Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA28770

Comparative Analysis of Electrochemical Oxidation and Biodegradation for Microplastic Removal in Wastewater

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Abstract. Microplastic contamination in wastewater is a pressing environmental challenge, as wastewater treatment plants are key pathways through which plastics enter natural water bodies. In this study, the effects of electrochemical oxidation (EO) and biodegradation on polystyrene removal were compared. EO achieved 65.5% degradation within 300 minutes, offering rapid treatment and minimal sludge production, but it required high energy input and risked generating secondary byproducts. In contrast, biodegradation with Bacillus spizizenii reached 85.9% efficiency over 30 days, with lower energy demand but significant sludge generation and slower treatment. Cost and environmental assessments reveal that EO is compact yet energy-intensive, while biodegradation is more sustainable but requires larger space. These trade-offs suggest that neither method alone is fully sufficient. A hybrid approach—integrating EO and biodegradation, potentially powered by renewable energy—could balance efficiency, cost, and sustainability, offering a scalable solution for microplastic removal in wastewater.

Keywords: microplastic, electrochemical oxidation, biodegradation, wastewater.

1. Introduction

Plastic pollution has become an increasingly severe issue, drawing global attention in recent decades, as over 300 million tonnes of plastic are produced each year [1]. Less than 20% of plastics are recycled worldwide today [1]. Plastic pollution is ubiquitous, appearing in aquatic, terrestrial, and atmospheric ecosystems [2,3]. Plastic pollutants can be classified into different categories based on particle size, including nanoplastics (1 to 1000 nm), microplastics (1 to 1000 μm), mesoplastics (1 to 10 mm), and macroplastics (1 cm and larger) [4]. Microplastics, in particular, can originate as primary microplastics, intentionally manufactured for use in cosmetics, industrial abrasives, and cleaning products. Microplastics can also appear as secondary microplastics, which are formed through the degradation of larger plastic particles via ultraviolet radiation, mechanical forces, and microbial activity [5].

Microplastics account for 92.4% of all plastic particles in the oceans [6]. They are considered a major threat to the environment for several reasons. For many aquatic species, microplastics resemble food, and fish often consume them [7]. The plastics then accumulate in their bodies and are

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DOI: 10.54254/2755-2721/2026.KA28770

transferred along the food chain, ultimately affecting human health [7]. Additionally, microplastics can sorb and transport organic pollutants as well as heavy metals [8]. Once released, microplastics can enter wastewater systems through domestic sewage, industrial effluents, surface runoff, and even atmospheric deposition [9]. Wastewater treatment plants (WWTPs) are major pathways for microplastics to reach natural water bodies. Conventional treatment processes are not specifically designed to target these small and chemically stable particles.

Current wastewater treatment processes—including preliminary screening, primary sedimentation, biological treatment (activated sludge), and disinfection —can partially remove microplastics, but their overall efficiency is limited. Lares et al. (2018) found that while primary and secondary treatment stages in WWTPs could remove up to 61% of microplastics, some particles, particularly fibers and fragments below 100 μm, frequently escape into the effluent [10]. Even with tertiary treatments, total removal efficiency varies and may not exceed 80%. Furthermore, advanced processes like membrane filtration and coagulation-flocculation are often cost-intensive, energy-demanding, and generate substantial amounts of secondary waste [11].

There is growing interest in emerging technologies that move beyond physical separation to achieve actual degradation of microplastics. Among the most promising are electrochemical oxidation (EO) and biodegradation. EO utilizes electric current to generate highly reactive species (hydroxyl radicals) that break down polymer chains into smaller, often mineralized products, without the need for added chemicals. Some studies have reported removal efficiencies of over 95% for nanoplastics using electrocoagulation and electrooxidation techniques [12]. Biodegradation, in contrast, relies on microbial organisms or enzymes to metabolize plastic polymers into carbon dioxide (CO_2), water (H_2O), and biomass under mild environmental conditions, offering a sustainable and low-energy alternative [13]. Biodegradation could be more environmentally friendly and less expensive, making it a promising method [10].

While most studies just focus on removal efficiency, few studies consider other real-world factors, including energy consumption, the production of byproducts, and sustainability over the long run [14]. Cost and environmental sustainability are equally important, as they affect the feasibility and long-term impact of applying these methods in real wastewater treatment systems. Hence, this paper compares electrochemical and non-electrochemical treatment for removal of microplastics from wastewater. It aims to: (1) compare how well they remove specific kinds of microplastics; (2) determine the energy consumption and cost; and (3) investigate their environmental sustainability and practicality.

2. Overview of electrochemical and biodegradation treatment

2.1. Electrochemical Oxidation (EO)

EO is viewed as a promising way to deal with microplastics in water for its high efficiency and relatively low secondary pollution [15]. This method is based on generating highly reactive oxidants and radicals such as hydroxyl radicals. The radicals will attack the polymer, break down the complex structures, and finally degrade the intermediates into nontoxic products. Such products usually refer to CO_2, hydrogen (H_2), and H_2O [15]. Factors including reactor design, electrode materials, and electrolyte materials influence the degradation of microplastics in different ways. Typically, the experiments are conducted in a batch reactor and rely on an electrode made of boron-doped diamond or titanium. Sodium sulphate (Na_2SO_4)is one of the commonly used electrolytes [16]- [18]. Under optimal conditions, the degradation efficiency can reach 90% in 8.2 hours for

DOI: 10.54254/2755-2721/2026.KA28770

polystyrene particles with a size of 0.15 micrometers [16]. However, despite the high removal rate, there is limited research on the large-scale and industrial application of EO [15].

2.2. Biodegradation treatment

Biodegradation is another promising alternative for the removal of microplastics [19]. It is characterized as less efficient but environmentally friendly [20,21]. The biodegradation process mainly includes three steps. First, the polymers turn into smaller particles. Second, the polymers are degraded into dimers and monomers. Third, microorganisms or enzymes mineralize the microplastics [20]. Microplastics are generally considered as synthetic materials that are not biodegradable and insoluble under natural circumstances [19]. Traditional plastics, such as polystyrene (PS), polyethylene (PE), and polypropylene (PP), degrade very slowly [20]. In recent years, with the rising awareness of plastic pollution, bioplastics like polyglycolide and polylactic acid (PLA) emerged and are produced in millions of tons per year [22]. These bioplastics, in contrast with traditional plastics, can be degraded more thoroughly and effectively. For instance, the mineralization level can reach 80% for PLA bottles under stimulated composting situations [23].

3. Degradation efficiency analysis

Different types of plastics have varying biodegradability and, therefore, varying degradation efficiency [20]. Here, we focused on PS as it is widely used in various fields, such as insulation materials and packaging [24].

3.1. Experimental set-up and degradation efficiency analysis

The EO experiments were conducted in a batch reactor under 25ºC for 300 minutes. The polystyrene particles have a standard size of 1 micrometer. Two boron-doped diamond electrodes were used in the electrochemical cell. The optimal degradation was reached with electrolyte Na_2SO_4 (0.02M), an applied current density of 60 A/m^2, and an initial PS concentration of 60 mg/L. As PS is the only source of organic carbon, total organic carbon analyses were conducted to determine the degradation efficiency of EO treatment [17].

The biodegradation experiments were conducted in 50 ml culture tubes under optimal temperature and pH ranges. The polystyrene particles have a size of ≥ 2 micrometers [24]. After being screened for purity, the bacteria Bacillus spizizenii grew overnight and were then inoculated with the PS culture. The initial PS concentration is 100 mg/L. Based on the retention time and area of the products, the degradation efficiency of Bacillus spizizenii was determined using the Gas Chromatography-Mass Spectrometry (GC-MS) method. GC-MS contributed to identifying and quantifying the products of PS degradation [24].

3.2. Comparative analysis

For both EO and biodegradation treatment, the degradation efficiency for PS of similar size was calculated under the optimal situation. Even though biodegradation reached a higher degradation efficiency than EO, it should be noted that biodegradation treatment took a much longer time than EO (Table 1).

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Table 1. A comparative analysis of degradation efficiency for EO and biodegradation.

Treatment	Particle size	Time spent	Degradation efficiency
EO	1 micrometer	300 min	65.5%
Biodegradation	≥ 2 micrometer	30 days	85.86%

4. Cost analysis

4.1. Energy cost

The operation cost of EO is usually higher than biodegradation since EO requires continuous electricity inputs to produce active oxidizing chemic [25]. In a study on biologically pre-treated textile wastewater, the EO process used about 19.16 kWh of electricity for each kilogram of Chemical Oxygen Demand (COD) removed, or 3.06 kWh for each cubic meter of water [26], [28]. This energy demand is much higher than that of biodegradation, which depends on bacteria and uses very little direct energy [29]. However, EO degrades the microplastics with higher efficiency (sometimes in minutes or hours) while biodegradation can take days or weeks, demonstrating slower degradation [29].

4.2. Extra costs

Extra costs for EO include paying trained workers to operate the system, buying and replacing electrodes, and maintaining the electrical parts of the reactor [25,28]. However, it should be noted that EO produces no sludge, leading to no sludge disposal costs and therefore saving approximately 86 USD/tonne [26]. Biodegradation needs more space for tanks and produces sludge that must be handled and disposed of, adding significant costs [29].

4.3. Maintenance and lifecycle

Over the system's lifetime, EO maintenance mainly involves replacing worn electrodes and examining electrical systems [23,25]. Biodegradation does not require expensive electrodes, but workers must keep the bacteria healthy, clean the tanks, and sometimes add nutrients, properly handling ongoing microbial management [29]. While EO has higher power bills, it can save on space and waste management (i.e., compact setup vs. large tanks [27,29]), which can balance costs in the long run.

4.4. Methods for reducing the cost of stoichiometry

There are mainly two ways to lower the cost of EO treatment. One is to use the lowest possible current while maintaining the efficiency [25,27]. The other is to choose the appropriate electrolyte; for example, sodium chloride can speed up the reaction and cut power needs [27], [30]. Combining biodegradation with EO can also lower costs (Table 2). Biodegradation removes the easy-to-degrade pollutants first, and then EO removes the recalcitrant ones in a hybrid system [29]. In the future, integrating renewable energy like solar or wind to power EO could further reduce running costs [27,30].

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Table 2. A comparative analysis of the cost for EO and biodegradation

Aspect	Electrochemical Oxidation (EO)	Biodegradation
Energy Demand	High, continuous electricity is needed to generate oxidizing species (≈19.16 kWh/kg COD removed [26])	Very low, mainly supports bacterial metabolism
Speed of Treatment	Fast (minutes to hours) [28,30]	Slow (days to weeks) [29]
Sludge Production	Almost none (zero-sludge concept) [26]	Produces significant sludge that must be disposed [29]
Space Requirement	Compact equipment (reactors, cells) [27]	Large tanks and more land are required [29]
Maintenance	Electrode replacement and electrical checks [25,28]	Maintain bacteria, tank cleaning, nutrient addition [29]
Cost Factors	Higher electricity cost, electrode replacement; but saves sludge disposal cost (~86 USD/tonne avoided) [25,26,28]	Lower power costs, but sludge disposal and land cost add up [29]
Future Improvements	Renewable energy integration, optimized current density, suitable electrolytes [25,27,30]	Coupling with EO can enhance performance and reduce overall cost [29]

5. Environmental friendliness assessment

5.1. Secondary pollution potential

Electrochemical oxidation (EO) breaks down microplastic with high efficiency, but it produces some extra pollutants [31]. As can be seen an accumulation of SO_4^{2-} of up to 35-50μM is observed in the EO process in which sodium sulphate (Na_2SO_4) is housed as an electrolyte such oxidation of dissolved organic matter such as to have a formation of aldehydes and carboxylic acids [32]. One way to mitigate secondary pollution is integrating GAC (a porous adsorbent material) with three-dimensional electrochemical reaction, which reduces the sulfate and persulfate formation by about 2 folds and 10 folds, respectively. The other way to mitigate the pollution involves the electrochemically-activated PS (E-PS) systems. In the system, the Fe-doped carbon membrane (FeCM) cathode is adopted in order to reduce the Fe ion discharge, improve the cycling stability, and lower the danger of secondary pollution such as biological oxidizer. The subsequent bio-degradability process only generates little secondary pollution. On the other hand, conventional biodegradation results in less than 5 mg/L of secondary soluble organic, mainly as volatile fatty acids (VFAs), which is less toxic and more biodegradable [10].

5.2. Carbon footprint

EO processes will require a lot more energy inputs and the electricity consumption will also differ greatly, from 0.2 - 345.5 kWh/kg COD removed [33]. Like the textile industry wastewater treatment which it was 0.26 - 100 kWh/m3 and electrocoagulation process which it was 1.7 - 17.5 kWh/m [34]. They imply that there are plenty of indirect CO_2 emissions. In contrast to this, a conventional WWTP has a total carbon footprint number (that includes both direct and indirect emissions) of 0.95-2.26 kg of CO_2 to treat 1m3 of wastewater [35]. An industrial park WWTP reportedly produces around 10.13kg CO_2/t, a domestic WWTP around 1.84 kg/t, and besides, microbe electrochemical

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system (mesh) such as microbial Electrochemical Carbon Capture (MECC), which can remove CO_2 net, thus the carbonic acid in water is precipitated as calcite, and the hydrogen gas is produced, resulting in the so-called negative carbon wastewater treatment process [1]. In general standards EO has more CO_2 footprint and by integrating advanced MES-approach, the CO_2 footprint will reduce and sometimes can become reverse.

5.3. Reagent usage, chemical inputs

EO needs a supporting substance, likely $NaSO_4$ (just Na_2S at some times) @0.014 - 0.10M (~ 2-14g/L), OR fixed dosed 5-7g/L; Na_2SO_4 > NaCl for COD w/o Cl_2 (Chlorine gas) And in practice, EO studies on real wastewater do batch additions often 12g Na_2SO_4 per run (or sometimes persulfate for E-PS, which lowers energy with the added chemical load). Biodegradation counts more on nutrient balancing [36]. COD:N:P ~ 100:5:1 is often a design target, and many industrial streams need the addition of N and P for biomass growth (observed yields ~ 0. 06 - 0. 31 kg VSS per kg COD removed). Bioprocesses used, routinely dewatering sludge requires coagulants/polymer—40 - 120 kg $FeCl_3$, 50 - 300 kg CaO, and 2 - 11 kg polymer per ton dry solid, amounts scaling with sludge amount [37]. In general, there's relatively more EO reagent demand, from electrolytes and occasionally oxidants added to the water mass, compared to biodegradation inputs, which happen mostly in nutrients and post-treatment chemicals as proportional outputs to biomass, which could be large in high-sludge-yielding systems [38].

5.4. Material sustainability and recyclability

Electrode performance relies on electrode material. Boron-doped diamonds (BDD) are very long-lasting and have very strong oxidation potentials, but MMO (Mixed Metal Oxide) or DSA (Dimensionally Stable Anode) are also long-lasting and work well for chlorine evolution (activity vs. selectivity) [39]. In 3D-EO systems, GAC can act as auxiliary sorbents that could be regenerated by commercial thermal approaches; more recent chemical/thermal recoveries are around 41% after one persulfate regeneration cycle, and are higher upon multiple cycles, showing circularity but with added energy costs. Biodegradation mainly creates waste activated sludge (WAS), around 0.2-0.3 kg solids per m^3 municipal wastewater, which needs dewatering and transportation, a considerable end-of-life footprint [40]. Although the sludge can be reused when applying it on the land based on the guidelines of the EPA, the restriction of heavy metals, organic pollutants, and PFASs, the BRR of biological sludge cannot be realized. EO can give durable electrodes as well as a sort of circularity for sorbents, but at an energy cost, whereas biodegradation creates usable biosolids but with the ongoing hassle of sludge.

6. Conclusion and discussion

This study examined how electrochemical oxidation (EO) and biodegradation were used to remove microplastics from wastewater. The two treatments were evaluated based on their degradation efficiency, cost, and environmental sustainability. EO has quick degradation rates and low sludge generation. However, this method has a higher energy demand and may produce more secondary pollutants [41]. Biodegradation, on the other hand, has lower energy demand and exerts a limited impact on the environment. The process is slow and produces sludge that needs further treatment. According to cost analysis, EO has higher operating expenses but it could be offset by compact reactor size and no sludge cost; biodegradation is cheaper to operate but there are long-term sludge

DOI: 10.54254/2755-2721/2026.KA28770

costs. From a sustainability perspective, EO offers material durability and partial recyclability, whereas biodegradation enables natural breakdown; however, the reuse of biosolids still poses risks due to potential contaminants. From all over, we can see that these two possess the ability to do so, EO for quick targeted degradation and biodegradation for environmentally compatible treatment [42]. A hybrid system, if combined with renewable energy input in the future, can lead to a more sustainable method to handle the microplastic pollution in the wastewater.

While this study provides valuable insights into microplastic removal, its findings have several limitations. First, when comparing the degradation efficiency of EO and biodegradation treatment, we only focused on PS and failed to include plastics with varying biodegradability. Future researchers could try to generalize the findings of our study by examining other types of microplastics. Second, the cost analyses of these two treatments are mainly qualitative due to limited data availability. Researchers can evaluate the economic cost of the treatments in a more quantitative way in the future. As microplastics threaten human health and the overall ecosystem, it is essential to propose efficient and applicable treatment to deal with microplastics.

Acknowledgment

All authors contribute the same, and all are considered as first author.

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