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Comparative Analysis and Optimization of Reactor Geometry and Voltage Density in Electrocoagulation for TDS, TSS, and COD Reduction from Pharmaceutical Wastewater

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Abstract-Pharmaceutical industrial wastewater typically contains high levels of organic and inorganic pollutants, such as TDS, TSS, and COD, that can harm ecosystems if discharged without treatment. This study examines the effectiveness of electrocoagulation using a pair of iron electrodes (Fe-Fe) in a laboratory-scale batch system for reducing these parameters. To improve process efficiency, this study compared two reconfigured reactor geometries: Design I (40 x 20 x 15 cm) and Design II (16 x 16 x 20 cm) by adjusting raw voltages (3–13 V) to evaluate the impact of applied voltage density over contact times of 90–240 minutes. Quantitative evaluation showed that Design II demonstrated a significant improvement in pollutant removal efficiency compared to Design I due to its compact geometry, which minimized dead zones and optimized the contact area. Specifically, Design I achieved a maximum removal of 66.67% for TSS and 73.50% for TDS at a lower voltage threshold of 9 V before fluctuating due to rapid saturation. In contrast, Design II consistently converted energy, achieving peak efficiencies of 76.05% for TSS (at 12 V) and 79.89% for TDS (at 13 V). Furthermore, for organic degradation, Design II outperformed Design I, achieving 84.95% COD removal (at 12 V) compared to Design I's peak of only 55.83% (at 13 V). This electrocoagulation process, utilizing the optimized Design II configuration, was very effective in reducing TDS and TSS levels to meet the quality standards stipulated in the Minister of Environment Regulation No. 5 of 2014. However, COD reduction still requires an advanced treatment unit.

Keywords: Electrocoagulation; Iron Electrode; Pharmaceutical Waste; Reactor Geometry; Percent Removal

1. INTRODUCTION

In recent years, environmental pollution caused by microorganism-related compounds in pharmaceutical industrial waste has become a critical global issue(Liu et al., 2024). Wastewater from the pharmaceutical sector is known to be highly complex, characterized by high Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), total suspended solids (TSS), and extreme pH fluctuations(Ningsih & Udyani, 2020; P et al., 2021). Furthermore, this wastewater contains persistent aromatic compounds, residual antibiotics, analgesics, and hormones, all of which exhibit high environmental stability(Bharti et al., 2023). The presence of these active compounds in water bodies not only threatens the sustainability of aquatic ecosystems through bioaccumulation but also leads to the emergence of antimicrobial resistance in pathogenic bacteria, posing a serious threat to global public health.

Pharmaceutical waste treatment processes using conventional biological methods, such as activated sludge systems, typically fail to achieve the desired results(Darmawan et al., 2017). Active pharmaceutical compounds typically damage decomposing microorganisms, slowing and reducing the efficiency of the natural decomposition process within the reactor(Darmawan et al., 2022). In contrast, traditional physicochemical processes, such as activated carbon adsorption or traditional chemical coagulation, produce large amounts of secondary sludge, which is classified as hazardous and toxic (B3)(Juliastuti et al., 2024a). This increases operational costs and complicates post-treatment waste management. Therefore, hybrid technologies are needed that are more efficient and environmentally friendly, and capable of effectively decomposing challenging pollutants without creating additional environmental problems.

One electrochemical technology that holds great promise for overcoming the limitations of conventional methods is electrocoagulation(Pratama et al., 2024; Yulita et al., 2025). The main principle of this technology is that the passage of an electric current through a solvent at a sacrificial electrode causes the in-situ formation of a coagulant. Hydrogen gas is then generated at the cathode to aid the flotation of pollutants(Juliastuti et al., 2024b; Ningsih et al., 2024). The main advantages of electrocoagulation are its relatively easy system operation, reduced chemical consumption, short residence time, and significantly smaller, more stable sludge volume. However, the removal efficiency of complex pharmaceutical pollutants is highly dependent on electrical operating parameters and the reactor's hydrodynamic conditions.

Two key factors in optimizing this technology are voltage density control and reactor design. Voltage density affects the rate of coagulant ion release from the anode, based on Faraday's Law, and also determines how quickly hydrogen gas bubbles form. If the voltage density is too low, the coagulant formation process will not be optimal for binding complex drug pollutants(Naldi et al., 2025). If the voltage density is too high, it will cause concentration polarization, increased temperature, and inefficient energy use. Furthermore, the reactor design, such as electrode placement and baffle use, significantly affects the electric field distribution and fluid flow patterns. An incorrect reactor

design can lead to the formation of no-flow areas and inefficient flow, thus reducing the effectiveness of contact between pollutants and coagulant flocs.

While the optimization of electrical parameters in EC batch cells is well documented, a critical gap persists in understanding how macro-scale hydrodynamic boundary conditions—specifically variations in spatial aspect ratios—directly dictate micro-scale DLVO colloidal destabilization and mass transfer kinetics. To address this, the reactor designs selected from this study are scientifically engineered to compare two polarizing hydrodynamic regimes. Design I (elongated channel geometry with a high aspect ratio) is evaluated to investigate the susceptibility of extended fluid domains to dead zones and mass transfer delays, where the distance between suspended colloidal particles and the electrode surface attenuates van der Waals attraction. Conversely, Design II (compact cubic geometry) is designed to minimize the ohmic resistance, shorten the diffusion path, and maximize uniform fluid-electrode contact area to accelerate perikinetic coagulation. Therefore, this study provides a precise comparative optimization between elongated and compact reactor geometries under dynamic voltage densities to deliver an energy-efficient configuration for removing TDS, TSS, and COD parameters from real pharmaceutical wastewater matrices.

2. RESEARCH METHOD

2.1 Equipment Design and Reactor Geometry Configuration

The primary materials used in this study were real wastewater samples taken directly from pharmaceutical factories. The initial pH of the raw wastewater was 7.2 ± 0.3, indicating a near-neutral matrix typical of mixed pharmaceutical formulation effluents. This natural pH was deliberately left unadjusted to evaluate the system's direct industrial applicability without chemical pre-treatment.

Variable variables included variations in reactor shape (Design I and Design II), changes in DC power supply voltage (3, 6, 9, 12, and 13 Volts), which corresponded to operational current densities ranging from approximately 15.0 A/m^2 to 85.5 A/m^2 calculated across the total active electrode surface area (100 cm^2 per reactor). To ensure data reproducibility and minimize experimental error, all experimental runs were conducted in triplicate, and the analytical results are reported as mean values

Both types of reactors operate with two sets of electrodes (two cathodes and two anodes) arranged in parallel. The sacrificial anodes and cathodes are made of iron (Fe) plates with an active surface area of 10 cm x 5 cm each. Direct current is continuously supplied by a DC power source, which is connected to the electrode circuit using a positive and negative cable system.

2.2 Materials and Operating Variables

The primary materials used in this study were real wastewater samples taken directly from pharmaceutical factories. The initial physical and chemical characteristics of the waste were measured as baseline data (initial conditions) before the electrocoagulation process.

To determine how operational conditions affect the effectiveness of pollutant reduction from the pharmaceutical industry, a number of experiments were conducted, dividing the parameters into two groups: fixed and variable. Fixed variables throughout the study included the type of pharmaceutical waste, the use of iron (Fe) electrodes, and the distance between the electrodes, which was set at 1.5 cm. Variable variables included variations in reactor shape (Design I and Design II), changes in DC power supply voltage (3, 6, 9, 12, and 13 volts), and different electrocoagulation contact durations (90, 150, 180, 210, and 240 minutes).

2.3 Experimental Procedure

The laboratory testing process consists of three main steps, carried out sequentially. The first step is electrode preparation, in which the iron (Fe) metal plates are manually cleaned using abrasive paper to remove any oxide or dirt on their surfaces. After scrubbing, the plates are washed with soap and water, rinsed with clean water, and then dried by repeatedly wiping with a tissue.

The second stage is the electrocoagulation process, in which each reactor is filled with wastewater from the pharmaceutical industry. Direct current (DC) is then applied at a voltage adjusted based on the factors being tested. During this process, the release of the Fe coagulant is released at the anode, while the reduction of water at the cathode produces bubbles and hydrogen gas, which help bind oil emulsions, colloids, and complex organic pollutants. This process is stopped periodically according to predetermined operating time variations.

The third stage refers to phase separation and sedimentation. After the contact period is complete and the electric current is turned off, the liquid is allowed to stand for a while to facilitate proper separation of the clean water (supernatant) and the resulting floc or sludge. The treated water in the upper layer will be sampled for further analysis.

2.4 Laboratory Analysis and Efficiency Calculation

The performance indicators of the electrocoagulation reactor are evaluated based on its effectiveness in removing the major pollutants in the pharmaceutical industry wastewater. After treatment, the water quality parameters examined include Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS), and Total Suspended Solids (TSS). The

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removal efficiency, or percentage reduction of each parameter, is calculated using the following mathematical formula(Ningsih et al., 2022):

$$Removal TSS(\%) = \frac{(TSS_{awal} - TSS_{akhir})}{TSS_{awal}} x100\% \quad (1)$$

$$Removal TDS(\%) = \frac{(TDS_{awal} - TDS_{akhir})}{TDS_{awal}} x100\% \quad (2)$$

$$Removal COD(\%) = \frac{(COD_{awal} - COD_{akhir})}{COD_{awal}} x100\% \quad (3)$$

Through these parameter tests, the simultaneous relationships between the reactor's hydrodynamic elements (the influence of chamber size variations) and its electrochemical elements (the influence of voltage density) can be comprehensively assessed to find the best pollutant removal efficiency.

3.1 RESULTS AND DISCUSSION

3.1 Initial Characteristics of Pharmaceutical Wastewater Samples

Prior to electrocoagulation treatment, an initial characterization of the waste samples was conducted to compare them with the Pharmaceutical Industry Wastewater Quality Standards set out in the Minister of Environment Regulation No. 5 of 2014. The initial analysis results showed the characteristics of the pharmaceutical liquid waste, with a TDS value of 356 mg/L, TSS of 263 mg/L, and COD of 2682.55 mg/L. Based on initial information on the nature of liquid waste from the pharmaceutical industry, all parameters tested, such as TDS, TSS, and COD, far exceed the quality limits stipulated in the Minister of Environment Regulation No. 5 of 2014. This condition indicates that the waste falls into a very high level of pollution. If this waste is disposed of without proper treatment, it can seriously damage the aquatic ecosystem, drastically reducing dissolved oxygen, causing sedimentation, and making the water in bodies of water that receive it. Therefore, this information is very important for the design of an efficient Wastewater Treatment Plant (WWT).

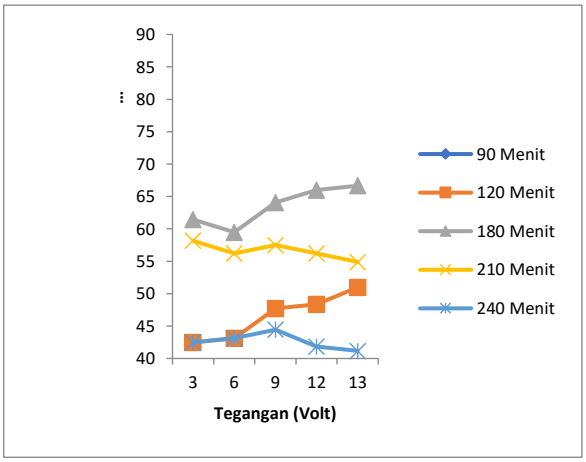

Figure 1. Graph of the Relationship between Voltage and TSS Removal in Design I

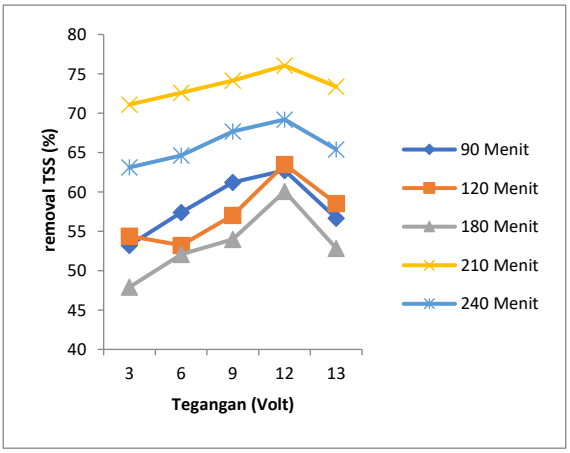

Figure 2. Graph of the Relationship between Voltage and TSS Removal in Design II

Analysis of the effectiveness of reducing Total Suspended Solids (TSS) levels in pharmaceutical wastewater using electrocoagulation techniques shows a clear difference in performance between Reactor Design I (Figure 1) and Reactor Design II (Figure 2). Suspended contaminants in pharmaceutical wastewater exhibit poor colloidal stability, leading to particles remaining suspended in the water. The electrocoagulation method relies on the release of iron cations (Fe^{2+}/Fe^{3+}) from the anode, which bind with hydroxide ions (OH^-) to form metal hydroxide flocs as charge neutralizers and solids scavengers. In general, both reactor geometries show that the variables of voltage density and operating duration have a significant impact on the percentage of TSS removal(Gouider et al., 2025; Niam et al., 2022).

Graphical evaluation shows that Design II (Figure 2) has significantly higher efficiency and stability in reducing TSS compared to Design I (Figure 1). In Design I, the performance in reducing TSS is relatively low to moderate. This behavior can be attributed to the geometric configuration of the reactors. In Design I, the high aspect ratio (elongated channel) increases the physical distance between the bulk fluid boundaries and the localized active electrode surface area (a = 17.75 cm). This extended path introduces mass-transfer limitations, restricting the rapid interaction between the generated iron flocs and the suspended pollutants. Conversely, Design II features a compact cubic configuration that shortens the lateral diffusion path (a = 5.75 cm). This geometric optimization enhances the fluid-electrode contact area per unit volume, creating a more uniform electrical field distribution that accelerates macro-floc growth without relying on extended retention times (Hashem et al., 2024).

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3.2 The Effect of Electrical Voltage and Contact Time on TDS Removal

A performance analysis of the effectiveness of reducing Total Dissolved Solids (TDS) levels in pharmaceutical wastewater using an electrocoagulation approach shows variations in kinetic characteristics that are strongly influenced by reactor geometry design factors (Design I in Figure 3 and Design II in Figure 4). TDS in pharmaceutical wastewater reflects the presence of dissolved ions, salts, and small organic molecules that are highly stable in the liquid phase. Through the electrocoagulation process using an Iron-Iron (Fe-Fe) electrode, the removal of these dissolved solids relies heavily on the formation of monomeric and polymeric iron (hydroxide) complexes ($Fe(OH)_2$), which function as ion-scavenging agents through coprecipitation, electrostatic adsorption, or charge compaction. Referring to the empirical data from both figures, the voltage density (3–13 volts) and residence time (90–240 minutes) settings provide a TDS reduction response with a unique transition pattern for each reactor design(Tapera et al., 2026).

Comparative evaluation shows that Design II (Figure 4) provides better, more targeted, and more consistent TDS removal efficiency than Design I (Figure 3). In Design I, the reactor's ability to remove dissolved ions fluctuates and can reach saturation levels quickly. The highest TDS efficiency in Design I is achieved at a medium voltage of 9 Volts with a maximum contact time of 240 minutes, and produces a removal percentage of 73.50%. When the voltage in Design I is increased to 12 V and 13 V, the efficiency graph actually shows a decrease (to 67.14% and 68.60%, respectively). In contrast, Design II can convert electrical energy consistently, achieving a peak efficiency of 79.89% at a peak voltage of 13 Volts with a duration of 210 minutes. The superiority of Design II is theoretically explained by the importance of reducing ohmic resistance and increasing the effective contact area. The large volume of liquid in Design I, combined with poor electrode contact area, leads to the formation of dead zones, where the distance between the dissolved ions and the electrode charge is too far, thus weakening the Van der Waals attraction force according to the DLVO theory. Meanwhile, mechanical engineering in Design II successfully distributes the electron flow evenly throughout the reactor space, accelerates the formation of active coagulants, and optimizes the capture of dissolved ions from low voltages(Kuokkanen et al., 2021).

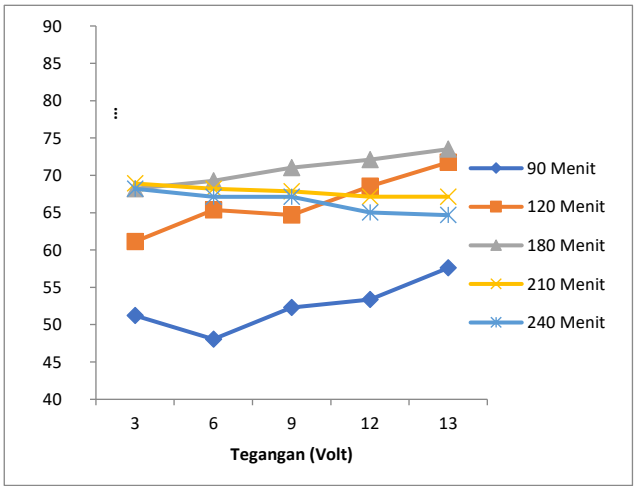

Figure 3. Graph of the Relationship between Voltage and TDS Removal in Design I

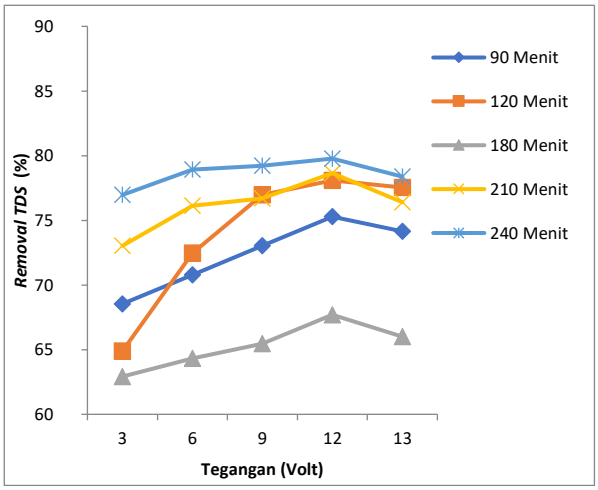

Figure 4. Graph of the Relationship between Voltage and TDS Removal in Design II

When the voltage was elevated to extreme levels (13 V), a slight decrease or plateau in removal efficiency was observed in both configurations (e.g., Design I dropping to 67.14% for TDS). This phenomenon is driven by concentration polarization and excessive water electrolysis at high voltage densities. At 13 V, the rapid evolution of hydrogen gas bubbles at the cathode and oxygen at the anode creates a "gas shielding effect" over the electrode surfaces. This blanket of microbubbles increases the internal ohmic resistance and disrupts physical contact between the in-situ formed iron coagulants and the target pollutants. Furthermore, excessive current generation induces localized thermal heating, which can partially destabilize or shear the weak organic-metallic macroflocs, causing a slight redissolution of parameters back into the aqueous phase

3.3. The Effect of Electrical Voltage and Contact Time on COD Removal

Analysis of the reduction in Chemical Oxygen Demand (COD) levels in wastewater from the pharmaceutical industry indicates a significant structural impact from variations in reactor geometry (Design I in Figure 5 and Design II in Figure 6) and the applied electrical parameters. COD is a parameter that describes the total concentration of organic compounds, including recalcitrant pharmaceuticals with complex carbon chains and strong chemical bonds. In electrocoagulation reactors using iron (Fe-Fe) electrodes, the reduction of these organic pollutants relies on the in situ formation of iron(II) hydroxide coagulant [Fe(OH)2]. This active coagulant binds organic molecules through electrostatic charge neutralization and surface complexation (macrofloc adsorption). Analysis of the empirical curves shown in both figures demonstrates that the voltage settings (3–13 volts) and contact time (90–240 minutes) produce organic reduction responses with different efficiencies across the two reactor designs(Lu et al., 2021).

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Through visual analysis of the data, Design II (Figure 6) demonstrated significantly superior, faster, and more effective performance in reducing COD loads compared to Design I (Figure 5). In Design I, the organic pollutant removal process was very slow, resulting in low efficiency. The highest COD removal rate in Design I was achieved under extreme conditions, with a maximum voltage of 13 volts for 240 minutes, yielding 55.83%. In contrast, Design II significantly destroyed organic compounds even at low voltages; with an initial voltage of only 3 volts, the removal rate exceeded 82%, and stabilized, reaching a peak at 12 volts in 210 minutes, reaching 84.95%. This striking advantage is explained by the difference in hydrodynamics within the cell chamber. Design I has a much larger ratio of fluid volume to the surface area of its active electrodes, thus creating numerous dead zones. Based on electrochemical principles and DLVO theory, the large distance between the dissolved organic molecules and the electrode charge reduces the van der Waals attraction, so that the barrier energy (gamma_R – gamma_A) remains high. Meanwhile, in Design II, geometric engineering evenly optimizes the contact area and shortens the mass-transfer distance, thereby increasing the interparticle collision rate (perikinetic coagulation) between the iron coagulant and dissolved organic compounds[4,20].

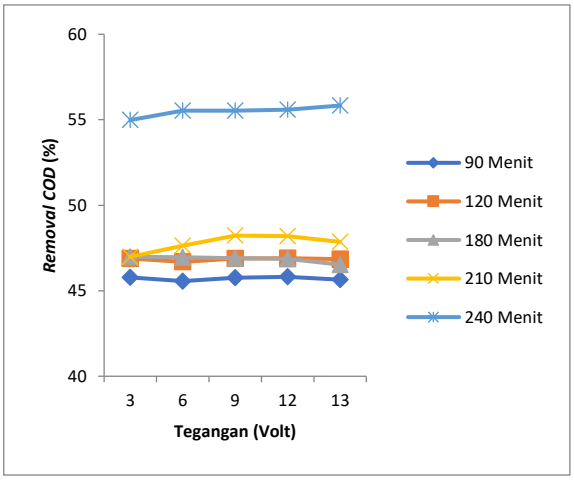

Figure 5. Graph of the Relationship between Voltage and COD Removal in Design I

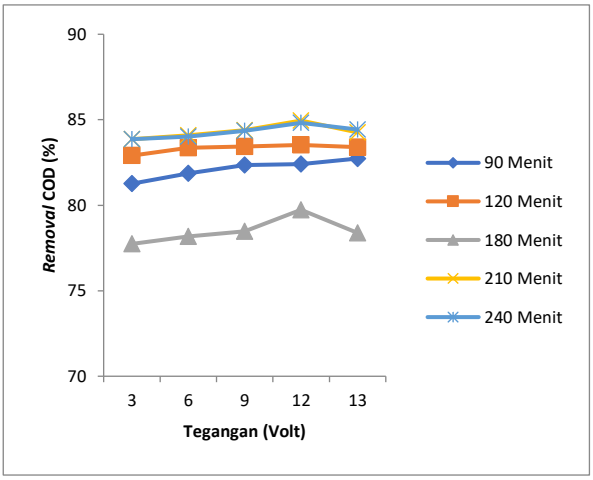

Figure 6. Graph of the Relationship between Voltage and COD Removal in Design II

4. CONCLUSION

This study demonstrates that adjusting the macrospatial aspect ratio of an electrocoagulation reactor offers a powerful mechanical lever to overcome mass-transfer limitations and enhance pollutant removal efficiency. Compared to traditional elongated channels (Design I), the compact cubic configuration (Design II) establishes a more uniform electrical field and optimizes the fluid-electrode contact area per unit volume. This structural re-engineering successfully accelerates macroscopic floc growth and minimizes internal cell resistance, providing a valuable contribution to electrocoagulation reactor design theory by proving that spatial configuration is as vital as chemical parameter optimization. From an industrial application perspective, Design II achieved high removal efficiencies for TSS and TDS, meeting the strict discharge thresholds of the Minister of Environment Regulation No. 5 of 2014. However, the residual refractory COD highlights that standalone electrocoagulation is insufficient for complex pharmaceutical matrices. A conceptual cost-benefit analysis indicates that utilizing Design II as a high-efficiency pre-treatment unit is highly viable; by heavily reducing the initial particulate and organic load at a low Specific Energy Consumption (SEC), it protects downstream units from fouling and significantly lowers the chemical and power costs of secondary advanced treatments (such as AOPs or membrane bioreactors). Therefore, this compact EC reactor design serves as an economically sound and high-performance foundation for integrated industrial wastewater treatment systems.

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