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Treatment of cellar rainwater by multi-dimensional electrode electro-flocculation/submerged ultrafiltration

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ABSTRACT

Rainwater cellars collect and store rainwater to make full use of water resources and improve the problem of drinking water shortages. The treatment of rainwater cellars is therefore of great significance. In this study, we tested the performance of the multi-dimensional electrode electro-flocculation/submerged ultrafiltration process on the removal of ammonia nitrogen, total phosphorus (TP), chemical oxygen demand (COD_{Mn}), and UV_{254} from cellar rainwater. The effects of plate spacing, current density, activated carbon dosage, and electro-flocculation time were analyzed. The integration of the submerged ultrafiltration and electro-flocculation/submerged ultrafiltration processes was found to promote cellar rainwater quality. The removal rates of ammonia nitrogen, TP, COD_{Mn}, and UV_{254} using the combined processes were 53.17%, 90.81%, 59.55%, and 37.67% respectively, corresponding to an optimal plate spacing of 10 mm, current density of 18.51 A/m^2, activated carbon dosage of 60 mg/L, and electro-flocculation time of 15 min. The energy consumption to remove pollutants using the multi-dimensional electrode electrocoagulation process was 0.215 KWh/g, which verifies that the process effectively purifies cellar rainwater.

Keywords: Cellar rainwater; Multidimensional electro-flocculation; Submerged ultrafiltration

1. Introduction

Rainwater is commonly collected, treated, and consumed in the arid and semi-arid regions of the Middle East, North Africa, Australia, midwestern United States, and northwestern China. Rainwater harvesting is a common source of drinking water in rural areas that face water shortages. However, the safety of drinking water derived from rainwater harvesting remains a problem. Many factors contribute to the pollution of collected rainwater, such as regional factors, overlying surfaces, rainfall volume, and cellar materials [1]. The long-term consumption of this untreated water poses a high potential health risk. Technically collected rainwater treatment protocol is therefore urgently required to improve drinking water safety in arid and semi-arid areas.

Ultrafiltration (UF) can remove particles, turbidity, microorganisms (e.g., bacteria, protozoa, algae), and some viruses, but performs poorly for the removal of dissolved organic materials [2]. The application of UF therefore only removes a portion of chemical oxygen demand (COD_{Mn}) and ammonia nitrogen [3], and total phosphorus (TP) and UV_{254} removal remain limited. Immersion UF is a relatively new technical process for separation from the liquid phase and is based on pressure UF technology [4,5].

Electro-flocculation technology [6,7] is environmentally friendly and generally does not require chemical additives. The involved equipment in electro-flocculation is small, the

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floor area is not wide, its operation is simple and flexible, and it also has a certain effect on the removal of ammonia nitrogen and total nitrogen.

Multi-dimensional electrode electro-flocculation–UF offers the advantages of convenient operation and controllable electro-flocculation cost and also shows excellent UF retention performance. The synergistic effects of the two approaches can enhance the removal of ammonia nitrogen, TP, COD_{Mn}, and UV_{254} in cellar rainwater. We performed experiments to investigate the main factors that affect the removal of ammonia nitrogen, TP, COD_{Mn}, and UV_{254} in the multi-dimensional electrode electro-flocculation immersion UF process combined with the single UF and common two-dimensional electrode electro-flocculation immersion UF processes. The treatment effects of electro-flocculation–UF were also compared. The optimized operating parameters were determined to meet the requirements of Chinese Standard GB 5749-2006 [8].

2. Materials and methods

2.1. Sampling

Natural rainwater and tap water were used to simulate cellar rainwater according to the water quality characteristics of cellar rainwater in villages and towns in Northwestern China [9,10]. Ammonia nitrogen, TP, COD_{Mn}, and UV_{254} of the cellar rainwater were simulated using kaolin, NH_4Cl, KH_2PO_4, glucose, and leaves, respectively. The experimental water quality is listed in Table 1.

2.2. Analytical methods

Turbidity was measured using a Hach-2100p turbidity meter. Ammonia nitrogen content was measured using the sodium reagent photometric method. TP content was measured by molybdenum-antimony anti-spectrophotometry. UV_{254} was determined using a 752N ultraviolet spectrophotometer. COD_{Mn} was determined using the acid permanganate method [11].

2.3. Experimental setup

A submerged ultrafiltration membrane was designed using polyvinylidene fluoride (PVDF) material (model mbr-0.4) with an area of 0.4 m^2. The maximum pressure difference through the membrane was 40 kPa, and the membrane aperture was 0.08–0.1 μm. The self-made electric flocculation reaction tank was 18 cm long, 10 cm wide, and 10 cm high. The effective contact area of the plate was 162 cm^2.

We adopted a stabilized DC power supply and aluminum plate as the polar plate. A switch was designed on the electrode to prevent passivation of the polar plate. The experimental process is illustrated in Fig. 1.

In the multi-dimensional electrode electro-flocculation experiments, we combined immersion UF and ceramsite activated carbon with a surface charge between the two-dimensional electro-flocculation electrodes as the working electrode of multi-dimensional electro-flocculation. The UF experimental conditions followed the same procedure; a stabilized DC power supply was used and switched every 5 min. We varied the electrode spacing, current density, electro-flocculation time, and activated carbon dosage over certain ranges. The measured removal rates of ammonia nitrogen, TP, COD_{Mn}, and UV_{254} are compared with those of UF alone and two-dimensional electrode electro-flocculation combined with submerged UF. The electrode spacing was adjusted to 10, 15, 20, 25, 30, 35, 40, 45, and 50 mm and the current was adjusted to 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5 A. The flocculation time was tested at 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, and 25 min. The activated carbon dosage was 20, 30, 40, 50, 60, 70, 80, and 90 mg/L. In the multi-dimensional electrode electro-flocculation immersion UF experiments, the initial current was set to 0.3 A, the current density was 18.51 A/m^2, the electro-flocculation time was 15 min, and the activated carbon dosage was 60 mg/L. Six plates were set with a spacing of 10, 15, 20, 25, 30, 35, 40, 45, and 50 mm. The influence of the electrode plate spacing on the removal rate of ammonia nitrogen, TP, COD_{Mn}, and UV_{254} is shown in Fig. 2a.

2.4. Electrocoagulation mechanism

The reaction of electrocoagulation technology mainly uses metals (e.g., Fe, Al) as anodes. After passing a direct current, a series of chemical reactions separate the colloidal impurities and suspended solids in the water due to condensation and precipitation.

The removal of ammonia nitrogen mainly depends on three types of effects.

- Cl^- in water decomposes ammonia nitrogen to N_2, and the reaction equation is as follows:

$$2Cl^- - 2e \rightarrow Cl_2\uparrow \tag{1}$$

Table 1
Main characteristics of the cellar rainwater

Parameter	Content	Average
Temperature (°C)	23.0–25.0	24.0
pH	7.0–9.0	8.0
Turbidity (NTU)	8.0–12.0	10.0
Ammonia nitrogen (mg/L)	0.60–1.00	0.80
Total phosphorus (mg/L)	0.10–0.30	0.20
Chemical oxygen demand (COD_{Mn}) (mg/L)	4.20–8.00	6.10
UV_{254} (cm^{-1})	0.140–0.180	0.160

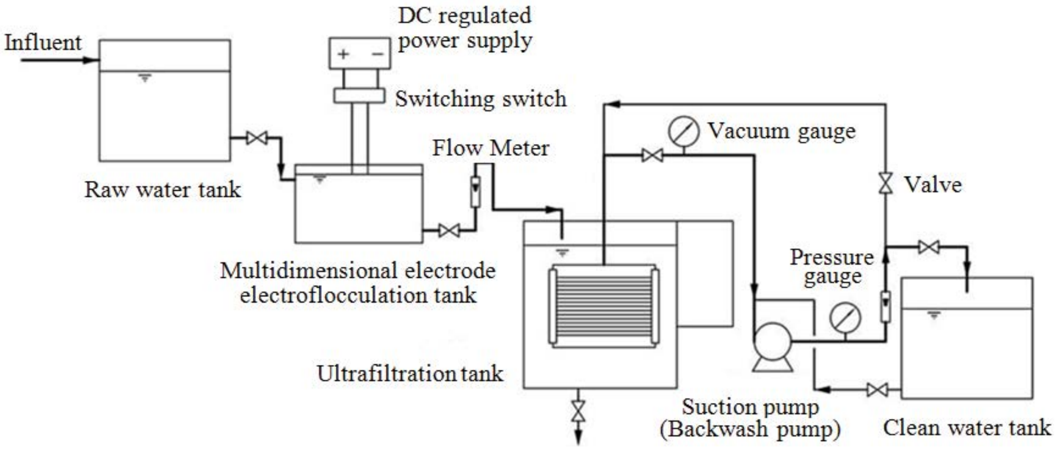

Fig. 1. Flow chart of the combination multidimensional electrode electro-flocculation and submerged ultrafiltration devices.

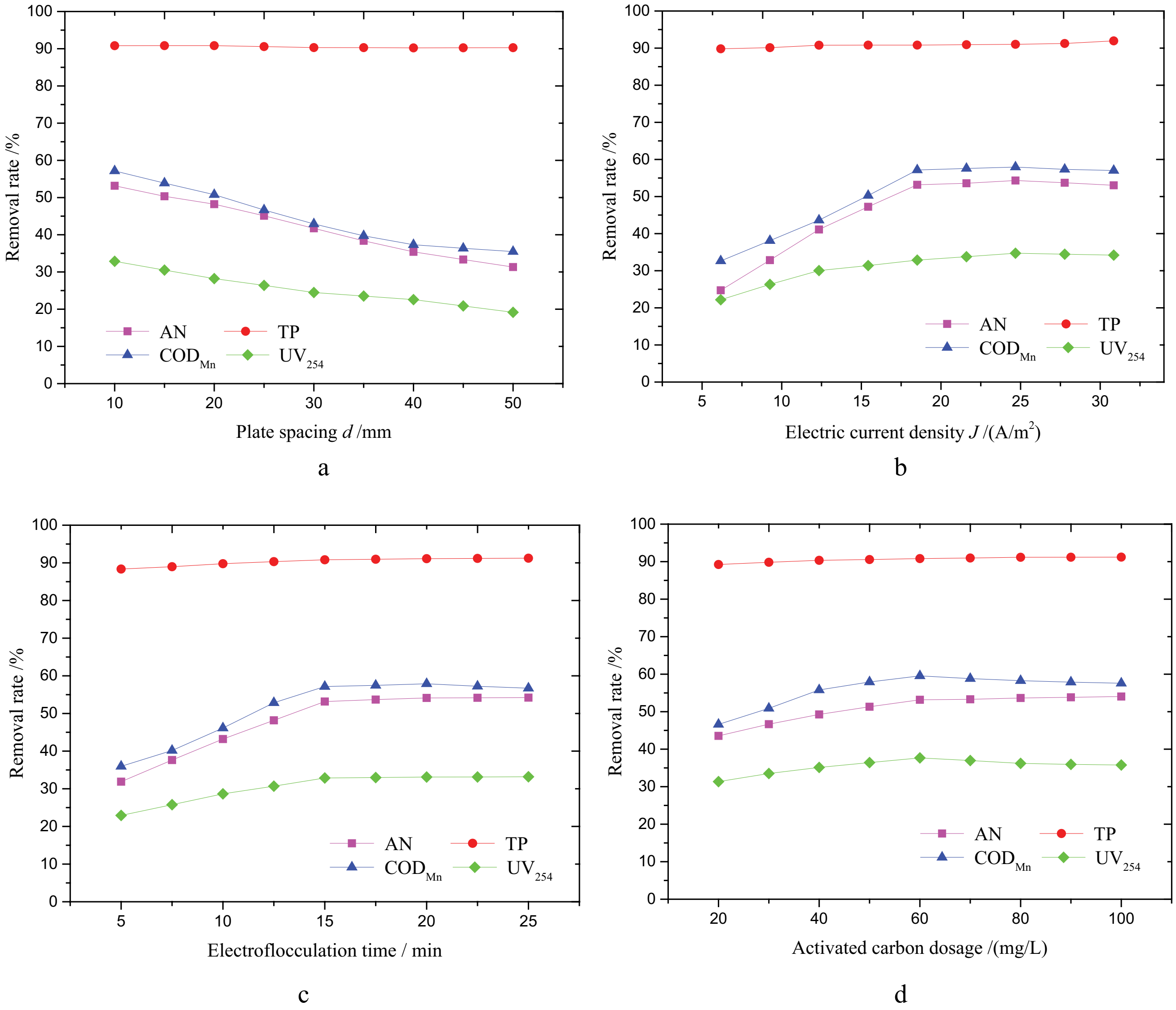

Fig. 2. Ammonia nitrogen, TP, COD$_{Mn}$, and UV$_{254}$ removal rates as a function of (a) plate spacing, (b) electric current density, (c) electro-flocculation time, and (d) activated carbon dosage.

$$Cl_2 + H_2O \rightarrow HCl + HClO \quad (2)$$

$$7HClO + 4NH^{4+} \rightarrow 7HCl + N_2\uparrow + N_2O\uparrow + 4H^+ + 6H_2O \quad (3)$$

However, the amount of Cl_2 produced by the above reaction does not meet the fluorination and chlorination requirements and is accompanied by certain side reactions, thus its effect is limited [12].

- Al^{3+} hydrolysis generated by electrolysis on the electrode plate produces flocculation effects such as aluminum hydroxide and aluminum complex ions, which form flocs and can effectively adsorb ammonia nitrogen in water, which are then trapped by UF [13,14]. The relevant reaction equation is as follows:

$$Al - 3e \rightarrow Al^{3+} \quad (4)$$

$$Al^{3+} + 6H_2O \rightarrow [Al(H_2O)_3]^{3+} \quad (5)$$

$$[Al(H_2O)_3]^{3+} + H_2O \rightarrow [Al(OH)(H_2O)_6]^{2+} + H_3O^+ \quad (6)$$

$$2[Al(OH)(H_2O)_6]^{2+} \rightarrow [Al_2(OH)_2(H_2O)_8]^{2+} + 4H_2O \quad (7)$$

$$Al^{3+} + 6H_2O + 6e \rightarrow 2Al(OH)^3 + 3H_2\uparrow \quad (8)$$

- Activated carbon has well-developed internal pores and a large specific surface area, which exerts certain adsorption effects on ammonia nitrogen. The addition of activated carbon also increases the number of micro-electrodes within the electro-flocculation cell. The two-dimensional electrode is transformed into a multi-dimensional electrode, which greatly increases the effective electrode area and small pitch of the activated carbon particles, shortens the reactants migration distance, and increases the mass transfer rate of the substances, thereby increasing the electrochemical reaction rate and removal rate of ammonia nitrogen.

The most important requirement for TP removal is electrochemical action in the flocculation tank. During the combined use of multi-dimensional electrode electro-flocculation and UF, the Al^{3+} produced by electrolysis of the electrode plate reacts with PO_4^{3-} in the water to produce $AlPO_4$.

$$Al - 3e \rightarrow Al^{3+} \quad (9)$$

$$Al^{3+} + PO_4^{3-} \rightarrow AlPO_4\downarrow \quad (10)$$

The solubility product constant of $AlPO_4$ is extremely small, and Ksp ($AlPO_4$) = 0.98 × 10^{-18} at room temperature readily leads to $AlPO_4$ precipitation [15]. Theoretical calculations have shown that to meet the requirement of TP mass concentration for drinking water (≤0.1 mg/L), the minimum generated concentration of Al^{3+} must be ≥0.122 pmol/L. As long as the amount of Al^{3+} produced by electrolysis is greater than this value, PO_4^{3-} can be made and precipitation occurs. Higher amounts of produced Al^{3+} are associated with more complete PO_4^{3-} removal under the operating conditions used in this study. The minimum concentration of generated Al^{3+} can be calculated according to Faraday's law to be 4.6 mmol/L. The amount of Al^{3+} is sufficient to cause PO_4^{3-} to precipitate and be removed by UF, which is why the TP removal rate is relatively high.

The removal of COD_{Mn} mainly occurs owing to an electrochemical reaction in the flocculation tank and is indirectly accelerated by activated carbon. The polyhydroxy complexes and hydroxides increase with the flocculant effect produced by Al^{3+} hydrolysis and complexes form. The structure itself plays the role of net catching and bridging. The aluminum complex ions and hydroxides produced in the electro-flocculation process therefore have a high adsorption activity and adsorption capacity higher than that of $Al(OH)_3$ obtained by the hydrolysis method using general agents. A portion of the generated flocs is also simultaneously removed by H_2 and other gases generated on the polar plate by the air floatation effect, and another portion of the flocs is trapped and removed in the subsequent UF process. The COD_{Mn} removal rate improves with the removal of organic pollutants and other reducing substances.

In terms of UV_{254} removal, previous studies have shown that UV_{254} strongly correlates with various water quality indicators, such as COD_{Mn}. The electrolytic oxidation in the electro-flocculation process and indirect acceleration effect of the activated carbon cause some large-molecule organic matter to decompose into small-molecule organic matter. A flocculant forms during the electro-flocculation process that produces several tiny flocs, which are more effective. A small part of the organic matter in the water is adsorbed. A portion of the generated flocs is removed by H_2 and other gases generated on the polar plate by the air floatation effect, and another portion of the flocs is trapped and removed in the subsequent UF process. The removal of a large amount of organic matter improves the UV_{254} removal rate.

2.5. Submerged ultrafiltration experiments

During the UF process alone, the membrane flux was maintained at 9.4 L/(h m^2) and the transmembrane pressure range was 17–21 kPa. An experimental period was 100 min, including 90 min of effluent and 10 min of backwash. The flushing strength was 70 L/(h m^2), and the effluent from six UF cycles was mixed to determine the contents of ammonia nitrogen, TP, COD_{Mn}, and UV_{254}.

2.6. Electro-flocculation/submerged ultrafiltration experiments

The conditions of the two-dimensional electrode electro-flocculation combined with immersion UF experiments were the same as in section 2.5. A stabilized DC power supply was used with a current density of 18.51 A/m^2, electrode plate spacing of 10 mm, and the electric flocculation time was 15 min and switched every 5 min. The effluent from the six-cycle experiments was mixed to determine the contents of ammonia nitrogen, TP, COD_{Mn}, and UV_{254}.

A submerged UF membrane of PVDF material (model mbr-0.4) was used with a membrane area of 0.4 m^2, membrane aperture of 0.08–0.1 μm, and maximum pressure difference through membrane of 40 kPa. The self-made electric flocculation reaction tank was 18 cm long, 10 cm wide, 10 cm high, and the effective contact area of the plate was 162 cm^2.

3. Results and discussion

3.1. Influence of operating conditions on cellar rainwater treatment

3.1.1. Effect of plate spacing

The effect of plate spacing on ammonia nitrogen, TP, COD_{Mn}, and UV_{254} removal is shown in Fig. 2a.

The removal rate of ammonia nitrogen, COD_{Mn}, and UV_{254} by multi-electrode electrocoagulation combined with UF decreased up to 53.17%, 57.16%, and 32.87%, respectively, when the plate spacing was increased from 10 to 50 mm, with minima of 31.32%, 35.48%, and 19.16%. The plate spacing had a negligible effect on the TP removal rate, which remained stable at approximately 90%. However, if the distance between the plates is too small, the electric field distribution between the plates becomes uneven and is prone to short circuit [16]. A plate spacing of 10 mm was therefore preferable.

The multi-dimensional electrode electro-flocculation combined with UF results show that a reduction of electrode plate spacing improved the indirect electro-oxidation and electro-adsorption of Cl^-, which enhances the ammonia nitrogen removal rate. Although increased plate spacing reduced the electrochemical reaction rate, the amount of produced Al^{3+} by electrolysis was sufficient to cause PO_4^{3-} precipitation, and therefore had little effect on TP removal. A reduction of the electrode spacing enhances electrosorption [17], which can thus effectively adsorb related organic pollutants and other reducing substances in the water, which strengthens the flocculation effect and improves the removal rate of COD_{Mn} and UV_{254}.

3.1.2. Effect of current density

In the immersion UF experiments of multi-dimensional electrode electro-flocculation, the electro-flocculation time was set to 15 min, the activated carbon dosage was 60 mg/L, six plates were set with a plate spacing of 10 mm, and the adjustment currents were 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, and 0.5 A with corresponding current densities of 6.17, 9.26, 12.34, 15.43, 18.51, 21.60, 24.68, 27.77, and 30.85 A/m^2, respectively. The effect of current density on the removal of ammonia nitrogen, TP, COD_{Mn}, and UV_{254} is shown in Fig. 2b.

The removal rate of ammonia nitrogen, COD_{Mn}, and UV_{254} increased rapidly with increasing current density below 18.51 A/m^2, and then gradually stabilized above 18.51 A/m^2. The TP removal rate increased with increasing current density to reach 91.95%, but further increase was limited. The result shows that the combination of multi-dimensional electrode electro-flocculation and UF yielded the best removal effect on ammonia nitrogen, TP, COD_{Mn}, and UV_{254} when the current density was between 18.51 and 24.68 A/m^2. Considering the removal effect and equipment energy consumption, the preferred current density was 18.51 A/m^2.

For the removal of ammonia nitrogen, higher current density was found to be associated with stronger electro-flocculation effects and higher amounts of adsorbed ammonia nitrogen. The floc impurities that adsorbed a large amount of ammonia nitrogen were directly trapped and removed through the UF membrane. However, when the current density was too high and excessive for Al^{3+}, the colloid surface charge reversed to form colloidal repulsion, which destroyed the flocs, reduced the flocculation capacity, and weakened the electrosorption of ammonia nitrogen [18].

For TP removal, the amount of Al^{3+} produced by electrolysis in the water increased with increasing current density. The removal rate of PO_4^{3-} increased but was limited.

For COD_{Mn} removal, the current density can determine the electro-flocculation efficiency and rate of floc and bubble generation. Higher current densities led to more Al^{3+} produced by electrolysis in the water body. The polyhydroxy complexes and hydroxides also increased owing to the flocculant effect produced by the increased Al^{3+} hydrolysis, thereby improving the flocculation efficiency. The rate of floc and bubble generation increased with increasing current density. The flotation effect was simultaneously strengthened and the aluminum complexes formed by flocculation floated out the anode, which accelerated the further dissolution of aluminum, allowed more flocculants to form, and enhanced the flocculation effect [19,20]. Larger amounts of flocs produced by electro-flocculation led to more conducive UF removal, thus the removal of COD_{Mn} increased with increasing current density. However, excessive current density produced excessive Al^{3+} in the water and reversed the colloid surface charge, which led to colloidal repulsion and a reduced flocculation effect [21], which was not conducive to COD_{Mn} removal.

For UV_{254} removal, increased current density enhanced the electro-flocculation efficiency and increased the floc and air bubble generation rate. A large amount of organic matter in the water body was adsorbed by the flocs produced by electro-flocculation and then intercepted and removed in the UF process, which further improved the UV_{254} removal rate.

3.1.3. Effect of electro-flocculation time

In the combined multi-dimensional electrode electro-flocculation and immersion UF experiments, the current density was set to 18.51 A/m^2, the activated carbon dosage was 60 mg/L, six electrode plates were set with a spacing of 10 mm, and the electric flocculation time was adjusted to 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, and 25 min. The effect of electro-flocculation time on the removal of ammonia nitrogen, TP, COD_{Mn}, and UV_{254} is shown in Fig. 2c.

For electro-flocculation times shorter than 15 min, the removal rate of ammonia, COD_{Mn}, and UV_{254} rapidly increased with increasing electro-flocculation time, reaching 53.17%, 57.16%, and 32.87%, respectively. The removal rate of TP slightly increased and remained approximately 90%. The removal rates of ammonia, TP, COD_{Mn}, and UV_{254} tended to stabilize upon further increase of the electro-flocculation time. The preferred electric flocculation time was therefore 15 min. For ammonia nitrogen, prolonging the electro-flocculation time strengthened the electro-flocculation effect and improved the removal effect of electro-adsorption on ammonia nitrogen, thus the removal rate of ammonia nitrogen increased with increasing electro-flocculation time.

For TP, the amount of Al^{3+} produced by electrolysis in the water also increased with increasing electro-flocculation time, which improved the removal rate of PO_4^{3-}. However, the amount of Al^{3+} met the requirements for PO_4^{3-} precipitation and a further increase of the TP removal rate was limited.

For COD_{Mn}, prolonged electric flocculation times increased gases such as Al^{3+} and H_2 produced by electrolysis of the electrode plate. The aluminum hydroxide produced by the hydrolysis of Al^{3+}, aluminum complex ions, and other substances owing to the flocculation effect thus increased, which strengthened the flocculation effect. A large number of bubbles with a certain floating capacity were also simultaneously generated and the agglomerates and suspended particles generated in the reaction were transported to the water surface [22], left to stand for 5 h, and intercepted by UF, thereby effectively removing COD_{Mn}. However, under constant current density and too long of hydraulic retention time, excessive Al^{3+} was generated and the colloid surface charge reversed. This caused colloid repulsion and the flocs were destroyed, thus the flocculation effect and removal of COD_{Mn} decreased. The removal trend is in a good agreement with the results presented by Özyonar et al. [23], who used EC to treat disperse Blue 60 dye.

For UV_{254}, prolonged electro-flocculation times allowed more macromolecular organics to be electrolyzed into small-molecule organics. Al^{3+} produced by electrolysis in water simultaneously increased, as well as the amount of polynuclear hydroxyl complexes and aluminum hydroxide produced by Al^{3+} hydrolysis and flocculation effect. The amounts increased, the electro-flocculation effect was strengthened, small-molecule organic matter was adsorbed by the flocs produced by electro-flocculation, and the flocs were then directly intercepted by the UF process. Organic matter in the water was therefore removed and UV_{254} removal improved.

3.1.4. Effect of granular activated carbon dosage

For this set of experiments, we set the current density to 18.51 A/m^2 and electro-flocculation time to 15 min. Six plates were set with a spacing of 10 mm. The adjusted activated carbon dosage was 20, 30, 40, 50, 60, 70, 80, 90, and 100 mg/L. The effect of activated carbon dosage on the removal of ammonia nitrogen, TP, COD_{Mn}, and UV_{254} in the multi-dimensional electrode electro-flocculation/submerged UF process is shown in Fig. 2d.

When the activated carbon dosage was less than 60 mg/L, the removal rates of ammonia, TP, COD_{Mn}, and UV_{254} increased with increasing dosage. The trends gently flattened when the activated carbon dosage was higher than 60 mg/L, and the removal rates of COD_{Mn} and UV_{254} even slightly decreased. The preferred amount of added activated carbon was 60 therefore mg/L.

The addition of activated carbon converted the two-dimensional electrode into a multi-dimensional electrode. The face-to-face ratio of the electro-flocculation tank increased with increasing activated carbon because the working electrode spacing over which the activated carbon acts was small, which indirectly increased the material. The transport speed increased the electrochemical reaction rate, thus the ammonia nitrogen removal rate increased with increasing activated carbon dosage [24]. However, when a certain amount of activated carbon had been added, the chemical reaction rate was too strong, excessive Al^{3+} was generated, the colloid surface charge reversed and led to colloid repulsion, the flocs were destroyed, and the flocculation capacity decreased, which weakened the effect on the electro-adsorption of ammonia.

For TP, the electrochemical reaction rate increased with increasing amount of activated carbon, as well as the amount of Al^{3+} produced by electrolysis in water. The PO_4^{3+} removal rate also increased but tended to stabilize because the amount of Al^{3+} produced by electrolysis in water was sufficient for precipitation, which only slightly enhanced the TP removal rate.

For COD_{Mn}, the addition of activated carbon transformed the two-dimensional electrode into a multi-dimensional electrode, which increased the speed of the electrochemical reaction and increased the amount of Al^{3+} produced by electrolysis. The polyhydroxy complex with the flocculant effect produced by Al^{3+} hydrolysis and hydroxides also increased, which improved the electro-flocculation effect [25]. The removal rate of COD_{Mn} therefore increased with increasing amount of added activated carbon. However, when a certain amount of activated carbon had been added, the chemical reaction rate was too large, excessive Al^{3+} was produced, the colloid surface charge reversed leading to colloid repulsion, the flocs were destroyed, and the flocculation capacity was reduced, which weakened the removal of COD_{Mn}.

For UV_{254}, the electrochemical reaction rate increased with increasing added activated carbon in water, thus more macromolecular organics were electrolyzed into small-molecule organics, the amount of Al^{3+} produced by electrolysis in water simultaneously increased, as well as the multinucleation with flocculation effects produced by Al^{3+} hydrolysis. The amount of hydroxy complex and aluminum hydroxide increased, the effect of electro-flocculation was enhanced, the small-molecule organic matter was adsorbed by the flocs generated by electro-flocculation, and the flocs were then directly intercepted by the UF process. The organic matter in the water was therefore removed, which improved the removal of UV_{254}.

3.2. Comparison of treatment effects

The submerged ultrafiltration process, electro-flocculation/submerged process, and multi-dimensional electrode electro-flocculation/submerged UF process were integrated for the treatment of cellar rainwater. The removal effect is shown in Table 2 and Fig. 3.

The results listed in Table 2 and Fig. 3 show that the removal rates of ammonia nitrogen, TP, COD_{Mn}, and UV_{254} by the multi-electrode electrocoagulation/UF process are substantially higher than that of UF alone with an increase of up to 40.9%, 81.09%, 51.83%, and 18.82%, respectively. The removal rates of ammonia nitrogen, COD_{Mn}, and UV_{254} are also significantly higher than those of the electro-flocculation/submerged process because the UF membrane generally more easily retains macromolecular organic matter. The interception effect on small-molecule organic matter, ammonia nitrogen, and TP is not apparent.

Table 2
Comparison of the removal effects of three types of processes

Water treatment process	Effluent water quality				
	Ammonia nitrogen (mg/L)	TP (mg/L)	COD_{Mn} (mg/L)	UV_{254} (cm^{-1})	Turbidity (NTU)
Ultrafiltration	0.53–0.88	0.09–0.27	3.88–7.38	0.11–0.15	0.3–0.6
EF-ultrafiltration	0.31–0.52	0.01–0.03	1.93–3.67	0.09–0.12	0.3–0.6
MDEF-ultrafiltration	0.28–0.47	0.01–0.03	1.70–3.24	0.09–0.11	0.3–0.6

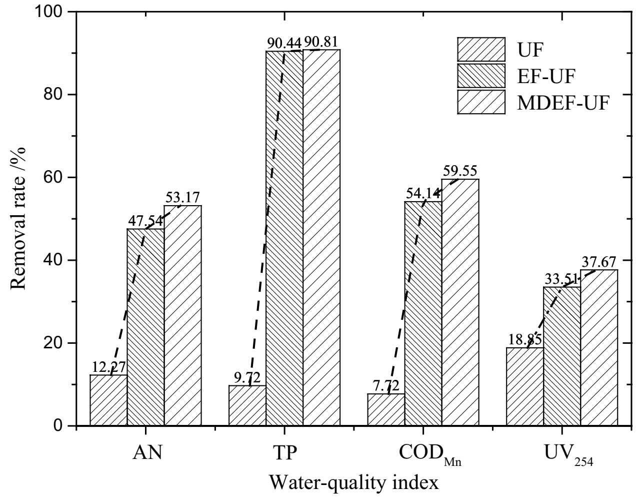

Fig. 3. Comparison of the removal rate using three types of treatment processes.

The effluent quality of the multi-dimensional electrode electro-flocculation combined with ultrafiltration process meets the GB 5749-2006 Chinese standard requirements, and its water quality indicators are clearly superior to the separate UF and common two-dimensional electrode electro-flocculation processes in addition to turbidity.

3.3. Comparison of the current efficiency of different processes

Calculation formula of electric flocculation technology current efficiency:

$$W = I_0 \left(N-1\right) \frac{U_0 t}{m} \tag{11}$$

where W is the energy consumption required to remove each gram of pollutant, KWh/g; I_0 is the unit electrolysis current, A; N is the number of plates in the electrocoagulation tank; U is the unit decomposition voltage, V; t is the electric flocculation time, h; m is the quality of removed pollutants, g.

Using Eq. (11), the energy consumption of the two-dimensional electrode electro-flocculation process is 0.25 KWh/g for a current density of 18.51 A/m^2 (current = 0.3 A, electric flocculation time = 15 min, distance between the six set plates = 10 mm). The energy consumption of the multi-electrode electric flocculation process is 0.215 KWh/g (current density = 12.34 A/m^2, electric flocculation time = 15 min, distance between the six set plates = 10 mm). Compared with the two-dimensional electrode, the electric flocculation of the multi-dimensional electrode reduces the energy consumption by 0.035 KW/g for the removal of pollutants per unit mass.

4. Conclusion

The results presented here demonstrate the effectiveness of a multi-dimensional electrode electro-flocculation/submerged ultrafiltration process for cellar rainwater treatment, and all tested parameters show significant reductions. The cost of the combined process is also lower because of the reduced membrane fouling. The multi-dimensional electrode electro-flocculation/submerged ultrafiltration process is therefore suitable for water treatment in low-income rural areas.

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