]. Furthermore, due to the production of CH_4, H_2O_2, H_2, and other elevated recovery products, such as heavy metals, the recovery of elevated products has recently been explored with respect to MFCs. As a result, MFCs have been designed as a viable option for producing bio-electricity with several advantages, including cleanliness, efficacy, recyclability, and fewer hazardous products [75].

The conventional treatment plant only requires pumps, fans, and a biological tank, while initial investments for MFCs may include electrodes, a DC/AC converter, membranes, pumps, and a fan. When considering a conventional system, various investments need to be calculated; costs for operating treatment plants with 100 m^3 of volume include labor costs that take up 35% of the investment, around EUR 3248/yr, and the management of sludge costs 19% of the investment, i.e., EUR 1763/yr, while 34% of the overall cost is utilized for electricity, i.e., EUR 3155/yr, indicating that most of the investment is carried out for providing labor and electricity for the plant. On the other hand, MFCs can reduce the overall cost because of their automation and no associated necessity for aeration at the wastewater treatment plant. Based on this estimation, it has been reported that MFCs can provide high economic benefits, and the overall operating cost can be around EUR

1700–2300/yr, which is comparatively much lower than the conventional process. However, this estimate is only valid if there is no requirement of replacing electrodes or membranes. It is necessary to construct highly durable parts for MFCs in order to make the process more economically viable because the capital cost is high in comparison to the operating cost, which is directly in contrast to the conventional treatment system.

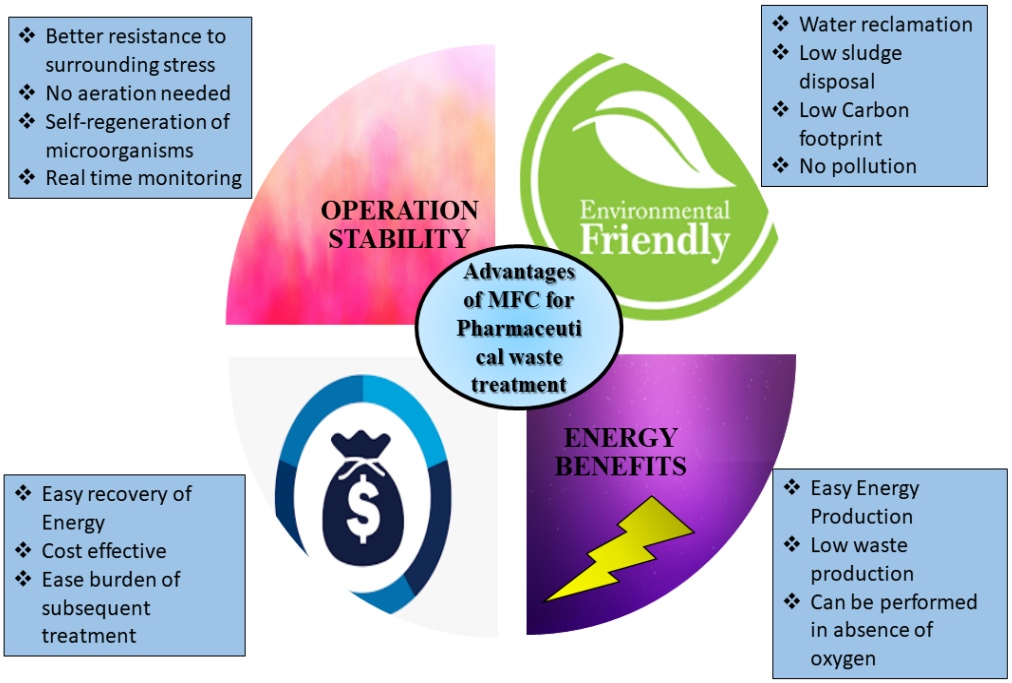

Figure 3. An illustration summarizing the benefits of employing MFCs to treat PWW.

6. Challenges and Future Perspectives

The efficient and cost-effective design for scaled-up versions of laboratory-size reactors is one of the most difficult issues in the commercialization of MFCs. In the case of decontamination and electricity production, laboratory-size MFCs have demonstrated outstanding results. However, many aspects must be addressed to duplicate such results on a large scale, including the separator's configuration, mechanical strength, electrode cost, manner of oxidant supply, energy and space requirements, and so on [76]. Most microbial electrochemical processes are based on oxidation–reduction reactions, which various operational variables affect. For practical applications, the commercialization of MFCs is a major concern. One of the primary flaws of MFCs is their low power output, which may be rectified in various ways. Electrodes heavily influence the performance of MFCs. Surface-treating electrodes to promote microbial affinity can improve the performance of an MFC. There are still several obstacles to resolve before MFCs may be used in the physical world, and few studies have been conducted on the long-term operation of MFCs. MFCs have a quick execution time when it comes to removing contaminants. The key to fully deploying MFCs in the field is to improve long-term operational stability.

Furthermore, the majority of present MFC research has been conducted in the laboratory and should be extended to actual applications [77]. CW-MFCs have demonstrated good results in complicated sewage treatment and recuperated green energy, reducing the demand for fossil fuels in the traditional treatment process. However, the low realistic power output for direct application is a key problem for CW-MFCs [78]. As a result, more research is required to better understand the operating mechanism of CW-MFC systems to enhance power generation while preserving financial sustainability. A techno-economic assessment of MFCs with dual cathode systems treating wastewater was conducted by Trapero et al. [74] under different scenarios considering the pessimistic, optimistic, and

maximum power density of the cell with and without Pt cathodes. The results under most of the scenarios revealed that MFCs are a more attractive and profitable option compared to conventional processes. However, Escapa et al. [79] reported several optimistic scenarios based on techno-economic parameters for hydrogen production, and they identified that hydrogen can be an important technical barrier if hydrogen is not well managed on the cathode side.

7. Conclusions

With the ever-rising global population, environmental regulatory authorities have pushed researchers to create or offer novel techniques and technologies for the betterment of environmental and human well-being. Because of the complexities of pharmaceutical processes, PWW possesses diverse characteristics resulting in the high concentration and limited biodegradability of pollutants. Appropriate treatments for PWW are thus critical, while the development and application of effective, feasible, and sustainable technologies is of utmost important for the efficient treatment of PWW. Although MFC technology has immense potential for PWW treatment and other wastewaters, the appropriate and cost-effective design of scaled-up versions of laboratory-size reactors is one of the most challenging aspects in the commercialization of MFCs.

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