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Synergy of Electrochemistry and Microbiology for Wastewater Treatment: Bio-electro-Fenton Processes

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Abstract

A major global problem is the degradation of the quality of water brought on by a broad range of persistent organic pollutants (POPs). The conventional superior oxidation technique often falls short, is dangerous, and requires post-treatment to get rid of any remaining H_2O_2. The bio electrochemical system-supported enhanced oxidation processes have found a position in this environment in which they could quickly take over, particularly for POPs elimination. Regarding electric power usage and operating costs, the Bio-electro-Fenton (BEF) system significantly lowered the costs associated with Wastewater (Ww) treatment when compared to existing Electro-Fenton (EF) systems. The BEF system is evolving into a multipurpose technology platform that provides a fresh approach to resolving significant environmental challenges associated with the treatment of Ww. In particular, the treatment performance connected to particle design and important operational variables is examined in this paper's comprehensive evaluation of published research on POP degrading in BEF systems. The review's objective is to aid scientists and engineers in developing a basic understanding and essential viewpoint of the BEF process. Therefore, given this information, new chances for the advancement of this exciting technology for Ww treatment are going to develop.

Keywords: Bio electrochemical system, Ww treatment, persistent organic pollutants (POPs), microbial fuel cell (MFC), microbial electrolysis cells (MEC)

Full length article **Corresponding Author*, e-mail: v.swarupa@jainuniversity.ac.in

1. Introduction

Synergy in electrochemistry is the additive or interactive impact of many electrochemical factors. The investigation of how chemical and electrical energy are transformed into one another is known as electrochemistry. Electrochemistry is the study of the interactions between an electrode and an electrolyte, specifically the flow of electrons and ions across this contact. The creation and growth of several electrochemical components and methods, electrolyzes, fuel cells, sensors, batteries, and corrosion protection systems, all depend on improving the synergy of these electrochemical characteristics. Electrochemical devices are used in a broad variety of fields, and their efficiency, performance, and sustainability may be greatly enhanced by tapping into the synergy of electrochemistry [1]. Treatment of Ww, also known as sewage treatment or water purification, is necessary before the water may be released into the environment or utilized for other uses. Water that has been used for anything other than its intended purpose such as in a toilet or sink contains a broad array of pollutants that may be detrimental to the environment and public health if not properly handled. To ensure that treated Ww does not pose a threat to aquatic life or human health, it must first have its pollutant concentrations reduced to an acceptable level. The field of microbiology is very important to the Ww treatment industry. To guarantee safe disposal or reuse, Ww must be treated to remove or reduce toxins and pollutants. Bacteria in particular play a crucial role in Ww treatment by decomposing organic materials, extracting nutrients, and degrading a wide range of contaminants. Water is essential for the world's environment and necessary for life. However, as the population has grown and the economy has grown quickly, water contamination has become worse [2]. In Ww treatment, the synergy of electrochemistry and microbiology refers to the integration of these two disciplines to increase the removal of contaminants and raise the overall effectiveness of the treatment process. It entails using electrochemical methods to speed up microbial reactions, encourages microbial expansion, and increase the breakdown of organic and inorganic pollutants found in Ww. Electrical energy is used in the field of

electrochemistry for accelerating chemical processes. To encourage microbiological action, improve the removal of contaminants, and sterilize the Ww, electrochemical processes may be used in the framework of the treatment of Ww. Such electrochemical methods involve electrochemical sterilization, electro-oxidation, electroflotation, and electrocoagulation. In contrast, the study of microorganisms and how they interact with their surroundings is the main objective of microbiology [3].

The BEF method is an advanced electrochemical oxidation technique for removing organic pollutants in water and Ww that combines the EF technology with biological processes. Drugs, pesticides, dyes, and other organic contaminants can be degraded and eliminated rapidly and sustainably. The BEF process shows promise as a novel and eco-friendly approach to water and Ww treatment, offering a realistic answer to the issues caused by organic pollution in a wide range of commercial and urban environments [4]. The advantages of electrochemistry and microbiology can be combined in the treatment of Ww by applying BEF techniques. These methods combine electrochemical and biological principles to better remove organic pollutants and boost Ww treatment efficiency. The electrochemical oxidation of Fe (II) at the anode in BEF processes results in the production of reactive oxygen species (ROS). Hydrogen peroxide (H_2O_2) and other highly reactive ROS may degrade organic pollutants in Ww. Using electrochemistry in this process is advantageous since it allows for efficient ROS production, which is otherwise challenging to do using only biological methods. Because of their role in facilitating the complete decomposition of organic pollutants, microbes play a pivotal role in BEF processes. In order to convert oxygen into hydroxide ions and hydrogen peroxide, microorganisms are commonly immobilized in these processes on the cathode surface or in biofilms. It's possible that the H_2O_2 formed might react with Fe (II) at the anode, producing OH [5]. The paper [6] concentrated on an iron phthalocyanine compound with aligned CNTs on the surface of a carbon felt electrode to improve the reaction rate of hydrogen peroxide and the electrical plate at the cathode of a BEF microbial fuel cell system. The cathode plate's properties were evaluated by experiments using polarization curves and power density, reactive black five decolourization, and scanning electron microscopy (SEM).

The paper [7] offered an overview of the combination of Advanced Oxidation Processes (AOPs) with Microbial electrochemical systems (MES) and highlighted the obstacles that must be overcome to establish AOP-MES systems for treatment. These difficulties include but are not limited to, an improved comprehension of electron flow processes, the creation of low-cost membranes, and the synergistic effects among useful substances and bacteria. The research [8] determined tremendous promise for the long-term treatment of antimicrobial Ww and is capable of maintaining its stability. To concurrently decompose levofloxacin and tetracycline Ww, a dual-chamber moving BEF device was built using Fe@Co/GF as the electrode. The study [9] used erythromycin as a model antibiotic component to test the simultaneous elimination of antibiotics and ARGs and the production of biological electricity in a microbial EF device. Antibiotic resistance genes are developing contaminants in the environment that represent a serious threat to the general population, and their development has been hastened by the antibiotics' widespread application. The paper [10] summarized the latest up-to-date literature on this topic, with an emphasis on electrochemical advanced oxidation methods that have shown to be effective in removing organic bio-recalcitrant molecules. Electrochemical methods that may eliminate xenobiotic chemicals from Ww, and biotechnology that allows minerals to form the biodegradable portion, would be an appropriate mixture. The article discussed novel reactor types, in particular, how changing the geometry, and oxygen supply might increase the efficiency of deterioration and decrease the cost of the EF process. Then, to facilitate expansion, the continuous nature of the process is taken into account. Ww treatment is a global issue because of the severe consequences for ecosystems and human health that improper disposal may have. The study [11] determined the basics of the EF process, including its main system, the characteristics of an extremely efficient heterogeneous catalyst, the heterogeneous EF system enabled by Fe-functionalized cathodic substances, and its crucial operational variables. This eco-friendly technology may be put to good use in solving the world's growing water problems. The research [12] provided the needle coke was loaded with ferrous ions to create a new EF cathode for use in a homogeneous EF device for treating coking Ww. The most effective electrode preparation conditions and key parameters influencing the treatment of coking Ww were studied.

The research [13] examined how well this technique works under varying electrical circuit conditions for treating synthetic Ww containing tetracycline and producing power. The unique concept of the microbial EF system may be used to remove persistent organic pollutants while also producing sustainable electricity from the metabolism of anaerobic microbes. The article [14] provided an overview of the EF process, including its primary system, key attributes of a highly effective heterogeneous catalyst, and the heterogeneous EF system enabled by Fe-functionalized cathodic materials, as well as its critical parameters for operation. The research [15] focused on how e microbial fuel cell (MFC) technology may be used, namely for the generation of energy. The MFC has shown significant promise as a renewable energy source in recent decades thanks to its electrochemical mechanism for creating bio-energy. Anode and cathode MFC have been used to generate electricity from organic materials like bacteria used in Ww treatment. The study comprehensively describes and systematizes the most current advancement, which might open up new opportunities for the advancement of BEF technology, to give timely updates in this crucial domain. Figure 1 demonstrated the BEF systems became the focus of considerable research and development.

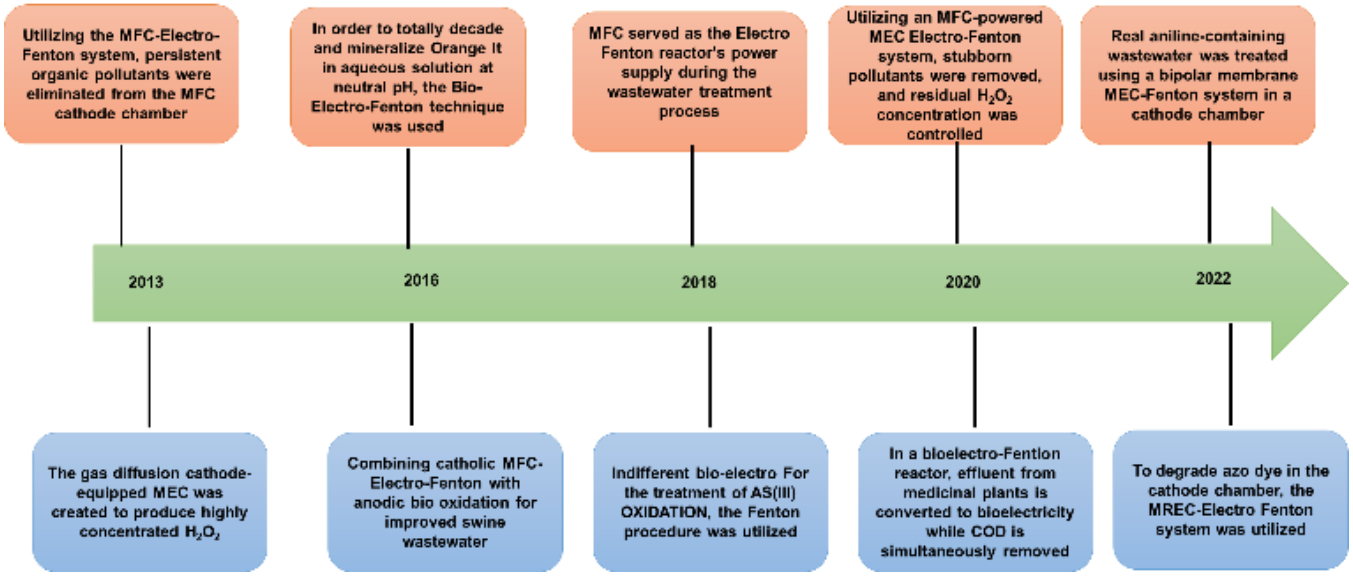

Figure 1: Significant developments in BEF systems

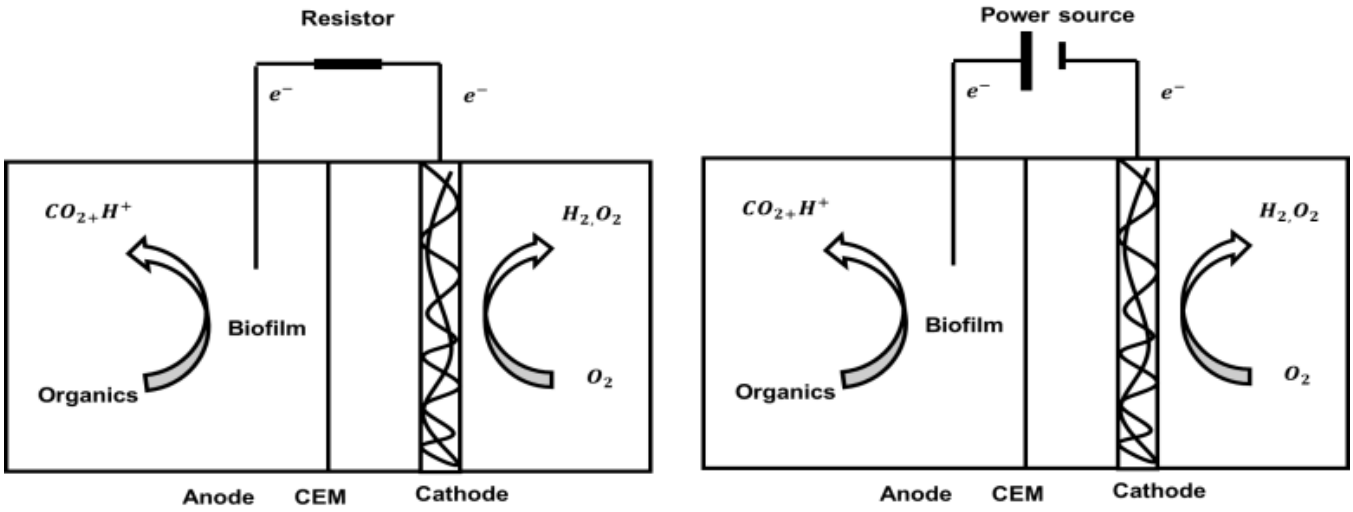

Figure 2: H_2O_2 production and MFC/MEC schematic

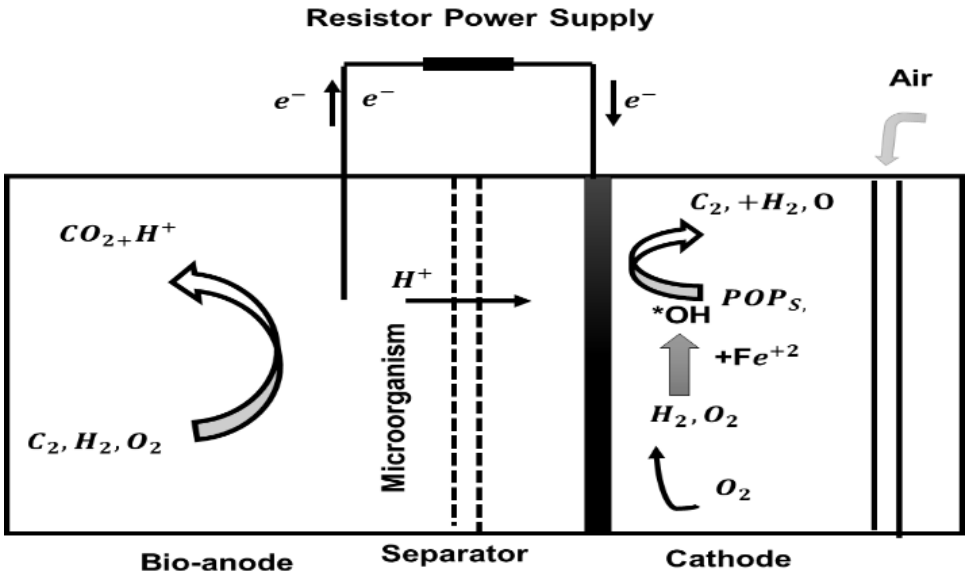

Figure 3: Typical bio-electro-Fenton system schematic

2. Bio-electron-Fenton system mechanisms

Bio electrochemical systems like Microbial Fuel cells (MFCs) and Microbial Electrolysis Cells (MECs) have recently been shown to be additional ways to produce H_2O_2. The separation barrier divides the bio-anode and cathode sections in MFCs in theory. The microbes that develop on an anode metabolize organic substances in Ww while simultaneously generating protons and electrons. The electrons, and protons approach the cathode space through the protective barrier and the circuit outside. Once inside, they can interact with oxygen to produce H_2O_2 while also generating energy. The cathode of MECs, which were created from MFCs, produces H_2O_2 with a low input of energy shown in Figure 2. However, compared to MFCs, the velocity of H_2O_2 generation in MECs was significantly higher. H_2O_2 synthesis in MECs uses substantially less energy than typical electrochemical processes; the published research's power consumption was just .93 kWh/kg H_2O_2. The optimal H_2O_2 generation parameters and optimum amount of H_2O_2 in various bio electrochemical processes are noticeably different shown in Table 1. With varied materials for the cathode and optimal operating settings, for instance, the highest H_2O_2 levels in MFCs were between 79 and 196 mg L-1. BEF technologies was the term given to the combined technologies. The BEF devices usually consist of a pair of chambers divided by a covering, as illustrated in Figure 3. POP-containing sewage is pumped into the aerobic cathode chamber when the anaerobic anode is supplied with Ww carrying biodegradable organic materials. Where biodegradable organic materials are oxidized by microbes, almost all BEF technologies adhere to the same basic concept. At the anode shown in Eq. 1, the oxidation activities liberate the electrons, which are then sent over a different circuit to the cathode. Similar to traditional bio electrochemical systems, BEF systems operate on a similar basis and may make use of almost any anode materials and microorganisms. The cathode chamber is where the EF reactions mostly take place. The EF reaction mechanism has received much elucidation. To oxidize pollutants, oxygen undergoes a 2-electron decrease on the cathode, resulting in the creation of H_2O_2 in Eq. 2 and a further reaction by Fe2+ to create •OH in Eq. 3. High H_2O_2 generation rate and concentration are required to achieve the extraordinary performance of contaminants in BEF schemes. Additionally, Eq. 4 may be used to regenerate Fe2+. The cathode chamber's reaction mechanism is comparable to the traditional EF technique.

$$C_aH_bO_c + (2x - z)H_2O \rightarrow x\,CO_2 + (4a + b - 2c)H^+ + (4a + b - 2c)e^- \quad (1)$$

$$O_2 + 2H^+ + 2e^- \rightarrow H_2O_2 \quad (2)$$

$$Fe^{2+} + H_2O_2 + H^+ \rightarrow Fe^{3+} + *OH + H_2O \quad (3)$$

$$Fe^{3+} + e' \rightarrow Fe^{2+} \quad (4)$$

3. BEF system configurations

The fast advancement in the construction of new bases has been made possible by intensive research into BEF systems. Many other BEF systems with various configurations have been suggested at the moment.

3.1 MFC-EF system

The capacity of the MFC-EF technology to breakdown and minerals POPs in water-based solutions. POPs are eliminated from the cathode area of the MFC-EF device through the use of an EF. Reaction in addition to biodegradable organic substances from the anode region. They also reported that by employing the MFC-EF system with a nanotube carbon (CNT/-FeOOH) combination cathode, Orange II had been effectively decolored and mineralization. In contrast to the more traditional EF and Fenton processes, the MFC-EF method offers several compensations. The electron-Fenton reaction is self-powered, with superior use of H_2O_2 and Fe2+ than other dosing techniques, since both the Fenton reagents may be created in situ and utilized quickly to make •OH. The current is generated by transferring electrons from the anode to the cathode, where they are obtained by exoelectrogenic microbes.

3.2 MEC-EF system

Production of H_2O_2 using MECs is a potential alternative strategy. Even though MECs only need a fraction of the power that MFCs need, their H_2O_2 generation rate and output are much greater. Since MECs have the potential to generate greater H_2O_2 than MFCs, they may be preferable for use in the Fenton process. This means that Wws with relatively significant amounts of contaminants are a good candidate for treatment using the MEC EF reactor. The MEC-EF system's primary differentiation from the conventional EF system is the incorporation of electroactive bacteria at the anode. EF procedure aniline treatment cost 74 kWh kg-1-aniline, whereas .728 kWh kg-1-aniline was used for the same amount of work. Aniline elimination within the EF system is much higher than in the MEC-EF system, although rates of elimination for other POPs are reduced in the EF system and may reach 315 mg L-1 h -1, in the MEC-EF system it was only 30±.4 mg L-1 h-1. The MEC-EF system has the potential for removing Ww with comparatively high concentrations of POPs, as opposed to MFC-EF systems. By using a separate power source to increase the voltage, elimination rates were dramatically increased above those of MFC-EF systems.

3.3 MEC-EF is driven by MFC

MFC is being utilized for powering the MEC-EF reaction as shown in Figure 4C to decrease the consumption of electricity. Two-chamber MEC-EF system could be powered by a single-chamber MFC, opening up new avenues for the treatment of stubborn contaminants. By using 4 MFC reactors as a power source, the H_2O_2 generation and pollutant degradation were enhanced. This approach offers two major benefits. (1) MFC may generate electricity without the need for external power sources or chemical additives, (2) Residue H_2O_2 elimination, among the major difficulties in Fenton-like processes, could be readily controlled and in-situ eliminated by modifying the operating mode. One of the most promising methods for eliminating POPs and organic contaminants from Ww is the MEC-EF system that is powered by MFC. However, many flaws still need to be fixed before the technology can be placed into action in business. When contrasted to the traditional EF technique, the contaminant's elimination rate, and electrical current density, for instance, continue to be poor.

Table 1: H_2O_2 generation in various bio electrochemical systems

Cathode material	**Cathode area**	**Cathode potential**	**Current or Current density[e]**	**Gas flow rate**	H_2O_2 **Concentration (mg L^{-1})**	**External voltage**	**Operation time**	**Cathode chamber volume**
Graphite/carbon	6 cm^2	-1.5 V	-	-	38.8±10.5	b	-	13 mL
Graphite rod	184 cm^2	-	5.4 ± 10.8A m^{-2}	-	~1400	0.4 V	5 h	-
Graphite rod	18.83 cm^2	-0.24 V	-	50 mL min^{-1}	78.86	-	10 h	60 mL
Graphite plate	8 cm^2	-0.45 V	1.44±.08 Am^{-2}	15 mL min^{-1}	779±15	-	70 h	30 mL
Graphite felt	24 cm^2	-	-	-	23.1±2.42	0.3 V	7 h	100 mL
Graphite felt	3 cm^2	-	1.15A m^{-2}	-	~15	-	-	15 mL
Graphite	3.13 cm^2	-	3.8 mA	-	500	c	22 h	10 mL
Graphite	32 cm^2	-1.8 V	7.5 ± 0.5Am^{-2}	850 mL min^{-1}	1448	b	48 h	50 mL
Graphite	14 cm^2	-	18.4A m^{-3}	-	196.6	-	20 h	168 mL
Graphite	49 cm^2	-	2.5 Am^{-2}	20 mL min^{-1}	440	a	15 h	250 mL
Graphite	15 cm^2	-0.84 V	-	-	711.3	0.4 V	9 h	63 mL
Graphene oxide	3.13 cm^2	-0.5 V	10 A m^{-2}	-	275	-	2 h	5 mL
Carbon felt	11 cm^2	-0.3 V	-	-	~.69	b	-	500 mL
Carbon cloth	78 cm^2	-0.7 V	1 A m^{-2}	-	240	-	5 h	100 mL
Carbon cloth	100 cm^2	-	3.4 Am^{-2} (c)	-	-	-	5 h	500 mL
Air cathode	48 cm^2	-	-	10 mL min^{-1}	3200	d	-	15 mL
Air cathode	31.3 cm^2	-	3.74 Am^{-2}	-	3200±350	d	-	15 mL

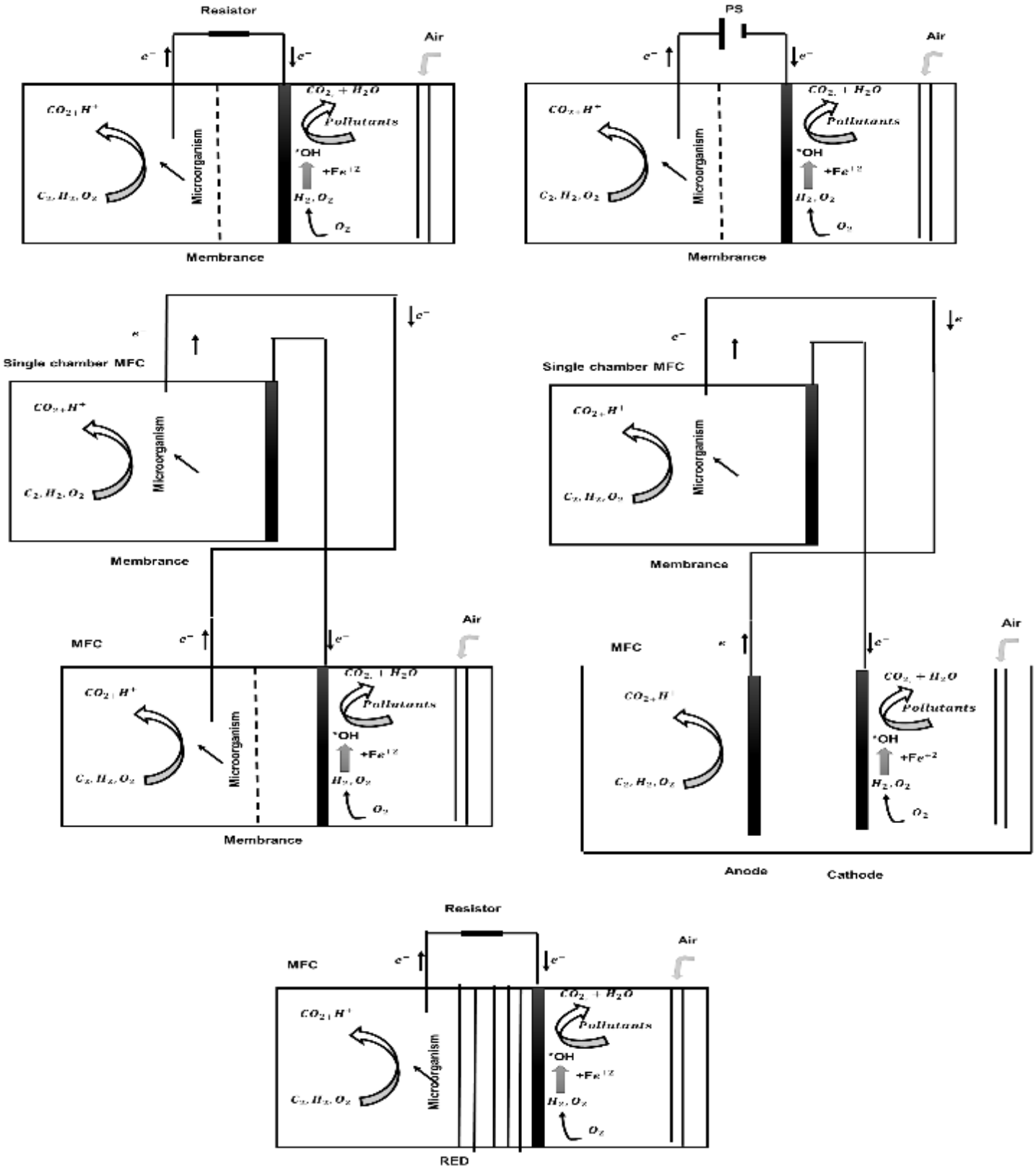

Figure 4: BEF systems diagram

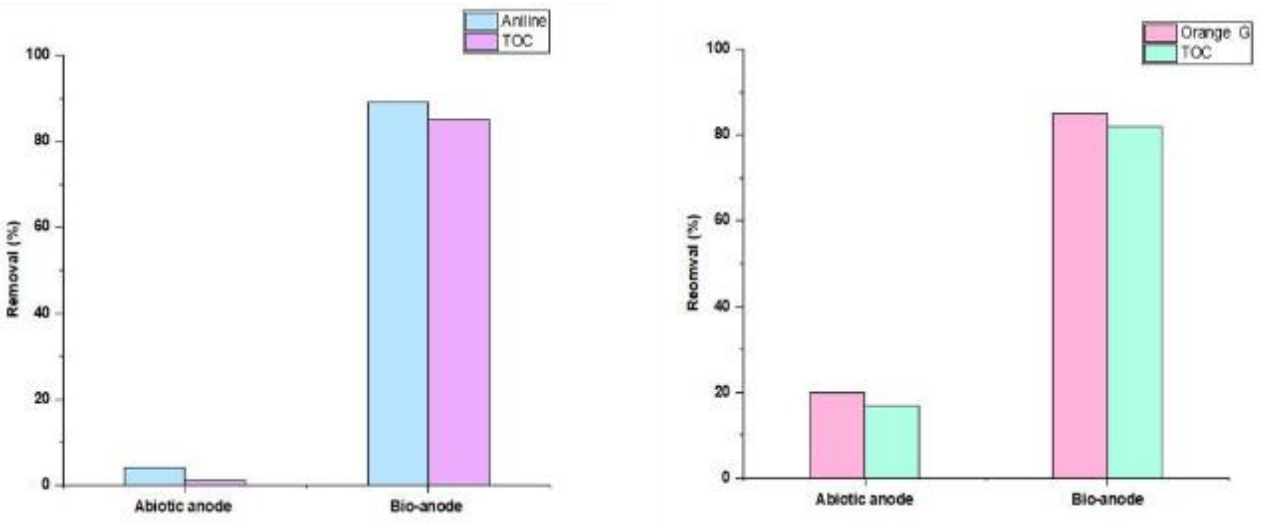

Figure 5: POP elimination in BEF and bio-anode.

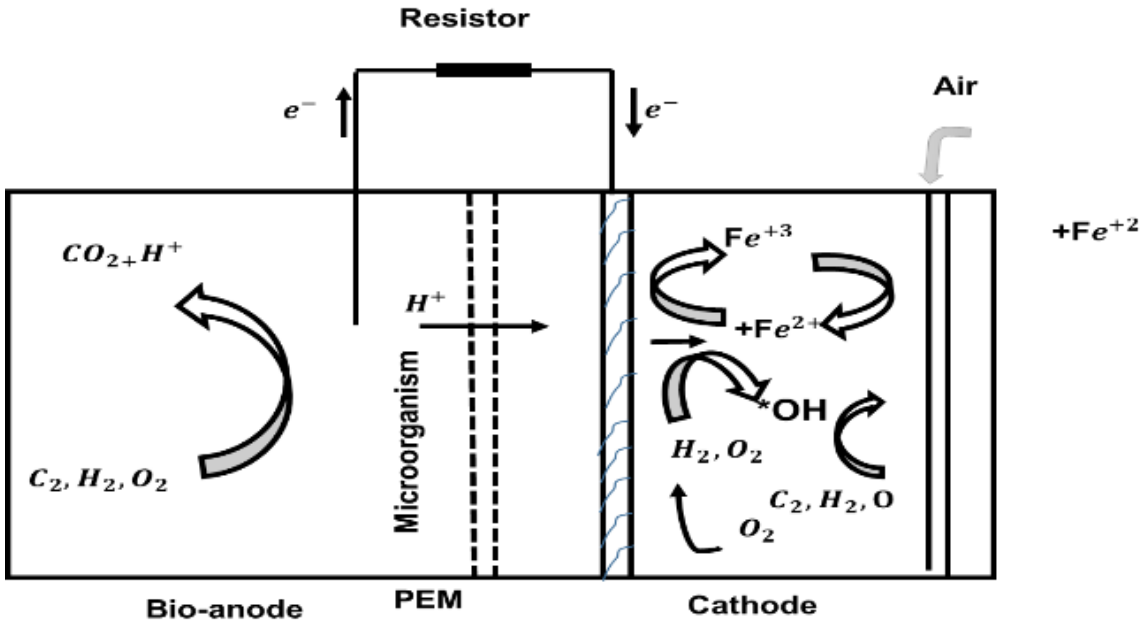

Figure 6: MFC-electro Fenton system with $FeFe_2O_3$/NCF cathode removing 17β-estradiol and 17α-ethyl-estradiol.

Table 2: Pollutant degradation in various bio-electro-Fenton system

Anodic inoculum	pH	Membrane	Concentration	Removal	Cathode chamber volume	Pollutants	Operating time
Shewanella discolorations	8	CEM	30 mg L−1	100%	70.6 mL	Orange II	40 h
Brewery wastewater	4	GORETEX cloth	18 mg L−1	95%	70 mL	Rhodamine B	15 h
Shewanella decolouration's S12	8	CEM	71 mg L−1	100%	70 mL	Orange II	55 h
Domestic wastewater	-	PEM	55 mg L−1	80%	140 mL	Reactive Black 5	10 h
Domestic wastewater	3	CEM and AEM	300 mg L−1	100%	20 mL	Orange G	15 h
Brewery wastewater	4	GORETEX cloth	1100 mg L−1	-	70 mL	2-propanol	70 h
Anaerobic sludge	4	PEM	30 µg L-1 30 µg L-1	85% 57%	70 mL	17β-estradiol 17α-ethynylestradiol	15 h
Domestic wastewater	3	CEM	30 µg L-1 .30 µg L-1 30 µg L-1. 30 µg L-1	62% 98% 87% 82%	150 mL	Ketoprofen Diclofenac Ibuprofen Naproxen	6 h
Brewery wastewater	2	GORETEX cloth	1600c	97.7%	400 mL	Swine Ww	13 h
Landfill leachate	4	CEM	2153±625c	85%	200 mL	Landfill leachate	-
Dairy wastewater	5	AEM	878.2c	78%	700 mL	Oily wastewater	180h
S. oneidensis MR-1	2	PEM	34.1 mg L−1	80.39%	20 mL	Triphenyltin chloride	200 h

Increasing the density of current and electricity generated by MEC through connecting several chamber MFCs in a series is possible, but the change in voltage makes this strategy impractical for prolonged use, and the amount of voltage used to power MEC also failed to increase proportionally when connected in this fashion. Therefore, additional studies could be conducted to enhance the power produced by MFC and the presence of MEC in future studies.

3.4 MREC-EF system

MREC, an identical hybrid bio-electrochemical structure, is an effective that allowing the generation of H_2O_2. In MREC, electric power generated by exoelectrogens and the salinity gradient among diverse salty and creative ways drove the production of H_2O_2 and the response of Fenton. This technology has enormous promise as an environmentally friendly way to treat non-biodegradable pollutants in the cathode chamber and biodegradable pollutants in the anode chamber without using any external power sources. The MREC-Fenton system's acceptable for the treatment of Ww covering azo dyes shown in Figure 4. Orange G Ww treatment only required 26 kWh kg-1 TOC, significant savings compared to the 45.7-865 kWh kg-1 TOC required by the standard EF procedure.

4. Bio-anode used in BEF systems

4.1 Anode materials

The economical anode components including a graphite felt, carbon, carbon cloth, activated carbon, or carbon mesh that are competent of effective transfer of electrons from microbes to the electrode in MFCs and MECs, could have a fantastic option for BEF systems because they communicate a comparable anode response with MFCs and MECs. In BEF mechanisms, carbon-based brushes, paper, cloth, and sensation have all been investigated so far shown in Table 2. The majority of research did not employ the anode's design and components as a goal. It is crucial to remember that the anode is an essential element since exoelectrogens that are developing with its surface send electrons to the electrode. Previous investigation has shown that the optimum material for anodes needs to have some of the following qualities: (a) great biological compatibility and excellent electric conductance; (b) suitable hardness and stiffness; (c)

chemical resistance and anti-corrosion; and (d) large area of activity on the surface.

4.2 Microorganisms on the Anode

Electrogenic bacteria catalyze electron transport from organic substances to an anodic state electrode, which is the primary feature of bio electrochemical processes. Domestic Ww, municipal Ww, brewery Ww, and anaerobic sewage sludge are only a few of the places where Electrogenic microbes have been discovered. Table 2 shows some common types of Electrogenic microorganisms utilized in BEF systems. Regarding TOC removal, Orange G mineralized followed an identical sequence as Orange G the decolourization process. The elimination of aniline and TOC when the bioelectric-Fenton system was employed to treat aniline Ww differed significantly among the systems utilizing abiotic anodes and bio-anodes shown in Figure 5. It takes a deep knowledge of microbe ecology to enhance the efficiency of mixed-culture BEF systems. To establish particular programs, which is the production of H_2O_2 in-situ for the elimination of POPs, it is necessary to comprehend the mechanisms and physiological actions of microbes. The microbial community structure of blended cultures is insufficiently established in BEF systems.

5. Main affecting parameters

The efficiency with which organic contaminants decay is influenced by a number of BEF system operating elements, such as Ww, cathode material, pH, catalytic dosage, airflow rate, cathode voltage, and starting contaminants concentration. A significant number of these factors need to be fine-tuned for optimal effectiveness in removal and least-expensive energy use.

5.1 Cathode material

The unique advantages of the BEF approach are the on-site electrolytic manufacturing of H_2O_2 via the oxygen reduction response and the degradation of the contaminants at the cathode electrodes. H_2O_2 production, a key component of the BEF reaction, is influenced by various types and characteristics of the materials used as cathodes. Different carbonaceous substances, such as carbon felt, graphite, gas-diffusion electrodes, and combination FePc/CNT/SS316 Cathodes, were extensively investigated as cathodes that enhance the reaction that reduces oxygen performance. Because of the carbon felts great particularly the outside, both components of the Fenton reaction may be formed quickly, and as a result, a small amount of H_2O_2 accumulates during the Fenton reaction, leading to the production of •OH. Three-dimensional carbonaceous materials such as active graphite felt, carbon felt, carbon felt, and carbon-PTFE oxygen dispersed electrodes are widely employed in the manufacturing of Fe customized carbonaceous cathode. Fe-functionalized carbonaceous cathodes are widely used efficiently as cathode to process Ww including contaminants at pH levels that are neutral.
These cathodes include carbon felt/-FeOOH, Fe@Fe2O3/NCF, Fe@Fe2O3/graphite, CNT/-FeOOH, Fe2O3/active carbon felt, and Fe@Fe2O3/carbon felt. In order to expedite the transit of the decreased form of Fe3+ to Fe2+ (Eq. 4), such electrodes might be employed as a solid Fe2+ source, negating the need for acidic pH changes.

5.2 Catalyst dosage

Since the velocity and amount of H_2O_2 generation in a bio electrochemical system could be kept consistent under controlled circumstances, the catalytic activity of Fe2+ may prove crucial to the system's overall efficacy. Recalcitrant organics elimination may improve when Fe2+ increases, as predicted by the interaction of Fe2+ and H_2O_2 for •OH production (Eq. 3). But there is a restriction to how much Fe2+ may be added. The reduction in the amount of •OH due to a high level of Fe2+ (Eq. 5) could decrease the effectiveness with which pollutants were degraded over time. Some of the problems facing solid iron oxides, including α-FeOOH, FeO, Fe3O4, and Fe2O3, have been studied as iron catalysts in the EF process because soluble Fe3+ may be converted to Fe2+ in cathode through reaction Eq. 4. How well iron oxides were able to release Fe2+ into the solution to catalyze the Fenton's reaction was correlated with how well they removed POPs.

$$Fe^{2+} + * OH \rightarrow Fe^{3+} + OH' \quad (5)$$

5.3 The current density

Since more H_2O_2 is produced at a given period, the rate of pollutant degradation generally rises according to rising power. The provided energy may alter the cathode potential, leading to unintended responses and diminishing the effectiveness of electricity and the elimination of contaminants. Therefore, it is not possible to permanently increase the current. The following are examples of possible close-to responses, 1) a high density of current by increasing the outside voltage to speed up the H_2O_2 lowering of potential by electrochemistry Eq. (6); 2) the H_2O_2 response with Fe3+ through Eqs. (7) And (8); and 3) the disintegration of •OH with H_2O_2 and Fe2+ through Eqs. (9) and (5).

$$H_2O_2 + 2H^+ + 2e' \rightarrow 2H_2 \quad (6)$$

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + HO^*2 + H^+ \quad (7)$$

$$Fe^{3+} + HO^*2 \rightarrow Fe^{3+} + O_2 + H^+ \quad (8)$$

$$H_2O_2 + * OH + H_2O + H_2 *_2 \quad (9)$$

The electrical charge effectiveness has to be taken into consideration being an important assessment criterion when selecting the best current or current density. The process of mineralization efficiency measurement (MCE) is frequently utilized to evaluate the effectiveness of single contaminant treatments. From Eq. (10), the MCE in batch mode is determined for a specific process time.

$$MCE(\%) = \frac{\Delta TOC\ n\ F\ V_S}{4.32\times10^7\ mlt} \quad (10)$$

6. Environmental applications

The goal of developing BEF methods to remove POPs from Ww is to safeguard aquatic environments and reuse water. In bio electrochemical systems, several exoelectrogenic bacteria on the anode can oxidize biodegradable organic substances. The Ww substrates that may be eliminated in bio electrochemical systems' anode chambers have been comprehensively reviewed in many prior papers. The primary focus of this study is a review of

POPs that can be broken down in the cathode chamber using the BEF method. This section will examine how medicines, dyes, and certain other industrial pollutants degrade in line with this categorization.

6.1 Pharmaceutical Wastewater

The pharmaceutical Ww was treated in conjunction with municipal wastewater as part of a co-treatment process. This wastewater was a significant source of medicines for sewage treatment facilities. Pharmaceuticals are notoriously difficult to destroy through biodegradation, making conventional WW treatment facilities particularly ineffective. A few drug poisons, including 17-estradiol, sulfadimidine, 17-ethynyl-estradiol, ketoprofen, paracetamol, diclofenac, naproxen, ibuprofen, and estrone, have remained analyzed to perceive how rapidly they corrupt in the cathode of the bio EF framework. MFCs with FeFe2O3/NCF cathodes, as shown in Figure 6, removed 17-estradiol at a rate of 81% and 17-ethynyl estradiol at a rate of 56%.

6.2 Dyes

Most of color were non-biodegradable and had an exceptionally high steadiness in soils and oceanic frameworks, making up a huge part of Ww release. Over 60% of all archived color parts are azo color, most of which are the salicylic corrosive subsidiaries of stringent azo color. However, the by-products are dangerous to ecosystems. Azo dyes including methylene blue, orange G, lissamine green B, crystal violet, and amaranth have been shown to be degraded and mineralized through the BEF technique in numerous earlier investigations. The azo requirement of orange II, for instance, might be broken by the electrochemical cycle in the cathode chamber.

6.3 Additional toxic substances from the industry

The major goal of these investigations was to show that contaminants may be degraded. P-nitrophenol, for instance, is often utilized in the production of insecticides, medications, explosives, herbicides, additional chemical products, and dyes. Ww containing p-nitrophenol is classified as hazardous waste due to its toxicity and carcinogenicity. A combination of the MFC-EF method, the p-nitrophenol that was previously contributing to the •OH oxidation was broken down. One of the most widely utilized organotin, triphenyltin tin chloride (TPTC), is poisonous, bio-resistant, and difficult to break down in the environment owing to the high degree of stability of the Sn-C connection.

7. Conclusion

The accomplishment of extraordinary deficiency rates, low energy requirements, also efficient removal has exposed the technological viability of BEF systems to degrade diverse forms of POPs. An evaluation of the benefits and drawbacks of several BEF system types has been done. It has also been rigorously assessed how operational parameters fit within the framework. Previous research mostly concentrated on using BEF systems at lab size to remediate synthetic Ww, pharmaceutical, often dye, or manufacturing Ww. Researchers have shifted their attention in recent years to actual Ww in flow reactors. Despite these advancements, nothing is known about how to enhance reactor design, scale it up, and use it commercially on an industrial scale. Moreover, determining the economic viability of BEF systems might be another fascinating yet challenging task. It is important to take into account the upfront expenditures for bio electrochemical systems as well as ongoing expenses for reagents, electrical energy use, and service.

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