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Abatement of Electrochemical Desalination for Resource Utilization of Phenolic Residues

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Abstract: As a typical phenolic residue and pollutant, 2,4-D wastewater has a complex composition and high salt content, which makes it difficult for a single wastewater treatment method to meet the discharge standard. To address this challenge, this study explores an integrated electrochemical treatment approach that specifically targets 2,4-D high-salt organic wastewater with the aim of achieving the resource utilization of the wastewater and optimizing the operating parameters of each treatment unit. The results show that under the best experimental conditions, the chemical oxygen demand (COD) is significantly reduced to 200 mg/L, and the COD removal efficiency is as high as 99.67%. In addition, the recovery efficiency of phenolic substances 2,4-dichlorophenol, glycolic acid, and sodium chloride in wastewater reached 99.70%, 99.99%, 96.89%, and 80%, respectively. Phenols are used as raw materials for 2,4-D production, glycolic acid is widely used as a cleaning agent in industry, and the purity of recycled sodium chloride is as high as 99.08%, which can be reused as industrial salt. According to the treatment cost estimate, the benefit of recycling can offset the cost of wastewater treatment and may generate a certain economic surplus. This method is of great significance for the treatment of furfural wastewater and the realization of zero discharge of wastewater, which not only contributes to environmental protection but also promotes the sustainable utilization of resources.

Keywords: high salinity organic wastewater; 2,4-D production wastewater; electrochemical combination method; resource

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1. Introduction

2,4-Dichlorophenoxyacetic acid (2,4-D) is a widely used phenoxy carboxylic acid herbicide known for its effectiveness in controlling weed growth at a low cost, making it one of the most commonly used herbicides worldwide [1]. Furthermore, 2,4-D at low concentrations serves as a plant growth regulator, capable of enhancing vegetative growth, stimulating root development, and augmenting the fruit set rate [2]. The industrial synthesis of 2,4-D employs phenol and chlorine gas as primary feedstocks to produce dichlorophenol, which is then condensed with chloroacetic acid to obtain the final product (the process production route is shown in Figure 1) [3].

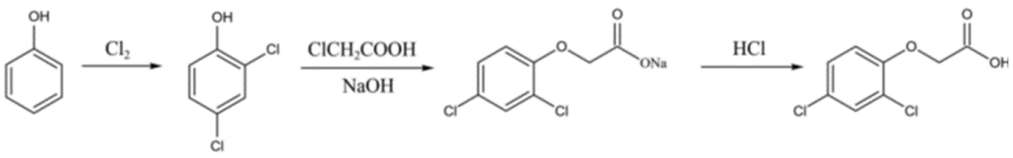


Figure 1. The process production route of 2,4-D.

Despite its commercial value, this process exhibits inefficiencies, leaving significant amounts of unreacted phenol, intermediate 2,4-dichlorophenol, and by-products such as glycolic acid and sodium chloride in the wastewater. This complex wastewater contains persistent aromatic compounds with high resistance to degradation, presenting serious toxicological risks to both biological systems and the environment [4,5]. Moreover, the high inorganic salt content in the wastewater intensifies treatment challenges [6,7].

Water is an essential resource for human production and existence. Although Earth is often referred to as the "blue planet" due to its abundant water coverage, the availability of directly usable freshwater resources is not ample. The unprecedented growth rate of the global population poses a major challenge to sustainable development, thereby intensifying the need for water treatment. Chinese agricultural production ranks among the world's leaders. With the ongoing advancement and modernization of the agricultural sector, the pesticide manufacturing industry has witnessed robust growth [7]. According to national statistics on chemical pesticide production volumes, China's cumulative output is projected to reach 2.148 million tons by the year 2020. It is estimated that every ton of pesticide production results in 3–5 tons of wastewater, with China alone generating approximately 1.5 billion tons annually, of which only 7% is treated [6]. High-salinity organic wastewater is characterized by the presence of organic compounds at significant concentrations, with a total salt content exceeding 1% [8]. Typically, industrial effluents exhibit salt concentrations surpassing 5%, and in some cases, these levels can reach up to 20%. In addition to the previously mentioned process of 2,4-D synthesis, there are two additional primary sources of saline organic wastewater [9,10]:

- First, the generation of substantial quantities of industrial wastewater in various manufacturing processes, including the production of pharmaceuticals, dyes, and pesticides. This wastewater contains not only inorganic ions such as Na^+, Cl^-, Ca^{2+}, and SO_4^{2-} but also a plethora of organic pollutants [11];
- Second, the direct utilization of seawater in coastal cities for industrial and domestic purposes results in the formation of high-salinity organic wastewater when seawater, inherently rich in salts, becomes contaminated with organic matter in use [12]. The chemical composition of high-salinity organic wastewater varies significantly across different production processes; however, the salts predominantly consist of inorganic salts like NaCl and Na_2SO_4, which are essential for microbial growth. Nevertheless, the excessive presence of organic matter and inorganic salts in high-salinity organic wastewater can exert inhibitory or toxic effects on microbial life. This wastewater is typically characterized by high levels of organic matter and substantial COD (chemical oxygen demand) values. The COD serves as a measure of the oxygen required to oxidize organic compounds in water. The elevated content of inorganic salts leads to increased osmotic pressure within the system, thereby creating conditions that are inhospitable to microbial life. As a result, the efficacy of biological treatment processes is compromised, making the degradation of such wastewater particularly challenging.

The discharge of this harmful and toxic liquid into natural water bodies can lead to serious contamination of groundwater and surface water, posing risks to animal and human health, and the recycling and treatment of the 1.5 billion tons of wastewater is urgent. Extensive research has been dedicated to the treatment of 2,4-D wastewater, which is summarized in Table 1. For instance, Li et al. [13] utilized biofortification to cultivate halophilic bacteria in 2,4-D wastewater, achieving a reduction in COD to below 200 mg/L in actual wastewater applications [14]. However, biological methods are often hindered by fluctuations in wastewater quality and the complexity of operational implementation [15]. Alternatively, Liu et al. applied electrochemical oxidation for continuous degradation of organic matter, reducing COD to less than 100 mg/L [16]. Additional studies have

implemented methods such as continuous extraction and rectification for 2,4-D wastewater treatment [17,18]. While effective, these methods produce complex mixtures of recovered components, requiring extra steps and high costs for further processing.

Table 1. The treatments of 2,4-D wastewater.

Treatment Method	Methods	Advantage	Flaws
Physical Treatment	Sedimentation, filtration, and adsorption	Simple operation; capable of removing some pollutants	Limited removal efficiency; may not meet strict discharge standards
Chemical Treatment	Chemical precipitation, oxidation, and reduction	Effectively degrades the molecular structure of 2,4-D, reducing toxicity	May generate secondary pollution; requires subsequent treatment
Biological Treatment	Utilizes microorganisms to degrade 2,4-D	Environmentally friendly; achieves harmless treatment	Longer treatment periods; significantly affected by environmental factors
Photocatalytic Oxidation	Employs photocatalytic agents to facilitate the degradation upon exposure to light irradiation	Highly efficient; capable of mineralizing organic pollutants	Requires specific photocatalysts and light sources; higher costs
Membrane Technology	Separates 2,4-D from water through semi-permeable membranes	Effectively separates and concentrates 2,4-D for subsequent treatment	Membrane materials are prone to fouling and blocking; require regular cleaning and replacement
Advanced Oxidation Processes	Includes processes like Fenton's process and ozonation, generating highly oxidative hydroxyl radicals	Efficiently decomposes 2,4-D with high mineralization rates	Requires strict operational conditions; may need additional energy input
Electrochemical Treatment	Removes 2,4-D through electrolysis	Strong controllability; operable at ambient temperature and pressure	Requires electrode materials; potentially high energy consumption

Electrodialysis, a technology with a pedigree exceeding half a century, originated in the desalination of brackish water for potable use. Since its inception, the fundamental principles of electrodialysis have been refined, and a suite of related processes have been developed, expanding its applications to wastewater treatment and across the food and chemical processing sectors. In the realm of saline water desalination [19], nanofiltration is progressively supplanting electrodialysis [20,21]. Nonetheless, in other domains, such as the production of high-quality industrial process water or the treatment of certain industrial wastewaters, electrodialysis retains a significant role [22]. Particularly when employed in conjunction with bipolar membranes [23] or ion exchange resins, electrodialysis has become a predominant method [24]. Zhang et al. deployed an electrodialysis pilot facility to process the effluent concentrated through reverse osmosis (RO) in a wastewater treatment facility. A comparative analysis between the concentrated RO feed and the electrodialysis effluent revealed that the electrical conductivity of the wastewater was reduced by only 31% post-electrodialysis treatment, underscoring the substantial desalination efficacy of the process. The wastewater recovery rate, when employing a combined RO and electrodialysis approach, can achieve 95% efficiency [25], thereby rendering electrodialysis an exemplary strategy for the treatment of wastewater subsequent to RO concentration.

To address the limitations of these existing techniques, an integrated treatment approach combining acid precipitation pretreatment, extraction, precipitation, electrodialysis, and electrochemical oxidation has been developed for treating 2,4-D production wastewater.

This approach prioritizes both economic efficiency and resource recovery, with optimized process parameters to reclaim valuable compounds such as phenols, glycolic acid, and sodium chloride. The resulting process achieves near-zero liquid discharge for 2,4-D high-salt organic wastewater, offering a cleaner treatment solution. By integrating resource recovery, this method not only meets wastewater remediation targets but also provides substantial economic benefits, reducing the overall treatment cost. Furthermore, the electrochemical oxidation method is employed to treat residual organic matter in wastewater, with a focus on exploring and optimizing process parameters. This approach aims to achieve near 'zero discharge' of wastewater, holding significant guidance for the treatment of high-salt and high-concentration organic wastewater.

2. Materials and Methods

2.1. Reagents and Instruments

Phenol, 2,4-dichlorophenol, glycolic acid, 2,4-D, ethyl acetate, and anhydrous sodium carbonate were obtained from Maclean's Reagent. Calcium oxide and calcium hydroxide were sourced from the Tianjin Damao Chemical Reagent Factory (Tianjin, China), while sodium chloride was supplied by the Beijing Chemical Plant (Beijing, China). Hydrochloric acid and concentrated sulfuric acid were provided by Guangzhou Chemical Reagent Factory (Guangzhou, China), and phosphoric acid was from Guangzhou Guanghua Chemical Factory Co., Ltd. (Guangzhou, China). Sodium hydroxide and silver nitrate were procured from Sinopharm Group Chemical Reagent Co., Ltd. (Shanghai, China), and methanol (chromatographic grade) from Merck Joint Stock Company (Darmstadt, German). COD-specific oxidizers (5–200 mg/L, 200–2000 mg/L) and COD composite catalysts were supplied by Shenzhen Side Spectrum Instrument Co., Ltd. (Shenzhen, China). A self-manufactured titanium–ruthenium–tin electrode was utilized for electrochemical processes [26].

Instruments used included the LC-10A High-Performance Liquid Chromatograph (HPLC) from Shimadzu Corporation (Kyoto, Japan); DIS-16B multifunctional numerical control digester, CNP-301CCOD ammonia nitrogen total phosphorus analyzer from Shenzhen Changhong Technology Co., Ltd. (Shenzhen, China); RMX35-3A DC power supply from KIKUSUI Company, (Yokohama, Japan); and an 85-2A digital display constant temperature magnetic stirrer from Changzhou Yuexin Instrument Manufacturing Co., Ltd. (Changzhou, China). Additionally, a laboratory electric membrane separator from Jinhua Jinqiu Environmental Protection Water Treatment Co., Ltd. (Jinhua, China) was used.

2.2. Wastewater Quality

Simulated wastewater was prepared based on the quality of wastewater produced during the chlorination step prior to condensation in the 2,4-D production process [27]. Table 2 summarizes the key parameters of the simulated wastewater composition.

Table 2. Water quality information of simulated 2,4-D wastewater.

Wastewater Composition	Concentration
Phenol	3 g/L
2,4-dichlorophenol	27 g/L
Glycolic acid	60 g/L
2,4-D	200 mg/L
NaCl	160 g/L
COD	60,000 mg/L

2.3. Experimental Methods

The flow chart for the 2,4-D wastewater treatment process is shown in Figure 2. The experimental procedure was as follows:

1. Acid Precipitation: Concentrated hydrochloric acid was added to the wastewater to adjust the pH to 1–3, enabling partial removal of organic matter through liquid separation;
2. Ethyl acetate was added to the wastewater in a specific ratio and stirred for 40 min to extract phenolic substances. The extractant and phenols were separated by vacuum distillation at 20 °C to isolate the organic phase;
3. Calcium Glycolate Precipitation: Calcium salt was introduced to the raffinate and stirred for 2 h to precipitate calcium glycolate. After filtration, glycolic acid was obtained by acidifying the solution to induce further precipitation;
4. Electrodialysis and Salt Recovery: The filtrate was subjected to electrodialysis. In the electrodialysis system, the dilute chamber contained 1 L of 2,4-D wastewater, while the concentrate chamber held 1 L of deionized water, and the polar water chamber contained 1 L of 1% sodium chloride solution. Sodium chloride was extracted from the wastewater, and the concentrate was then evaporated, concentrated, cooled, and crystallized to recover salt crystals.

Electrochemical Treatment: The wastewater in the dilute chamber underwent electrolysis in a 100 mL single-chamber electrolytic cell. The anode was a Ti/Ru-Ti-Sn electrode (3 × 3 cm^2), and the cathode was a titanium mesh (4 × 4 cm^2), with a 10 mm gap between electrodes. This step effectively removed 2,4-D and residual organic matter from the wastewater.

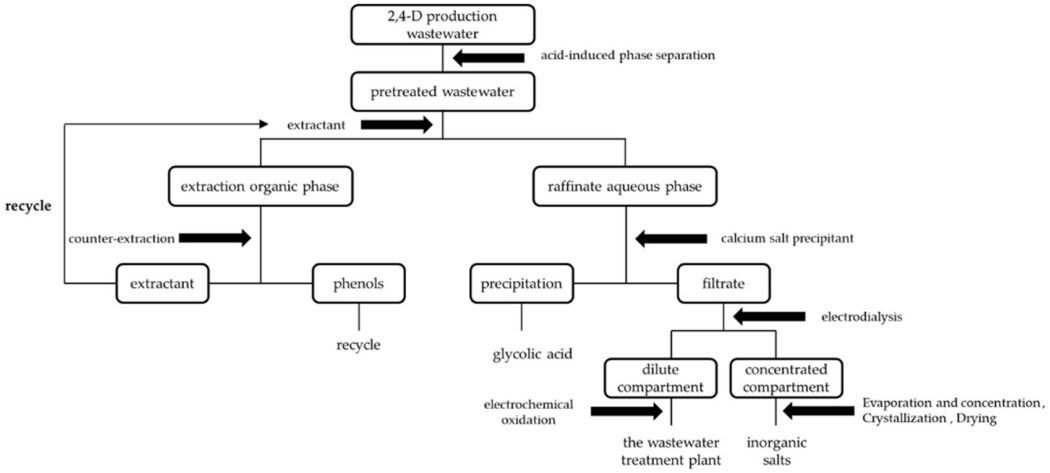


Figure 2. Flow chart of 2,4-D wastewater treatment process.

2.4. Analytical Methods

The mass concentration of organic compounds in the wastewater was determined by HPLC. The chromatographic column (C18, 5 μm, 4.6 mm × 150 mm) was operated at room temperature with a sample injection volume of 10 μL. Detection wavelengths were set to 280 nm for phenols and 220 nm for glycolic acid. For phenols and glycolic acid, the mobile phase consisted of methanol and water (pH adjusted to 3 with phosphoric acid) in a 70:30 ratio, with a flow rate of 1 mL/min. For 2,4-D detection at 210 nm, the mobile phase ratio was methanol to water (pH adjusted to 3 with phosphoric acid) at 60:40, with a flow rate of 0.8 mL/min. Sodium chloride purity was determined using silver nitrate titration, while COD content was measured via the potassium dichromate method.

3. Results and Discussion

3.1. Acid Elutriation Pretreatment

In the acid precipitation step, the solubility of chlorophenol and 2,4-D is reduced in an acidic environment. After adjusting the wastewater pH to 1–3, the concentration of 2,4-D decreased to 2.96 g/L, achieving an 89.0% removal rate. Similarly, the concentration of 2,4-D was reduced to 80.30 mg/L (59.8% removal rate), while phenol concentration decreased to 2.47 g/L (17.7% removal rate). Approximately 25 g of organic matter per liter of wastewater was recovered for 2,4-D production. The wastewater color changed from yellowish-brown to light yellow after acid extraction, indicating significant chroma reduction.

3.2. Phenol Extraction

The choice of extractant significantly affects phenol extraction efficiency [28]. We use ethyl acetate as the extractant, which is well-suited for large-scale industrial applications. It demonstrates exceptional water solubility, enabling it to efficiently extract 2,4-D and ethylene glycol from wastewater. The solution maintains a post-extraction pH of 1–3. Figure 3 shows the impact of varying oil-to-water ratios on extraction efficiency. An oil–water ratio of 1:2 provided optimal results, with phenol concentration reduced to 68.55 mg/L (97.7% removal rate) and 2,4-dichlorophenol concentration reduced to 2.05 mg/L (99.99% removal rate). Following liquid separation, ethyl acetate was recovered by vacuum distillation at 20 °C, and the organic matter was reused in production.

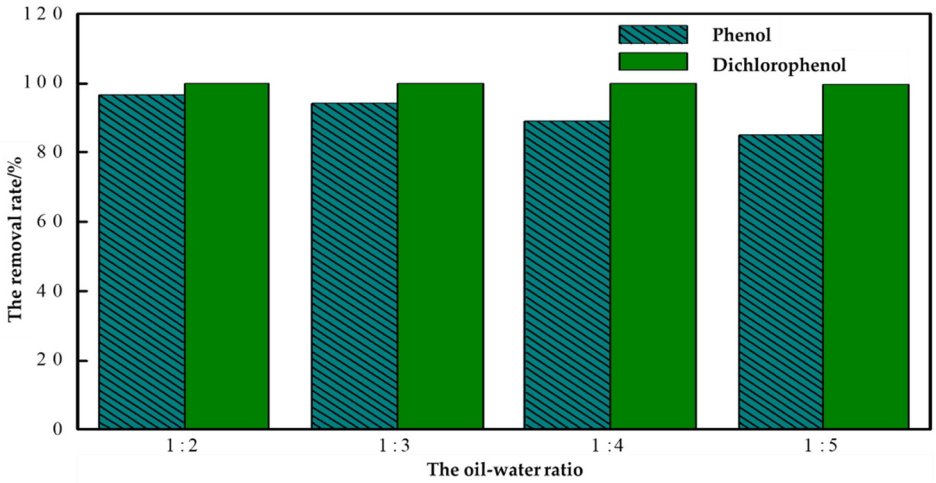


Figure 3. Influence of oil-water volume ratio on extraction efficiency of ethyl acetate.

3.3. Separation of Glycolic Acid by Precipitation

Calcium salt precipitation was employed to separate glycolic acid by forming calcium glycolate [29]. The precipitate was then acidified to recover glycolic acid, commonly used in industry as a cleaning agent in a 70% solution [30]. Table 3 summarizes the impact of different calcium salts on glycolic acid removal efficiency. The equation for the formation of calcium glycolate is provided below.

$$CaCl_2 + 2CH_3COOH \rightarrow Ca(C_2H_3O_2)_2 + 2HCl$$

Table 3. Effect of calcium salts on the extraction efficiency of glycolic acid.

Precipitant	Dosage/g	Concentration Removal Rate/%	COD Removal Rate/%
CaO	1.11	75.75	73.98
$Ca(OH)_2$	1.47	82.89	79.78

The concentration of calcium hydroxide and the pH level significantly influence the extraction efficiency of glycolic acid. When the wastewater pH is below 2, excess HCl and other substances in the wastewater compete for extraction, resulting in an increase in COD in the wastewater. Optimal results were obtained with calcium hydroxide at a pH of 2 and a molar ratio of calcium hydroxide to glycolic acid of 1:2, achieving the highest extraction efficiency.

Due to the high content of glycolic acid in the wastewater, the amount of precipitation generated by the reaction and the low solubility of calcium hydroxide may lead to problems such as inadequate contact of reactants and prolonged reaction time. Therefore, after the first precipitation, the experiment should be repeated to find the best glycolic acid removal efficiency. The results are shown in Table 4. After calcium hydroxide is added in the same proportion for the second time, the glycolic acid content changes significantly, and the glycolic acid removal rate is 96.89%. In the third reaction, even with an excess of calcium hydroxide, the glycolic acid concentration changes very little, so the precipitation reaction can be repeated twice. After extraction, the concentration of glycolic acid was reduced to 1.66 g/L, the removal rate was 97.24%, and the COD was 2715 mg/L.

Table 4. Effect of precipitation times on glycolic acid removal.

Times	$m_{Ca(OH)_2}$/g	Concentration Removal Rate/%	COD Removal Rate/%
1	1.47	82.89	79.78
2	0.30	96.89	90.22
3	0.30	97.26	92.51

3.4. Electrodialysis Desalting

To remove dissolved calcium salts, sodium carbonate and hydrochloric acid were added prior to electrodialysis. The limit current density was determined by monitoring the current–voltage curve, with an optimal desalination voltage identified at 17.6 V (Figure 4). In the electrodialyzer at low voltage, ion migration is primarily governed by the applied voltage, with the current being directly proportional to the voltage. As the voltage is incrementally increased, a limit current density is attained, at which point the current density peaks (marking the crossing point). A voltage below 17.6 V was chosen to minimize energy consumption [31] and avoid water decomposition on the membrane surfaces.

The change of electrical conductivity was used to judge the desalting efficiency of wastewater, and the change curve of standard electrical conductivity of sodium chloride was made, as shown in Figure 5a. Desalination ends when the conductivity or current value in the wastewater approaches zero or no longer changes. Figure 5b shows the change in the electrical conductivity of wastewater over time. When sodium ions cross the membrane into the freshwater compartment, there is a rapid decrease in conductivity, and the ions are rapidly eliminated from the wastewater, which means the effective removal of pollutants. After desalting at a voltage of 9 V, the conductivity of the wastewater in the fresh chamber after 80 min is 742 μS/cm, and the mass fraction of sodium chloride in the wastewater is less than 1%. After distillation and drying at 80~85 °C, about 80% sodium chloride was recovered. The purity of sodium chloride was 99.08% by the silver nitrate titration method.

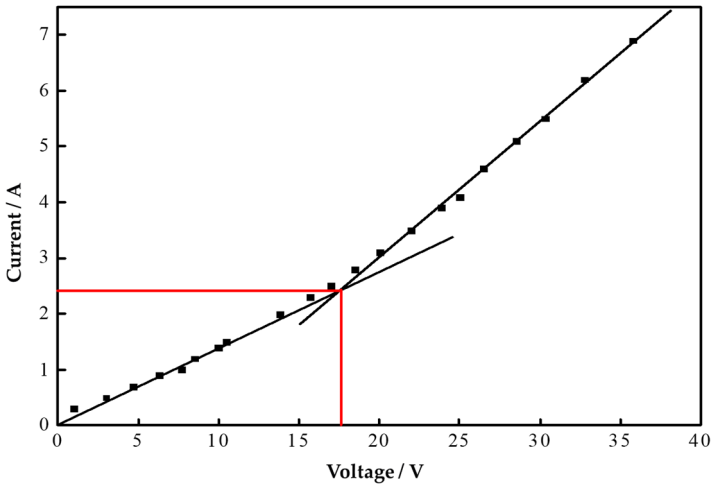


Figure 4. The curve of current versus voltage. The red line represents the current density as a function of the applied voltage during the electrodialysis process. The horizontal section of the red line indicates the region where the current density remains constant with increasing voltage, showing that ion migration is primarily governed by the applied voltage. The vertical drop marks the limit current density, beyond which the current density peaks and then decreases, indicating the optimal desalination voltage of 17.6 V.

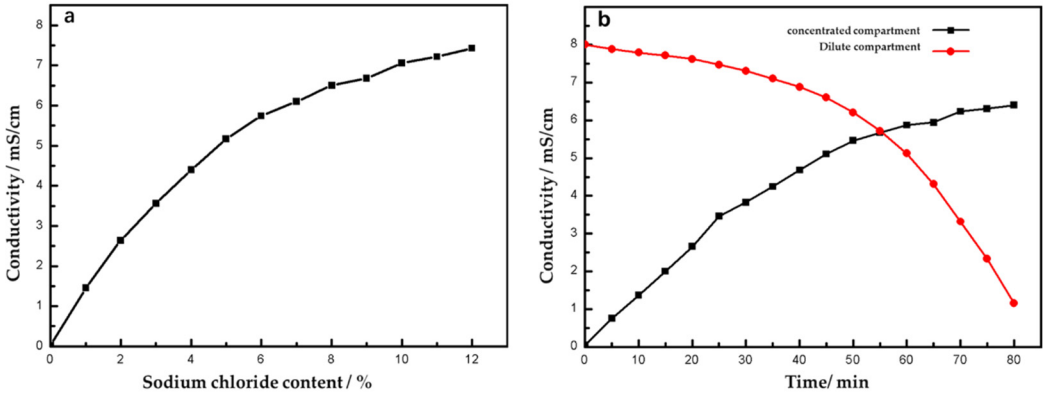


Figure 5. Conductivity changes with (**a**) sodium chloride content and (**b**) desalting time.

3.5. Electrochemical Degradation of 2,4-D

Electrochemical oxidation was applied to 100 mL of 2,4-D wastewater, investigating the effects of current density, electrolyte concentration, and pH on degradation (Figure 6) [32]. As current density increased, degradation efficiency also rose, though at the expense of higher energy consumption. A current density of 50 mA·cm^{-2} was found to maximize degradation while balancing energy consumption. Before 50 mA·cm^{-2}, current density mainly affects efficiency. When the current density increases to 60 mA·cm^{-2}, efficiency plateaus despite increased density, maximizing degradation with minimal energy and cost. Optimal degradation of 2,4-D was achieved when the sodium chloride concentration reached 0.10 mol/L. After optimizing electrolytic conditions, the desalinated 2,4-D wastewater underwent electrolysis, resulting in the complete removal of 2,4-D and phenolic compounds, with residual glycolic acid concentration measured at 322 mg/L. Due to its short-chain structure, glycolic acid is suitable for direct biodegradation. Consequently, the COD of the treated wastewater dropped significantly to 200 mg/L, greatly enhancing its biodegradability and overall treatment efficiency.

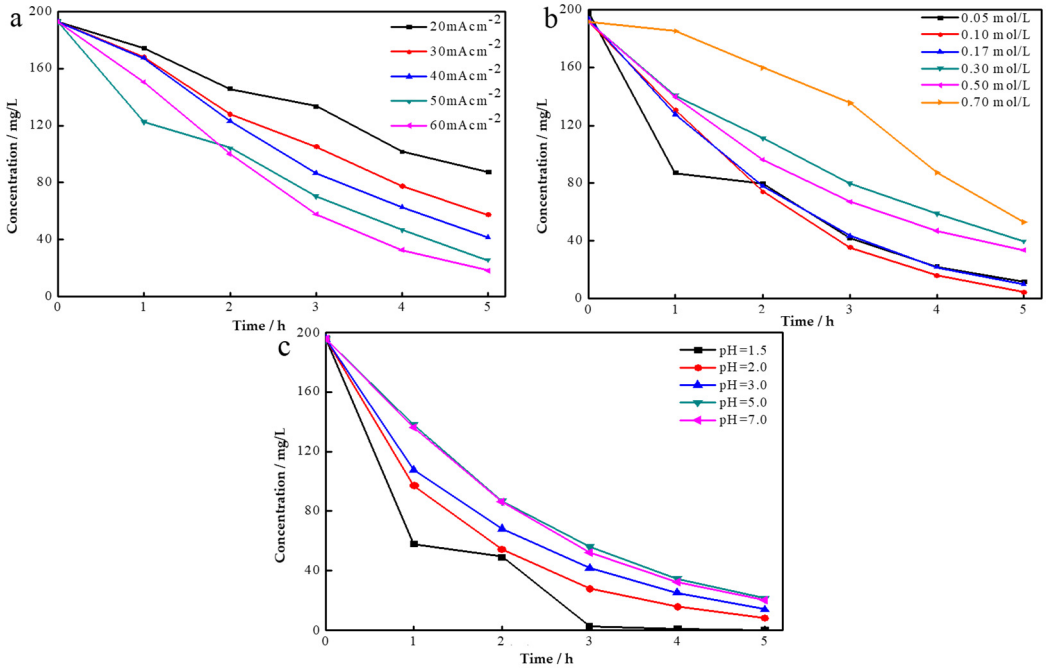


Figure 6. Concentration curve of 2,4-D wastewater with time under different electrolytic conditions: (**a**) current density, (**b**) electrolyte concentration, and (**c**) pH.

Here are the steps to convert the concentration value to a percentage and make a comparison:

The initial concentration of 2,4-D or other target pollutant in the wastewater is known as "200 mg/L". Assuming the density (ρ) of the solution is 1 g/mL, then the initial concentration C_0 can be converted to

$$C_0\% = (1000\ \text{mg}/200\ \text{mg}) \times 100\% = 20.0\%;$$

The final concentration of pollutants in the wastewater after treatment C_f = 322 mg/L;

$$C_f\% = (1000\ \text{mg}/322\ \text{mg}) \times 100\% = 32.2\%;$$

Degradation efficiency E can be calculated by the following formula:

$$E = (1 - C_f/C_0) \times 100\%;$$

Using the converted percentage values above, we can calculate the degradation efficiency. The proposed ideal degradation efficiency is 85.0%, so the comparison between the actual degradation (67.8%) efficiency and the ideal degradation (85.0%) is as follows:

$$\text{Conversion rate} = \text{the actual degradation}/\text{the ideal degradation} \times 100\% = 79.76\%$$

4. Cost Estimation and Benefit Analysis

The estimated cost of treating 2,4-D production wastewater was calculated based on current market prices. Ethyl acetate, used as the extractant, was assumed to have a reuse rate of 85%. Table 5 provides a breakdown of specific treatment costs. Following treatment, both organic and inorganic materials in the wastewater were recovered and reused, yielding economic value. Cost analysis indicates that the revenue from recovery can offset treatment expenses and even generate a surplus, potentially covering equipment costs over time with large-scale wastewater treatment.

Table 5. Estimated cost per ton of wastewater treatment.

Materiel	Mass/(kg)	Unit Price/ (CNY/ton)	Total/ (CNY)
Ethyl acetate	75	5500	412.5
$Ca(OH)_2$	30	800	24
HCl	3.5	1000	3.5
Electricity and labor	—	—	100
Total recovery	—	—	540
Phenol	3.0	6800	20.4
2,4-dichlorophenol	27	5400	145.8
70% glycolic acid	68.4	15,000	1026
NaCl	128	400	51.2
Total cost	—	—	1243.4

5. Conclusions

This study developed and optimized an integrated treatment approach tailored to the unique water quality characteristics of high-salt organic wastewater from 2,4-D production. Through a synergistic combination of acid elutriation pretreatment, extraction, precipitation, electrodialysis, and electrochemical oxidation, the proposed method achieved an impressive COD removal rate of 99.67%, with a residual COD concentration of approximately 200 mg/L. The predominant organic component in the treated effluent was glycolic acid (320 mg/L), a short-chain molecule that is readily biodegradable, supporting subsequent treatment stages or environmental discharge.

The integrated treatment process demonstrated high efficiency for 2,4-D wastewater management while providing substantial economic advantages by facilitating the recovery of valuable resources, including phenols, glycolic acid, and sodium chloride. Cost analysis suggests that the revenue from resource recovery can offset treatment costs and potentially generate a surplus. This method supports the principles of resource efficiency and a green economy, aligning well with industrial objectives of sustainable wastewater management and zero liquid discharge. The results of this study indicate that this treatment approach has strong potential for broader application in industrial wastewater treatment, offering a viable pathway toward enhanced resource utilization and environmental stewardship.

6. Perspectives

The innovative integrated electrochemical treatment approach for 2,4-D high-salinity organic wastewater, as detailed in this study, represents a momentous stride forward in the domain of industrial wastewater management. This pioneering methodology not only accomplishes a significant reduction in chemical oxygen demand (COD) but also demonstrates economic feasibility, seamlessly aligning with the burgeoning global trend towards sustainable development and the embrace of a circular economy. Moving forward, various perspectives can be explored to further advance the application of this groundbreaking treatment technology.

First and foremost, from a technological optimization standpoint, continuous research and development efforts should be focused on enhancing efficiency and reducing the energy consumption of each treatment unit. For example, exploring innovative electrode materials and configurations for electrochemical oxidation could result in more effective degradation of organic pollutants while minimizing energy costs. Moreover, optimizing the operational parameters of electrodialysis, such as selecting appropriate membrane types and designing efficient stack configurations, could further improve salt recovery rates and desalination efficiency.

Secondly, in terms of process integration, there is significant potential for combining this innovative treatment approach with other cutting-edge wastewater treatment technologies. For instance, integrating biological treatment processes following the electrochemical oxidation step could substantially reduce residual COD levels and enhance overall water quality, making it suitable for direct discharge or reuse in industrial processes. Furthermore, coupling the resource recovery aspect with the demands of other industries, such as providing recovered phenols and glycolic acid to chemical manufacturers, could cultivate a more interconnected and sustainable industrial ecosystem, promoting circular economy principles.

Thirdly, taking into account the more extensive application scope, this treatment approach could be modified and expanded to handle other categories of high-salinity organic wastewater generated by diverse industrial sectors. As each industry possesses its distinctive wastewater features, tailored alterations to the treatment process may be required. Nevertheless, the essential principles and comprehensive strategy presented in this study offer a significant point of reference for overcoming comparable hurdles in various industrial contexts.

Lastly, from a policy and regulatory perspective, it is imperative to establish robust incentives and regulations that encourage industries to embrace this environmentally sound and resource-efficient wastewater treatment technology. Governments can play a pivotal role by offering financial assistance, tax incentives, or subsidies to enterprises that invest in upgrading their wastewater treatment infrastructure. Additionally, implementing stricter discharge standards and regulations on resource recovery can provide the necessary impetus for industries to strive towards achieving zero liquid discharge and optimizing resource utilization, thereby fostering a more sustainable future.

In summary, the future application of this integrated electrochemical treatment approach for managing 2,4-D high-salinity organic wastewater holds considerable promise. Ongoing research efforts, coupled with technological advancements and supportive policies, could position this method as a key solution for sustainable industrial wastewater treatment, thus contributing significantly to both environmental conservation and economic prosperity.

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Conflicts of Interest: The authors declare no conflicts of interest.

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