Optimizing sludge dewatering with an alternate pressure and electric field

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Abstract

Sludge dewatering is a prerequisite for the subsequent utilization of sludge. However, the existing mechanical dewatering cannot achieve satisfactory water content (< 60%). Herein, pressure and electric dewatering in alternate operation (P/EDW$_{alt}$) was proposed to improve dewatering efficiency. Compared with conventional simultaneous mode, P/EDW$_{alt}$ performed better in sludge dewatering. Its optimal dewatering conditions were voltage of 30 V for 20 min in two electric dewaterings, and pressure of 0.04, 0.07 and 0.10 MPa in three pressure dewaterings. Such conditions, the water content of sludge was reduced from 83.7% to 53.3%, the dewatering efficiency was 36.3%, and the energy consumption was 0.138 kWh/kg$_{total\ removed\ water}$. These phenomena such as electroosmosis, the ohmic heating and electrophoresis facilitated the removal of water in sludge, and the dewatered sludge has good reusability in incineration, landfill and agriculture. Therefore, P/EDW$_{alt}$ could serve as a promising method for the sludge dewatering.

1. Introduction

During the last decades, domestic wastewater has increased dramatically due to the acceleration of urbanization and the rapid increase of population. To treat domestic wastewater, the activated sludge process is widely used (Abusoglu 2017), but it generates huge volume of sewage sludge that results in a high economic burden. Therefore, the disposal of sewage sludge is becoming a serious problem all over the world (Guo et al. 2019).

There are many options for the disposal of sludge, such as waste-to-energy production (Abusoglu et al. 2017), land application (Rumky et al. 2018) and reuse for building materials (Okuno et al. 2004). No matter which way of disposal, the water content of sludge is severely restricted to 60% (GB/T 23485 – 2009 and GB 4284 – 2018). However, the sewage sludge usually possesses a very high water content more than 99% (He et al. 2015). Hence, sludge dewatering is considered as a prerequisite for the subsequent utilization of sludge.

Mechanical methods (pressure dewatering, vacuum dewatering and centrifugal dewatering) are the most widely used for sludge dewatering (Gronchi et al. 2017). They are just efficient to remove free water (not attached to the particles), but inefficient to remove bound water (tightly bound onto the flocs by chemical or physical force) (He et al. 2017). Thus the water content of sludge can only be reduced to 75% – 85% (Lee et al. 2002), which is far from the requirement of landfill and farmland utilization (< 60%, GB/T 23485 – 2009 and GB 4284 – 2018). Therefore, in order to meet the requirement, it is necessary to design an efficient dewatering procedure.

Recently, pressure dewatering combined with electric, microwave or ultrasonic dewatering was studied to improve the dewatering efficiency (Apaolaza et al. 2015; Xu et al. 2019; Yu et al. 2017). Among them, the dewatering process combined pressure and electric field is considered as the most effective process. A simultaneous operation mode of pressure and electric dewatering (P/EDW$_{sim}$) is commonly used (Zhang et al. 2017). However, the results from Lee et al. (2002) and Qian et al. (2019) showed that the water content of sludge was only reduced from 78–62% – 68% based on P/EDW$_{sim}$, failed to meet the requirement of sludge utilization. The low efficiency of P/EDW$_{sim}$ may due to the suppression of electroosmosis in electric dewatering by continuous pressure (Barton et al. 1999).

Hence, in this paper, we proposed a new dewatering mode, pressure and electric dewatering in alternate operation (P/EDW$_{alt}$), to increase the dewaterability. The process starts from a low-pressure dewatering, and then electric and pressure dewaterings are implemented alternately twice. The dewatering performance of P/EDW$_{sim}$ and P/EDW$_{alt}$ was systematically compared at voltage, dewatering time, and pressure. In addition, the dewatering mechanisms were explored via analyzing the moisture distributions, the passages through water and EPS variations of sludge. The calorific value and the removal of heavy metals were also determined to show the potential application of dewatered sludge.

2. Materials And Methods

2.1. Sludge sample

The activated sludge sample used in this study was collected from a wastewater treatment plant in northwest Beijing, and stored in our laboratory at 4°C. It was a mechanically dewatered cake with water content of 83.7%. The major characteristics are shown in Table 1 and their test methods are shown in SI. 1.

Table 1
Major characteristics of the sludge sample.

Characteristics	Water content	pH	Sludge conductivity (μS/cm)	Zeta potential (mV)	Volatiles	Organic matter (g/kg)
Values	83.7%	7.13	717	-22.14	69.21%	413

2.2. Experimental design

2.2.1. Experimental device

Figure 1 represents a conceptual diagram of the pressure and electric dewatering system. The apparatus mainly consists of four parts: air compressor, DC power, a central dewatering section combining pressure with electric field (a Teflon material cylindrical chamber of 70 mm in diameter and 150 mm in height with a good electric insulation), and filtrate collector. Air can be sent into the device by the air compressor and push the piston to apply mechanical pressure to sludge, and at the same time, the electric field is supplied to the sludge layer between C – anode and Ti – cathode by DC power to realize electric dewatering. The filtrates are collected in the filtrate collector. Pressure is measured by air pressure gauge and current is recorded by multimeter. A 100 g sludge sample was adopted for each dewatering test to make sure the initial cake thickness was about 2 cm (Lv et al. 2019).

2.2.2. Experimental operation

(1) Pressure and electric dewatering in simultaneous operation (P/EDW_{sim})

Sludge was dewatered for T_0 min under pressure of P_0 MPa and voltage of E_0 V. The optimal dewatering parameters for the pressure, voltage and dewatering time were selected and corresponding dewatering efficiency was determined.

(2) Pressure and electric dewatering in alternate operation (P/EDW_{alt})

The P/EDW_{alt} mode consists of five successive steps:

 a pressure dewatering under pressure of P_1 MPa;

 an electric dewatering at a voltage of E_1 V for T_1 min;

 a second pressure dewatering under pressure of P_2 MPa;

 a second electric dewatering at a voltage of E_2 V ($E_1 = E_2$) for T_2 min (T_1, T_2 = 0, 5, 10, 15, 20, 30);

 a third pressure dewatering under pressure of P_3 MPa ($P_1 < P_2 < P_3$).

In P/EDW_{alt} mode, the dewatering effects under different pressure combinations and dewatering time were tested to choose the optimal dewatering parameters. Under the same processing conditions, each experiment was repeated three times to evaluate the reproducibility of the results. The curves shown in graphs represent the average results and the error bars represent the standard deviations. The dewatering effects of P/EDW_{sim} and P/EDW_{alt} were compared to determine the better dewatering mode and corresponding optimal dewatering parameters.

2.3. Analytical methods

2.3.1. Dewatering effects

The water content of sludge was calculated as follows:

$$\mathrm{w} = \frac{m_0 - m}{m_0} \times 100\%$$

1

where m_0 and m are the mass of initial and dried sludge, respectively (g).

The percentage of water removal:

$$\delta = \frac{w_0 - w}{w_0} \times 100\%$$

2

where w_0 and w are the water content of initial and dewatered sludge, respectively (g).

2.3.2. Calorific value

The calorific values of initial and dewatered sludge were measured by the oxygen bomb calorimeter. The specific measurement method is as follows: A certain amount of substance to be measured was put into the oxygen bomb and combusted completely under excessive oxygen. The temperature of medium was raised due to thermal effect of combustion, and the increased value ΔT was calculated. The combustion heat of measured substance was calculated according to ΔT and the specific heat of the medium.

2.3.3. Heavy metal

The sludge sample was pretreated by air–drying, grinding and passing through a 100-mesh nylon sieve. It was weighed 0.2–0.5 g (accurate to 0.0002 g) into 50–ml polytetrafluoroethylene crucible and wetted with water. 10 ml hydrochloric acid (ρ = 1.19 g/ml, GR) was added. The sample was heated at low temperature on hot plate to decompose preliminarily until there was about 3 ml left. Then it was removed from the hot plate and slightly cooled. 5 ml nitric acid (ρ = 1.42 g/ml, GR), 5 ml hydrofluoric acid (ρ = 1.49 g/ml) and 3 ml perchloric acid (ρ = 1.68 g/ml, GR) were added to the crucible. The sample was heated first at medium temperature on hot plate for 1 h after lidding, and then at 150 ℃ with opening lid. The crucible was shaken frequently to remove silicon better. When the sample was heated to fume thick white smoke, it was lidded again to decompose the black organic carbides. After the black organic matter on the crucible wall disappeared, the lid was opened to disperse the white smoke, and the matter was vaporized until it was sticky. Depending on the result of digestion, 3 ml nitric acid, 3 ml hydrofluoric acid and 1 ml perchloric acid could be added to repeat above digestion process. When the crucible was removed and cooled slightly, 3 ml of 2% nitric acid was added to dissolve the soluble residue under warm condition. Finally, the solution was transferred to a 50–ml volumetric flask and diluted with 2% nitric acid to volume after cooling. The concentrations of heavy metals were determined by inductively coupled plasma spectrometer (ICP, Leeman, Prodigy, America) after mixing well and passing through 0.45 μm water system filter membrane.

2.3.4. Mechanism explorations

(1) Moisture distribution

The content of free water and bound water in sludge was determined by thermogravimetry differential thermal synchrometer (TGA–DSC–DTA, TA, Q600 SDT, America). The results were used to analyze the influence of different dewatering steps on water removal.

(2) Environmental scanning electron microscope

The initial and the dewatered sludge cakes were cut into a cube with a side length of 5 mm. Apparent morphological characteristics of cakes in different planes (the surface of the initial sludge cube, the anode, cathode, and the middle parts of the dewatered cube) were observed by an environmental scanning electron microscope (ESEM, FEI Quanta 200F).

(3) EPS extraction

EPS content was determined through ultrasonic and heating methods. The specific EPS extraction steps can be seen in SI. 2.

3. Results And Discussion

3.1. Pressure and electric dewatering in simultaneous operation (P/EDW$_{sim}$)

3.1.1. Effects of voltage

Dewatering performance is highly dependent on voltage, pressure and dewatering time, and thus their effects on P/EDW$_{sim}$ mode were evaluated. Figure 2a illustrates the residual water content of sludge at different voltages (dewatering time was 20 min and fixed pressure was 0.1 MPa). The water content decreased rapidly as the voltage increased from 10 to 30 V, and then showed a very small drop from 30 to 35 V. Energy consumption should also be considered when choosing the optimal voltage. Compared with 35 V, the dewatering process at 30 V had similar efficiency but consumed less energy (Gronchi et al. 2017). Hence, the optimum voltage was 30 V.

3.1.2. Effects of pressure

In order to evaluate the optimal pressure, dewatering experiments under different pressure (0, 0.02, 0.04, 0.06, 0.08 and 0.10 MPa) were conducted at a fixed voltage of 30 V for 20 min. Obviously, higher pressure resulted in a better dewatering effect (Fig. 2b), because high pressure improves the efficiency of electric utilization by enhancing the contact between sludge and electrodes (Mahmoud et al. 2011). In addition, high pressure squeezes more water from sludge pores to reduce energy consumption of electric dewatering. When pressure of 0.1 MPa was applied, the residual water content of sludge reached the minimum of 60.5%. Due to the limited anti-pressure ability of the electrode materials, we did not further raise the pressure. In P/EDW$_{sim}$ mode, 0.1 MPa was appropriate pressure for further study.

3.1.3. Effects of dewatering time

Figure 2c shows the variations of sludge water content with time at a voltage of 30 V and pressure of 0.1 MPa. In the first 20 minutes, the residual water content of the sludge exhibited gradual decrease over time, and then it almost unchanged. This trend may be caused by the continuous pressure. In the early stages of dewatering (0–20 min), pressure mainly promotes the contact between sludge and electrodes.

However, long-term compression (20–40 min) caused a decline in sludge porosity and passages through water, so that the discharge of water was hindered (Raynaud et al. 2010). As a result, only the first 20 minutes were effective for the removal of water, and it was appropriate to dewater for 20 min.

In summary, the optimal operating parameters of P/EDW_{sim} mode were dewatering at a voltage of 30 V and a pressure of 0.1 MPa for 20 min. Under these conditions, the water content of sludge was reduced from 83.7–60.5%, failed to meet the requirement (< 60%) for further application (landfill and agricultural use).

3.2. Pressure and electric dewatering in alternate operation (P/EDW_{alt})

3.2.1. Effects of dewatering steps

Pressure and electric dewatering in alternate operation (P/EDW_{alt}) was applied to dewater sludge. The applied pressure is designed to increase gradually to avoid the rapid decrease of the passages through water due to high pressure. In order to maintain a good electric contact between sludge and electrodes, a low–pressure was applied first. Subsequently, electric and pressure dewaterings are conducted alternately. As shown in Fig. 3a, the first alternation of P/EDW_{alt} (electric dewatering at 30 V for 20 min and then pressure dewatering at 0.07 MPa) just reduced the water content of sludge to 67.2%, while the second alternation (electric dewatering at 30 V for 20 min and then pressure dewatering at 0.10 MPa) further decreased the water content to 53.3%, meeting the requirement (< 60%). Consequently, after the first low-pressure application, the electric and pressure dewatering next were implemented twice, meaning the P/EDW_{alt} mode consists of five successive steps: the pressure – electric –pressure – electric – pressure dewaterings, with the pressure increasing gradually.

The changes of current can explicitly reflect the electric dewatering strength (Wu et al. 2019), thus they were recorded to explain the continuous increase of dewatering efficiency in P/EDW_{alt}. As shown in Fig. 3b, the current decreased from 2.95 A to 0.27 A in the first electric dewatering, and reduced from 1.67 A to 0.22 A in the second electric dewatering. Obviously, the initial current of the second electric dewatering was lower than that of the first, which was comprehensible because the sludge resistance increased due to the decrease of water content after the first electric dewatering (Olivier et al. 2014). However, it was much higher than the terminal current of the first, probably due to the application of the second pressure. During the electric watering, the water flowed from anode to cathode, forming a dry layer of sludge at the anode and accumulating plenty of water at the cathode. As a result, the water in sludge became discontinuous and the conductivity of sludge declined (He et al. 2020). When the pressure was applied, the water in the sludge might flow back and diffuse from cathode to anode, causing the water in sludge to be continuous again and the decline of conductivity to be prevented (Gopalakrishnan et al. 1996). Thus, the second electric dewatering has a higher initial current and dewatering performance than that of the first end.

3.2.2. Effects of dewatering time and pressure

Three tests were conducted to determine the optimal dewatering time and pressure of P/EDW_{alt}. The voltage of electric dewatering was set to 30 V (according to 3.1.1), the dewatering time varied from 0 to 30 min, and the pressure combinations were 0.04, 0.06 and 0.08 MPa (test 1), 0.04, 0.07 and 0.10 MPa (test 2), 0.06, 0.08 and 0.10 MPa (test 3), respectively.

The results of three tests are shown in Fig. 4a, c and e. As the dewatering time prolonged, the water content of the sludge decreased. When the dewatering time of both the first and the second electric dewatering were 20 min, the water content of sludge below 55% was obtained. Longer dewatering time did not make much difference in the water content of the sludge, but consumed more energy. Thus, electric dewatering for 20 min each time was appropriate.

Under this condition of time, different pressure combinations produced sludge with different water content, which was 54.9% (test 1), 53.3% (test 2) and 54.1% (test 3), respectively. Obviously, the water content of test 2 was the lowest, stating the pressure combination of 0.04, 0.07 and 0.10 MPa was optimum.

The changes of current were recorded to analyze the different dewatering effects of three tests (Fig. 4b, d and f). During the first electric dewatering, the current was reduced gradually in three tests. However, in the second electric dewatering, the current of test 2 and 3 exhibited higher initial values (1.78 A and 1.67 A) and slower rates of decline than test 1. This indicates the higher pressure in the second pressure dewatering could lead to higher current and better dewatering performance in the second electric dewatering. Further comparing test 2 and 3, the current was similar but the sludge water content of test 2 was lower, suggesting higher pressure step promotes dewatering (Raynaud et al. 2010).

In summary, the optimal dewatering parameters of P/EDW_{alt} was a voltage of 30 V for 20 min in two electric dewaterings and pressure of 0.04, 0.07 and 0.10 MPa in three pressure dewaterings, respectively. Under these conditions, the water content of sludge was reduced from 83.7–53.3%.

3.2.3. Energy consumption comparison

When evaluating the dewatering performance, the energy consumption is an important consideration so as to obtain the most economically feasible process (Mahmoud et al. 2016), which can be calculated from Eq. (3):

$$\mathrm{Q} = \sum_{1}^{n} \int_{0}^{t} U^{*}\mathrm{I}dt$$

3

where U is the applied voltage (V), I is the recorded current (A), t is the electric dewatering time (min), and n is the time of electric dewatering.

The energy consumption under optimal dewatering conditions (test 2) was 0.138 $kWh/kg_{total\ removed\ water}$, within the range of 0.038–0.371 $kWh/kg_{total\ removed\ water}$ calculated by Gazbar et al., (1994) and Saveyn et al., (2006), and at a low level. The data demonstrate that the P/EDW_{alt} is a relatively economic dewatering mode.

In contrast to P/EDW_{sim}, P/EDW_{alt} performed better in sludge dewatering. In the P/EDW_{sim} mode, long-time pressure resulted in the gradual decrease of sludge porosity and passages through water, so that the discharge of water was obstructed and only the first 20 min was effective during the whole electric dewatering of 40 min. However, in the P/EDW_{alt} mode, electric dewatering of 40 min was bisected and followed by transient pressure dewaterings, so that the second electric dewatering was enhanced because the second pressure dewatering improved the moisture distribution and conductivity of sludge (Jumah et al., 2005). Thus, the effective time of the electric dewatering was prolonged and the dewatering efficiency of P/EDW_{alt} was elevated.

In the following experiments, we explored the dewatering mechanisms and the additional applications of P/EDW_{alt} mode. The dewatered sludge sample referred to the sludge with water content of 53.3% under the optimal dewatering conditions of P/EDW_{alt}.

3.3. Mechanism explorations of P/EDW_{alt}

3.3.1. Moisture distribution

The moisture distributions in sludge were measured via simultaneous TGA–DSC–DTA to analyze the effects of each dewatering step on free water and bound water. As shown in Fig. 5 and Fig. S2, the first application of pressure did not remove water, because the sludge sample have been mechanically dewatered in the wastewater treatment plant. Accordingly, we speculated that the first pressure dewatering is to promote electrical contact. Thereafter, as dewatering proceeded, both free water and bound water decreased, but their decrease occurred at different dewatering steps. For free water, it was reduced by more than 50% after the first electric dewatering. Then its decline slowed down. By the end of dewatering, 84.6% of free water was removed. For bound water, it almost unchanged until the second electric dewatering, and ultimately was decreased by 19.0%. The data show that the first electric dewatering mainly promoted the removal of free water, and the bound water was discharged since the second electric dewatering. Besides, the removal efficiency of free water was much higher than that of bound water.

These results could be explained by electroosmosis, which is dominant in electric dewatering. Due to the weaker bound between free water and sludge, the free water can be preferentially removed by electroosmosis (Gazbar et al. 1994). Thus, in the first electric dewatering, the free water was discharged first from the sludge pores. After most free water was removed, the second electric dewatering began to act on bound water. Furthermore, electroosmosis is only efficient for the removal of surface water and interstitial water (two types of bound water), hence, only a small amount of bound water was removed so that the removal efficiency of free water was much higher than that of bound water (Mowla et al. 2013).

In addition, the dewatering is likely promoted by ohmic heating, which generated by the rising resistance during the electric dewatering (Citeau et al. 2011). Ohmic heating could rupture cells and reduced the sludge viscosity via raising sludge temperature, so that the bound water was released and flowed more easily (Weber and Stahl 2002; Zhen et al. 2012). Besides, ohmic heating decreases the yield stress of sludge, thus the cake could be easier to be compressed in subsequent pressure dewatering (Wheeler et al. 2009).

3.3.2. ESEM morphology of sludge

The pores in sludge, which impact on the electroosmosis flux (Feng et al. 2014), were observed by ESEM at 2500, 5000 and10000 times (Fig. 6). The initial sludge was loose and porous. After dewatering of P/EDW_{alt} mode, the dewatered cake at the anode contained many pores, whereas the cakes in the middle and at the cathode were relatively compact, with only several passages through water. This may be because the activated sludge has a negative zeta potential (-22.14 mV), so the water moves from anode towards cathode by electroosmosis (Pham et al. 2010). Consequently, at the anode, the sludge clusters became unsaturated and shrank because of continuous water loss, resulting in many pores. At the cathode, due to a large amount of water accumulation, the sludge clusters became larger and the passages through water were clogged so that the pores were little (Feng et al. 2014; Kondoh and Hiraoka 1990; Zhou et al. 2001). This phenomenon caused that the dewatering effect gradually declined from anode to cathode. Also, the decrease in pores of cathode sludge increased the resistance of the water flow, and hence the electric dewatering gradually stopped (Chu et al. 2004).

3.3.3. EPS variations in sludge

Extracellular polymeric substances (EPS) are complex high-molecular-weight extracellular polymers produced by microbial aggregates, mainly including polysaccharides and proteins (Zhang et al. 2014). According to the combination degree to cells, EPS is roughly divided into two parts: loosely bound EPS (LB-EPS) and tightly bound EPS (TB-EPS) (Poxon and Darby 1997). TB-EPS can capture water inside the cells and flocs and LB-EPS can increase the sludge viscosity and bring a large quantity of water into the flocs, so the higher contents result in worse dewatering performance (Li and Yang 2007). To understand the correlation between EPS changes and sludge dewatering performance, we measured EPS contents (Fig. 7). After dewatering under P/EDW_{alt} mode, both TB-EPS and LB-EPS decreased, although the decrease of TB-EPS was more marked. Hence, the dewatering was promoted.

Besides, the dewatering performance is related to proteins and polysaccharides, and proteins play a greater role in attenuating dewaterability through holding bound water in sludge than polysaccharides (Kim et al. 2016; Xiao et al. 2017). Thus, their contents were measured to explain the increased dewatering efficiency (Fig. 7). Compared with the initial sludge, the content of proteins in TB-EPS and LB-

EPS decreased by 67.9% and 74%, respectively. For polysaccharides, them decreased by 34.9% in TB-EPS, but increased by 23.5% in LB-EPS. Obviously, the reduction of proteins improved dewatering.

The variations of EPS ingredients likely due to electrolysis, which converts TB-EPS into LB-EPS and makes LB-EPS separate from flocs via destroying the floc structures (Yuan et al. 2011). This could also explain the fact that polysaccharides increased in LB-EPS (Zhen et al. 2012). At the same time, electrolysis helps proteins and polysaccharides to be released into soluble states and removed with water (Yuan et al. 2011). Ultimately, the sludge dewaterability in P/EDW_{alt} mode was improved.

3.4. Sludge characteristics after P/EDW_{alt}

3.4.1. Calorific value

In recent years, several researchers have studied the additional applications of the sludge dewatered by pressure and electric field. An important application is waste-to-energy production (Abusoglu et al. 2017), in which the calorific value is a key factor to determine whether it can be used. Hence, we measured the calorific value of the dewatered sludge that was 7484 kJ/kg. According to the requirements of GB/T 24602 – 2009 (Table S1), the dewatered sludge had the potential to be burned by combustion supporting or drying. If its water content is further reduced below 50%, self-incineration can be achieved without adding auxiliary fuel. This result proves that the dewatering method of P/EDW_{alt} is an effective way to realize waste-to-energy production of sludge.

3.4.2. Heavy metal

The another use of sludge is agricultural purpose (Pham et al. 2012). However, toxic heavy metals concentrated in the sludge make sludge less attractive for agricultural use (Wong et al. 2006). Navab-Daneshmand et al. (2015) pointed out that electric field has the potential to remove heavy metals by electromigration, so we explored the changes of heavy metals in sludge (Table 2) and calculated their removal efficiency by Eq. (4):

$$\mathrm{W} = \frac{c_i - c_i^{'}}{c_i} \times 100\%$$

4

where c_i is the concentration of i metal in initial sludge (mg/kg) and $c_i^{'}$ is that of dewatered sludge (mg/kg).

Except for Cd, all the concentrations of heavy metals in dewatered sludge decreased at different extent. Among them, Cu reduced most significantly, from 2069.17 mg/kg to 446.34 mg/kg, and the removal efficiency reached 78.4%. The concentration of Cu in the initial sludge far exceeded the standard restriction (1500 mg/kg, GB 4284 – 2018), and after dewatering, it reached the discharge standard. As for

Hg, Pb and As, the removal efficiency was 24.5%, 23.9% and 13.9%, respectively. For Cd、Zn、Cr and Ni, there were not obvious removal effects. When the electric field is applied, the metallic cations move from anode to cathode by electromigration, and are removed with water finally (Pham et al. 2010). Their migrations are related to their existing forms in sludge (Wang et al. 2005), so the removal efficiency of various heavy metals were different. Even so, all the concentrations of heavy metals were below the standard of farmland utilization, stating that the P/EDW$_{alt}$ mode can eliminate the risk of heavy metals to agricultural use and has good value of land use.

Table 2
Concentrations of heavy metals in the sludge.

Heavy metal	The standard limits (mg/kg dry sludge)	Initial sludge (mg/kg dry sludge)	Dewatered sludge (mg/kg dry sludge)	Removal efficiency
Cu	1500	2069.17	446.34	78.4%
As	75	14.81	13.05	11.9%
Pb	1000	16.12	12.27	23.9%
Hg	15	4.74	3.58	24.5%
Ni	200	27.87	27.32	2.0%
Zn	3000	614.93	605.65	1.5%
Cr	1000	57.86	57.31	1.0%
Cd	15	0.63	0.71	-

(The standard limits are from GB 4284 – 2018 and the dewatered sludge refers to the sludge after P/EDW$_{alt}$ mode.)

4. Conclusion

In this paper, a system that combined pressure dewatering and electric dewatering was established. The dewatering performance of two dewatering modes – pressure and electric dewatering in simultaneous or alternate operation (P/EDW$_{sim}$ or P/EDW$_{alt}$) – were compared. The results showed that the P/EDW$_{alt}$ mode was more efficient for sludge dewatering and its optimal dewatering conditions were evaluated: voltage of 30 V for 20 min in two electric dewaterings, and pressure of 0.04, 0.07 and 0.10 MPa in three pressure dewaterings. Under these conditions, the water content of sludge was reduced from 83.7–53.3%, the dewatering efficiency was 36.3%, and the energy consumption was 0.138 kWh/kg$_{total\ removed\ water}$. The separate applications of pressure and electric field avoided the obstruction of continuous pressure to electroosmosis and improved electric utilization. The efficient dewatering mainly owes to electroosmosis and the reduction of EPS by electrophoresis. The dewatered sludge had high calorific value, and the contents of heavy metals also met the relevant standards, suggesting it has good reusability in incineration, landfill and agriculture.

In short, P/EDW$_{alt}$ has a good dewatering effect and additional applications. It provides a new way to optimize the process design of sludge dewatering and reduces energy consumption in practical projects. Therefore, P/EDW$_{alt}$ is a promising method for the sludge dewatering.

Declarations

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Authors' contributions

Yunyi Li: conceptualization, methodology, investigation, writing - original draft, review and editing, funding acquisition. **Xinmiao Huang:** investigation, data curation, and writing - original draft, validation. **Ying Wei**: investigation, data curation, software, validation. **Yangsheng Liu**: resources, supervision, funding acquisition.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Competing interest: The authors declare that they have no competing interests

Ethical approval and consent to participate: Not applicable.

Consent for publication: Not applicable

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Figures

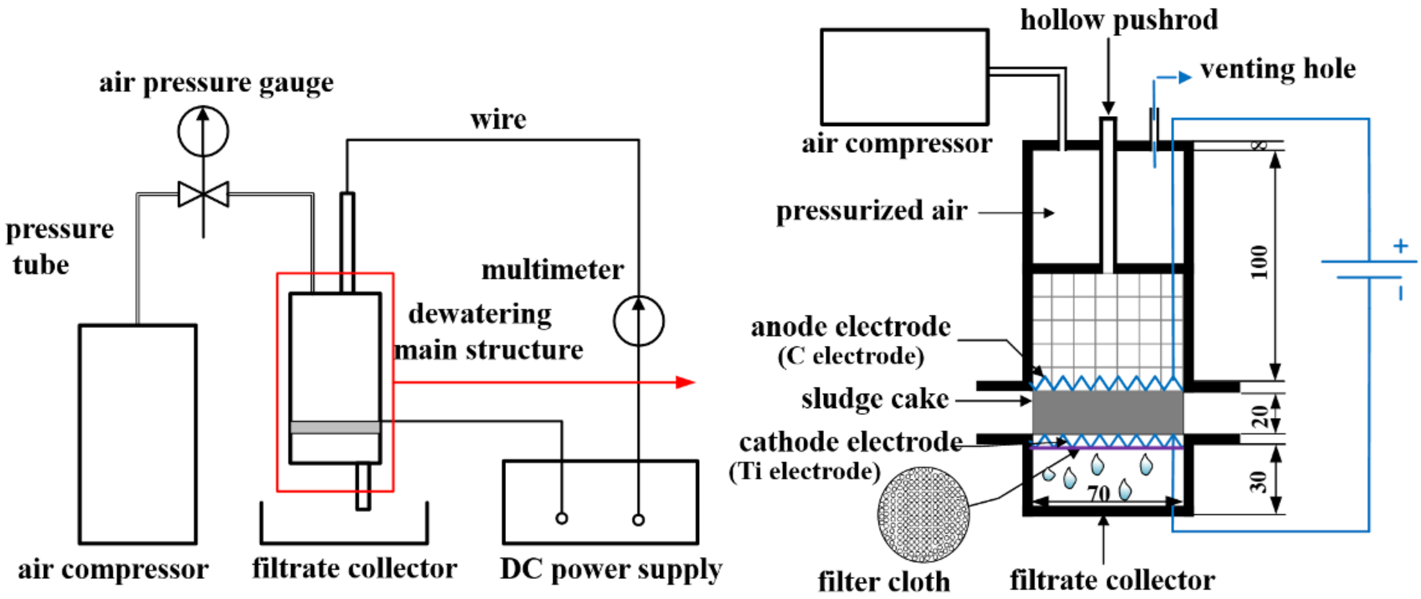

Figure 1

Schematic representation of the laboratory–scale pressure and electric dewatering reactor.

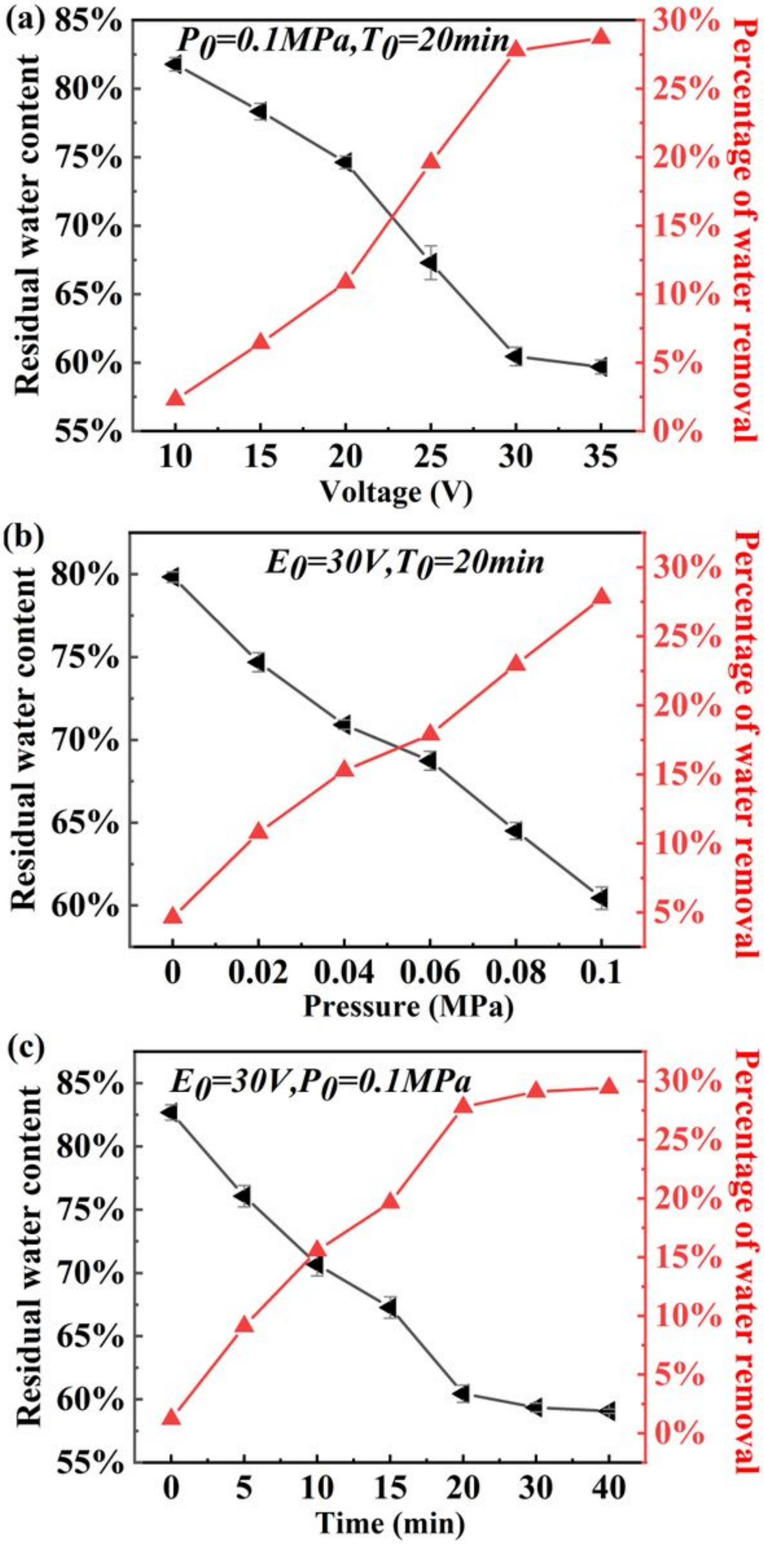

Figure 2

Effects of (a) voltage, (b) pressure, and (c) time in P/EDWsim mode. Error bars represent standard deviations from triplicate experiments (n = 3).

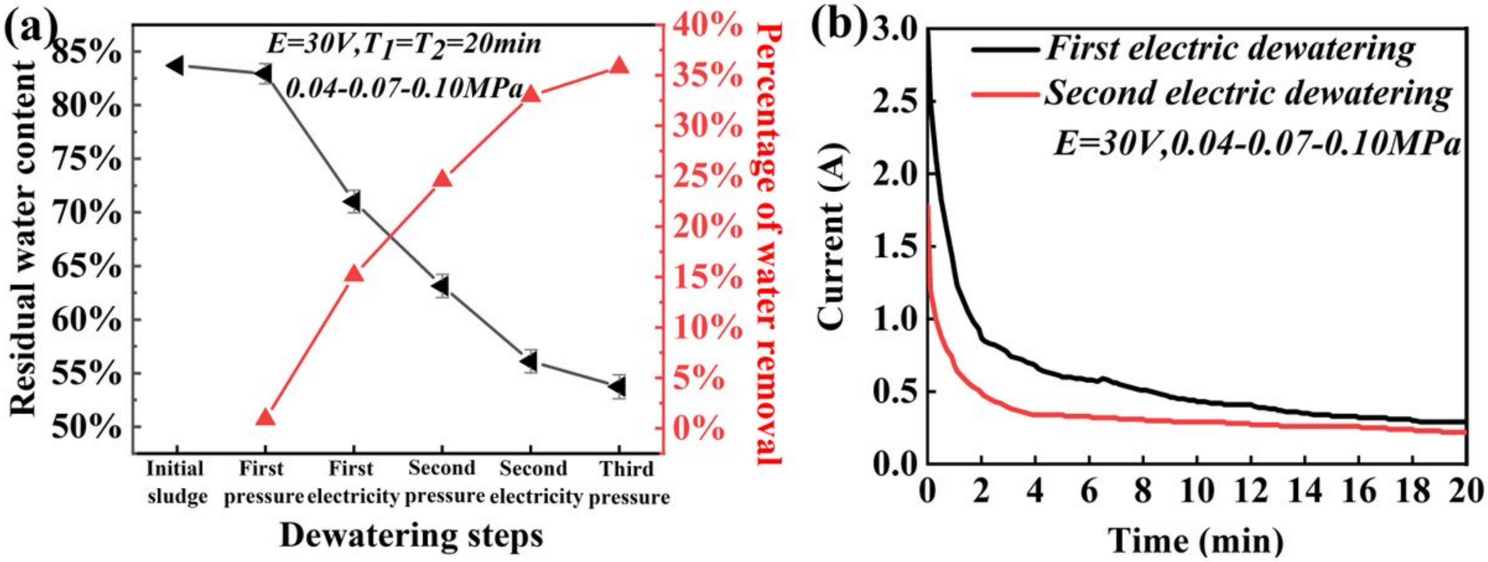

Figure 3

(a) Residual water content of sludge after each step in P/EDWalt mode. (b) Variations of current with time in two electric dewaterings. Error bars represent standard deviations from triplicate experiments (n = 3).

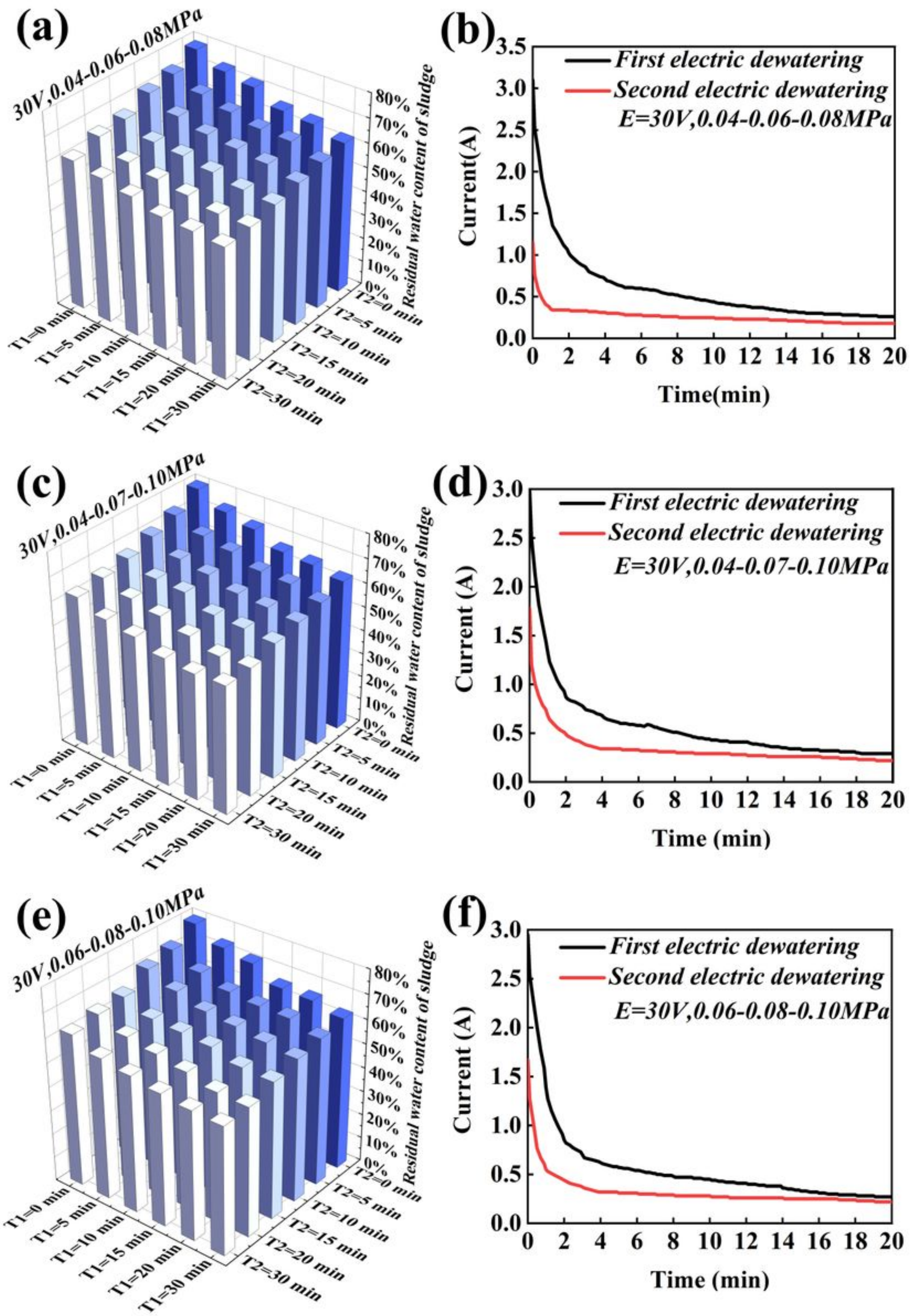

Figure 4

Residual water content of sludge and variations of current with time of (a, b) test 1, (c, d) test 2, and (e, f) test 3 in P/EDWalt mode.

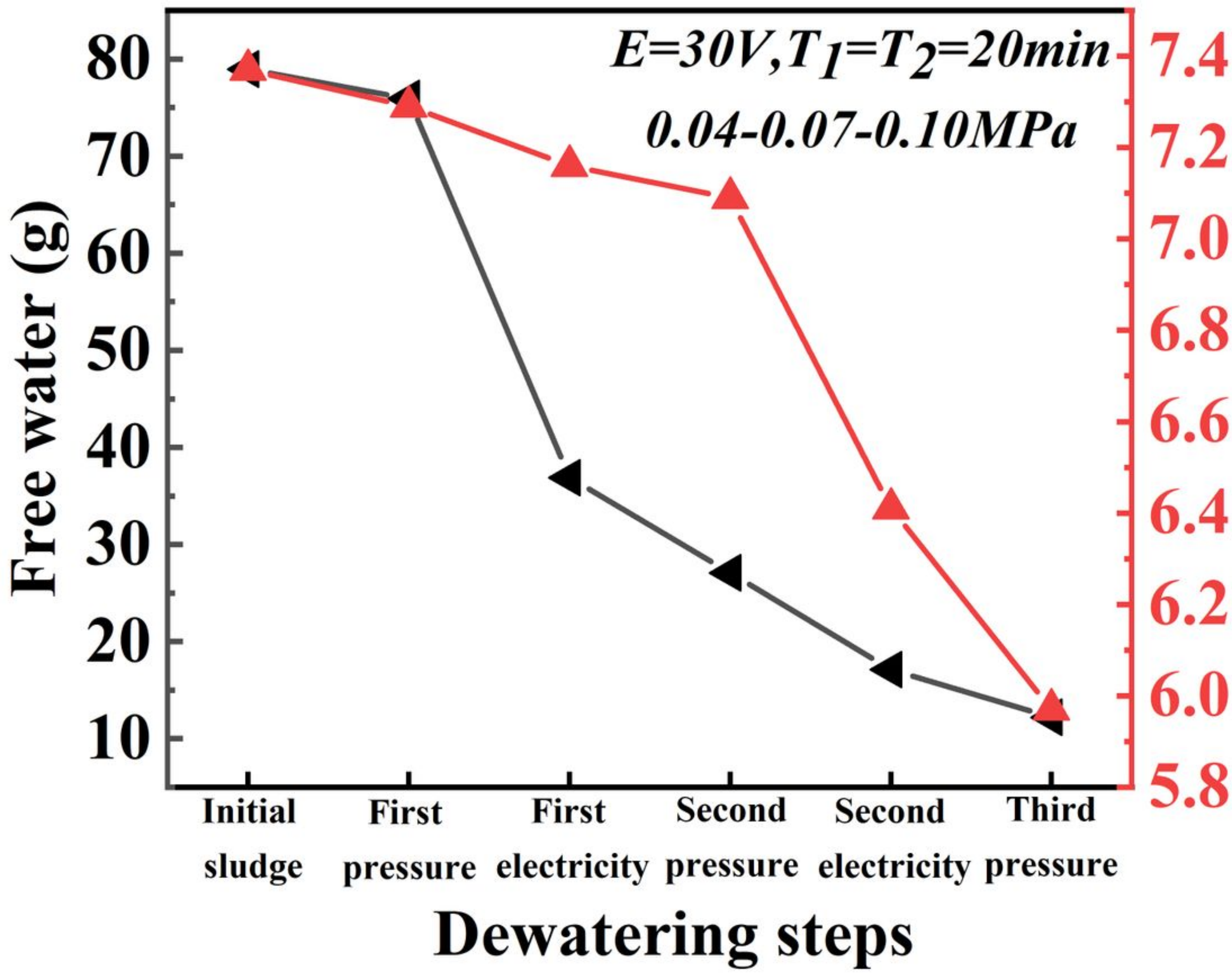

Figure 5

Moisture distributions of sludge at different dewatering steps in P/EDWalt mode.

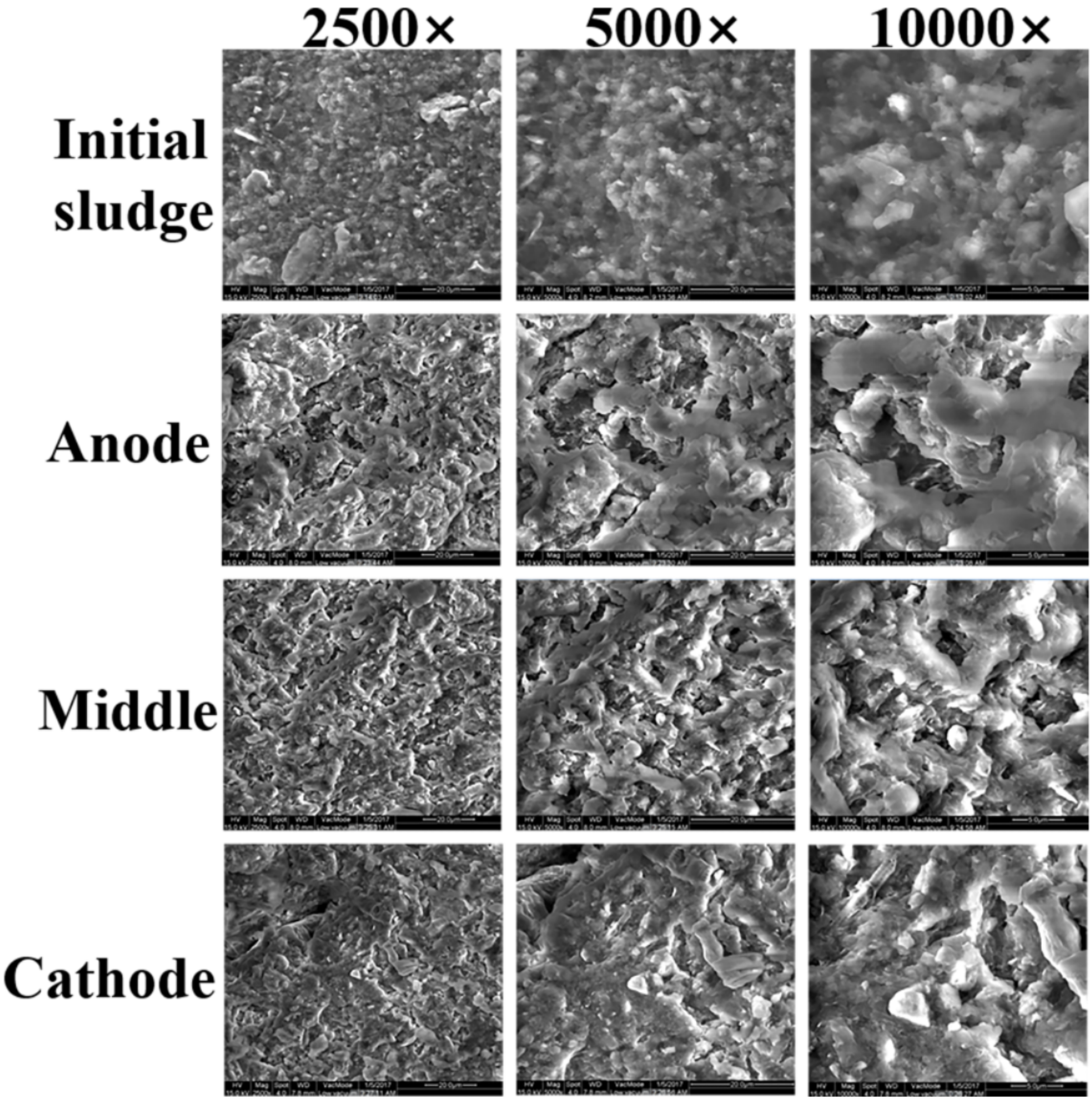

Figure 6

ESEM images of initial sludge and dewatered sludge of anode, middle and cathode in P/EDWalt mode.

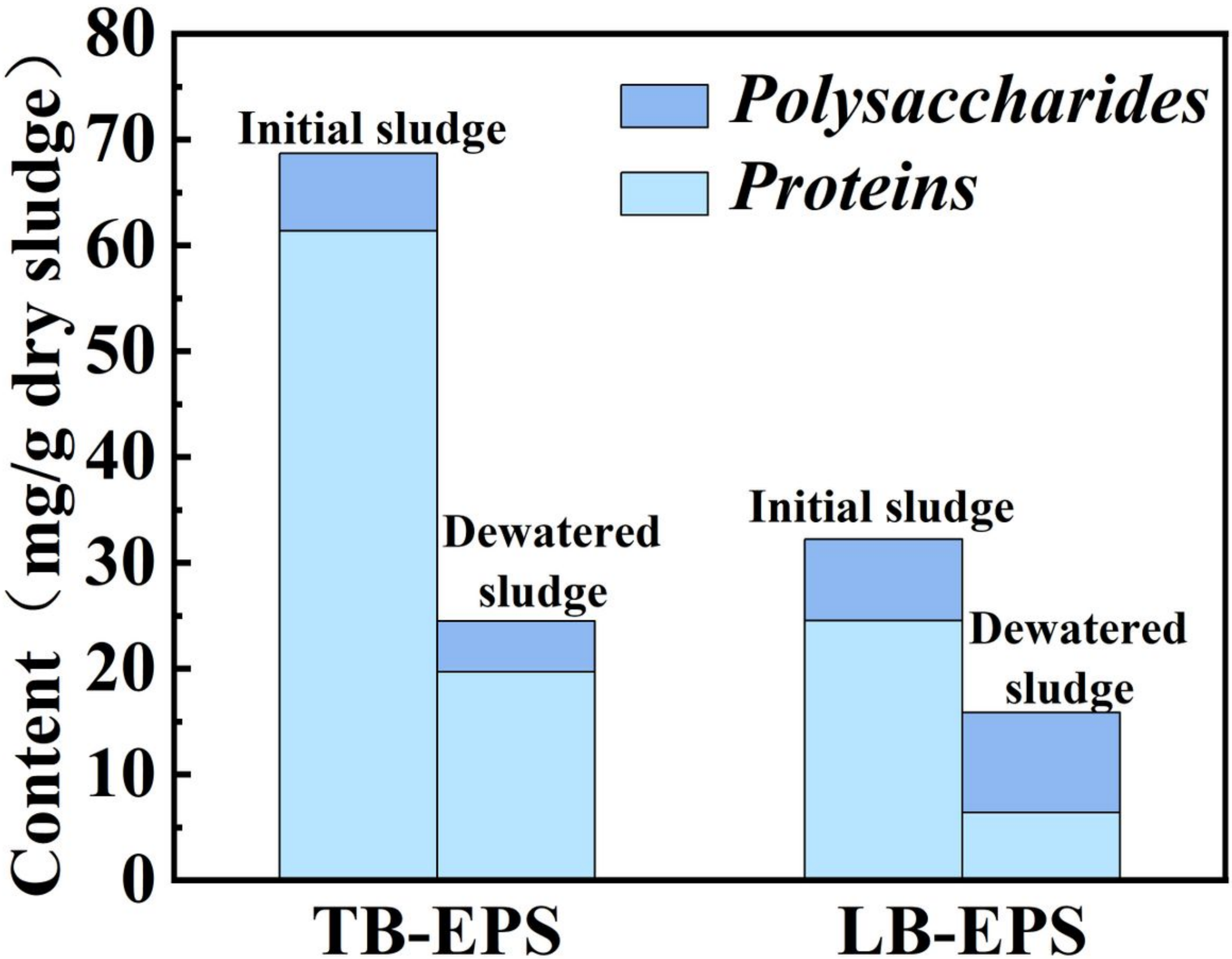

Figure 7

EPS contents of initial and dewatered sludge in P/EDWalt mode.

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