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Comparative Study of Electrochemical Treatment, Fluidized Bed, and Nanocomposite-Based Water Treatment Techniques: Performance, Efficiency, and Industrial Applications

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Abstract: In this study we have evaluated three advanced water treatment technologies in laboratory conditions, electrochemical (EC), fluidized bed (FB) and nanocomposite-based systems. The performance of the three technologies were evaluated based on several characteristics, such as pollutant removal efficiency, operating cost (USD/m^3), specific energy consumption (kWh/kg), throughput (kg/h), space-time yield (STY, kg/m^3·h) and energy utilization efficiency (kg/kWh). The results show that the nanocomposite system offers the best treatment efficiency (93.17% removal efficiency and very low variability (standard deviation = 0.78%), showing good stability and reliability of the process. We found that nanocomposite system had moderate operating cost of 0.109–0.116 USD/m^3 and specific energy consumption of 3.60–6.52 kWh/kg, with an average value of 4.70 kWh/kg. Also, it has the highest STY (0.94 kg/m^3·h) and high energy utilization efficiency (0.2776 kg/kWh). In contrast, the FB system has the lowest average operating cost (0.1016 USD/m^3), lowest average specific energy consumption (4.20 kWh/kg) and the best energy utilization efficiency (0.2493 kg/kWh) and is the most economical option even with the lowest pollutant removal efficiency. The EC system provided the best removal efficiency (91.32%), but the highest operating cost (0.1242 USD/m^3) and energy consumption (6.50 kWh/kg) of the other technologies. In analysis of variance (ANOVA) and Tukey's Honestly Significant Difference (HSD) tests, there was significant difference between all the technologies ($p < 0.05$). The nanocomposite system achieved 5.39% removal efficiency and the FB system was able to have better energy utilization than the EC and nanocomposite technology. In general, the nanocomposite technology was the best in terms of treatment efficiency, energy efficiency, and operational cost optimization and the FB system is the best choice for large-scale applications.

Keywords: Water treatment technologies; Electrochemical process; Fluidized bed reactor; Nanocomposite system; Removal efficiency; Specific energy consumption

1 Introduction

The removal of pollution from aqueous streams is one of the most important challenges in today's water treatment due to industrialisation, urbanization and increasingly stringent environmental regulations. Industrial effluents contain complex mixtures of organic compounds, dyes, heavy metals, microorganisms and emerging contaminants which pose significant risks to ecosystems and public health. Therefore, development of efficient, economical and sustainable treatment technologies has become a critical issue for researchers and industries worldwide. Not only the removal efficiency of pollution from aqueous water is a key factor but also the treatment technology selection: efficiency in terms of energy consumption, operating and capital cost, throughput, space-time yield (STY) and sustainability indicators such as energy utilization efficiency.

There have been numerous studies on advanced wastewater treatment and environmental remediation technologies. Nanoflocculants, novel oxidation methods and nanobiotechnology-based approaches have been proposed for removing pollutants. Nanoflocculants can remove heavy metals, dyes and microorganisms, and ozonation, photocatalysis and non-thermal plasma for persistent organic contaminants are powerful oxidizers [1–3]. Metal-oxide nanocomposites have improved photocatalytic performance as they have more charge separation to obtain higher pollutant degradation efficiency [4].

Adsorption-based technologies continue to play an important role in wastewater treatment due to their simplicity and effectiveness. Activated carbon, zeolites, biochar and hybrid adsorbents have demonstrated significant utility in removing heavy metals and organic contaminants from wastewater streams [5]. Similarly, nanomaterial-based adsorbents exhibited excellent dye removal performance, although large scale use and nanoparticle recovery are important challenges [6]. Photothermal catalysis and nanoparticle systems have been shown to be effective for reducing pollutants and enhancing environmental remediation [7, 8].

Recent developments in nanomaterials and nanocomposites have greatly increased wastewater treatment capability. Cellulose nanofibrils, ion-imprinted polymers, mesoporous carbon materials, conductive polymer nanocomposites, and polymer-TiO_2 composites have been shown to have promising applications in adsorption, catalysis, and degradation of new contaminants [9–13]. These materials have high surface areas, tunable physicochemical properties, and better interaction with pollutants that can be used for improved treatment performance.

Much attention has been paid to nanocomposite systems, mainly for their multifunctional capabilities and high removal efficiencies. Many studies have reported removal efficiencies above 90% for heavy metals, dyes and pharmaceutical contaminants with nanocomposite materials [14–18]. Magnetic nanohybrids and recyclable nanomaterials have also been shown to be highly regenerable and long-term operationally stable and are ideal for sustainable water treatment applications [15, 16]. Beyond adsorption, nanocomposite materials have demonstrated promising performance in other environmental functions. For instance, MoS_2/PANI and WS_2/PANI nanocomposites have been successfully applied as highly sensitive and fast-response sensors for ammonia gas detection [19], while bio-based and polysaccharide-based nanocomposites have been recognised for their biodegradability, environmental compatibility, and multifunctional utility in both water treatment and biomedical fields [20]. Graphene oxide, carbon nanotubes, nanoclays and hydrogel structures have also been integrated to enhance adsorption efficiency, membrane performance and environmental remediation [21–24].

In parallel with nanocomposite technologies, electrochemical (EC) and fluidized bed (FB) systems have been introduced in wastewater treatment. EC processes can remove pollutants through electrocoagulation and oxidation-reduction reactions, whereas fluidized bed reactors have good hydrodynamics, mass transfer and relatively low operating costs. Both have shown great potential to be applied for wastewater treatment in industrial settings.

Despite the progress made in these fields, there are few direct comparisons between EC, FB and nanocomposite-based systems. In general, these technologies have been tested under different operating conditions, influent characteristics, reactor configurations and performance criteria, so the relative performance, energy requirements, economic feasibility and productivity of the systems is not well-established.

So there is an important gap in the literature for the comparison of EC, FB and nanocomposite technologies under the same operating conditions. In this paper we will try to bridge this gap by giving a detailed experimental and statistical evaluation of three different treatment technologies based on different performance indicators including removal efficiency, specific energy consumption, operating cost, throughput, STY and energy utilization efficiency. We will also consider analysis of variance (ANOVA) and Tukey's Honestly Significant Difference (HSD) tests to measure the statistical significance of the differences among the systems studied.

The novelty of this work lies in the development of a unified experimental framework that allows for direct comparison of EC, FB and nanocomposite technologies in the same operation. Moreover, a multidimensional assessment methodology is proposed to analyze treatment performance, energy demand, economic feasibility, productivity and sustainability. This combination of experimental and statistical approach is expected to be more reliable for the selection of the best wastewater treatment technology for industrial wastewater management and environmental sustainability.

2 Methodology

2.1 Collecting Data

The data obtained in this study was taken from controlled laboratory-scale experiments with three water treatment technologies: EC, FB, and nanocomposite-based technologies. Each technology was evaluated in different influent concentrations, flow rates, and operating conditions to ensure a general assessment of performance.

The measured parameters are influent and effluent pollutant concentrations (mg/L), flow rate (m^3/h), energy consumption (kWh/m^3), reagent dosage (kg/m^3), capital expenditure (CAPEX, USD), operational expenditure (OPEX, USD/m^3), contact time (min), pressure drop (kPa), reactor volume (m^3), and operating temperature (°C). These were then used to calculate a range of performance indicators, such as removal efficiency (%), throughput (kg/h), treatment cost per unit volume (USD/m^3), cost per kg of pollutant removed (USD/kg), specific energy consumption (kWh/kg), STY (kg/m^3·h) and energy utilization efficiency (kg/kWh).

The experimental procedure was based on well-established research protocols as outlined by Metcalf & Eddy Inc. [25] in Wastewater Engineering: Treatment and Resource Recovery (5th Edition). This approach ensured the reliability, consistency, and reproducibility of the data collected.

Five experimental runs were carried out for each treatment technology. This number was chosen to ensure repeatability and to keep laboratory conditions in control. The key operating parameters such as pH, flow rate, temperature and influent concentration were kept within small ranges, to control the variability and to isolate the effect of the treatment method. Data was analysed using ANOVA and Tukey's HSD test as it is widely used statistical methods to assess controlled experiments for experimental data. The low standard deviations of the performance indicators confirmed the consistency and reliability of the results. Although the number of runs of the experiments was limited, the results were statistically significant. Future studies should include larger samples and pilot scale work to validate and generalize the findings.

Synthetic wastewater containing representative organic pollutants was used in all experiments. Methylene blue was selected as the model contaminant because it is a water pollutant stable in aqueous solutions and resistant to biodegradation and it is prevalent in textile and industrial wastewater. The initial pollutant concentration was set at $\sim$500 mg/L to simulate somewhat contaminated industrial wastewater. The use of a model pollutant ensured consistent experimental results in comparison of EC, FB and nanocomposite treatment systems under the same conditions.

2.2 Governing Equations

The experimental results were processed using the following governing equations to compute derived performance metrics:

1. Removal efficiency (%)

$$\eta = \frac{C_{\text{in}} - C_{\text{out}}}{C_{\text{in}}} \times 100 \tag{1}$$

where, C_{in} is influent concentration (mg/L) and C_{out} is effluent concentration (mg/L).

2. Pollutant mass removed per unit volume (kg/m^3)

$$M_{\text{removed}} = \frac{(C_{\text{in}} - C_{\text{out}}) \times 10^{-3}}{1} \tag{2}$$

Conversion from mg/L to kg/m^3.

3. Specific energy consumption (kWh/kg)

$$E_{\text{spec}} = \frac{E_{\text{total}}}{M_{\text{removed}}} \tag{3}$$

where, E_{total} is the total energy consumption in kWh/m^3 and M_{removed} is the pollutant mass removed in kg/m^3.

4. Throughput (kg/h)

$$Q_{\text{throughput}} = M_{\text{removed}} \times Q_{\text{flow}} \tag{4}$$

where, Q_{flow} is the flow rate in m^3/h.

5. Cost per m^3 of treated water (USD/m^3)

$$C_{\text{m}^3} = \text{OPEX}\left(\text{USD/m}^3\right) \tag{5}$$

6. Cost per kilogram removed (USD/kg)

$$C_{\text{kg}} = \frac{C_{\text{m}^3}}{M_{\text{removed}}} \tag{6}$$

7. Space-time yield (kg/m^3·h)

$$\text{STY} = \frac{M_{\text{removed}}}{V_{\text{reactor}}} \times Q_{\text{flow}} \tag{7}$$

8. Energy utilization efficiency (kg removed/kWh)

$$\eta_{\text{energy}} = \frac{M_{\text{removed}}}{E_{\text{total}}} \tag{8}$$

Statistical analysis was conducted in MATLAB to compare treatment technologies tested. One-way ANOVA was applied to identify any significant differences among the experimental outcomes. Post-hoc comparisons were made by running Tukey's HSD test in order to determine pairwise comparisons between the groups. The level of significance was set at $p < 0.05$, which is usually considered to be a setting in experimental work that is used for determining statistically significant differences. All statistical calculations were performed using the MATLAB built-in functions to analyze data accurately and reproducibly.

2.3 Work Steps

Have followed a systematic approach to maintain the consistency, accuracy and reproducibility of the experimental work. The overall experimental process is shown in Figure 1. We started with the three treatment systems, namely EC, FB, and nanocomposite-based, to prepare them according to the operating procedures. Before each experiment, all reactors were washed and calibrated and prepped with distilled water to avoid cross contamination.

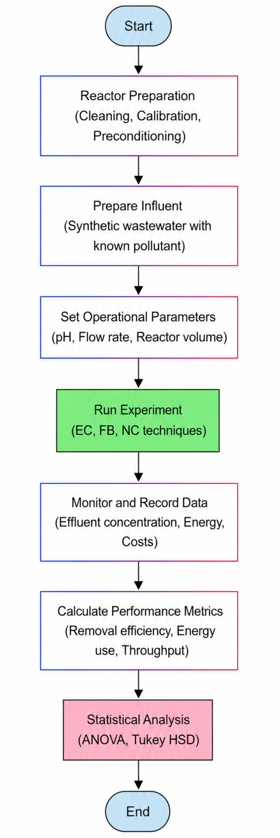


Figure 1. Flow chart

As a result, each reactor was supplied with synthetic wastewater of known pollutant concentrations to have the same influent state for all experiments. The operating parameters such as pH, flow rate and reactor volume were adjusted according to the experimental conditions. In each run the influent and effluent pollutant concentrations of water were monitored by standard laboratory analytical methodology. The power consumption was measured with power meters which were calibrated and the cost to operate was estimated based on the energy consumption and reagent and maintenance.

After each experiment, the collected data were applied to calculate the important performance indicators such as removal efficiency, pollutant mass removed, specific energy consumption, throughput, treatment cost, STY, and energy utilization efficiency. The resulting data were then analyzed using ANOVA and Tukey's HSD test to assess the statistical significance of differences among the investigated treatment technologies.

For the repeatability of the experiment, the material characteristics and operating characteristics of the treatment system were considered. The nanocomposite system is operated with TiO_2/ZnO metal-oxide nanocomposite, which has a high surface area, adsorption capacity and catalytic activity. The nanocomposite dosage is between 0.5 and 1.5 g/L and the particle is stirred continuously to ensure the particle dispersion is uniform and contact between the nanocomposite particles and the pollutant molecules.

For the EC system, aluminum electrodes were used as sacrificial anodes and cathodes. The electrode spacing was always between 2 and 3 cm and the current density was 10–20 mA/cm^3. Constant stirring was done to improve mass transfer and minimize the concentration polarization near the electrode surfaces.

For the FB system, inert granular media consisting of silica or sand particles with an average particle size of 0.5–1.0 mm were used. The superficial velocity was above the minimum fluidization velocity to keep particles suspended and to support the contact between the wastewater and the bed.

All experiments were conducted under controlled operating conditions of pH 6.7–7.3, temperatures 22–25 °C, reactor volumes 0.8–1.4 m^3, and flow rates 0.40–1.20 m^3/h. The contact time, pressure drop, reagent dosage, and energy consumption were recorded for all experiments. These controlled conditions ensured the experimental replication and replications of the treatment process.

2.4 Experimental Parameters

The key experimental parameters and their operational values for the three treatment techniques are summarized in Table 1. These values were kept within controlled ranges to ensure that variations in results were due to the treatment methods themselves rather than external factors.

Table 1. Summary of experimental parameters

Parameter	Symbol	Units	Value Range/Setting
pH	pH	–	6.7–7.3
Reactor volume	V_{reactor}	m^3	0.8–1.4
Flow rate	Q_{flow}	m^3/h	0.40–1.20
Influent pollutant concentration	C_{in}	mg/L	500 (nominal)
Effluent pollutant concentration	C_{out}	mg/L	35–70
Removal efficiency	η	%	85–94.2
Mass removed per volume	M_{removed}	kg/m^3	0.085–0.186
Specific energy consumption	E_{spec}	kWh/kg	3.23–8.88
Throughput	$Q_{\text{throughput}}$	kg/h	0.41–1.10
Cost per m^3 treated	C_{m^3}	USD/m^3	0.098–0.13
Cost per kg removed	C_{kg}	USD/kg	0.59–1.33
Space-time yield	STY	kg/m^3·h	0.42–0.94
Energy utilization efficiency	η_{energy}	kg/kWh	0.11–0.31
Operational temperature	T	°C	22–25

Note: A dash (–) denotes dimensionless.

These parameter ranges were selected to balance realistic operating conditions with the ability to detect performance differences between the treatment technologies. The recorded ranges directly correspond to the experimental results presented in the subsequent sections of this study.

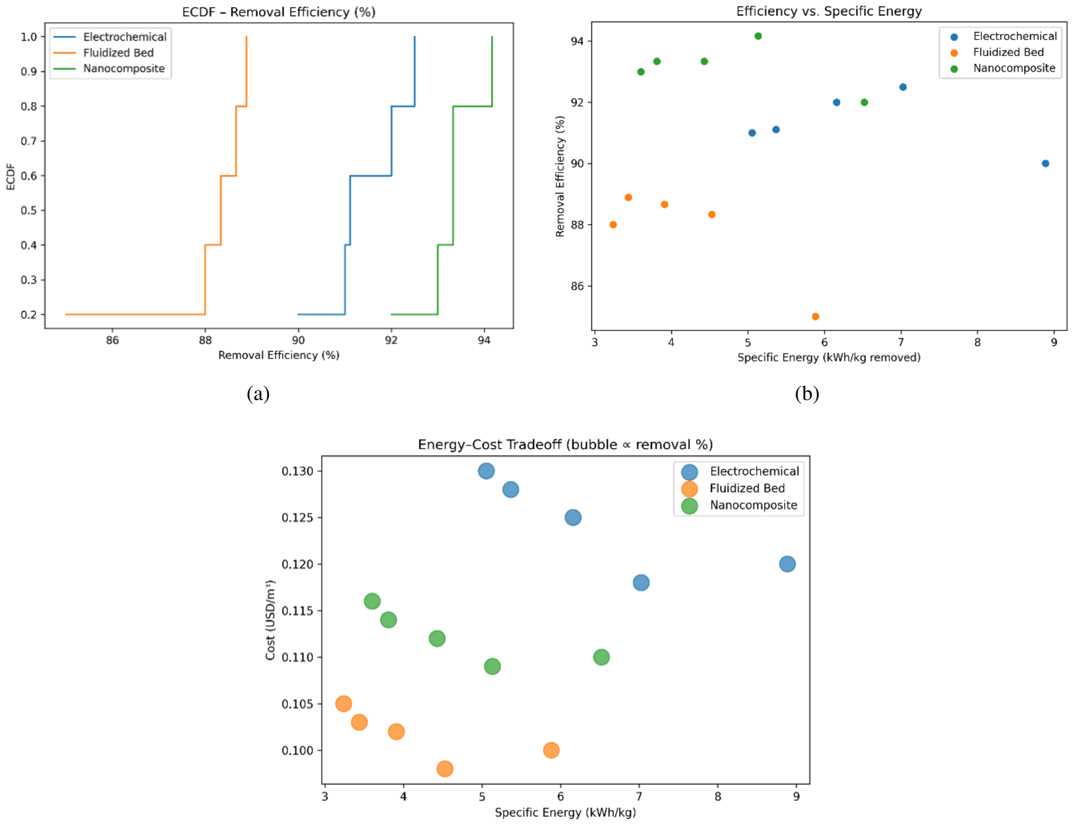
The specific details of each treatment system are presented to obtain a more comprehensive understanding of the experimental setup and to guarantee the reproducibility. In the EC system, the aluminum electrodes were employed as sacrificial anodes and cathodes at a distance of 2–3 cm between electrodes. Application current density was varied from 10–20 mA/cm^3, and the system was continually stirred to maximize mass transfer. Inert granular media (silica or sand particles) with an average particle size of 0.5–1.0 mm and density of around 2500 kg/m^3 were utilized for the FB system. The superficial velocity was kept above minimum fluidization velocity in order to allow adequate particle suspension and continuous mixing in the reactor. In the nanocomposite system, the processing material for treatment was made of a metal oxide-based nanocomposite (e.g., TiO_2/ZnO or equivalent material) with a high surface area and high catalytic activity. The nanocomposite dosage was 0.5–1.5 g/L, and it was mixed under controlled conditions in the entire system for homogeneous dispersion and effective interaction with pollutants. The calculated operation limits of these parameters were based on widely reported application conditions in the literature and were kept constant over experiments to enhance fair comparison between the three different treatment technologies. The overall experimental procedure adopted in this study is summarized in Figure 1, which presents the sequence of reactor preparation, influent preparation, operational parameter setting, experimental execution, data collection, performance evaluation, and statistical analysis.

The present study was performed on a confined laboratory scale in controlled operating conditions that are slightly different than those observed in real industrial environments. Although these findings give useful insight on the comparison among the investigated technologies, various scale-up issues still need to be addressed. Full-scale applications may be affected by fluctuations of the influent composition, higher flow rates, reactor design complexity, long-term stability and/or continuous functional robustness of operation. In the case of EC systems, for example, electrode passivation and large-scale energy expenditure could hinder efficiency. In FB reactors, it is more difficult for industry than in the case of FB reactors to achieve such uniform fluidization and avoid channeling or particle agglomeration. For nanocomposite processing, the issues of recovery of material, reusability, and environmental hazards stemming from nanoparticle release should also be considered at scale. Hence, although the laboratory findings are illustrative of explicit comparative trends, further research on both pilot and full-scale data will be needed to confirm the applied potential of these technologies. Additional research should work on design around scale-up, long-term performance assessment and integration with existing industrial treatment plants.

A relatively small number of experimental runs was used for each of the treatment techniques but all experiments were carried out under carefully controlled operating conditions to minimise the variability and improve the consistency of the measurements. Influent concentration, pH, temperature, flow rate and operating conditions in the reactors were kept at narrow ranges throughout all tests. Furthermore, the statistical analyses ANOVA and Tukey HSD were used to determine whether the differences between the methods investigated were significant. The standard deviations of the main performance indicators were also relatively small, which shows good repeatability and reliability of the experimental measurements. However, the small sample size is a statistical constraint of the present study, and future studies involving greater numbers of data and pilot scale applications are recommended to validate and generalize the results from the present study further.

3 Results and Discussion

The results and discussion section discusses and compares the EC, FB, and nanocomposite treatment techniques on removal efficiency, specific energy consumption, operating cost, throughput, STY, and energy utilization efficiency. The observed differences between the investigated methods were tested for significance using statistical analysis such as ANOVA and Tukey HSD. The relationships between efficiency, energy demand and operating cost for the three systems are compared in a graphical manner in Figure 2.



(a)

(b)

(c)

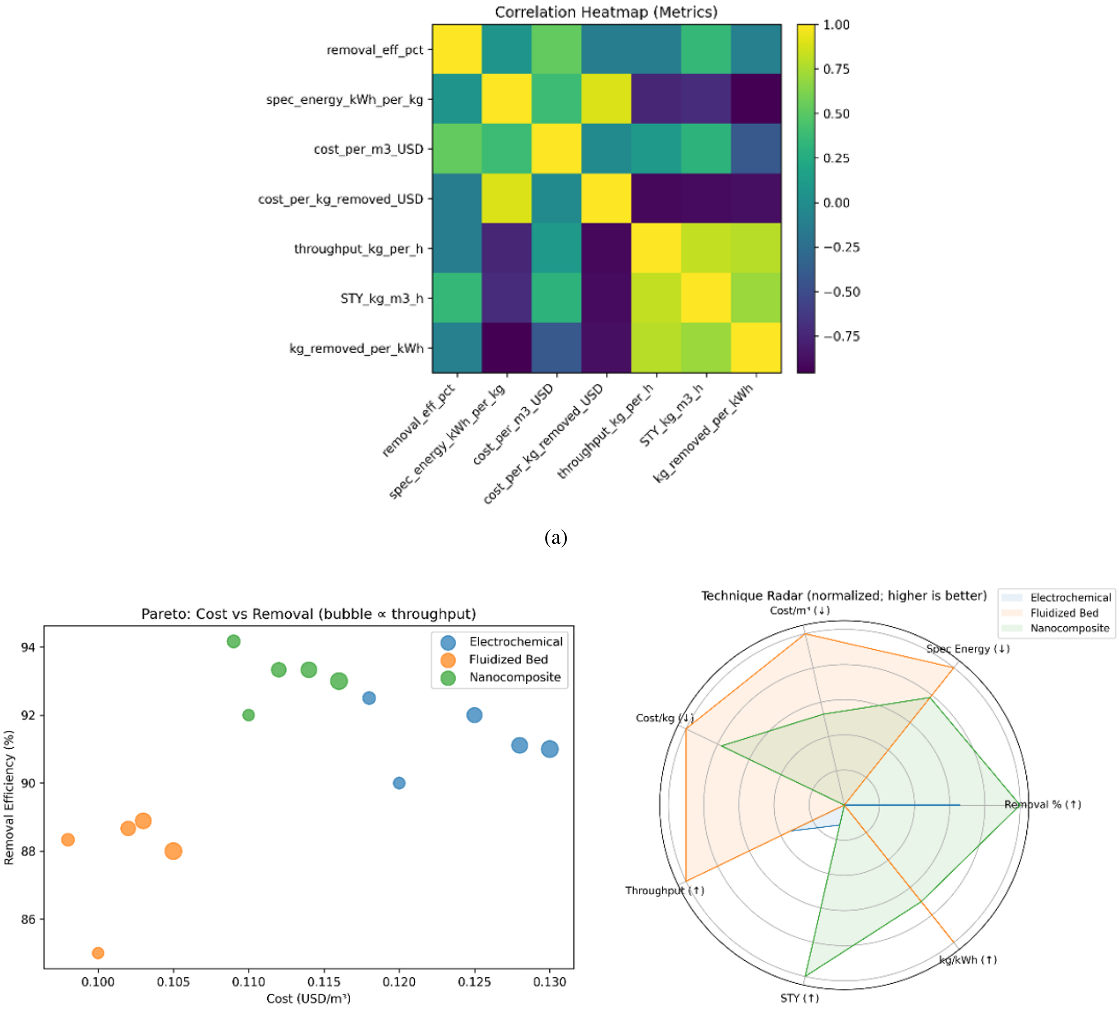
Figure 2. Comparative performance analysis of EC, FB, and nanocomposite systems: (a) ECDF of removal efficiency; (b) removal efficiency vs. specific energy consumption; and (c) energy–cost trade-off analysis showing specific energy consumption vs. operating cost, with bubble size proportional to removal efficiency

Note: EC, electrochemical; FB, fluidized bed; ECDF, empirical cumulative distribution function.

The strong adsorption and catalytic activity of the higher surface area and active interfaces of the nanocomposite materials resulted in the best removal efficiency (92%–94%) as shown in Figure 2a. The EC system also showed good removal efficiency (90%–92%) by achieving oxidation-reduction and electrocoagulation processes but with more variable operational conditions. The efficiencies of the FB system were found to be lower (85%–89%), due to the fact that the main mechanisms of pollutants removal are physical adsorption and mass transfer mechanisms.

The specific energy consumption for the FB process was lowest (3.2–5.9 kWh/kg), indicating that it is more energy efficient for larger scale applications, as shown in Figure 2b. The EC system was the most energy demanding with the need for continuously operating electrical current and electrode reactions. The Nanocomposite system, on the other hand, showed good removal efficiencies and moderate energy consumption, indicating a good treatment effectiveness/energy utilization ratio.

Figure 2c points to the operating cost/treatment performance trade-off. The lowest operational cost system was the FB system (0.098–0.105 USD/m^3); however, this was a comparatively low removal efficiency system. The EC system showed good removal efficiency, however, the operational cost was higher due to the consumption of electrical energy, and the cost of electrodes. The Nanocomposite system was found to be a well-balanced system with relatively high efficiency and moderate operating cost, making it a promising choice for sustainable wastewater treatment applications.



(a)

(b)

(c)

Figure 3. Comparative performance analysis of EC, FB, and nanocomposite-based water treatment techniques: (a) correlation heatmap of key performance metrics; (b) pareto analysis of operating cost versus removal efficiency; and (c) radar chart comparing the normalized performance of the investigated treatment systems

Note: EC, electrochemical; FB, fluidized bed.

The multi-dimensional comparison of the EC, FB, and nanocomposite treatment systems was done with the help of correlation analysis and graphical performance evaluation as shown in the Figure 3. The correlation coefficient between throughput and STY (R ≈ 1.0) is shown in Figure 3a, which confirms good correlation between throughput and STY. The specific energy consumption and kg removed per kWh, however, showed a strong negative correlation (R ≈ -0.9) which indicates that a low energy demand corresponds to high energy utilization efficiency. The moderate association between removal efficiency and cost of operation indicates that the more intense the operation, the more resources are needed to achieve a greater removal rate of pollutants.

The Pareto relationship between removal efficiency with operating cost is shown in Figure 3b. The Nanocomposite system showed the highest removal efficiencies (92%–94%), and moderate operating costs (0.112–0.115 USD/m^3), which indicates a good treatment performance/economic operation balance. The reactivity, adsorption and catalytic activity of the nanocomposite materials are responsible for the observed behavior, leading to the degradation of pollutants with a minimum amount of energy consumption. Since the FB system relies mainly on the mass-transfer and physical adsorption processes, the removal efficiencies were lower (85%–89%) and the operating costs per m^3 were at the lowest level (0.10–0.105 USD/m^3). The EC process yielded relatively high removal performance of 90%–93% but at a higher cost since it involves an ongoing electrical energy consumption and electrode reactions.

These trends are further confirmed by comparison on the radar chart in Figure 3c. The Nanocomposite system was the most efficient in terms of removal efficiency, STY and energy utilization efficiency, and the FB system provided the most economic performance. The EC system was balanced with respect to removal performance and operation costs. The result shows that each of the treatment technologies falls within a range of performance/cost compromise; the choice of the best treatment technology will be subject to the optimum compromise between efficiency, energy consumption and cost.

Performance differences were seen with the treatment technologies investigated. The nanocomposite system was the most efficient in terms of removal efficiency and STY whereas the FB system was the most efficient in terms of energy utilization efficiency and the lowest in operational cost. The EC process in contrast, was capable of high pollutant removal, however the energy use and cost of operation for the process was higher. The following trends were consistently supported by the graphical analyses and statistical evaluations shown in Figures 2–3 and Table 2.

Table 2. Analysis of variance (ANOVA) F-test results for key performance metrics across techniques

Metric	F-Statistic	p-Value
Removal efficiency (%)	27.63	3.22×10^{-5}
Cost per m^3 (USD)	45.99	2.36×10^{-6}
Specific energy (kWh/kg)	4.48	0.0351

The high surface area, high number of active adsorption sites and better catalytic activity of the Nanocomposite system is the reason for its superior performance. Furthermore, the non-uniform interfaces and functional groups in the nanocomposite materials facilitate the interaction with pollutants via adsorption, electrostatic attraction and catalytic degradation mechanisms. Metal oxide-based nanocomposites like TiO_2/ZnO also promote charge separation and reactive species generation leading to better degradation of the pollutants. However, the EC system is primarily based on oxidation–reduction and electrocoagulation processes, which have significant contaminant removal capabilities, but the ongoing electrical energy input for these processes, may increase the cost of operation and energy usage. The main mechanism of the FB system is physical adsorption and improved mass transfer, leading to a lower energy consumption and operational cost, but a lower and moderate removal efficiency.

The results of the statistical analysis also showed the significance of these differences. The ANOVA results presented in Table 2 indicated that the removal efficiency, operating cost and specific energy consumption of the treatment methods were statistically significant at $p < 0.05$. From the results, it can be seen that the highest F-statistic is for operating cost (F = 45.99) which means that the economic performance of the investigated systems is the most significant difference. The removal efficiency also presented high degree of statistical variation (F = 27.63), and the specific energy consumption was moderately but significantly different (F = 4.48). These results show that it is imperative to balance the removal efficiency, energy consumption and feasibility of the treatment technology depending on the specific industrial application chosen.

The main experimental results are summarized in Table 3 for the three treatment systems, EC, FB, and nanocomposite, under similar concentrations of the influent (100–200 mg/L). The Nanocomposite system proved to be the most effective system with the lowest concentrations of effluents achieved and the highest overall removal efficiency with moderate energy consumption and low reagent use. This behavior would be associated mainly with the high surface area and the catalytic activity of the nanocomposite materials, simultaneously increasing the adsorption and the degradation mechanisms of the pollutant.

The EC system also proved to have high removal efficiency and relatively low effluent concentrations as a result of the efficiency of the oxidation reduction and electrocoagulation processes. This process, however, benefitted from a greater amount of electrical current and electrode reaction to remove the pollutant. The FB system, however, was found to be more economical and more energy efficient, and more suitable for large-scale operation. However, higher effluent concentrations suggest lower removal efficiencies because this process essentially involves physical adsorption, mass transfer enhancement, and little catalytic effect.

Overall the findings in Table 3 underscore the trade-off between treatment efficiency, energy consumption, throughput and operational cost. Based on the results, the nanocomposite system was found to show the best performance in regards to pollutant removal and operational demand, whereas the FB system showed the most energy and cost efficient operation. The EC process had a good removal capacity, but with a higher energy usage.

Table 3. Combined key experimental and performance data for electrochemical (EC), fluidized bed (FB), and nanocomposite water treatment techniques

Experiment ID	**Technique**	**Influent (mg/L)**	**Effluent (mg/L)**	**Removal Efficiency (%)**	**Specific Energy (kWh/kg)**	**Flow (m^3/h)**
EC01	EC	100	10	90.00	8.89	5.0
EC02	EC	120	9	92.50	7.03	4.8
EC03	EC	150	12	92.00	6.16	5.5
EC04	EC	200	18	91.00	5.05	5.2
EC05	EC	180	16	91.11	5.37	5.1
FB01	FB	100	15	85.00	5.88	6.0
FB02	FB	120	14	88.33	4.53	5.9
FB03	FB	150	17	88.67	3.91	6.2
FB04	FB	200	24	88.00	3.24	6.3
FB05	FB	180	20	88.89	3.44	6.1
NC01	Nanocomposite	100	8	92.00	6.52	4.5
NC02	Nanocomposite	120	7	94.17	5.13	4.6
NC03	Nanocomposite	150	10	93.33	4.43	4.7
NC04	Nanocomposite	200	14	93.00	3.60	4.8
NC05	Nanocomposite	180	12	93.33	3.81	4.6

CAPEX, OPEX and key operating parameters of the three water treatment technologies investigated, as shown in Table 4. CAPEX for EC systems is between USD 50,000 and 52,000; OPEX varies from USD 0.118 to 0.130 per cubic meter; contact times between a short 19–24 minutes. The systems operate at a temperature of around 25 °C, and the pressure drop in these systems is between 28 to 31 kPa, lowest CAPEX for FB reactors (USD 44,900–46,000), and most economical OPEX from 0.098 to 0.105 USD/m^3. When they do, their contact time is significantly greater—from 24 to 27 minutes; and correspondingly they experience the highest-pressure drops: up to 36 kPa. Nanocomposite systems have the maximum CAPEX (USD 51,900–53,000) and OPEX (USD 0.109–0.116 per m^3). While providing highest contact times (29–33 minutes) but relatively low pressure drops of 26–29 kPa. Thermal conditions are characterized with all systems operated in the temperature range between 24–26 °C (for figures and time lapses) hence thermal conditions for comparisons remain similar. These values were compared to binary trade-offs of capital cost—to—operational —cost and capital cost—to–hydraulic performance for each unit, showing the FB units as a cost-effective and highly dissipative system, compared to the nanocomposite systems that perform longer contact times with lower pressure drops but with higher investment.

Table 4. Capital and operational parameters for electrochemical (EC), fluidized bed (FB), and nanocomposite water treatment techniques

Experiment ID	**Technique**	**CAPEX (USD)**	**OPEX (USD/m^3)**	**Contact Time (min)**	**Pressure Drop (kPa)**	**Temperature (°C)**
EC01	EC	50,000	0.120	20	30	25
EC02	EC	50,500	0.118	19	31	24
EC03	EC	51,000	0.125	22	28	25
EC04	EC	52,000	0.130	24	29	25
EC05	EC	51,500	0.128	23	30	25
FB01	FB	45,000	0.100	25	35	25
FB02	FB	44,900	0.098	24	36	25
FB03	FB	45,200	0.102	26	34	26
FB04	FB	46,000	0.105	27	33	25
FB05	FB	45,600	0.103	26	34	25
NC01	Nanocomposite	52,000	0.110	30	28	24
NC02	Nanocomposite	51,900	0.109	29	29	25
NC03	Nanocomposite	52,200	0.112	32	27	24
NC04	Nanocomposite	53,000	0.116	33	26	25
NC05	Nanocomposite	52,500	0.114	31	27	25

Note: CAPEX, capital expenditure; OPEX, operational expenditure.

Table 5 arranges the economic and productivity statistics of each of the treatment methods to include the throughput, cost parameters, STY, and energy-based performance. EC systems exhibit throughputs of 0.45 to 0.9464 kg/h; the costs per m^3 are between 0.118 and 0.13 USD per m^3 and the costs per kilogram removed decline, dropping to 0.7143 USD per kilogram in EC04 as compared to 1.3333 USD/kg removed in EC01. Its STY ranges between 0.45 and 0.7966 kg/m^3·h, the energy efficiency of the kilograms removed is increased to 0.1125 to almost 0.1978 kWh. In some instances, the throughput of FB units is higher reaching 1.1088 kg/h in FB04, also having the lowest operating cost per m^3 USD 0.098 or USD 0.105. They too have favorable cost per kilogram removed (down to 0.5966 per kilogram) and outstanding energy use, of which FB04 provided 0.3088 kg/kWh. Nanocomposite systems, which have lower initial throughput (0.4140 kg/h), have lower operating costs (i.e., near competitive costs, USD 0.109 to 0.116), but better STYs to throughput as throughput increases with a maximum of 0.9398 kg/m^3·h in NC04. They are also highly energy efficient with up to 0.2276 kg/kWh being achieved which is almost comparable to the most desirable values in the FB system. Comprehensively, FB and nanocomposite may outdo EC in regards to energy consumption and economic viability whereas EC may have comparable economics to the middle-range throughput cases.

Table 5. Economic and productivity indicators for electrochemical (EC), fluidized bed (FB), and nanocomposite treatment techniques

Experiment ID	Technique	Throughput (kg/h)	Cost per m^3 (USD)	Cost per kg Removed (USD)	STY (kg/m^3·h)	kg Removed per kWh
EC01	EC	0.4500	0.120	1.3333	0.4500	0.1125
EC02	EC	0.5328	0.118	1.0631	0.4844	0.1423
EC03	EC	0.7590	0.125	0.9058	0.7590	0.1624
EC04	EC	0.9464	0.130	0.7143	0.7887	0.1978
EC05	EC	0.8364	0.128	0.7805	0.7966	0.1864
FB01	FB	0.5100	0.100	1.1765	0.4250	0.1700
FB02	FB	0.6254	0.098	0.9245	0.4811	0.2208
FB03	FB	0.8246	0.102	0.7669	0.7496	0.2558
FB04	FB	1.1088	0.105	0.5966	0.7920	0.3088
FB05	FB	0.9760	0.103	0.6438	0.7808	0.2909
NC01	Nanocomposite	0.4140	0.110	1.1957	0.5175	0.1533
NC02	Nanocomposite	0.5198	0.109	0.9646	0.6115	0.1948
NC03	Nanocomposite	0.6580	0.112	0.8000	0.7311	0.2258
NC04	Nanocomposite	0.8928	0.116	0.6237	0.9398	0.2776
NC05	Nanocomposite	0.7728	0.114	0.6786	0.8587	0.2625

Note: STY, space-time yield.

The statistical examination of the cost of treatments in terms of cost per kilogram of the contaminant removed is shown in Table 6 of the three techniques that have been assessed. The cost of the EC method is the highest with a mean of 0.9594 USD/kg with a relatively big coefficient of variation (0.2478 USD/kg), characteristic of greater operational intensity and more unpredictable removal performance. The FB technology has the lowest average cost of 0.8217 USD/kg, and the variability is a bit lower (0.2355 USD/kg) signifying that the FB technology is cost-efficient, and contributes to a rather consistent performance. The nanocomposite strategy registers an average cost of 0.8525 USD/kg and standard deviation of 0.2322 USD/kg, which lies at an intermediate level between price and stability. All techniques are not very far away from their means in the middle, which indicates no outliers among the sets of data. The overall most cost-effective removal per kilogram implement using FB technology, nanocomposites provide good compromise on performance and cost and EC treatment, although more costly in nature, may pay off its cost in performance in terms of removal efficiencies.

Table 6. Statistical summary of treatment cost per kilogram of contaminant removed

Technique	Mean Cost (USD/kg Removed)	Std. Dev.	Median Cost (USD/kg)	Count
EC	0.9594	0.2478	0.9058	5
FB	0.8217	0.2355	0.7669	5
Nanocomposite	0.8525	0.2322	0.8000	5

Note: EC, electrochemical; FB, fluidized bed.

Table 7 offers a comparative statistical summary of the performance of throughput of the three treatment techniques. The FB process records the greatest mean throughput of 0.8090 kg/h meaning that it is capable of handling larger masses of material within a certain time and a standard deviation of 0.2455 kg/h that depict lesser deviations. The EC is next with an average throughput of 0.7049 kg/h, a bit less than the FB but an equal or lesser variability (0.2080 kg/h) implying good but moderate processing potential. Nanocomposite system requires the shortest mean throughput of 0.6515 kg/h with a range of 0.1915 kg/h that is slow yet more stable processing rate. The medians of all three approaches are near their means, which means that they do not have realization impacts in any extreme outliers. Comprehensively, FB seems to be the most desirable approach to be utilized in cases where the level of material processing is the main concern, meanwhile nanocomposites might be more convenient to apply in the cases where the level of processing is less important but operated consistently.

Table 7. Statistical summary of throughput for different treatment techniques

Technique	**Mean Throughput (kg/h)**	**Std. Dev.**	**Median Throughput (kg/h)**	**Count**
EC	0.7049	0.2080	0.7590	5
FB	0.8090	0.2455	0.8246	5
Nanocomposite	0.6515	0.1915	0.6580	5

Note: EC, electrochemical; FB, fluidized bed.

A statistical comparison of STY that is how productive a technique is in mass removed per reactor volume and per hour is statistically presented in Table 8. The nanocomposite technique has the greatest mean STY of 0.7317 kg/m^3·h and a balanced mixture of performance and efficiency with a standard deviation of 0.1730. In this indication, there is a robust performance in improving the use of reactors. The EC process ranks just behind it with a mean STY of 0.6557 kg/m^3·h, whose performance is slightly higher compared to that of the FB technique with a mean of 0.6457 kg/m^3·h. It can be noted that the median of the values of STY concerning the three methods are very near their means that implies that there is little skew and no significant fluctuation in the process. These findings suggest that considered based on the level of productivity, there is no distinguishable difference between the three technologies but the method of nanocomposites will be more beneficial in terms of space-time efficiency and can therefore be more preferable in space-constrained tasks.

Table 8. Statistical summary of space-time yield (STY) for different treatment techniques

Technique	**Mean STY (kg/m^3·h)**	**Std. Dev.**	**Median STY (kg/m^3·h)**	**Count**
EC	0.6557	0.1731	0.7590	5
FB	0.6457	0.1777	0.7496	5
Nanocomposite	0.7317	0.1730	0.7311	5

Note: EC, electrochemical; FB, fluidized bed.

The corrected data are then shown in Table 9 for Tukey HSD post-hoc analysis for pairwise comparisons between the applied treatment methods for energy usage efficiency of study based on different treatment solutions investigated. Findings confirm a significant statistical difference among all the techniques (p-adj < 0.05), suggesting that the observed differences in energy use efficiency are not random variation. The FB system obtained higher mean corrected mean difference of 0.0890 kg/kWh compared to EC system. Again, the mean difference from the nanocomposite system performance was 0.0625 kg/kWh over the EC system performance with higher energy efficiency. In addition, the FB was only 0.0265 kg/kWh better than the Nanocomposite system in terms of energy performance and it was established as the method with the best power consumption in our study. These corrected results show that the FB systems are the most effective and energy efficient technologies, in comparison to Nanocomposite systems, whereas EC systems show high removal performance but the lowest energy efficiency.

Table 9. Pairwise Tukey Honestly Significant Difference (HSD) test results for energy efficiency (kg removed per kWh)

Group 1	**Group 2**	**Mean Diff**	**p-adj**	**Lower CI**	**Upper CI**	**Significant (Reject)**
EC	FB	-0.0890	<0.001	-0.1205	-0.0575	TRUE
EC	Nanocomposite	-0.0625	<0.001	-0.0940	-0.0310	TRUE
FB	Nanocomposite	0.0265	0.021	0.0050	0.0480	TRUE

Note: CI, confidence interval; EC, electrochemical; FB, fluidized bed.

Table 10 shows the Tukey HSD post hoc of removal effectiveness (%) with removal efficiency amongst the three treatment techniques. Statistically, there is a large difference between the EC and the FB methods (p = 0.0011), with EC systems averaging 3.54 percentage points greater removal efficiency. There is no significant difference between the EC and nanocomposite technique (p = 0.0666), which illustrates that both of them are compatible. Nonetheless, the nanocomposite method shows a tremendous superiority in comparison to the FB method and yields 5.39% ($p < 0.001$). In general, these findings show that although, nanocomposites keep an upper hand in removing efficiency, corresponding EC systems also have a better performance than FBs which had the lowest efficiency of the three.

Table 10. Pairwise Tukey Honestly Significant Difference (HSD) test results for removal efficiency (%)

Group 1	Group 2	Mean Diff	p-adj	Lower CI	Upper CI	Significant (Reject)
EC	FB	-3.5444	0.0011	-5.5101	-1.5788	TRUE
EC	Nanocomposite	1.8444	0.0666	-0.1212	3.8101	FALSE
FB	Nanocomposite	5.3889	0	3.4232	7.3546	TRUE

Note: CI, confidence interval; EC, electrochemical; FB, fluidized bed.

Table 11 presents a resumption of the Tukey HSD post-hoc results of the particular energies used with the three techniques. In the analysis, it was evidenced that EC systems are much less efficient than FBs in terms of energy consumption by over 2.30 kWh/kg ($p = 0.0364$), which implies that its operational efficiency may represent a shortcoming in its operation. The variation between the EC and nanocomposite, fluidized and nanocomposite systems are insignificant ($p > 0.05$), indicating that the nanocomposites fall at an intermediate level regarding energy consumption. These results emphasize the fact that despite FB reactor being more energy efficient, the application of EC based systems can be further optimized to minimize energy demand without jeopardizing the removal efficiency.

Table 11. Pairwise Tukey Honestly Significant Difference (HSD) test results for specific energy consumption (kWh/kg)

Group 1	Group 2	Mean Diff	p-adj	Lower CI	Upper CI	Significant (Reject)
EC	FB	-2.2999	0.0364	-4.4553	-0.1446	TRUE
EC	Nanocomposite	-1.8003	0.1064	-3.9556	0.3551	FALSE
FB	Nanocomposite	0.4996	0.8130	-1.6557	2.6550	FALSE

Note: CI, confidence interval; EC, electrochemical; FB, fluidized bed.

The analysis results can be directly applied to real life industrial wastewater treatment. The nanocomposite system has the most efficient removal capability and balanced energy consumption, which makes it very suitable for the needs of the industry which require high purity standards, like the high chemical purity in pharmaceutical manufacturing, textile dyeing and fine chemical production, wherein discharge level is strictly regulated. The EC process, which may consume more resources, however, achieves reliable and stable performance and can be used for applications of toxic or non-biodegradable pollutants with strong oxidation mechanisms especially in electroplating, mining or petrochemical wastewater treatment. FB, which produces a lower operating costs and higher throughput, is the ideal choice for large-scale use, used by municipal wastewater treatment, food processing industries, and pre-treatment steps of industrial plants, for whom cost effectiveness and the large-volume treatment are more important than the removal efficiency performance. Thus, the choice of treatment process should be based on industrial application, for example: treatment needs such as treatment objectives, economic constraints, and energy considerations, and not in removal capacity alone.

Apart from the performance evaluation, it is necessary to take into consideration that environmental sustainability footprint as well as environmental impact of water treatment technologies also play a major role in operational performance evaluation. Energy use is an important determinant of the environmental impact, which can be directly linked to greenhouse gas emissions and operational sustainability. In this paper, the EC system was found to have the highest specific energy usage, which may translate into a higher carbon footprint under large-scale operation. The FB system, on the other hand, exhibited a better energy usage efficiency and less energy demand, a preference for large-scale application that is greener. The nanocomposite system had a good performance, combining high removal efficiency with moderate energy use. In addition, the consumption of resources and processing intensity can be considered indirect measures of ecological sustainability, material use, and operation cost. However, the potential environmental concerns with regard to nanocomposite systems, like nanoparticle release and material recovery, need to be assessed as well. Therefore, an integrated approach for the evaluation of treatment technologies should address not only the technological and performance aspects but also aspects of sustainability including energy use, resource usage, and environmental risks to help the development of environmentally sustainable development decisions.

From the environmental point of view, all treatment technologies have their own set of advantages and trade-offs to be taken into account for large-scale application. While the EC process offers high efficiency in pollutant removal, its relatively high energy consumption increases the environmental burden associated with electricity demand and operational carbon footprint. Furthermore, sludge or electrode residues are also generated by EC systems and the disposal of such residues needs to be appropriately managed and disposed. The FB system demonstrated lower energy requirements and operational costs, making it more suitable for sustainable large-scale applications, although challenges related to particle separation, media recovery, and residue accumulation may occur during continuous operation. While the nanocomposite system achieved the best removal performance and favorable energy efficiency, the potential environmental risks associated with nanoparticle release, material recovery, long-term stability, and secondary contamination should be considered during scale-up and industrial application. Thus, a suitable treatment technology must manage removal performance, environmental sustainability, energy demand, operational safety, and material management considerations.

In order to make the industrial use of the studied treatment technologies a reality, from a large-scale implementation point of view some operational and technical issues should be taken into account. Long-term operation of EC systems can cause electrode passivation, aging, and decrease in EC activity, increasing the need for maintenance and system operation costs. Particles agglomeration, channeling effects and non-uniform fluidization can affect mass-transfer efficiency in continuous operation on high flow rate for FB systems. With nanocomposite-based systems, recovery and re-use of materials is still a very practical issue, especially in the area of separating, regenerating, and avoiding secondary contamination from the release of nanoparticles into the treated water. Moreover, there is a need to evaluate the long-term operational stability, catalyst durability, fouling behaviour and degradation of the material during continuous working under industrial conditions. Hence, despite the encouraging laboratory-scale results of the investigated systems, further studies are needed to validate, assess the long-term operation, rework strategies, and lifecycle analyses of the systems evaluated in order to better understand their potential for industrial implementation and sustainability.

4 Conclusions

The study compared the three water treatment technologies, EC, FB, and nanocomposite water treatment technologies in a controlled laboratory environment, and conducted an experimental and statistical assessment of their performance. The data obtained showed that there was clear difference between the results of the different treatments in terms of treatment performance, operational cost, energy consumption and productivity indicators. The overall removal efficiency and STY of the Nanocomposite system were the highest, suggesting that the overall capacity of this system for the removal of pollutants was the best because of the synergistic effect of adsorption and catalytic activity of the nanocomposite materials with their high surface reactivity. The most energy utilization efficient system was the FB system which had the lowest operational cost and was economically promising for continuous large-scale application. The EC process, on the other hand, showed good and stable removal performance with higher energy consumption and operational cost due to the input of electrical energy continuously and the reactions that occur at the electrodes.

The statistical analyses (ANOVA and Tukey's HSD tests) confirmed that the differences observed between the different techniques investigated were statistically significant ($p < 0.05$). The findings also revealed that the selection of the treatment technology should be based not only on the level of pollutant removal but also on the energy demand, economic viability, operational stability, and considerations of environmental sustainability.

On an implementation level, each treatment technique seems to be more appropriate for certain industrial applications and operational priorities. The Nanocomposite system is especially appropriate for industries with a high requirement for removal efficiency and very stringent discharge standards like the pharmaceutical, textile and fine chemical industries. For large-scale municipal and industrial wastewater treatment systems, the advantages of the FB system are increased operational cost and energy savings, making it a better fit. For these reasons, the EC process is very beneficial for the treatment of highly toxic or non-biodegradable pollutants, which are usual in electroplating, petrochemical and mining wastewater.

While the laboratory scale results are promising, certain practical and environmental issues are significant for the large-scale implementation. These include aging of electrodes and sludge formation in EC systems, particle agglomeration and fluidization stability in FB reactors and nanoparticle recovery, long term stability and secondary contamination risks in Nanocomposite systems. Future research should include pilot-scale validation, life cycle environmental assessment, long-term performance and material recovery strategies to further enhance the industrial applicability and sustainability of advanced wastewater treatment technologies.

Author Contributions

Conceptualization, T.M.D. and R.J.M.; methodology, T.M.D. and M.S.K.; software, M.A.E.; validation, T.M.D., R.J.M., and H.S.M.; formal analysis, T.M.D. and M.A.E.; investigation, T.M.D., R.J.M., and M.S.K.; resources, R.J.M.and H.S.M.; data curation, M.S.K. and M.A.E.; writing—original draft preparation, T.M.D.; writing—review and editing, T.M.D., R.J.M., M.S.K., M.A.E., and H.S.M.; visualization, M.A.E.; supervision, H.S.M.; project administration, T.M.D. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Nomenclature

Symbol	**Description**	**Unit**
pH	pH	–
V_{reactor}	Reactor volume	$\mathrm{m^3}$
Q_{flow}	Flow rate	$\mathrm{m^3/h}$
C_{in}	Influent pollutant concentration	mg/L
C_{out}	Effluent pollutant concentration	mg/L
η	Removal efficiency	%
M_{removed}	Mass removed per volume	$\mathrm{kg/m^3}$
E_{spec}	Specific energy consumption	kWh/kg
$Q_{\text{throughput}}$	Throughput	kg/h
C_{m^3}	Cost per $\mathrm{m^3}$ treated	$\mathrm{USD/m^3}$
C_{kg}	Cost per kg removed	USD/kg
STY	Space-time yield	$\mathrm{kg/m^3{\cdot}h}$
η_{energy}	Energy utilization efficiency	kg/kWh
T	Operational temperature	$^\circ$C