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Analysis of Chemical-Biological and Physical-Biological Hybrid Systems for Wastewater Treatment Utilizing Aeration and Ozonation

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Abstract: Due to the high amounts of pollutants found in clean drinking, the availability of safe drinking water has appeared as a serious global concern. To achieve this, the most recent new concepts or methods must be devised in which a hybrid wastewater treatment method can efficiently eradicate contaminants. Many treatment approaches, including biological, physical, and chemical procedures, have been developed to remove various contaminants. Unfortunately, no single technology can presently remove pollutants effectively; hybrid systems have consistently proved more successful. Wastewater contains power in the form of decomposable organic material. The notion of cleaning wastewater while producing electricity has recently gained popularity, and a hybrid treatment system for wastewater makes this possible. In this study, hybrid wastewater systems are classified as physical-biological or chemical-biological. Compared to isolated systems, hybrid methods have demonstrated considerable possible benefits, including significantly better treatment efficacy, more sustainable and steady voltage production, and economic gains.

Keywords: hybrid system; wastewater treatment; aeration; pollutants; ozonation; bioenergy.

1. Introduction

The unprecedented doubling of freshwater utilization in recent years has positioned water as a critically finite resource, a trend exacerbated by its intensive use in agriculture, industry, domestic use, and transportation and exacerbated further by the emerging challenges of climate change [1,2]. As a result, scientists have increased their efforts in water purification innovation to enable water recycling, putting wastewater improvement approaches at the forefront of environmental research. The amounts of particle matter, chemicals, minerals, pollutants, and microbes, which include high-priority contaminants that define water purity, are crucial to water quality issues. Organic pollutants, often known as emerging contaminants (ECs), have recently received significant public and scientific attention. These ECs, which include a wide range of substances such as pharmaceuticals, personal care products (PPCPs), pesticides, and various industrial chemicals, pollute water and pose significant removal challenges for conventional wastewater treatment technologies [3]. Emerging contaminants such as PPCPs, which include sunscreen agents, stimulant drugs, lipid regulators, antibiotics, nonsteroidal anti-inflammatory drugs (NSAIDs), antiseptics, and cosmetic products, have been linked to ecological disruptions and human health problems such as decreased reproductive health and increased antibiotic resistance [4-7]. Pesticides, for example, have been shown to harm aquatic fauna and change key hematopoietic tissues in fish [8]. Surfactants, another type of EC, have the potential to disrupt endocrine systems by changing the stability of human growth hormone formulations [9].

Traditional wastewater treatment methods such as membrane filtration, photocatalysis, ultrafiltration, the Fenton process, electrochemical oxidation, activated carbon adsorption, ozonation, and hybrid membrane photocatalytic processes have demonstrated efficacy in addressing a wide range of pollutants [5,10-13]. Activated carbon therapy and ozonation are two of the most effective in the tertiary treatment phase [14]. Despite their success in eliminating ECs at high concentrations, conventional wastewater treatment facilities (WWTPs) have limits. Membrane processes consume much energy, activated carbon is less effective against bacteria, and ozonation can produce hazardous by-products [15]. Newer technical solutions, such as Advanced Oxidation Processes (AOPs), have been carefully studied for their ability to remove considerable levels of ECs from municipal wastewater, but widespread adoption is still in its early stages [16,17].

Furthermore, though still in the experimental stage, new treatment technologies like built wetlands, enzymatic treatment, and bioelectrical systems have demonstrated outstanding results in removing ECs in WWTPs where they have been trialed [18,19]. The variety of water purifying methods adds to the complexity of developing rules and regulations that may effectively prevent human and environmental health hazards while still using a massive, untapped water supply during times of scarcity. As a result, hybrid wastewater treatment systems are gaining popularity as sophisticated approaches for contamination removal [20]. Such technologies manage pollutant loads and capitalize on the energy content of biodegradable organic matter in wastewater—energy that we typically invest to remove rather than recover [21]. With a growing worldwide population and growing concern about environmental sustainability and fossil fuel dependency, there is a noticeable movement towards the development of renewable energy sources [22,23]. This trend is directing the global focus toward developing technical solutions that are not only sustainable but also contribute to clean and eco-friendly energy production. This paradigm change is embodied by hybrid treatment systems, which turn the wastewater treatment process from an energy-consuming to an energy-producing activity, potentially generating electricity or hydrogen.

This study comprehensively catalogs composite wastewater treatment facilities suitable to the treatment process, forecasts future trends, and provides a comprehensive resource for readers wishing to analyze hybrid system amalgamation. These technologies improve purifying efficiency and contribute to bioenergy generation, which might be used to power the facilities themselves, promoting operational energy efficiency.

2. Emerging Contaminant Source and Transport into Water

ECs are commonly found in wastewater discharged by WWTPs, manufacturing units, health-care services, housing neighborhoods, farmland runoff, and landfill effluent [24,25]. They can originate through both non-point and point sources, and their concentrations in water range from parts per billion(s) (p.p.b. or g/L) to parts per trillion(s) (p.p.t. or ng/L^{-1}) [26]. Despite the fact that EPs have been present in the environment for a long time, involvement in them has only risen over the past twenty years due to advances in analysis methods like Ultra High-Performance Liquid Chromatography (UHPLC), Solid Phase Extraction (SPE), Solid Phase Micro Extraction (SPME), High Performance Liquid Chromatography Coupled Mass

Spectrometry (HPLC-MS) and Liquid Chromatography Mass Spectrometry Tandem Mass Spectrometry (LC-MS/MS) which enable identification at lower concentration in water (including surface and groundwater), earth, air, and silt [27,28]. WWTPs effluents are rapidly being recognised as the primary source of ECs in the ecosystem, as drainage through both commercial and domestic areas gathers in WWTPs [29]. EC elimination effectiveness ranged from 20-50% in initial WWTP treatments to 30-70% in subsidiary treatment and a little over 90% in final treatment [12]. As a result, the final treatment stage in WWTPs is regarded as the most important for EC removal.

Nonetheless, complete EC eradication remains impossible. After being discharged into WWTPs, ECs either remain largely unaltered or are converted into molecules that are significantly more damaging and poisonous than their counterparts. This will also be observed in locations where they've not previously been employed. Commercial trash, industry smoke, municipal sewage, and agricultural waste are the principal sources of these pollutants, which may travel fast through the air and water from one place to another. Pharmacological wastes and biological compounds decomposition in neutral locations can also produce ECs. These organic micropollutants can also be encountered in water that is consumed [30,31]. Excessive chemical and organic micropollutants lead WWTPs to become a significant source of these poisons [32]. After being collected from wastewater, these poisons are disposed of or burned up, which essentially describes the source-to-receiver connection as sorption, dispersion, and volatilization between locations. Despite the fact that this contains certain additional toxins that may or may not be removed from WWTP, many people continue to rely on groundwater. Nonetheless, freshwater, including groundwater as well as surface water, includes trace levels of micropollutants generated by aquatic species.

2.1. Negative effects of rising pollutants on human well-being and the ecosystem.

The impacts of ECs on wildlife have been widely documented, but the direct consequences on people are still being studied. Humans are exposed to Endocrine Disrupting Chemicals (EDCs) come primarily from consuming infected types of food and refreshments with water, soil, microbes, animals, and plants. This can take the form of bioaccumulation as well as bio-magnification, particularly for animals at the supreme level of the food chain. However, there is little evidence on the toxicity and effects of heavy metal ions, EDCs, and Bisphenol-A (BPA), which are primarily found in runoff from surface water, landfill sites, seepage, and WWTPs [33,34]. Pharmaceutical and personal care items can have an impact on the development, reproduction, and development of organisms in the environment. The entire knowledge catalog is limited due to these contaminants' intricacy and physical-chemical characteristics in soil, air, and water.

2.2. Physical treatments.

Physical purification of wastewater denotes the elimination of ECs without modifying the contaminants' biochemical attributes, as these treatment methods overlook the impact of any chemical or biological agents. Physical therapies are often performed before either chemical or biological treatments. Screening, skimming, sedimentation, adsorption, membrane-based technologies, heat treatment, aeration, and other physical treatment procedures are routinely used. The mass and heat transfer approach is used in the physical and chemical methods [35]. The main benefit of employing mechanical treatments is that they have been technically simple and adaptable since they require minimal equipment that may be modified to a range of therapeutic forms [36,37]. Also, when compared to other processes, the creation of particulate waste is substantially lower.

2.3. Biological treatments.

In biological therapy, ECs are eliminated by utilizing various biological species or biological processes. This therapy aims to create a mechanism for efficiently disposing of breakdown products [38]. Biological therapy is popular since it is less expensive than physical or chemical therapies [39]. This therapy employs a natural cellular mechanism and relies on bacteria, nematodes, and other organisms for organic waste decomposition [40]. These treatments generally occur in the tertiary or secondary phase of the process and aim for the considerable elimination of pollutants by biodegradation. Since hazardous pollutants impede microbe development, co-metabolism, in most situations, benefits microorganisms in growing and promotes EC breakdown [37,41].

As a fine-grained therapy, the final products of physical methods are frequently subjected to biological treatment. "conventional biological therapy" refers to traditional biological procedures like Biological nitrification-denitrification, biofilm reactor, bioremediation, microorganism-based therapy, biofilters, and anaerobic/aerobic treatment. Biological remediation is a sort of classical biological treatment that uses live materials to isolate ECs (e.g., plant, fungus, and phytoplankton). Restoration has been demonstrated to be especially effective regarding EC removal due to its fast disintegration and surface assimilation capacities [42]. Non-traditional remediation employing biological methods is still a new field that is often being researched for future progress. Membrane Bio Reactor (MBR) and biosorption, microbial fuel generation, and built wetlands are now the most important unconventional biological wastewater remediation methods. Biosorption is the process of inactivating microorganisms on the receptive [43,44].

2.4. Chemical treatments.

Chemical treatment is frequently used to describe the employment of toxic chemicals in a series of operations to help decontaminate sewage [45]. Chemical therapy for treating sewage drives soluble contaminants in sewage to segregate by adding specifically targeted chemicals [38]. Chemical wastewater treatment methods come in useful when mechanical and biological wastewater treatment techniques are inadequate for allowing purified water to make it into water bodies. Chemical treatment is necessary to clean up various wastes from agriculture and industry because the pollutants must be further handled [46]. Chemical sewage treatment procedures include Ozone disinfection, UV, precipitation, ion exchange, neutralization, and chlorination [47]. The precipitation procedure entails converting a previously dissolved chemical into a dissoluble compound that can be filtered out. The catalytic oxidation treatment method is widely categorized into two approaches: standard oxidation and enhanced oxidation [48]. Table 1 highlights the critical research linked to the chemical treatment methods reviewed in this study.

Table 1. A summary of wastewater treatment chemical approaches.

Approaches to conventional and advanced oxidation	**Primary task (s)**	**End Result**	**Remarks**	**Ref.**
Ozonation	Capable for considerably enhancing the biodegradability of sewerage	Very effective in removing drugs and personal care items	Since mineralizing chemicals have low utilization effectiveness and oxidative power, hazardous by-products might develop.	[49]
Photocatalysis	Catalysts must be used to assist in the photon transfer of energy to a molecule of water.	Total carbon content (TOC) reduction is three times more intense than color reduction.	Decreased cost and reusability of the catalyst, as well as operation at ambient pressure and temperature. It is difficult to obtain uniform radiation throughout the whole catalyst surface.	[50]
Photolysis	Radiation is used to degrade the chemical, producing hydroxyl radicals.	Color removal from sewage	Associated with greater media turbidity, which obstructs UV light transmission through dirty water.	[51]
Fenton process	As ferrous ions combine with hydroxyl radicals and hydrogen peroxide, they are formed, which break down and eliminate persisting biological contaminants.	Effective in lowering toxic metal levels, such as aluminum, chromium, and copper.	A narrow pH range, the danger and cost of shipping, managing, and holding chemicals.	[52]
Photo-Fenton	Water purification is done using UV light and the Fenton process.	The great effectiveness of antibacterial elimination.	Secondary chlorinated items that are technically simple, cost-effective, and restricted in number.	[50]

3. Hybrid Wastewater Treatment System

A hybrid energy system is often made up of two or more energy sources or processes that work together, using adequate power transformation strategies to deliver fuel economy, energy recapture, and total system efficiencies [53]. Several different types of wastewater hybrid technology may be utilized for wastewater treatment. In this context, a hybrid technology is described as a mixture of deuce or more treatment approaches, namely the biological assimilation process of chemical and physical unit operations. The hybrid treatment method may integrate various unit functions and procedures to enhance the caliber of the effluents discharged. A hybrid system is any process that falls in the green area. Unit activities and procedures are combined to give multiple stages of treatment, commonly referred to as initial, basic, enhanced, intermediate (with or without nutrient removal), and advanced (or tertiary). The kinds of hybrid wastewater technologies chosen are determined by the kinds of contaminants present in the sewage. Biological wastewater treatment procedures are typically required to remove contaminants from wastewater, including volatile organic material, degradable organics, phosphorus, nitrogen, and refractory hazardous organics. Pollutants like suspended solids are often treated using physical methods such as membrane filtration, screening, and flotation. Moreover, contaminants such as metals will often need a chemical treatment step. Because most wastewater contains over one contaminant, hybrid wastewater treatment is usually required for a more comprehensive elimination [54]. A hybrid wastewater treatment plant aims to purify sewage to a level where it can supply clean water.

3.1. System of chemical-biological hybridization.

A chemical-biological system is typically used to remove pollutants from wastewater, including ammonia, phosphorous, and refractory hazardous organics, typically recorded as COD, BOD, and TOC levels. Table 2 illustrates the proportions of pollutants removed by different sorts of chemical-biological hybrid systems. MBBR with ozone preprocessing hybrid performed better than single MBBR without ozone preprocessing. Stand-alone MBBR removed 18.350 percent of Acid Extractable Fraction (AEF) as well as 34.800 percent of Naphthenic Acids (NAs), whereas ozonation combination MBBR removed 41.0% of AEF and 78.8% of NAs. Hybrid systems that incorporate oxidative mechanisms possess the capacity to reduce harmfulness and improve biodegradability of wastewater in a quicker response time [54-56].

Table 2. Catalog of hybrid systems employing chemical-biological hybridization with percentages of contaminants removed (%) and generation of bio-energy.

Kind of wastewater	System of chemical-biological hybridization	The density of power (mW/m^2) and generated bioenergy	Pollutants and percentage of removal (%)	Ref.
Synthetic	MFC-integrated up-flow built wetland	It comes out to be 6.12 mW/m^2	COD = 100.00% NH_4^+ = 91.00% NO_3 = 40.00%	[56]
Municipal	Anaerobic digester (AD)	• Methane produced is (3.9L) 76.7% • 0.13 mW/m^2	Not reported	[57]
Synthetic	MFC for activated sludge and combined spirits suspended solids with batch sequencing	2.34 W/m^3	Greater than 90%	[58]
Starch	Biofermentor	Production of hydrogen = 2.85 mol.H_2/ mole glucose) 4200 mW/m^3	COD = 71%	[59]
Sanitary	MFC in anaerobic fluidized bed	410 mW/m^2 (activated carbon) 530 mW/m^2 (graphite granule)	88%	[60]

According to Table 3, the oxidation process with SBR is capable of removing 45% of TOC, 76.5% of COD, and 96% of phenol, mostly from petrochemical industry effluent. Sewage contains significant biodegradable organic waste, which can be harnessed to generate energy.

Table 3. The proportion of pollutants removed by different kinds of biological-physical hybrid systems.

Kind of wastewater	Hybrid physical-biological system	Pollutants and percentage reduction (%)	Ref.
Blended wastewater like landfill leachate, black water, and domestic wastewater	Anaerobic-oxic-anoxic biofilm filtration (AOBF/MF) AOBF through membrane filtration (MF) (AOBF/MF)	COD, soluble nutrients, and TSS are more than 90–95%	[61]
Municipal	Membrane filtration in conjunction with a moving bed anaerobic biofilm reactor	Dissolved organic carbon > 98% TP = 100% Organic matter = 100%	[62]
Domestic	Dissolved air flotation with pressurized aeration in a bioreactor.	NH_4^+–N = 100% (approx) (C/N = 3) COD = 86% TN = 80% (C-N = 5)	[63]
Synthetic	Biofilm reactor with aerated membrane (FT-MABR)	TN = 83.5%	[64]
Synthetic	Mesh filter anaerobic hybrid membrane bioreactors (AnHMBR)	COD = 82.473.4 2-chlorophenol =96.875.2	[65]
Sago	Aeration with filtering for a longer period of time	BOD = 84% COD = 88% • TSS = 73%	[66]
Leachate	Aerated biofilm reactor with a membrane	COD = 50–93% • TN = 80–99%	[67]

Technologies employing MFC (Microbial Fuel Cell) represent an exciting but fundamentally distinct concept in treating wastewater since the treatment technique may be changed into a method of collecting power as electrical power or hydrogen energy instead of consuming electrical energy [21]. Microbial Fuel Cells (MFC) have advanced from theoretical research to actual application in the realm of wastewater treatment technologies, demonstrating flexible applicability across diverse environmental conditions. Recent real-world MFC installations highlight its promise, particularly in resource-constrained situations and applications where traditional energy inputs are limited [68,69]. MFCs, for example, have been used in isolated villages to treat residential wastewater, resulting in both pollutant reduction and energy recovery [70]. Such applications demonstrate the technology's versatility and highlight its contribution to sustainable waste management practices [71]. Furthermore, experimental projects in industrial settings have proved MFCs' ability to treat high-strength effluents while harvesting energy outputs, which aligns with the global pursuit of circular economy concepts [72]. These practical applications, which are supported by the data in Table 2, confirm the function of MFCs in improving the efficacy and sustainability of wastewater management systems [55,56].

Fluidized bed materials like graphite-granule particles were employed to compare fluidizing mediums in the MFC-Anaerobic Fluidized Bed (AFBMFC) hybrid systems. It was discovered that using both materials can reduce start-up time while increasing power density and removing COD. When the charcoal was used in the AFBMFC, the beginning duration decreased, and COD removal was increased because of its larger specific surface area and wearability. In terms of producing electricity, the greatest power density produced by the Granule-graphite AFBMFC was found to be 530.0 mW/m^2, which was much greater than the 410.0 mW/m^2 produced by AFBMFC utilizing the technique of granular activated carbon inside the same reaction chamber. Employing a combined MFC Sequencing Batch Reactors (SBR) hybrid led to a significant COD reduction in effluent, with a reduction in COD of more than 90%. Therefore, this integrated system's capital and operational costs are cheap [73]. In a laboratory-scale combined SBR-MFC system, the highest power output achieved by a typical cycle was 2.34 W/m^3.

3.2. Physical–biological hybrid system.

A physical-biological hybrid technology can be used when contaminants contain large levels of suspended particles, grease oil, and both inorganic and organic components. The MBR is a popular physical-biological hybrid technology that is progressively being used in wastewater treatment facilities. The benefits of utilizing MBR technology for sewage include:

(i) The capacity to handle large volumetric natural loadings [74,75].

(ii) Improved water effluent quality for reuse because the membrane will hold microorganisms and colloidal solids bigger than the pore diameter of the membrane [76-78].

(iii) Full and steady nitrification due to the accumulation of sluggish nitrifying bacteria over a long solids maintenance time [79,80].

Table 3 contains a thorough list of numerous physical-biological hybrid systems that have been tested with distinct wastewaters so far. MBRs can replace the process of activated sludge and the final clarity phase in municipal wastewater treatment [81]. The method employs appropriate membranes to contain undesired contaminants while enabling pure filtering water to pass through. The membrane bioreactor (MBR) reduces Biochemical Oxygen Demand

(BOD), Chemical Oxygen Demand (COD), and Ammonia Nitrogen (NH_3-N) significantly [76]. Using designs such as the up-flow anaerobic sludge barrier reactor utilizing a submerged aerated contamination hybrid model [82], physical-biological hybrid systems can achieve considerable energy savings. UASB has the capacity to anaerobically stabilize 70% of organic substances coming to the plant. As a result, reduced sludge output and considerable energy savings will be realized with this hybrid system. Due to the efficient, low-energy, high-rate, and efficient reactor, the hybrid system's average total elimination efficiency for COD, BOD, and SS were 88%, 95%, and 95%, respectively.

4. The Benefits of a Hybrid System over a Stand-alone System

Previous research [82] on hybrid fuel cell techniques has shown the viability and advantages of hybrid systems over a single system for a wide range of uses other than discharge or treatment of wastewater. Among the noteworthy benefits are:

(i) Voltage is created that is steadier and more sustainable.
(ii) Improved overall treatment efficiency
(iii) Potential for energy savings

MFCs have the ability to collect energy stored in wastewater treatment plants, which is immediately converted into electricity [83]. Employing MFCs can contribute to offsetting the operational expenses of sewage treatment plants, making advanced sewage treatment more economically viable for both developing and industrialized nations [84].

5. The Benefits of a Hybrid System over a Stand-alone System

In terms of efficacy, hybrid treatment systems might be an excellent choice among wastewater treatment methods. Nevertheless, the whole expense of hybrid power technology must be considered, including capital, maintenance, and operational expenses [85]. Most expenses are location, and for a complete system, these expenses are heavily influenced by the discharge rate of flow, reactor type, effluent nature (concentration), and treatment extent. Due to the high running cost regarding energy use, hybrid systems with various mechanical treatments, such as membranes, may provide a hurdle. However, if hybrid innovation is not designed to generate positive energy throughout the scheme, the cell membrane hybrid model may not be worth the investment. Additionally, according to the degree of pollution and the implementation of a hybrid membrane module, biological methods may necessitate significant maintenance expenses. Changing membranes on a regular basis can be highly expensive. Physiological precipitation is simple, predictable, and successful, but it has certain downsides, such as higher capital expenses due to the utilization of various chemicals and the dissolved salts of some substances, which may pose extra challenges [86]. Furthermore, if the sludge formed is not recyclable, extra sludge development due to aggregating, coagulation factors, and precipitate may pose disposal concerns. Certain biochemical and molecular combinations, such as activated sludge, may necessitate a substantial oxygen supply. Such hybrid systems may have substantial operational costs, making the whole hybrid system unprofitable. To make the total system profitable, an equilibrium must be achieved between the energy used and the energy gained by the hybrid system.

6. Emerging Directions in Hybrid Approaches for Wastewater Treatment

The hybrid system's future trend is projected to be the transformation of garbage into bioenergy using bioelectrochemical technology. MFC technologies offer the most recent method of energy generation—bioelectricity production from biomass utilizing microorganisms. Presently, most MFCs are performed in the lab, and individuals are shifting more towards pilot-scale MFCs, which require much work. The MFC hybrid system is anticipated to take the place of the trickling filter systems and activated sludge (AS) [87]. Since the MFC is a synthetic chemical processing technique, it can remove organic contaminants much as the AS aeration tanks or the trickling filters (TF). The inclusion of MFC into a hybrid purification process has several benefits, including:

(i) Bioenergy generation in conjunction with pollution treatment, where the current produced is determined by the strength of the wastewater and the columbic effectiveness.

(ii) Oxygenated unit is removed: Aeration is not necessary for air-cathode MFC systems. Aeration systems in AS are quite expensive, consuming up to 50% of the power utilized at a treatment facility.

(iii) Reduced solids production: According to studies, the anaerobic environment of MFC reduces bacterial biomass output by up to 50% when compared to aerobic systems such as TF and AS [88,89].

(iv) Reduction in the odor issue in the system for treatment.

MFC is a closed environment; thus, smell would not be a significant issue in the treatment system. Electricity generation via salinity gradients may become common in the coming years. Because of the salinity gradient, energy can be generated using reverse electrodialysis (RED) [87,90]. It has been claimed that a RED may create an action voltage of 0.1-0.2 V per combination of membranes by passing saltwater and groundwater (treated wastewater) over a couple of ion-exchange membranes. Salinity gradient energy, which occurs as groundwater drains into the sea, has the potential to create up to 980 GW of electricity globally [91]. A RED stack can be used to connect the anode as well as the cathode chamber of an MFC or Microbiological Electrolysis Cell (MEC), resulting in a hybrid technology known as a Microbial Reverse-electrodialysis Cell (MRC).

4. Conclusions

Given the pressing need to address the persistent problem of developing contaminants in wastewater, this study examined the efficacy of various treatment approaches, particularly emphasizing the creative use of hybrid systems. Emerging contaminants, which include a wide range of synthetic substances discovered at trace levels, have emerged as a major environmental and public health problem. These chemicals' complexity and resistance to traditional treatment methods highlight the need for innovative treatment strategies. Although current wastewater treatment facilities (WWTPs) can significantly reduce the levels of numerous emerging contaminants (ECs), the search for a solution capable of complete removal continues. Advanced oxidation processes (AOPs), particularly ozonation, have been established as a highly effective mechanism for EC elimination. Nonetheless, the transformation of these pollutants during ozonation frequently results in the development of hazardous by-products, needing additional treatment to protect the environment and human health.

The investigation of hybrid systems in this study provides a comprehensive picture of their potential for bridging the gap between existing treatment capabilities and desired outcomes. Systems that combine oxygenation and advanced oxidation stand out for their ability to reduce the levels of developing contaminants. The complexities of these hybrid systems, which incorporate several treatment methods, provide a multidimensional approach to wastewater management that balances efficiency with environmental concerns. Furthermore, introducing Microbial Fuel Cells (MFC) as a component of these hybrid systems signals a paradigm shift in wastewater treatment tactics. MFCs contribute to the breakdown of pollutants while also facilitating energy recovery in the form of hydrogen or electricity by utilizing the bioelectrochemical potential of microbial communities. The combination of MFCs and adsorption technologies, such as activated carbon columns, offers a symbiotic strategy that improves contaminant removal while simultaneously recapturing energy, potentially offsetting operational expenses.

While obstacles remain in the field of wastewater treatment, particularly with regard to new pollutants, this comprehensive analysis indicates that the advancement and deliberate application of hybrid systems offer a hopeful horizon. These systems, particularly when combined with MFC technology, offer a unique approach to addressing the dual goals of effective wastewater purification and energy sustainability. Future research should concentrate on scaling these technologies, optimizing their operating parameters, and assessing their long-term performance and economic sustainability, ultimately contributing to constructing a more environmentally friendly and resilient wastewater management infrastructure. As we progress, it is critical to encourage the transition from traditional treatment frameworks to more integrated, energy-efficient, and long-term platforms. By doing so, we can ensure the maintenance of water quality, public health protection, and environmental integrity for future generations.

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Conflicts of Interest

The authors declare no conflict of interest.

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