Effect of on-Site Sludge Reduction and Wastewater Treatment Based on Electrochemical-A/O Combined Process

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Abstract: Working on sludge with electrochemical oxidation is beneficial to promote the subsequent recessive growth of microorganisms in the sludge. To achieve the on-site sludge reduction, this study combined the anoxic/oxic (A/O) process with the electrochemical oxidation process based on the cell lysis-cryptic growth theory by determining the experimental conditions and mechanism of electrochemical cell lysis. The sludge reduction and effluent treatment of the combined process in practical operation were studied. The results showed that the cumulative sludge discharge had been reduced by 37.1% compared with that of the A/O process, and the apparent sludge yield had been reduced by 39.1% during the 30-day operation time, indicating that the electrochemical-A/O combined process could have a considerable sludge reduction effect. After the treatment, chemical oxygen demand (COD), ammonium nitrogen, and total nitrogen in the effluent of the combined process reached 33.02 mg/L, 0.83 mg/L, and 9.95 mg/L, respectively. Due to the limitation of the A/O process, the removal of total phosphorus was poor. As a result, poly aluminum chloride (PAC) was employed to achieve a chemical removal of phosphorus, by which the total phosphorus (TP) of the effluent was controlled to be lower than 0.5 mg/L.

Keywords: electrochemical oxidation; electrochemical-A/O combined process; Ti/SnO$_2$-Sb; sludge reduction; cell lysis rate

1. Introduction

Conventional municipal sludge is usually agglomerated by suspended particles in sewage, which has a loose structure, high porosity, irregular shape, and a large amount of toxic and harmful substances adsorbed on the surface [1]. Generally, the moisture content of sludge is above 97%, which makes it bulky and creates great difficulties for transportation and treatment [2,3]. Compared with sewage treatment, excess sludge is more difficult to dispose and the treatment is costly. In a wastewater treatment plant, thickening, digestion, and dewatering are usually used for the treatment of excessive sludge [4–6]. After treatment, the sludge volume can be significantly reduced, with relatively better biostability. Nevertheless, the treated sludge cannot be directly discharged into the environment. Sludge disposal technologies such as landfilling, land application, composting, incineration, and building materials will then be required to prevent adverse effects on the ecological environment [7–9]. However, sludge disposal is usually restricted due to the associated disadvantages such as negative environmental impacts, large land occupation, and high energy consumption [10,11]. As a result, a reduction from the source is regarded as the most direct and efficient strategy to solve the sludge issue [12].
Electrochemical technologies are widely used for the treatment of special wastewater over the past decades due to several advantages such as high treatment efficiency, zero chemical addition, less sludge emission, and automation [13,14]. Some typical applications involve the simultaneous removal of heavy metals and organic contaminants [15], the degradation of hardly degradable organic pollutants [16], electrochemical disinfection, and electro-coagulation [17,18]. For instance, the utilization of boron-doped diamond electrodes had good performance for the decolorization of azo dye [19], while a high removal rate of azo dye was found during the combined use of photocatalysis and electrochemical oxidation [20]. Additionally, UV assisted electrochemical degradation could significantly mineralize coumarin within a short operation period [21].

Conventional sludge treatment technologies, for instance, uncoupling metabolism, endogenous metabolism, and the predation of bacteria usually have several disadvantages such as harsh operating conditions, causing secondary pollution and affecting the effluent quality [22,23]. Electrochemical oxidation is also used in the study of sludge reduction. Since only one cell lysis unit is required in the reflux line, the cell lysis-cryptic growth technology is of great advantage including simple and convenient operation, neglectable impact on the effluent quality, and being able to improve sludge sedimentation to some extent. Through optimizing the experimental conditions such as electrolysis time, Fe/C mass ratio, and the dosage of iron powder, Ning et al. [24] observed that the capillary suction time (CST) of sludge could be decreased from 34.1 to 27.8 s, while the settling velocity (SV) of sludge was reduced from 75 to 60%. However, with conventional cell lysis methodologies, it is difficult to simultaneously realize low cost, optimum cell lysis effect and minimum environmental impact. In contrast, electrochemical oxidation is an environmentally friendly technique with low requirements for chemicals, little pollution, and good application prospects for sludge cell lysis [25–28]. At present, there are two main research directions regarding sludge treatment using electrochemical oxidation. One is to improve the dewaterability of excess sludge and the other one is to promote subsequent anaerobic/aerobic digestion or cryptic growth as a pretreatment before cell lysis [29–31]. In the study by Song et al. [30], with a waste activated sludge concentration of 12.9 g/L, electrolysis time of 30 min, and 5 W electric power, the electrochemical pre-treatment could remove 2.75% of volatile solids (VS) and 7.87% of volatile suspended solids (VSS). Although the application of electrochemical treatment for sludge reduction has currently been gradually increased, there are few studies combining electrochemical sludge treatment with existing wastewater treatment processes, for instance, the A/O process, which has a number of merits such as high efficiency in ammonium removal and pollutant degradation, high loading volume, simple for operation as well as low investment and operating costs [32–35].

In this study, the performance of an A/O process combining electrochemical cell lysis was investigated, using Ti/SnO$_2$-Sb as the electrodes. The operating efficiency of the combined process and the sludge reduction effect were monitored. The influence of electrochemical lysis on the treatment performance was studied by measuring COD, ammonium nitrogen, total nitrogen, and phosphorus. The current work could provide technical guidance for sludge reduction based on electrochemical lysis, and new insights for developing sludge reduction technology in wastewater treatment plants.

2. Materials and Methods

2.1. Electrochemical-A/O Combined Sludge Reduction Device

The electrochemical-A/O combined process consisted of two parallel experimental devices. The control group was a conventional A/O sewage treatment system including four parts: raw water bucket, anoxic tank, aerobic tank, and secondary sedimentation tank. To operate the device for 24 h, the raw water bucket volume was 120 L. The anoxic tank volume was 10 L, equipped with a stirrer (90 rpm) for mixing. The aerobic tank volume was 30 L, and the secondary sedimentation tank volume was 12 L. The operating conditions of the main A/O process were determined through preliminary experiments, as shown in
Table 1. The sedimentation tank was discharged according to the amount of sludge that needed to be discharged daily. Afterward, the sedimentation tank was stirred to prevent blocking when the sludge was recycled.

Table 1. Operating parameters of A/O process.

| Operating Parameters                  | Value |
|--------------------------------------|-------|
| Hydraulic retention time (HRT) (h)   | 8     |
| Temperature (°C)                     | 22–25 |
| Dissolved oxygen (mg/L)              | 2–3   |
| Mixed liquor suspended solids (MLSS) concentration (mg/L) | 3000 |
| Return sludge ratio (%)              | 100   |
| Internal sludge recycle ratio (%)    | 400   |
| Sludge retention time (SRT) (d)      | 14    |
| Influent flow rate (L/d)             | 120   |

On the basis of the control group, the experimental group added a sludge reduction unit. Part of the sludge in the secondary sedimentation tank returned normally to ensure that the sludge concentration in the aerobic tank was maintained within a certain range, and the other part passed through the electrochemical cell lysis reactor. After electrochemical cell lysis treatment, sludge flowed into the anoxic tank. The schematic diagram and physical diagram of the device are shown in Figure 1.

Figure 1. Electrochemical-A/O combined process device diagram: (a) physical diagram; (b) schematic diagram.

Before coupling the A/O reactor with the electrochemical sludge reduction unit, the two sets of A/O reactors had been running for 10 days to achieve sludge acclimation and a relatively stable effluent quality. To achieve consistent initial experimental conditions, before the experiment, the sludge in the two sets of devices was mixed. The sludge reduction effect and treatment performance of the combined process were investigated.

2.2. Sludge Characteristics and Methods of Inoculation and Domestication

The sludge used in the combined device was obtained from the Nanshan Wastewater Treatment Plant (an A²/O process) in Shenzhen, China. After gravity settling for 24 h, the concentrated sludge and the supernatant were stored at 4 °C for 72 h. The basic characteristics of the concentrated sludge were: pH 6.3–6.9, MLSS 12.2–18.5 g/L, and MLVSS (mixed liquid volatile suspended solids) 5.9 g/L–9.5 g/L. A 24 h aeration (without adding wastewater) was conducted before the seed sludge was transferred to the parallel A/O reactor for domestication. The operating parameters of the A/O reactor are shown in
Table 1. Artificial synthetic wastewater was applied as the influent during the acclimation period, which was similar to that of the experimental period. Tap water was used to prepare the artificial synthetic wastewater that contained (per liter): 170 mg glucose, 230 mg sodium acetate, 153 mg ammonium chloride (NH$_4$Cl), 18 mg potassium dihydrogen phosphate (K$_2$HPO$_4$), 350 mg sodium bicarbonate (NaHCO$_3$), and 5 mg calcium chloride (CaCl$_2$). The water quality indicators of artificial synthetic wastewater were: 360 mg/L COD, 4.0 mg/L TP, 40 mg/L TN, 40 mg/L NH$_4^+$-N. After 10 days of acclimation, the sludge had basically adapted to the synthetic wastewater used in the experiment, and all the indicators of the effluent reached a stable level, meaning that the sludge settlement was good. At the same time, it could be observed through a microscope that the sludge bacteria micelles had a compact structure, and the growth of various protozoa such as *Vorticella* and *Rotifer* indicated that the sludge was mature. The sludge was of yellowish brown color, with thick flocs, indicating a good sedimentation performance.

2.3. Electrochemical Cell Lysis Experimental Setup

The experiment was conducted in a cylindrical glass reactor (500 mL) with a sludge volume of 400 mL throughout the experiment. A Ti/SnO$_2$-Sb [36–39] mesh electrode was used as the anode, with a titanium mesh as the cathode. Both the cathode plate and anode plate were of an area of 5 cm$^2$, while the distance between both plates was 1 cm. During the electrochemical treatment, the electric current varied from 300 to 450 mA as a static working voltage of 18 V was utilized. The pH of the system was 6.8–7.0, with an electrolysis time of 90 min. A magnetic stirrer was used during the electrolytic process for mixing.

2.4. Experimental Methods

2.4.1. Evaluation Method for Sludge Reduction

The calculation method of the observed sludge yield ($Y_{obs}$) of A/O process and electrochemical-A/O combined process was calculated as shown in Equation (1):

$$Y_{obs} = \frac{X_w Q_w + (Q - Q_w) X_e}{Q (S_0 - S_e)}$$

where $Y_{obs}$ is the observed sludge yield (kgMLSS/kgCOD$_{removed}$); $X_w$ is the excess sludge concentration (mg/L); $Q_w$ is the excess sludge volume (L); $Q$ is the daily water intake (L); $X_e$ is the effluent sludge solid (SS) concentration (mg/L); $S_0$ is the influent COD concentration (mg/L); and $S_e$ is the effluent COD concentration (mg/L).

The sludge reduction efficiency (SRE) of the electrochemical-A/O combined process was calculated according to Equation (2):

$$SRE = \frac{Y_{obs1} - Y_{obs2}}{Y_{obs1}} \times 100\%$$

where SRE is the sludge reduction efficiency of the electrochemical-A/O combined process compared with the A/O process (%); $Y_{obs1}$ is the observed sludge yield of the A/O process (kgMLSS/kgCOD$_{removed}$); and $Y_{obs2}$ is the observed sludge yield of the electrochemical-A/O combined process (kgMLSS/kgCOD$_{removed}$).

2.4.2. Operation Mode of Sludge Reduction Unit

For the electrochemical sludge reduction unit, the amount of sludge that needed to be processed every day was the amount of excess sludge that needed to be discharged every day in the main A/O process. However, in the actual operation of the process, the amount of excess sludge that needed to be discharged every day was not a fixed value. In order to maintain the sludge concentration in the aerobic tank at a relatively stable level (around 3000 mg/L), the amount of excess discharged sludge needed to be adjusted according to the variation of the sludge concentration in the aerobic tank.
The daily sludge production ($M_t$) in the device was calculated by Equation (3):

$$M_t = \frac{X_w V_w + (V_a - V_w) X_e}{1000}$$  \hspace{1cm} (3)

where $M_t$ is the daily sludge production in A/O process (g); $X_w$ is the excess sludge concentration (mg/L); $V_w$ is the volume of excess sludge (L); $V_a$ is the daily water intake (L); and $X_e$ is the effluent sludge concentration (mg/L).

According to the calculation and modeling based on the data acquired during the previous experiment, the daily growth of activated sludge was about 10 g. Therefore, in order to maintain the sludge concentration in the aerobic tank at about 3000 mg/L, the amount of excess sludge daily discharged should also be about 10 g. When the excess sludge concentration was 7000 mg/L, the corresponding excess sludge volume was about 1.43 L.

After calculating the amount of sludge that needed to be processed each day, the A/O process and the electrochemical-A/O combined process were run separately. The excess sludge produced by the former was directly discharged, and the excess sludge of the combined process was returned to the electrochemical cell lysis reactor through a peristaltic pump for electrochemical cell lysis treatment, and then returned to the anoxic tank.

The daily direct electrolysis sludge $M_a$ in the device was calculated by Equation (4):

$$M_a = M_{0\text{min}} - M_{90\text{min}}$$  \hspace{1cm} (4)

where $M_a$ is the daily direct electrolysis sludge (g); $M_{0\text{min}}$ is the sludge without electrolysis (g); and $M_{90\text{min}}$ is the sludge with electrolysis for 90 min (g).

2.4.3. Other Analytical Methods

Scanning electron microscopy was used to observe the microscopic morphology of the sludge. Water content (WC), MLVSS, and MLSS were measured following the standard analysis methods [40]. Experimental results in the figures and tables are presented as mean value ± SD (standard deviation). The statistical significances of the results were analyzed by the T-test.

3. Results

3.1. Sludge Reduction Effect of Two Sets of Processes

3.1.1. Analysis of Sludge Reduction Effect

Through ten-day acclimation, a relatively stable activated sludge was obtained for this experiment. When evaluating the sludge reduction effect of the combined process, this study first measured the volume of cumulative sludge discharge within 30 days of operation (Figure 2a). Compared with the A/O process, the electrochemical-A/O combined process had significantly lower cumulative excess sludge emissions within 30 days, which were 319.1 gMLSS and 200.7 gMLSS, respectively. At the 30th day, the volume of cumulative excess sludge discharge of the combined process was 37.1% lower than that of the A/O process. The initial sludge volume index (SVI) was 64.3 ml/g. The SVI after electrochemical oxidation was 44.3 ml/g.

The lower the $Y_{\text{obs}}$ referred to the net increase when microorganisms consume a unit mass of nutrients. The lower the $Y_{\text{obs}}$, the less the net sludge was produced when the same amount of nutrients were consumed, and the better the sludge reduction effect could be achieved.

In the study, the fitting of $Y_{\text{obs}}$ within 30 days of the two processes was shown in Figure 2b. The $Y_{\text{obs}}$ of the A/O process and electrochemical A/O combined process were 0.34 kgMLSS/kgCOD and 0.21 kgMLSS/kgCOD, respectively. Compared with the A/O process, the sludge reduction rate of the combined process was 39.1%, which was not much different from the reduction rate calculated from the sludge involving emissions.
Figure 2. (a) Cumulative sludge discharge within 30 days. (b) Relationship between cumulative sludge discharge and cumulative COD removal. (c) MLVSS/MLSS changes in the two sets of processes.

3.1.2. Analysis of Sludge Reduction Process

Through the above analyses of the sludge reduction effect by the electrochemical-A/O combined process, the experimental results showed that the combined process had a better sludge reduction effect (about 40%) than the A/O process. The study put forward that the sludge reduction process of the combined process mainly included the following two aspects:

(1) Direct cell lysis

In the electrochemical cell lysis process, the sludge flocs were broken while cell damage could be observed. With the dissolution of the EPS and intracellular substances, the MLSS of the sludge was reduced, which could directly reduce a certain amount of sludge. After calculation, the daily reduction of MLSS caused by direct electrolysis during the test period was about 895.1 mg/L, and the reduction of cumulative sludge discharge within 30 days was about 121.8 g. The sludge reduction effect contributed by electrochemical direct lysis accounted for about 31.5% of the total sludge reduction effect.

(2) The effect of the cryptic growth

After conducting the electrochemical cell lysis treatment, the content of dissolved organic matter in the liquid phase of the sludge was greatly increased. At an electrolysis time of 0 min, the dissolved COD was 34.5 mg/L. When the electrolysis time was 90 min, an increase of 469 mg/L was seen in terms of the dissolved COD (503 mg/L). After the sludge was returned to the anoxic tank of the combined process, the organic matter could be directly used by microorganisms as the growth substrate to achieve cryptic growth. In addition, the solid-phase sludge after lysis treatment had greatly destroyed its floc structure, reduced the particle size, increased specific surface area, and better
biodegradability. The sludge was hydrolyzed under the action of microorganisms in the combined process, and could also be reused by microorganisms to promote the cryptic growth. Through the secondary utilization of organic substances in the solid and liquid phases of the returned sludge, the cryptic growth could contribute 69.5% of the total reduction of the combined process.

3.1.3. Determination of MLVSS and MLSS

Since electrochemical oxidation mainly affected the organic matter in the sludge, the effect on inorganic matter was very limited. In order to investigate whether the backflow of electrochemical lysed sludge would cause the accumulation of inorganic substances in the sludge during the process, this study monitored the MLSS and MLVSS of the A/O process and the electrochemical-A/O combined process, and calculated the value of MLVSS/MLSS (Figure 2c). During the operation of the two processes, MLVSS/MLSS both increased slightly. This might be due to the usage of synthetic wastewater, which contained almost no heavy metals, sediments, and other inorganic substances. At the same time, the sludge acclimation time was relatively short, and the MLVSS/MLSS was not completely stable. As a result, the MLVSS/MLSS of the sludge increased with the extension of the operating time. Within 30 days, the average MLVSS/MLSS of the A/O process and electrochemical-A/O combined process was 0.74 and 0.72, respectively, indicating that the backflow of electrochemical lysed sludge did not cause significant inorganic matter accumulation.

3.2. Sewage Treatment Performance of Combined Processes

It is important to note that the sewage treatment efficiency was the most critical factor for evaluating the rationality of the process. Even if the combined process could have an active performance in terms of sludge reduction, it would be meaningless once the sewage treatment effect had been adversely interfered. Therefore, the study focused on the changes of COD, NH$_4^+$-N, TN, and TP in the A/O process and electrochemical-A/O process.

3.2.1. COD Removal

After electrochemical cell lysis of the excess sludge, the COD concentration in liquid phase increased sharply, indicating that the organic matter in solid phase became more degradable and easily utilized by microorganisms. Returning it to the anoxic tank could increase the COD load of the combined process and affect the COD removal. During the experiment, the COD removal of the two processes was as shown in Figure 3a. The combined sewage treatment process did not significantly influence the COD treatment efficiency. During the operation, the average COD level of the effluent of the A/O process and the electrochemical-A/O combined process were 30.5 mg/L and 33 mg/L, respectively, and the corresponding COD removal rates were 91.4% and 90.7%.

3.2.2. NH$_4^+$-N Removal

During operation, the NH$_4^+$-N treatment effect of the A/O process and electrochemical-A/O process was as shown in Figure 3b. The NH$_4^+$-N concentration of the effluent of the A/O process and the electrochemical-A/O combined process were 0.71 mg/L and 0.83 mg/L, respectively, and the corresponding removal rates were 98.2% and 97.9%, respectively. The addition of the sludge reduction unit did not have an obvious impact on the removal effect of NH$_4^+$-N, and the NH$_4^+$-N treatment effect of the combined process was almost the same as the A/O process.
Comparison of Technologies for Reducing Sludge Production

The advantages and disadvantages of treatment technologies applied in wastewater treatment are summarized in Table 2. It should be highlighted that the selection of the treatment technologies would not only depend on the sludge reduction performance, but also on the cost and possible side effects such as deteriorated sludge settleability and effluent quality. This study only estimated the operating cost of the technology when the same sludge reduction effect was achieved, and did not include the initial investment cost.

The results show that compared with other physical technologies, electrochemical lysis technology has a lower cost for sludge reduction. In addition, compared with other chemical technologies, electrochemical lysis technology has better effluent quality, while there is almost no byproduct formation. Moreover, the combination of electrochemical lysis technology and the cryptic growth also had better effluent quality. It can be seen that the electrochemical-A/O combined process is of relatively better treatment performance and process prospects.

3.2.3. TN Removal

For the conventional A/O process, the nitrifying mixed liquor was returned to the anoxic tank, and then the nitrate nitrogen was converted to nitrogen through denitrification under anoxic conditions, which was the main pathway to remove TN. In this process, denitrification was the rate-limiting step, which was mainly restricted by two aspects: one was whether the nitrification process could provide sufficient raw materials (NO$_3$-N, NO$_2$-N), and the other was whether there were enough organic carbon sources as electron donors. The research in the previous section showed that the nitrification efficiency of the combined process was 97.9%, which could provide sufficient denitrification raw materials. The backflow of sludge, which was electrochemically lysed, not only increased the TN load, but also introduced a large amount of organic carbon sources, promoting the denitrification of the combined process. The TN removal is shown in Figure 3c. The average effluent TN concentration of the A/O process was 11 mg/L, and the TN removal rate was 72.8%; the average effluent TN concentration of the electrochemical-A/O combined process was 9.95 mg/L, and the removal rate was 75.4%. Compared with the conventional A/O process, the TN removal efficiency of the electrochemical-A/O combined process was increased by 2.6%.

Previous studies have demonstrated that the high COD concentration in the return sludge could supplement the organic carbon source required by denitrification [41]. In addition, the study by Nishijima et al. [42] also pointed out that the lysis treatment could convert the refractory organics in the sludge into easily biodegradable substances, which being refluxed could enhance the denitrification activity of the overall process.
3.2.4. TP Removal

For the A/O process, as there was a lack of anaerobic units, the ability to remove TP was originally limited, which was difficult to meet the emission standards. After adding the electrochemical cell lysis treatment and refluxing of the excess sludge, the TP load of the process rose again, which adversely affected the total phosphorus removal of the combined process. Therefore, it could be seen from Figure 3d that the difference in TP removal efficiencies between the A/O process and the electrochemical-A/O combination process were not significant. The average TP concentrations in the effluent were 3.38 mg/L and 3.75 mg/L, respectively, and the removal rates were 23.6% and 15.2%, respectively. In contrast, the TP removal rate of the combined process was even lower, which was consistent with the prediction. The main reason was that the removal of phosphorus by the A/O process depended on the discharge of excess sludge. For the combined process, due to the on-site sludge reduction effect, although the amount of sludge discharged was greatly reduced, the TP removal efficiency was still low. In the study of Qiang et al. [43], it was also found that due to the reduction in sludge discharge, the ozone oxidation coupled A²/O sludge reduction process would reduce the removal efficiency of TP to a certain extent. The use of PAC for enhanced chemical phosphorus removal, according to a 2.5-fold dosing factor, adding 44.1 mg of PAC per liter of water could stabilize the TP concentration of the effluent to below 0.5 mg/L. Finally, the chroma of effluent was maintained at 33 mg/L.

4. Comparison of Technologies for Reducing Sludge Production

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Table 2. Effectiveness and treatment cost of sludge reduction technologies applied in wastewater treatment.

| Treatment Technologies | Treatment Conditions | Sludge Reduction Effect | Sludge Reduction Cost | Advantages | Disadvantages | References |
|------------------------|----------------------|------------------------|-----------------------|------------|--------------|------------|
| Ozone                  | 0.03 g O$_3$/g TSS   | 25%                    | 260.8 $/t TSS         | Improved sludge settleability; process applied at full scale | High investment and operating costs; increase in effluent COD | [44]       |
| Chemical               | Clorine              | 0.23 g Cl$_2$/g TSS   | 45%                   | Low investment and operating costs compared to ozonation | Formation of by-products; worsened sludge settleability; increase in effluent COD; only applied at lab scale | [45]       |
| Chemical               | Chloride dioxide    | 0.01 g ClO$_2$/g TSS  | 36%                   | Low investment and operating costs compared to ozonation | Formation of by-products; increase in effluent COD | [46]       |
| Physical               | Ultrasonic           | 25 kHz; 120 kW/kg TSS; 15 min | 91% | 2637.4 $/t TSS | Low investment costs | Erosion of sonotrodes; high operating costs; Worsened sludge settleability | [47]       |
| Physical               | High pressure homogenization | 10,700 kJ/kg TSS | 94% | 253 $/t TSS | Improved sludge settleability | High investment and operating costs; increase in effluent COD; only applied at pilot scale | [48]       |
| Physical               | Thermal              | 90 °C; 45 min          | 60%                   | Improved sludge settleability | Improved sludge settleability; increase in effluent COD; only applied at pilot scale | [49]       |
| Physical               | Electrical           | 18 V; 90 min           | 37%                   | 186.2 $/t TSS | Improved sludge settleability; low investment and operating costs compared to other physical technologies | Only applied at lab scale | This study |
| Others                 | Un-coupler          | para-nitrophenol (pNP)100 mg/L | 25% | 156.2 $/t TSS | Improved sludge settleability | Formation of by-products; increase in effluent COD Large space required for predation reactor; difficult to control the quantities of protozoa and metazoa | [50]       |
| Others                 | Predation            | Lumbriculus variegatus | 33% | – | Improved sludge settleability; process applied at full scale | | [51]       |
5. Conclusions

During the operation of the electrochemical-A/O combined process, the cumulative sludge discharge was reduced by 37.10% compared with the A/O process, and the $Y_{obs}$ of the two processes were 0.21 kgMLSS/kgCOD and 0.34 kgMLSS/kgCOD, respectively. The sludge reduction rate of the combined process was 39.1%. Electrochemical cell lysis could contribute 31.5% of the sludge reduction, and the remaining 68.5% of the sludge reduction was contributed by the cryptic growth. The analysis of the variation of the MLVSS/MLSS ratio showed that the backflow of electrochemically lysed sludge did not cause significant inorganic matter accumulation. In addition, the sewage treatment effect of the A/O process and the electrochemical-A/O combined process was monitored. The removal effect of COD and NH$_4^+$-N in the electrochemical-A/O combined process was only reduced by 0.7% and 0.31%, compared with the A/O process. In terms of TN, since the recirculation of lysed sludge could provide a sufficient carbon source for denitrification, the TN removal rate of the combined process was 2.6% higher than the A/O process. The results showed that the use of electrochemical cell lysis for sludge reduction did not affect the effluent quality. As a result of the low phosphorus removal ability in the A/O process, the excess sludge discharge in the combined process declined, in which the TP removal rate was only 15.2%. With PAC for enhancing the chemical phosphorus removal, the TP of the effluent could be lower than 0.5 mg/L. The electrochemical-A/O combined process has better economic benefits and application prospects. The current study has laid a research foundation for the combination of electrochemical lysis and the existing treatment technology of wastewater treatment lines.

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