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Purification of Farmland Drainage Water Using Electrochemical Materials

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ABSTRACT

With the growing global population and the intensification of agricultural production, the pollution issues associated with farmland drainage have become increasingly severe. The excessive discharge of nutrients, particularly nitrogen and phosphorus, has emerged as a major cause of water eutrophication and environmental pollution. Traditional treatment methods have struggled to effectively remove these pollutants, highlighting the urgent need for efficient, economical, and sustainable water purification technologies. Electrochemical materials, known for their efficiency, controllability, and environmental friendliness, are gaining attention in environmental remediation, especially for the purification of farmland drainage water. However, current research has largely focused on laboratory conditions, lacking validation in large-scale practical applications and facing challenges in technology integration, cost control, and long-term stability. This paper investigates the application of electrochemical denitrification and dephosphorization technologies for farmland drainage water purification. It comprises two main parts: the development of electrochemical denitrification and dephosphorization technologies tailored for farmland drainage purification, and the experimental methods for testing the purification of farmland drainage water using electrochemical materials. This paper aims to systematically investigate the application of electrochemical nitrogen and phosphorus removal technologies for purifying farmland drainage water. By optimizing key parameters such as voltage, electrode spacing, and pH, the optimal operating conditions were determined and validated through experiments on actual farmland drainage. The study found that the electrochemical technology performed excellently in removing organic pollutants, achieving chemical oxygen demand (COD) and biochemical oxygen demand over five days (BOD5) removal rates of 92.68% and 96.96%, respectively. Meanwhile, the removal rates for total phosphorus and total nitrogen were 35.15% and 35.08%, respectively.

1. INTRODUCTION

With the continuous growth of the global population and the intensification of agricultural production, the pollution issues associated with farmland drainage have become increasingly severe, particularly the excessive discharge of nutrients such as nitrogen and phosphorus. These pollutants have become significant causes of water eutrophication and environmental pollution [1-4]. Traditional farmland drainage treatment methods often fail to effectively remove these pollutants, resulting in water quality deterioration, which subsequently affects the ecological environment and human health [5-9]. Therefore, it is imperative to find efficient, economical, and sustainable water purification technologies.

In recent years, the application of electrochemical materials in environmental remediation has gradually gained attention. Due to their efficiency, controllability, and environmental friendliness, electrochemical technologies are considered to have potential application prospects in addressing nitrogen and phosphorus pollution in farmland drainage [10, 11]. Research on the role of electrochemical materials in farmland drainage water purification can not only improve the efficiency of water treatment but also promote sustainable agricultural development [12, 13].

The purification of farmland drainage is a critical issue in environmental protection, as it is directly related to water resource management in agriculture and the health of ecological environments. Phosphorus and nitrogen are the primary pollutants in farmland drainage, and their excessive presence can lead to water eutrophication, triggering algal blooms and water quality deterioration, which severely disrupt the balance of aquatic ecosystems. Therefore, developing efficient water purification technologies, especially those capable of effectively removing phosphorus and nitrogen, is essential for protecting water resources and preserving ecological environments. Although some studies have attempted to apply electrochemical technology to water purification, most of them focus on theoretical exploration and small-scale experiments under laboratory conditions, lacking validation in large-scale practical applications [14-18]. Moreover, the existing research methods have deficiencies in technology integration, cost control, and long-term stability, making it difficult to meet the complex requirements of actual farmland drainage treatment [19-22]. Therefore, it is necessary to conduct more systematic and comprehensive research to overcome the limitations of existing methods and explore more effective technical approaches.

Based on the specific natural conditions and economic development status of Hongsibao District of the Ningxia Hui Autonomous Region, China, this paper takes a typical area in Tianshuihe Village on the east side of Hongsibao District as the research object. Through the application research of electrochemical denitrification and dephosphorization technologies in farmland drainage water purification, this study aims to provide technical support for agricultural pollution control and water quality target management in Hongsibao District, as well as scientific data support for farmland drainage water quality monitoring technologies in this area. This will help to take more effective measures to purify water, reduce harm to the surrounding environment, decrease agricultural non-point source pollution, and improve the ecological environment. This paper mainly includes two parts: the development of electrochemical denitrification and dephosphorization technologies for farmland drainage water purification, and the experimental methods for testing the purification of farmland drainage water using electrochemical materials. The innovation of this paper lies in proposing a systematic application of electrochemical technology for the purification of farmland drainage, particularly excelling in the removal of organic pollutants. By optimizing specific parameters, the study provides valuable technical references, laying a theoretical foundation for the development of electrochemical materials and further technological improvements. It also demonstrates promising potential for practical applications. Through this research, we hope to provide an efficient, economical, and sustainable solution, offering new technical support and theoretical foundations for farmland drainage treatment and water quality protection.

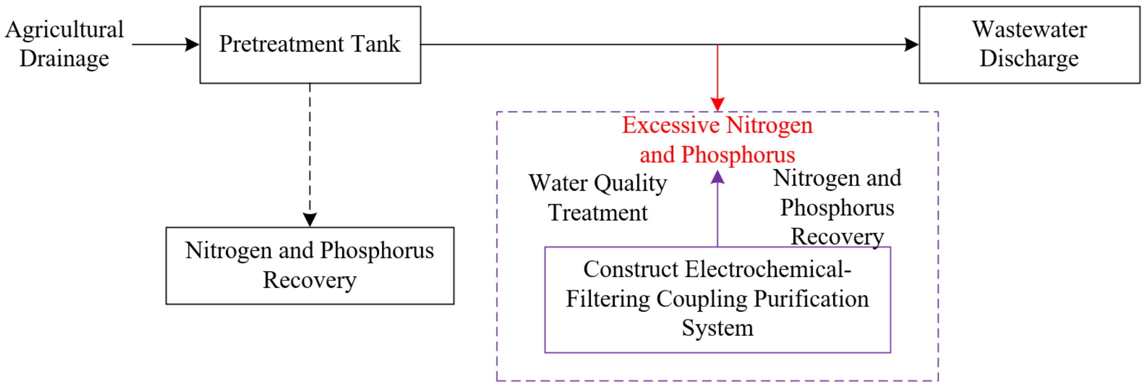


Figure 1. Farmland drainage treatment process

2. ELECTROCHEMICAL DENITRIFICATION AND DEPHOSPHORIZATION TECHNOLOGIES FOR FARMLAND DRAINAGE WATER PURIFICATION

Electrochemical denitrification and dephosphorization technologies for farmland drainage water purification differ significantly in design and application from those used in other scenarios. Farmland drainage usually contains high concentrations of nitrogen and phosphorus, which mainly come from fertilizers and pesticides used in agricultural activities. In contrast, other scenarios such as urban sewage treatment plants or industrial wastewater treatment have more complex and diverse pollutant compositions, which may include heavy metals, organic pollutants, and various chemical additives. In the treatment of farmland drainage, the goal of electrochemical technology is to efficiently remove nitrogen and phosphorus to prevent downstream water eutrophication. Therefore, technical solutions need to consider large-scale, low-cost, and environmental friendliness. Specifically, the application of electrochemical technology in farmland drainage focuses more on the selection of electrode materials to ensure high selectivity and stability under conditions of low current density and low energy consumption. Additionally, the large discharge volume and seasonal fluctuations of farmland drainage require the treatment system to have strong adaptability and flexibility. In other scenarios, electrochemical technology pays more attention to the comprehensive removal of multiple pollutants and, due to the more centralized and systematic nature of wastewater treatment processes, can adopt higher current densities and more complex electrode structures to achieve higher treatment efficiency. Therefore, electrochemical denitrification and dephosphorization technologies for farmland drainage need special optimization in terms of low cost, high efficiency, durability, and adaptability to address the unique challenges of agricultural drainage.

Figure 1 illustrates the treatment process for farmland drainage, which involves several key steps. First, a pretreatment tank removes large particles and sediments to enhance the effectiveness of subsequent processes. Next, sludge produced during the treatment is concentrated and dried in a sludge drying tank, reducing its volume and improving processing efficiency. In the water treatment phase, electrochemical methods are employed for advanced purification, effectively removing organic pollutants and some nitrogen and phosphorus contaminants. Following this, the nitrogen and phosphorus recovery stage recycles nutrients from the water, minimizing resource waste. The entire process integrates electrochemical and filtration technologies, forming a coupled purification system to enhance overall efficiency, ultimately achieving safe discharge of wastewater in compliance with environmental standards. This process is designed to ensure efficient and sustainable management of water resources in agricultural settings. Figure 2 presents the migration of pollutants during the electrochemical nitrogen and phosphorus removal process. In the electrochemical reaction, these ions migrate toward the electrodes under the influence of the electric field, with their movement affected by the electrode materials and reaction conditions. High voltage and optimal pH levels promote ion migration and improve removal efficiency. Additionally, the migration and transformation of organic matter and solid particles in the water also impact the purification performance, ultimately enabling the effective removal of contaminants from farmland drainage.

For nitrogen pollution in farmland drainage, the main source is the application of nitrogen fertilizers, which convert into different forms of inorganic nitrogen in the soil and flow into water bodies with drainage, causing environmental pollution. Electrochemical denitrification technology for farmland drainage water purification aims to efficiently remove ammonia nitrogen (NH4+-N) and other inorganic nitrogen compounds from farmland drainage. This technology achieves nitrogen removal through the synergistic effect of electrochemical anodic oxidation and cathodic reduction, mainly including direct oxidation and indirect oxidation methods. Direct oxidation occurs at the anode, where ammonia nitrogen (NH3) loses three electrons and is directly oxidized to nitrogen gas (N2), thereby achieving denitrification. Indirect oxidation involves the anode oxidizing chloride ions (Cl^-) to free chlorine (Cl_2), which dissolves in water to form the strong oxidant hypochlorous acid (HClO), which then oxidizes ammonia nitrogen to nitrogen gas. The process can be simplified as:

$$NH_3 + 3OH^- \rightarrow 1/2\,N_2 + 3H_2O + 3e^- \quad (1)$$

$$2Cl^- \rightarrow Cl_2 + 2e^- \quad (2)$$

$$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^- \quad (3)$$

$$2NH_4^+ + 3HOCl \rightarrow N_2 + 3H_2O + 5H^+ + 3Cl^- \quad (4)$$

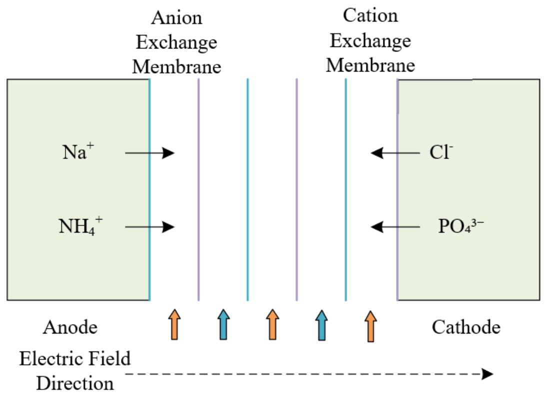


Figure 2. Migration in electrochemical denitrification and dephosphorization technologies

In the application process, it is necessary to consider the characteristics of farmland drainage, such as large water volume, high nitrogen concentration, and seasonal fluctuations. Therefore, the electrochemical system needs to have high stability and low energy consumption, and select corrosion-resistant electrode materials to ensure long-term operational reliability. Additionally, the chlorinated byproducts produced during the indirect oxidation process need to be strictly controlled to avoid secondary pollution and ensure the environmental friendliness of the entire process.

The high content of nitrates in farmland drainage mainly comes from the residual nitrogen fertilizers used in agricultural fertilization. These nitrates, when discharged into water bodies, cause serious eutrophication problems. Therefore, researching and applying electrochemical technologies to remove these nitrates has important environmental significance and practical application value. The principle of electrochemical nitrate removal mainly includes two methods: direct reduction and indirect reduction. Direct reduction involves the cathode directly providing electrons to reduce nitrates to nitrogen gas (N2). This process does not require the addition of extra carbon sources, is not easily affected by temperature, and is easy to operate. The direct reduction reaction pathway is a 5-electron process that reduces nitrates to nitrogen gas. However, in practical operations, side reactions may occur during nitrate reduction, leading to the over-reduction of nitrates and an 8-electron reduction process that produces ammonia (NH3). The reaction equations are as follows:

$$NO_3^- + 6H^+ + 5e^- \rightarrow 1/2\,NH_3 + 3H_2O \quad (5)$$

$$NO_3^- + 9H^+ + 8e^- \rightarrow NH_3 + 3H_2O \quad (6)$$

To improve reduction efficiency and reduce byproduct generation, electrochemical technology also utilizes atomic hydrogen on the cathode surface for indirect reduction. After atomic hydrogen is generated on the cathode surface, it can effectively reduce nitrates to nitrogen gas, thereby improving nitrogen removal efficiency and reducing the chances of ammonia byproduct formation.

Farmland drainage often contains high concentrations of phosphorus, mainly from the residual phosphorus fertilizers used in agricultural fertilization and soil erosion. When this phosphorus enters water bodies, it promotes the proliferation of algae, leading to eutrophication and severely affecting the aquatic environment. Electrochemical dephosphorization technology for farmland drainage water purification mainly adopts electrocoagulation methods. The principle of electrocoagulation dephosphorization is to use metals such as iron or aluminum as anode materials. When current passes through the electrolytic cell, the anode undergoes an electrolytic reaction, releasing metal cations such as Fe^{2+} or Al^{3+}. These metal cations hydrolyze in water to form metal hydroxides or polynuclear metal complexes, which react with phosphates (PO_4^{3-}) in the water to form insoluble precipitates such as ferric phosphate ($FePO_4$) or aluminum phosphate ($AlPO_4$), thereby removing phosphorus from the solution. The main reactions are as follows:

Aluminum electrode electrocoagulation dephosphorization:

$$2Al \rightarrow 2Al^{3+} + 6e^- \quad (7)$$

$$2Al^{3+} + 6H_2O \rightarrow 2Al^{3+} + 6e^- \quad (8)$$

Iron electrode electrocoagulation dephosphorization:

$$4Fe \rightarrow 4Fe^{2+} + 8e^- \quad (9)$$

$$4Fe^{2+} + 10H_2O + O_2 \rightarrow 4Fe(OH)_3 + 8H^+ \quad (10)$$

The precipitates generated by electrocoagulation are easy to collect and handle and can be further utilized as resources, such as fertilizers or soil conditioners, promoting sustainable agricultural development. This not only helps to reduce phosphorus pollution in water bodies but also realizes the recycling of agricultural resources.

3. EXPERIMENTAL METHODS FOR PURIFICATION OF FARMLAND DRAINAGE BASED ON ELECTROCHEMICAL MATERIALS

3.1 Methods for electrochemical recovery of nitrogen and phosphorus from farmland drainage

The experimental setup consists of a cylindrical glass container with a diameter of 9 cm and a height of 25 cm, equipped with a DC power supply, a stainless steel electrode, and a magnesium electrode (dimensions: 120 × 18 × 4.5 mm). The stainless steel electrode serves as the anode for oxidation reactions, while the magnesium electrode functions as the cathode to ensure efficient electron transfer. During pH adjustment, H_2SO_4 and NaOH are used to maintain the desired reaction conditions. A microporous filter may be employed during the filtration process to remove precipitates and particles, ensuring accurate evaluation of the purification performance. The experimental setup is depicted in Figure 3. The experimental procedure begins by adding 1000 mL of simulated farmland drainage into the container, followed by adjusting the solution's pH to the target value using H_2SO_4 and NaOH. The power supply is then connected to initiate the electrochemical reaction, with the current and voltage monitored and the reaction time recorded. After completing the reaction, the water sample is processed using a microporous filter to remove solid particles. Samples are then collected for water quality analysis to evaluate the removal efficiency of COD, BOD5, total phosphorus, and total nitrogen.

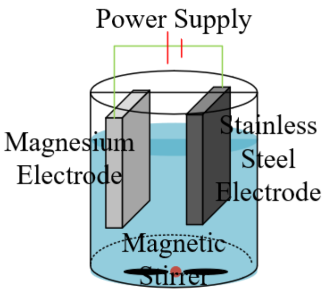


Figure 3. Experimental setup for electrochemical recovery of nitrogen and phosphorus from farmland drainage

Orthogonal experiments are used to explore the effects of the initial pH value of the solution, voltage, and electrode spacing on the recovery of nitrogen and phosphorus. The experimental design references previous studies and sets three factors (pH value, voltage, electrode spacing) and four levels (pH values of 8, 9, 10, 11; voltages of 5V, 7V, 9V, 10V; electrode spacings of 2 cm, 3 cm, 4 cm, 5 cm), for a total of 16 experiments. Through the orthogonal experimental method, the impact of various parameters on the efficiency of nitrogen and phosphorus recovery is systematically investigated and optimized. Samples are taken every 10 minutes, filtered through a 0.5 µm filter, and measured with a spectrophotometer to ensure data accuracy and reliability.

After the experiment, the recovery product $Mg{\cdot}NH_4PO_4$ is collected by centrifugation, washed three times with deionized water to remove impurities, and dried in an oven to ensure product purity. The washed product is stored for further analysis and utilization. Meanwhile, the anode is washed with deionized water after use, dried, and weighed to determine the anode loss. Assuming the initial concentration is represented by Z_0 and the concentration at time s is represented by Z_s, the removal rate of $PO^{3-}{}_4$-P and $NH^+{}_4$-N can be calculated using the following formula:

$$x = (Z_0 - Z_s)/C_0 \times 100\% \tag{11}$$

Assuming the molar amount of $NH^+{}_4$-N is represented by v, the molar mass of $Mg{\cdot}NH_4PO_4$ is represented by L, and the mass of the precipitate is represented by l, the purity of $Mg{\cdot}NH_4PO_4$ can be calculated using the following formula:

$$f = v \times L/l \tag{12}$$

3.2 Construction of an electrochemical-filtration farmland drainage water purification system

(1) Electrochemical Method

The experimental method for farmland drainage water purification based on electrochemical materials aims to efficiently remove phosphates $PO^{3-}{}_4$-P from farmland drainage to prevent water eutrophication and promote sustainable management of agricultural wastewater. This experiment is conducted in an electrochemical-filtration system device, which does not require additional filter media, simplifying operation and reducing costs. First, 1000 *mL* of simulated farmland drainage sample is prepared, and the *pH* value of the solution is adjusted with H_2SO_4 and *NaOH* to ensure consistency of experimental conditions. The electrochemical reaction system uses stainless steel electrodes as the cathode and magnesium electrodes, aluminum electrodes, and iron electrodes as the anode. A single-factor experiment explores the effects of electrode spacing, initial *pH* value of the solution, and voltage on the electrochemical removal of $PO^{3-}{}_4$-P.

In the experimental design, considering the complexity and variability of farmland drainage, three factors and four levels are set: *pH* values of 8, 9, 10, 11; voltages of 6V, 7V, 8V, 9V; electrode spacings of 2 cm, 3 cm, 4 cm, 5 cm. Through 16 experiments, the impact of various parameters on the efficiency of phosphate removal is systematically evaluated, providing a scientific basis for optimizing electrochemical treatment conditions. During the experiment, samples are taken every 10 minutes, filtered through a 0.5 µm filter, and measured for phosphate concentration using a spectrophotometer to ensure data accuracy and reliability. After the experiment, the anode is treated, washed with deionized water, dried in an oven, and weighed to assess anode loss.

Removing ammonium nitrogen $NH^+{}_4$-N from farmland drainage aims to reduce nitrogen pollution and improve water quality. Unlike the phosphate removal experiment, this experiment uses Dimensionally Stable Anode (DSA) electrodes as the anode and stainless steel electrodes as the cathode. A single-factor experiment explores the effects of voltage, *pH* value, electrode spacing, and *NaCl* content on the electrochemical removal of $NH^+{}_4$-N. Considering the actual situation of farmland drainage, four factors and four levels are set. The *NaCl* content is set at 0.1 mol·L⁻¹, 0.15 mol·L⁻¹, 0.2 mol·L⁻¹, and 0.25 mol·L⁻¹. A total of 16 experiments systematically evaluate the impact of various parameters on the efficiency of ammonium nitrogen removal.

(2) Double Anode Electrochemical Method

The experimental design comprehensively considers the impact of different electrode materials and operating parameters on the removal efficiency. Using stainless steel as the cathode, magnesium electrodes and DSA electrodes, aluminum electrodes and DSA electrodes, and iron electrodes and DSA electrodes are used as double anodes. Through the orthogonal experimental method, the effects of *pH* value, voltage, and *NaCl* content on the simultaneous removal of $PO^{3-}{}_{4}$-P and $NH^{+}{}_{4}$-N by double anode electrochemical methods are systematically explored. The experimental parameters reference the results of previous single-factor experiments to ensure that the levels of each factor are reasonable and representative. During the operation, samples are collected every 10 minutes and filtered through a 0.5 μm filter to ensure measurement accuracy. The samples are measured for $PO^{3-}{}_{4}$-P and $NH^{+}{}_{4}$-N concentrations using a spectrophotometer. The orthogonal experimental design effectively evaluates the impact of various parameters on removal efficiency and identifies the optimal combination of conditions to achieve efficient removal of pollutants from farmland drainage. After the experiment, the anode is washed with deionized water, dried in an oven, and weighed to evaluate the consumption and durability of the electrode materials.

(3) Filtration Method

The experimental parameters include hydraulic retention times of 35 minutes, 40 minutes, 50 minutes, and 100 minutes; filter layer thicknesses of 3 cm, 6 cm, 9 cm, and 12 cm; and filter media types of activated carbon, activated alumina, micro-nose filter media, and quartz sand. Through the orthogonal experimental design, 16 experiments are conducted with four factors and four levels to comprehensively explore the impact of various factors on removal efficiency. During the experiment, the prepared simulated farmland drainage samples are sequentially passed through different filter media layers and operated under different *pH* values, hydraulic retention times, and filter layer thickness conditions. Samples are collected at regular intervals, filtered through a 0.5 μm filter, and measured for $PO^{3-}{}_{4}$-P and $NH^{+}{}_{4}$-N concentrations using a spectrophotometer. The choice and thickness of the filter media directly affect the removal efficiency of pollutants, while the *pH* value and hydraulic retention time influence the chemical reaction rate and contact time. The orthogonal experimental design effectively evaluates the comprehensive impact of various parameters on removal efficiency, using variance analysis to determine the significance and optimal combination of each factor. After the experiment, the filter media are cleaned, dried, and weighed to assess their service life and regeneration capability.

(4) Electrochemical-Filtration System

The experimental setup consists of a 2 cm-thick support layer, a 6 cm-thick filter media layer, a 10 cm-high solution reaction layer, and a 2 cm supernatant layer, with an effective reaction volume of 500 mL. The choice of filter media for the filter layer is based on the optimal filter media selected in previous experiments, including activated carbon, activated alumina, micro-nose filter media, or quartz sand. During the experiment, the simulated farmland drainage samples pass through the device, and a DC regulated power supply provides a stable current through stainless steel electrodes and selected double anodes to promote electrochemical reactions. The redox reactions generated during the electrolysis process not only effectively break down and remove organic pollutants but also remove $PO^{3-}{}_{4}$-P and $NH^{+}{}_{4}$-N through electrocoagulation and adsorption. In the experiment, the system operates for a predetermined time, and treated water samples are collected at regular intervals, filtered through a 0.5 μm filter, and measured for $PO^{3-}{}_{4}$-P and $NH^{+}{}_{4}$-N concentrations using a spectrophotometer to evaluate removal efficiency. Simultaneously, current and voltage changes are regularly monitored to ensure the stability and effectiveness of the electrochemical reactions. Figure 4 shows a schematic diagram of the electrochemical-filtration system.

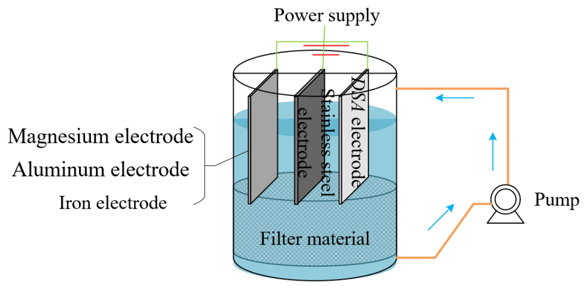


Figure 4. Schematic diagram of the electrochemical-filtration system

3.3 Optimization methods for farmland drainage water purification system

In the simulated farmland drainage treatment experiment, aluminum electrodes and DSA electrodes are selected as the double anode, and stainless-steel electrodes are used as the cathode. Through orthogonal experimental design, *pH* value, Hydraulic Retention Time (HRT), and voltage parameters are systematically adjusted and optimized to evaluate their impact on the removal effect of $PO^{3-}{}_{4}$-P and $NH^{+}{}_{4}$-N. After each experiment, the anode electrodes are washed with deionized water, dried, and weighed to assess the anode loss. By comprehensively considering the pollutant removal efficiency, energy consumption, and anode loss, the optimal operating conditions are determined. Assuming energy consumption is represented by Q, voltage by I, current by U, and electrolysis time by s, the energy consumption calculation formula is:

$$Q = I \times U \times s \tag{13}$$

After determining the optimal operating conditions, further experiments are conducted to treat actual farmland drainage. Under optimized conditions, the electrochemical-filtration system's effectiveness in simultaneously removing $PO^{3-}{}_{4}$-P, $NH^{+}{}_{4}$-N, and Chemical Oxygen Demand (COD) from actual farmland drainage is evaluated. COD measurement is conducted using the potassium dichromate method to comprehensively assess the system's overall purification capacity. Assuming the amount of ferrous sulfate consumed by the blank group is represented by N, the amount consumed by the measurement group is represented by N_1, and the concentration of ferrous sulfate is represented by Z, the COD removal is calculated using the following formula:

$$z = \left[\left(N_0 - N_1 \right) \times Z \times 8 \times 1000 \right] / 10 \tag{14}$$

The enhanced nitrogen removal efficiency achieved with the method proposed in this study is primarily due to the optimization of key parameters, such as voltage, electrode spacing, and pH, creating optimal reaction conditions. This optimization makes the electrochemical process more efficient, significantly improving nitrogen removal rates. In addition to effectively decomposing organic matter, the electrochemical reactions also facilitate nitrogen transformation and removal through electrode processes, demonstrating remarkable purification performance.

4. EXPERIMENTAL RESULTS AND ANALYSIS

This paper takes Tianshuihe Village on the east side of Hongsibao District, Ningxia, as a typical research area, focusing on agricultural pollution control and water quality target management in this region. Hongsibao District has unique natural conditions and economic development status, and the pollution generated during its agricultural production process has a significant impact on the surrounding environment and water quality. Therefore, this study aims to conduct a detailed water quality monitoring and analysis of Tianshuihe Village, a representative area, to explore the main pollutants in agricultural drainage and their variation patterns. Specifically, the study will focus on the changes in key water quality indicators such as COD, Biochemical Oxygen Demand (BOD5), $NH^{+}{}_{4}$-N, Total Phosphorus (TP), Total Nitrogen (TN), *pH* value, and conductivity. Through the monitoring and analysis of these indicators, this study not only provides scientific basis and technical support for agricultural pollution control and water quality management in Hongsibao District, but also offers important data support for farmland drainage water quality monitoring technology in the region. This paper first discusses the results of nine experimental groups conducted under three different pH levels and three different voltages.

Table 1. Performance test results of optimization methods

	PH Value	Voltage (*V*)	*NaCL* Content	$PO^{2}{}_{4}$-P Removal Rate (%)	$NH^{2}{}_{4}$-N Removal Rate (%)	Anode Loss (*mg*)	Energy Consumption (*kW.h*)
1	7	5	0.16	97.65	8.00	4.02	3.65
2	7	7	0.21	95.26	68.95	4.12	4.05
3	7	9	0.24	96.32	71.21	11.32	11.68
4	9	5	0.21	98.87	23.26	5.89	6.56
5	9	7	0.24	98.32	31.21	8.65	10.24
6	9	9	0.16	99.62	100.00	8.12	12.35
7	11	5	0.24	42.13	45.26	7.32	10.42
8	11	7	0.14	74.65	31.25	7.36	7.89
9	11	9	0.2	90.12	100.00	8.89	12.36

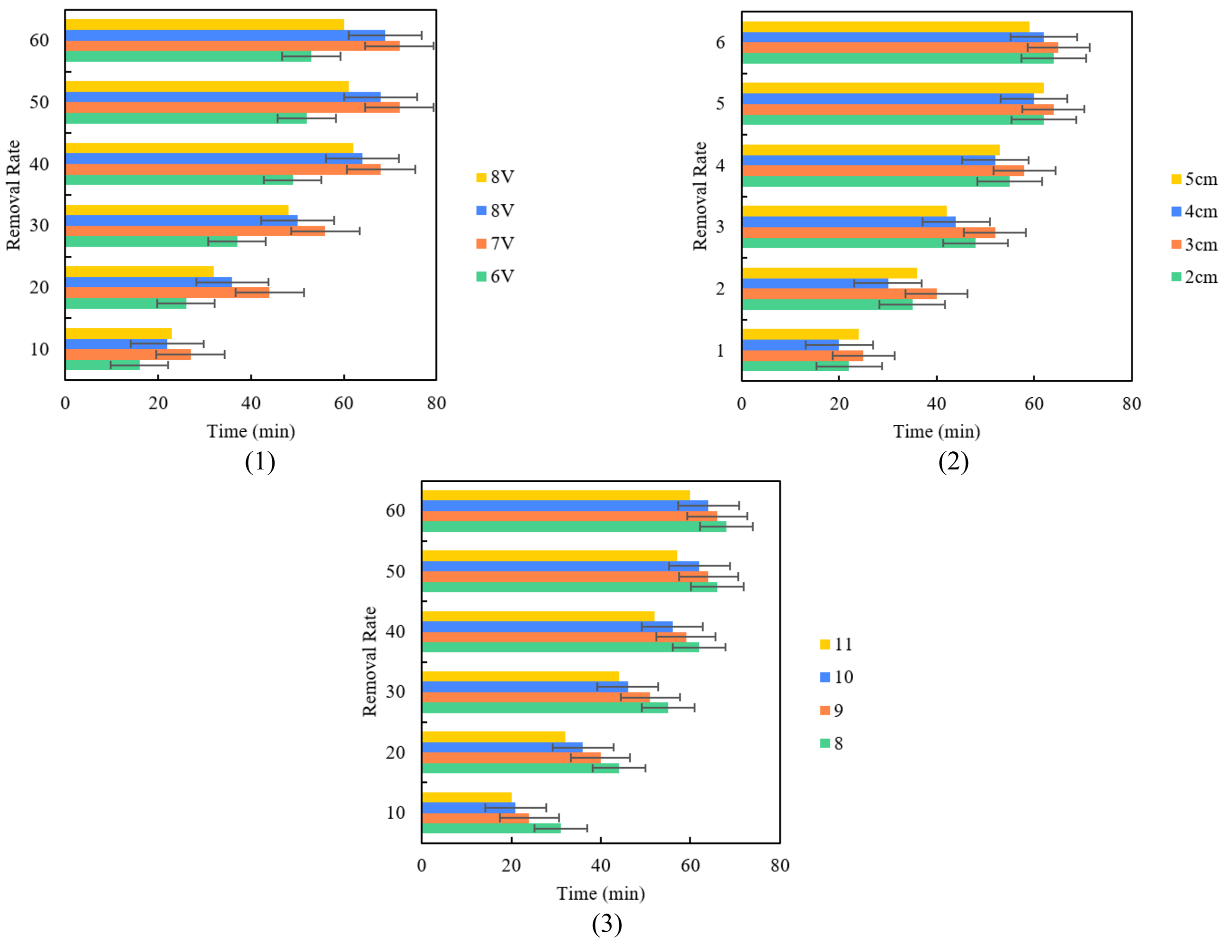
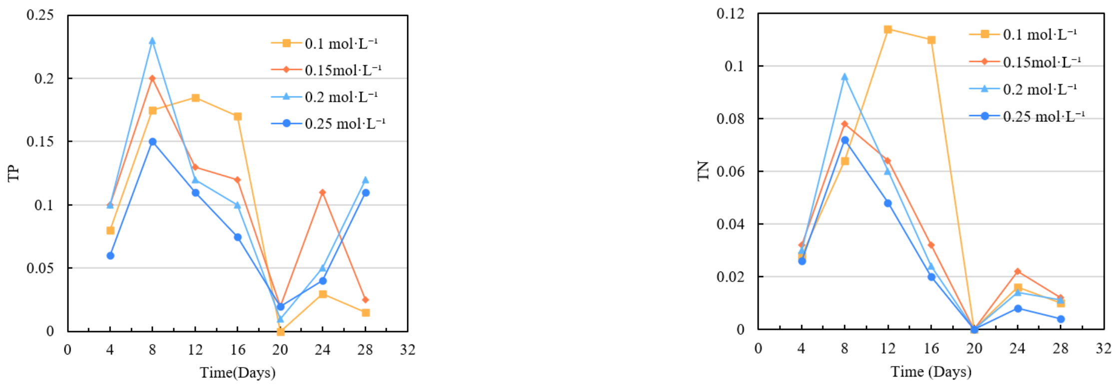


Figure 5. Effects of voltage, electrode plate distance, and *pH* on optimization algorithm performance



(1) (2)

Figure 6. TP and TN at different stages of farmland drainage purification

From the results in Table 1, it can be seen that the removal rates of $PO^{3-}{}_4$-P and $NH^+{}_4$-N vary significantly under different *pH* and voltage conditions. At a *pH* of 7, the $PO^{3-}{}_4$-P removal rate is relatively high, stabilizing between 95.26% and 97.65%, and when the voltage is increased to 9V, the $NH^+{}_4$-N removal rate significantly rises to 71.21%. At a *pH* of 9, the $PO^{3-}{}_4$-P removal rate can reach a maximum of 99.62%, and at 9V, the $NH^+{}_4$-N removal rate reaches 100%. However, when the pH reaches 11, the $PO^{3-}{}_4$-P removal rate drastically drops to between 42.13% and 90.12%, while the $NH^+{}_4$-N removal rate achieves 100% at 9V. Additionally, it is noted that anode loss and energy consumption significantly increase with higher voltage and *pH* values, with the highest energy consumption reaching 12.36 kWh at 9V. The experimental results indicate that the electrochemical denitrification and dephosphorization technology exhibits significant performance differences under varying *pH* and voltage conditions. $PO^{3-}{}_4$-P removal rate is higher under neutral to slightly alkaline conditions, particularly reaching a maximum of 99.62% at *pH* 9 and 9V. The $NH^+{}_4$-N removal effect is optimal under high voltage and high *pH* conditions, showing a 100% removal rate. However, high voltage (9V) and high *pH* (11) conditions also lead to significant anode loss and energy consumption, suggesting a need to balance treatment effectiveness and economic costs in practical applications. Therefore, optimizing voltage and *pH* is crucial for improving electrochemical denitrification and dephosphorization efficiency while considering anode material durability and energy consumption for sustainable and efficient farmland drainage water quality purification.

From the analysis of the experimental results shown in Figure 5 on voltage, electrode plate distance, and pH value, it is evident that these parameters significantly impact the removal rates of $PO^{3-}{}_4$-P and $NH^+{}_4$-N. In the voltage experiment, as the voltage increased from 6V to 7V, the removal rate improved significantly from 53% to 72% within 60 minutes, whereas 8V was less stable, maintaining around 69% at 60 minutes. In the electrode plate distance experiment, as the distance increased from 2cm to 5cm, the removal rate first increased and then decreased, with a 3cm distance achieving the highest removal rate of 65% at 60 minutes. In the *pH* experiment, a *pH* of 8 yielded the highest removal rate, reaching 68% at 60 minutes; as the *pH* increased to 11, the removal rate gradually declined to 60% at 60 minutes. The experimental results demonstrate that voltage, electrode plate distance, and *pH* significantly influence the removal efficiency in the electrochemical denitrification and dephosphorization process. An optimized voltage of 7V can significantly enhance the removal rates of $PO^{3-}{}_4$-P and $NH^+{}_4$-N while maintaining high stability. The optimal electrode plate distance is 3cm, indicating that a smaller distance is beneficial for increasing reaction efficiency, while a larger distance leads to decreased removal rates. The *pH* optimization shows that a lower *pH* enhances the removal rate, and efficiency decreases with increasing *pH*. Thus, under conditions of 7V voltage, 3cm electrode plate distance, and *pH* 8, the best removal effects for $PO^{3-}{}_4$-P and $NH^+{}_4$-N can be achieved.

From the experimental results of TP removal rate at different electrode plate distances shown in Figure 6, it can be seen that the electrode plate distance has a significant impact on the TP removal rate. Within 60 minutes, when the electrode plate distance is 3 cm, the TP removal rate reaches the highest, at 65%; at distances of 2 cm and 4 cm, the TP removal rates are 64% and 62%, respectively, while at 5 cm, the rate is lower, at 59%. The experimental results for TN indicate that the pH value has a significant impact on the TN removal rate. Within 60 minutes, at a *pH* value of 8, the TN removal rate is highest, at 68%; as the *pH* value increases to 9, 10, and 11, the removal rates gradually decrease, to 66%, 64%, and 60%, respectively. The experimental results indicate that electrode plate distance and *pH* value significantly influence the TP and TN removal efficiency in the electrochemical denitrification and dephosphorization process. For TP removal, the electrode plate distance of 3 cm is optimal, suggesting that smaller distances result in more efficient reactions; excessively large distances lead to reduced removal efficiency due to increased electrolyte resistance affecting the reaction efficiency. For TN removal, lower *pH* values are beneficial for improving the removal rate, and efficiency decreases with increasing *pH* values. This is due to changes in the electrochemical conversion path of nitrogen under high *pH* conditions, affecting the removal effect. Therefore, selecting appropriate electrode plate distances and *pH* values can effectively enhance the removal efficiency of TP and TN in the electrochemical denitrification and dephosphorization process.

Table 2. Water quality of actual farmland inflow and outflow

	COD ($mg.L^{-1}$)	***BOD₅*** ($mg.L^{-1}$)	***TP*** ($mg.L^{-1}$)	***TN*** ($mg.L^{-1}$)
Inflow	5326.21	4562.28	345.68	921.54
Outflow	389.65	138.69	224.26	598.32

From the data on the water quality of actual farmland inflow and outflow provided in Table 2, it can be seen that the electrochemical denitrification and dephosphorization technology significantly improves the water quality of farmland drainage. The COD in the inflow is 5326.21 mg/L, which is reduced to 389.65 mg/L in the outflow, with a removal rate of approximately 92.68%. The BOD_5 is reduced from 4562.28 mg/L to 138.69 mg/L, with a removal rate of approximately 96.96%. The TP is reduced from 345.68 mg/L to 224.26 mg/L, with a removal rate of approximately 35.15%. The TN is reduced from 921.54 mg/L to 598.32 mg/L, with a removal rate of approximately 35.08%. The experimental results show that electrochemical denitrification and dephosphorization technology exhibits significant effects in farmland drainage water quality purification. The removal rates of COD and BOD_5 reach 92.68% and 96.96%, respectively, indicating the technology's high efficiency in removing organic pollutants. This is due to the strong oxidizing substances generated during the electrochemical process, which can effectively decompose and oxidize organic substances. The removal rates of TP and TN in actual farmland inflow are 35.15% and 35.08%, respectively, showing a certain removal effect. Overall, the electrochemical denitrification and dephosphorization technology can effectively improve farmland drainage water quality, significantly reducing its environmental pollution impact. However, there is a need to further optimize process parameters and reaction conditions to improve the removal rates of TP and TN.

The results of this study show that electrochemical technology performs exceptionally well in removing organic pollutants, such as COD and BOD5, but is relatively less effective in removing total phosphorus and total nitrogen. This trend may be attributed to the selectivity of electrochemical reactions, where organic matter is more easily decomposed through redox reactions, while the removal of phosphorus and nitrogen requires longer reaction times or higher energy input. Additionally, the choice of electrode materials—specifically, the characteristics of stainless steel and magnesium electrodes—can impact the reaction rate and efficiency. Existing literature also indicates that electrochemical technology generally excels in removing organic pollutants, whereas achieving effective phosphorus and nitrogen removal often requires further optimization of operating conditions or the integration of auxiliary processes, such as precipitation or adsorption. The study demonstrates that electrochemical nitrogen and phosphorus removal has significant potential for treating farmland drainage, especially for organic pollutants, with COD and BOD5 removal rates reaching 92.68% and 96.96%, respectively. Although the removal efficiencies for total phosphorus and total nitrogen are relatively low (35.15% and 35.08%), they still contribute to some degree of purification. By optimizing key parameters—such as voltage, electrode spacing, and pH—the study identifies the optimal operating conditions, providing valuable references for the practical application of electrochemical technology. This approach not only holds promise for farmland drainage purification but also lays a theoretical foundation and provides data support for developing new electrochemical materials and improving existing processes. It is expected to contribute to the sustainable management of agricultural water environments.

5. CONCLUSION

This paper systematically studied the application of electrochemical denitrification and dephosphorization technology in farmland drainage water quality purification, achieving significant results. Firstly, by optimizing key parameters such as voltage, electrode plate distance, and *pH* value, the optimal operating conditions were determined. Under the conditions of a 3 cm electrode plate distance and a *pH* value of 8, the highest TP and TN removal rates were achieved, at 65% and 68%, respectively. Secondly, the actual farmland drainage water quality purification experiments showed that electrochemical technology significantly improved the water quality, with COD and BOD_5 removal rates reaching 92.68% and 96.96%, respectively, demonstrating strong organic pollutant removal capability. Although the removal rates of TP and TN were relatively low, at 35.15% and 35.08%, respectively, they still exhibited a certain purification effect. This indicates that electrochemical technology is highly efficient in removing organic pollutants and some nutrients when treating farmland drainage. Compared with other methods, the innovation of this study lies in the systematic application of electrochemical nitrogen and phosphorus removal technologies for farmland drainage purification. In particular, it enhances removal efficiency by optimizing key operating parameters, such as voltage, electrode spacing, and pH. This approach not only excels in the removal of organic pollutants but also offers a new perspective for the broader application of electrochemical technology in water purification, demonstrating significant technological advancements.

The value of this study lies in providing an effective electrochemical method for farmland drainage purification, especially excelling in organic pollutant removal. By optimizing operating parameters such as voltage, electrode plate distance, and pH value, the research results provide important technical references for farmland drainage treatment and have practical application prospects. Additionally, this study explores the application methods of electrochemical materials in water quality purification, providing fundamental data and theoretical support for future technological improvements and new material developments. Despite significant achievements, there are some limitations. Firstly, although electrochemical technology performs excellently in removing COD and BOD_5, there is room for improvement in TP and TN removal efficiency. Secondly, the research mainly focuses on optimization and testing under laboratory conditions, while practical applications may be influenced by more external factors, such as water quality fluctuations and long-term operational stability. Furthermore, the energy consumption and cost issues in the electrochemical process need further evaluation and optimization to ensure the economic feasibility of the technology. From the perspectives of cost and operability, the electrochemical method proposed in this paper exhibits high versatility. Although the current research primarily focuses on laboratory conditions, the optimized operating parameters can provide guidance for practical applications, adapting to variations in water quality. In the future, with further evaluation and optimization of energy consumption and costs, this electrochemical technology has the potential for widespread adoption in farmland drainage management, meeting the demands for economic feasibility and practicality.

Future research should focus on addressing the lower removal efficiency of TP and TN, potentially combining other treatment methods, such as biological treatment or chemical precipitation, to improve overall purification effectiveness. Additionally, further studies on the long-term stability and durability of electrochemical materials are needed, aiming to develop more cost-effective and efficient new materials. Moreover, the research should extend to actual application environments, with long-term monitoring and evaluation to verify the reliability and applicability of laboratory research results, ensuring the technology's operability and economic viability in practical farmland drainage treatment. Finally, for the energy consumption issue in the electrochemical process, exploring more energy-efficient power designs and optimizing operating conditions are essential to enhance the overall sustainability of the technology.

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