

Dewatering and valorizing lake sediments by electroosmotic dewatering for lakes restoration

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Abstract

Dredging eutrophic lake sediments can improve water quality, but it also requires dewatering and valorizing the dredged material to avoid wasting resources like phosphorus. This study investigated the basic mechanism and performance of electroosmotic dewatering of dredged sediments using different electric currents (20 mA, 40 mA, and 60 mA) after gravity filtration. The dewatering performance, moisture content and distribution, effect of electrochemical reaction on dewaterability, energy consumption, and changes in metals and phosphorus (P) distribution and pH values were analyzed. The results showed that electroosmotic dewatering could effectively reduce the mass of sediments by removing free and part of interstitial water, but the optimal duration and current should be considered to balance water removal and energy consumption. Ohmic heating may have both positive and negative effects on dewatering efficiency. The current conditions did not significantly extract heavy metals or P from the sediments, which may facilitate the disposal of the removed water and the reuse of the treated sediments for different purposes. This technology is easy to operate and suitable for the treatment of dredged sediments, but future work should aim to improve its electric energy efficiency and stability for commercial viability.

Keywords: Electrochemical treatment; Electroosmosis; Lake sediments; Resource recovery; Moisture distribution

1 Introduction

Many lakes suffer from eutrophication [1,2]. Dredging the sediment is one way to deal with this problem, as it enhances the water quality and preserves the waterway's function [3]. However, dredging produces a large amount of sediment that needs to be disposed of. If these sediments are landfilled or buried, they may waste valuable resources like phosphorus, an essential and limited resource in Europe [4–6]. Therefore, finding a proper use for these sediments is another environmental challenge. Before that, dewatering is necessary to make them easier to transport and store. Some common mechanical dewatering methods are gravity settlers, centrifuges, belt filter presses, and plate and frame filter presses. They have low energy requirements but cannot sufficiently reduce the water content in many applications[7]. Conventional thermal drying processes can remove more water and control and destroy pollutants better. However, they need a lot of energy to evaporate the water, and they have high capital and operating costs that depend on the amount of water removed from the material [7,8]. Thermal drying uses about 617 - 1200 kWhm⁻³ of water removal [9]. Therefore, improving the dehydration capacity of conventional processes is the goal of current research that seeks potential alternatives.

Electroosmotic dewatering is a potential method for extracting water from porous materials by applying a low electric current, which induces electroosmosis phenomena [10]. Colloidal particles in sediments/sludge usually have a negative surface charge. They are therefore surrounded by a layer with a higher density of positive charges, a phenomenon known as an electric double layer. When an electric field is applied, these negatively charged particles move toward the electrode with the opposite charge. Water from pores and interstitials, along with cations, is driven towards the electrode with the negative charge [11,12]. Dehydration occurs when water drains out at the negative electrode (cathode), and no water enters the positive electrode (anode), creating negative pore water pressure. Electrical dehydration offers several advantages, such as low energy consumption and no filter media clogging, a common issue in filtration[13,14]. Therefore, researchers have extensively studied this technique in recent years. Most of the electro-dehydration technologies developed so far use pressurized electro-dehydration. This process applies an electric field, often combined with vacuum filtration or mechanical pressure [15–19]. The pressurized electro-dehydration process is especially suitable for reducing the moisture content of materials that conventional methods have not treated adequately [18,20–22]. A wide application area is colloidal systems where strong surface effects complicate dehydration. Due to the high bonding force of water to solid matter and strong electrostatic forces between small particles, strong mechanical forces must be applied at room temperature for purely mechanical dehydration. Other applications of these combined technologies are fine

56 particle sediments, colloidal sludge, vegetable juice extraction, vegetable waste, and barely filterable activated
 57 sewage sludge. Although molecular interactions play a much smaller role, they still dominate the kinetics of water
 58 reduction.

59 Various researchers have extensively studied electro-dehydration, but these works mainly focused on the
 60 effects of process parameters, regulation, and process variables, including process design and operational
 61 improvements. Few publications concentrate on how electro-physicochemical properties affect its electrical
 62 behavior in terms of electrical dewatering capacity. Due to the complexity of the pressurized electro-dehydration
 63 process, it is necessary to study the mechanism of electroosmotic dewatering to better couple it with mechanical
 64 or other dehydration methods. Moreover, the discussions about sediment characteristics changes and possible
 65 valorization of dewatered sediments were also limited. Applying an electric field could cause the migration of
 66 negatively charged organic matter (e.g., fatty acids, humus, etc.) in sediments/sludge [23,24]. Heavy metals and
 67 other elements like P also migrate in their various forms: in abiotic forms (e.g., soluble, adsorbed, exchangeable,
 68 precipitated, organic complexes, residues, etc.) or in biological forms (e.g., extracellular and intracellular species)
 69 [25–29]. The toxic metals usually restrict the agricultural reuse of sediments, so any decrease in heavy metals may
 70 help public health and the environment. Changes in the distribution of P and other sediments characteristics
 71 influenced by electrochemical and physical reactions produced by the application of electric fields will also affect
 72 the utilization of dewatered sediments.

73 In this study, lake sediments were electroosmotic dewatered without pressure. The changes in moisture
 74 distribution were estimated by fitting a step function to the drying curve using non-linear least-squares
 75 minimization to investigate the effect of an electric field on sediments' dewaterability. The main aims are to
 76 experimentally explore 1) the understanding of fundamental mechanisms involved in electroosmotic dewatering
 77 and 2) the overall assessment of characteristics changes of treated sediments and energy consumption to propose
 78 potential lake restoration strategies.

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80 2 Materials and methods

81 2.1 Source and preparation of lake sediments samples

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Table 1. Experimental conditions of electroosmotic dewatering

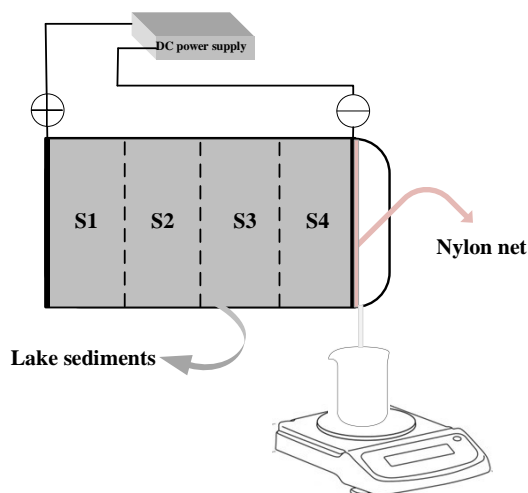
Water content (wt.%)	pH values	Conductivity (mS/cm)	Redox potential (mV)
93 ± 1	6.5 ± 0.5	560 ± 50	250 ± 10
Ca (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Fe (mg/kg)
17500 ± 500	70 ± 5	100 ± 10	11500 ± 500
Pb (mg/kg)	Zn (mg/kg)	S (mg/kg)	P (mg/kg)
40 ± 5	200 ± 20	11000 ± 600	800 ± 20

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85 The dredged lake sediments sample was obtained from Bagsværd lake, Copenhagen, Denmark. The lake
 86 sediments were removed from large debris, such as leaves and branches, and stored at 5 °C before use. Table 3
 87 shows the main heavy metal content of Cr, Cu, Pb, and Zn, the valuable P content, the main elemental content of
 88 Ca and S, the water content, the initial pH values, the conductivity, and the redox potential in raw sediments.

89 2.2 Laboratory-scale electroosmotic setup

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Figure 1. Diagram of the electroosmotic dewatering setup

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Table 2. Experimental conditions of electroosmotic dewatering

Experiment	A0	B0	C0	A1	D1
Sediments	1 L raw sediments sieved with gravity				
Current	20	40	60	20	40
Duration (hours)	6	6	6	24	24

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1 L of sediments was filtrated with gravity before being subjected to the electroosmotic dewatering setup. The electroosmotic dewatering apparatus is a 10 cm long Plexiglas cylinder with an 8 cm internal diameter, as shown in Fig.1. The entire sample is divided into four sections, from near the anode to near the cathode as S1-S4. A constant DC was applied (by a Hewlett Packard E3612A) through two mesh-shaped dimensionally stable electrodes of titanium coated with mixed metal oxides (MMO) to prevent corrosion. The experimental layout is shown in Table 2. A water mass balance was used to monitor the mass of filtrated moisture collected in a beaker. Digital multimeters were used for checking and monitoring voltage and current measurements in electroosmotic dewatering systems. Electrically insulated thermocouples were used to test temperature changes inside the setups in different sections during electroosmotic dewatering, and the computer recorded the experimental data every 60 seconds.

2.3 Analytical methods

Elements concentration changes of lake sediments before and after experiments were analyzed by ICP-OES before being digested through the US EPA 3015A method. During the digestion, 10 mL concentrated HNO₃ was mixed with 0.5 g sediments sample and then heated at 175 °C for 20 mins. The sediments' redox potential, conductivity, and pH changes before and after experiments were measured with distilled water at a liquid-to-solid ratio (L/S) of 2.5 and then subjected to a Radiometer Analytical electrode. The conductivity and pH changes were measured by the pH electrode, and the redox potential changes were measured by the ORP electrode. A rapid moisture analyzer (HC103, METTLER TOLEDO, Switzerland) was used to measure the different moisture fractions in the lake sediments by thermal drying at 40 °C [30]. About 5 g of each sediment sample was spread evenly on the balance dish, and the mass change was recorded every 60 s until it reached a constant value. The sample was then heated at 105 °C for 12 h to obtain the final dry mass. The transition points between free, interstitial, surface, and bound moisture were identified by the slope of the drying curves. A step function was fitted to the curves using non-linear least-squares minimization to estimate the moisture content more accurately.

2.4 Calculations

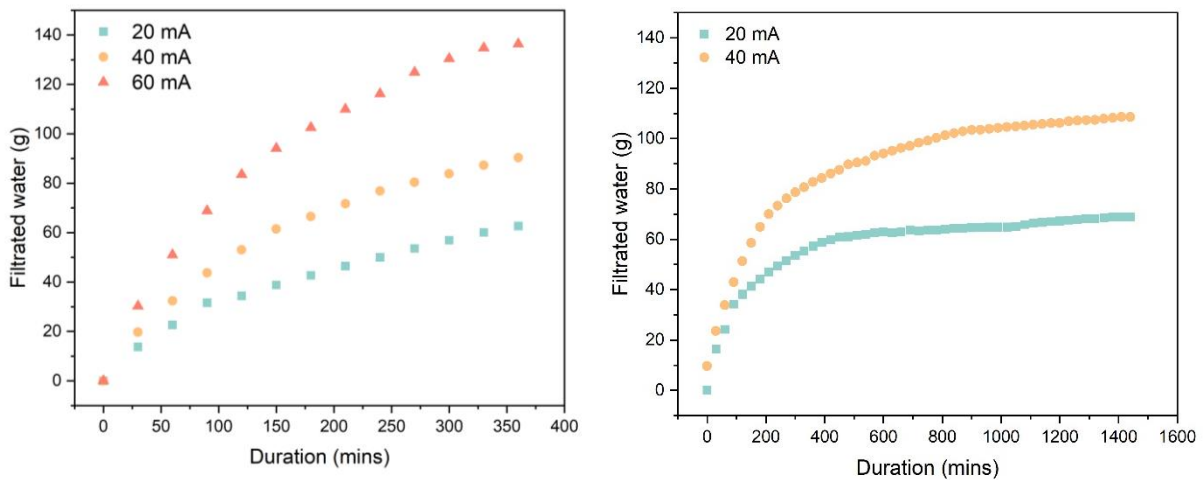
The energy consumed by the DC power supply to provide a constant current across the setup and to create the electric field was calculated as Eq. (1)

$$E = \int_0^t UI dt \tag{1}$$

Where E represents the energy consumption by the DC power supply (Wh); t represents the treatment duration (hours); I is the current intensity (A); U means the voltage (V).

3 Results and discussions

3.1 Sediments' electroosmotic dewatering performance

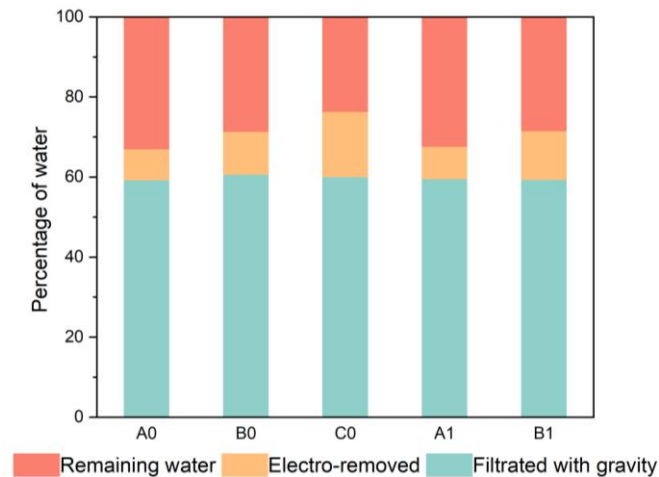


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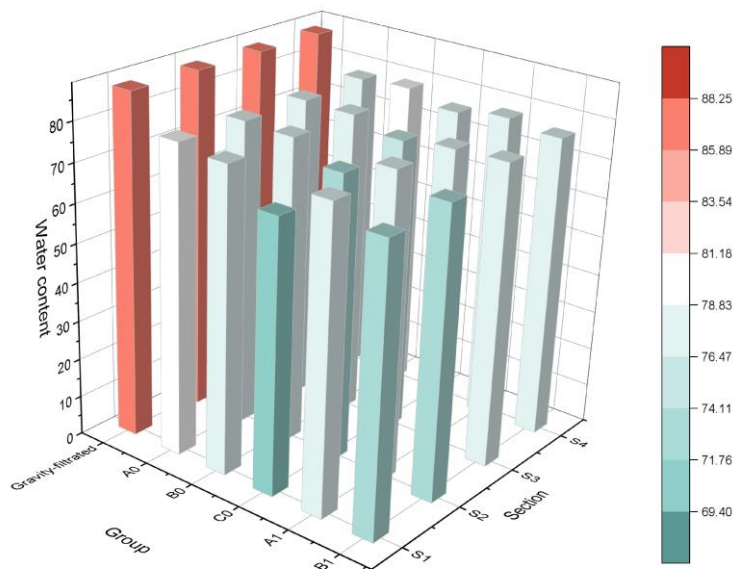
Figure 2. Evolution of filtrate volume with different currents and duration

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130 The current density applied during electroosmotic dewatering affects both the final solid dryness and the
 131 dewatering kinetics. Fig.2 shows a continuous effluent flow for all the tests during the treatment. The effluent
 132 flow and time relationship reveal three distinct phases of electroosmotic dewatering: the fast drain phase, which
 133 depends on the electric field strength, the transition phase, and the termination phase. The effluent rate is constant
 134 at the initial stage of filter cake formation, explained by the Helmholtz–Smoluchowski theory [9]. However, the
 135 effluent rate decreases as the dry cake develops with dewatering. After six hours, more effluent is collected with
 136 a higher current. Beyond this duration, there is no significant increase in effluent, especially at a lower current.
 137 As shown in Fig.3, the percentage of water removal and the remaining water in dewatered sediments at the end
 138 indicate that gravity filtration can eliminate about 60% of the moisture. Applying an electric field (20 mA, 40 mA,
 139 and 60 mA) can further reduce the moisture content by 7% - 20%, significantly decreasing the mass for
 140 transportation or storage. However, 20% - 35% of the moisture remains in the sediments after the experiments.
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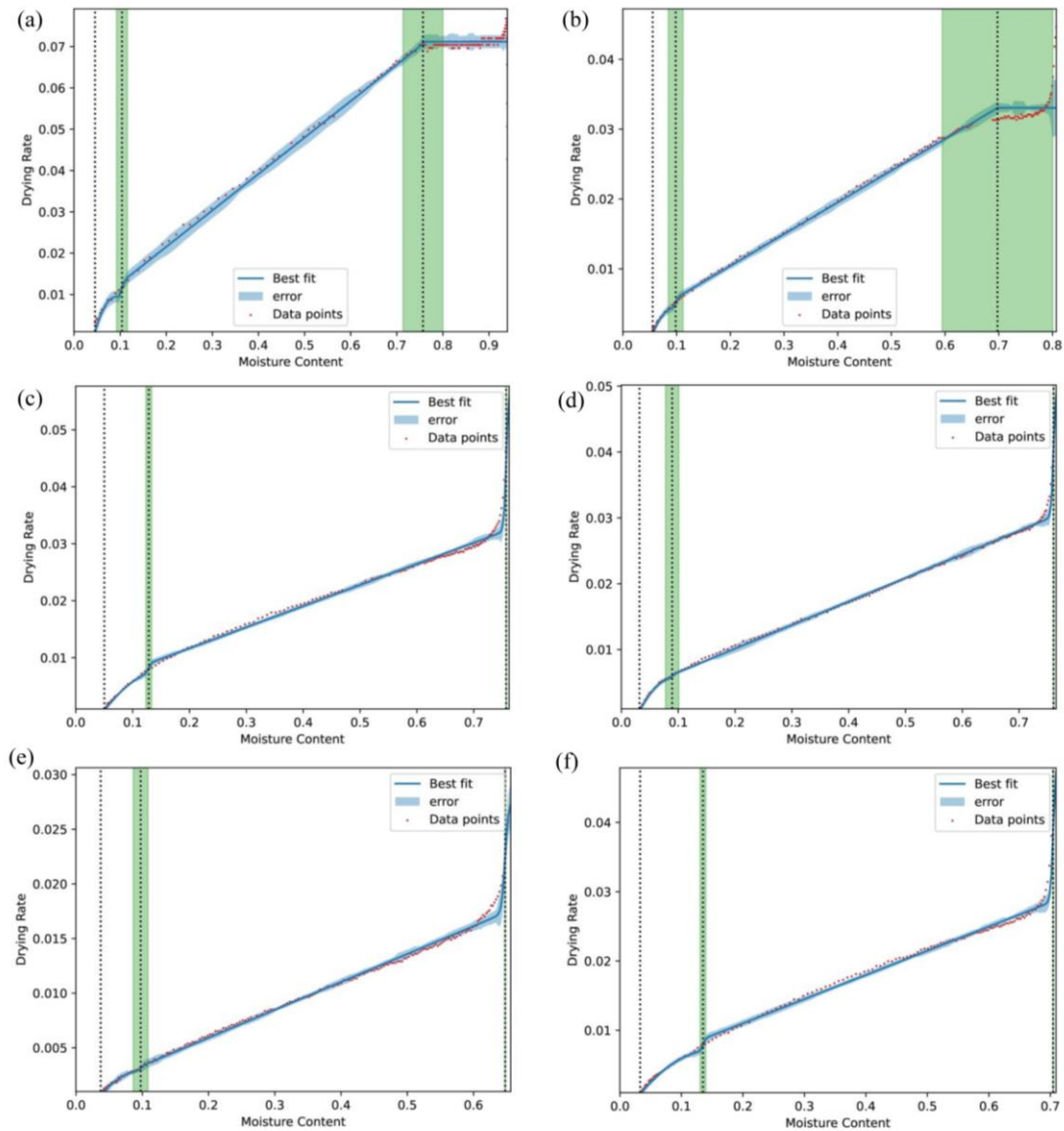
142 Figure 3. Percentage of removed water and the remaining water
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145 Figure 4. Changes in water content
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148 Fig.4 shows that the water content of the sediment samples was significantly reduced by electroosmotic
 149 dewatering after gravity filtration. The initial water content of about 93% was lowered to around 85% by gravity
 150 filtration and then further reduced to about 65% to 80% by electroosmotic dewatering. The effect of electroosmotic
 151 dewatering on the water content depended on the applied current and duration. After 6 hours of electroosmotic
 152 dewatering with a current of 20 mA, the water content of the samples in each section was similar. It did not change
 153 significantly with a further increase in duration. However, when a current of 60 mA was applied, or 40 mA was

154 applied for a longer duration, the water content of the samples varied from anode to cathode, showing a stepwise
 155 pattern. The samples near the anode had slightly lower water content than those near the cathode, possibly due to
 156 the electroosmotic flow from the anode to the cathode. Moreover, the higher current increased the system voltage,
 157 resulting in more ohmic heating and changes in pH and redox potential due to electrode reactions. These factors
 158 affected the sediment characteristics and enhanced the release and removal of water. When using a current of 60
 159 mA, the voltage fluctuation was observed after a few hours, which may be caused by local polarization phenomena
 160 such as crack formation at the anode and bubble formation at the electrodes due to water electrolysis. These
 161 phenomena could reduce the contact between the sediments and the electrodes, increase the resistance, and affect
 162 the stability of the dewatering system.
 163 3.2 Changes in moisture distributions
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165 Figure 5. Drying curve of raw sediments (a), sediments after filtration with gravity (b), A0-S1 (c), A0-S4 (d),
 166 C0-S1 (e), and C0-S4 (f)
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168 The water within the sediments behaves differently in terms of enthalpy, entropy, vapor pressure,
 169 viscosity, and density due to the presence of solids and differs in the difficulty of removal [31]. The thermal drying
 170 test was first proposed by Tang and Vesilind to investigate the moisture distributions based on the analysis of the
 171 drying curve [32]. The drying curve shows the evolution of evaporation flux versus the average moisture content
 172 and classically presents four phases. As the moisture content decreases, the classical drying curve shows a constant
 173 rate period, a first falling rate period, a second falling rate period, and finally equilibrium period. The different
 174 periods present the bond type between the solid particles (or material structure) and the water [33,34]. The constant
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rate period shows the free (unbound) water evaporation at the particle surfaces. Then, the drying boundary progresses into the hygroscopic materials, and the first falling rate period appears. During the first falling rate period, the evaporated water may mainly be mechanically bonded with solid particles (e.g., capillary trapped inside interstitial spaces of organisms and flocs) and is classified as interstitial water, the increase of mass and heat transfer resistance resulting in evaporation flux decrease. The second falling rate period appears owing to the evaporation of more hardly bounded water (surface water). That water may be physically adsorbed or adhesive onto the solid particle surface. During the equilibrium period, the remaining bond water is chemically bonded (e.g., intracellular or internal water) by powerful linkage and removed at 105 °C for 12 hours. Accurately defining the critical points referring to transitions between the constant rate and the first falling rate period, as well as the first falling rate and second falling rate period, is essential for distinguishing different moisture content. Thus, the step function was defined to describe the development of the drying curve, and non-linear least-squares minimization and curve fitting was applied to determine the critical points more accurately. The drying curves of raw sediments, sediments after filtrated with gravity, A0-S1, A0-S4, C0-S1, and C0-S4 were shown in Fig.5.

From Fig. 5(a), the results show that four periods are present clearly when drying the raw sample indicating all four types of moisture existed in the raw sediments. The critical point between free and interstitial water was observed around 70% - 80% moisture content basis. This shows that free water in raw sediments only accounts for small proportions, which may explain why reducing the water content to below 70% with electroosmosis was difficult, whether using a higher current or a longer duration (Fig.4). Interstitial water was found around 10% - 80% moisture content basis and accounts for the major proportion in raw sediments. The surface water and bond water were observed around 5% - 10% and 0% - 5% moisture content basis, respectively. After filtration with gravity, parts of free water were removed, and other moisture content was not influenced significantly. In general, the drying curve of sediments after electroosmotic dewatering present similar tendencies as raw and gravity-filtrated sediments. However, after electroosmotic dewatering, most free water was removed. Even some interstitial water was removed with the application of high current (Fig. 5 (e)). However, the surface water and bound water might not be affected significantly. Similar phenomena were observed by the study of Tang etc., when investigating moisture redistributions of sludge after being drained, filtered, and centrifuged [34].

3.3 Influence of electrochemical reaction on dewaterability

The moisture distribution analysis reveals that even a lower current can significantly remove the free water in the raw sediments after 6 hours (Fig. 5). Consequently, the differences in the final water content can be attributed to the release of interstitial water. Varying the current intensity in the electroosmotic dewatering system results in changes in the strength of the electrochemical reaction, affecting sediment properties and moisture status. These discrepancies influence the duration and timing of the rapid drain phase, transition phase, and termination phase during electroosmotic dewatering (Fig. 2). With a higher current, the fast drain and transition phases are prolonged, and the presence of transition and termination phases are delayed, leading to differences in the final water content. The temperature development shows significant differences under different currents, which might affect the release of interstitial water in different experimental groups. The temperature inside the sediments changed during electroosmotic dewatering due to ohmic heating. Ohmic or Joule heating is the heat generated due to the electrical current flowing through sediments and the increased resistance [35]. According to Joule's law, the ohmic heating is expressed as Eq. (2), and the R_{cell} can be calculated as Eq. (3)

$$Q = I^2 R_{cell} \quad (2)$$

$$R_{cell} = U_{Cake\ sediments\ bed} / I \quad (3)$$

Where Q is the ohmic heating (J); R_{cell} presents electrical resistance (ohm); I is the electric current (A); $U_{Cake\ sediments\ bed}$ is the ohmic drop in the sediments cake bed.

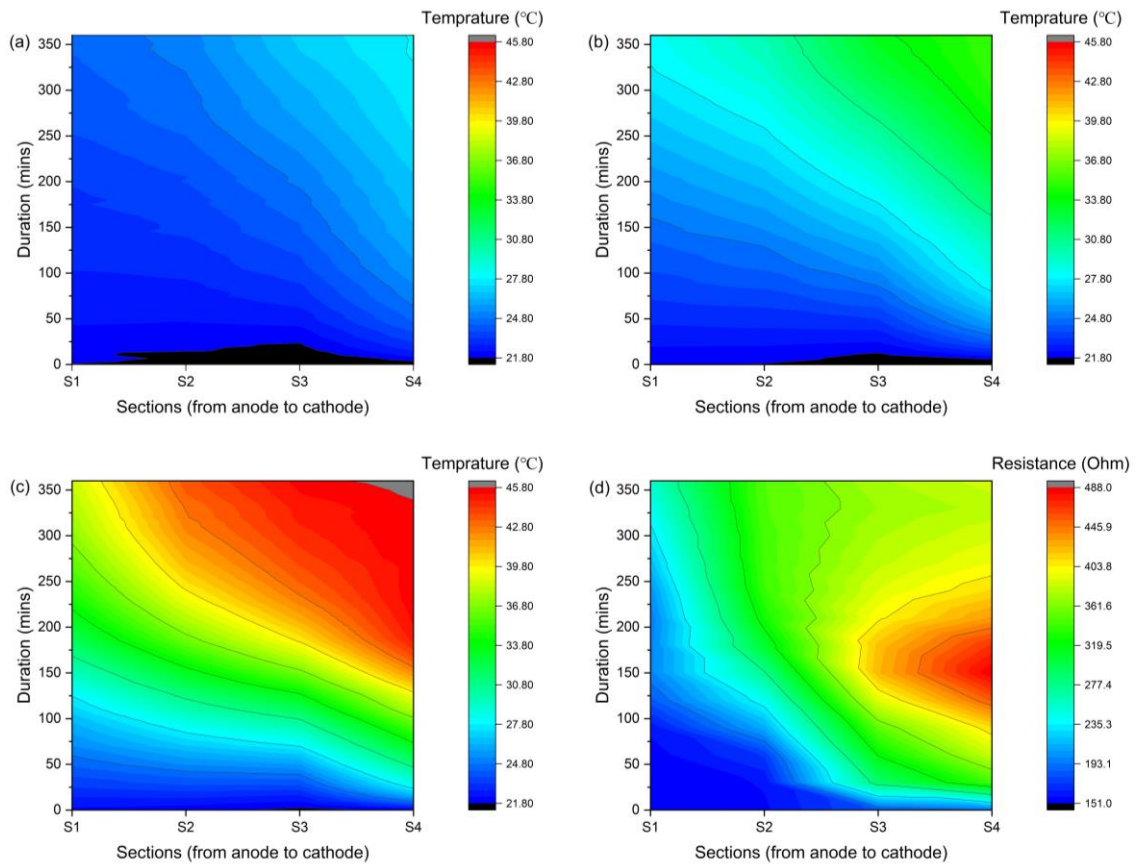


Figure 6. Development of temperature in group A0 (a), B0 (b), and C0 (c), and resistance changes of group C0 (d).

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224 The Ohmic heating plays a substantive role during electroosmotic dewatering. It internally heats the
225 sediments and raises the temperature, which will decrease the viscosity of the liquid, potentially expelling
226 moisture from the solid capillaries [36,37] and accelerating electroosmotic flow. The development of temperature
227 varies under different currents, as shown in Fig. 6 (a, b, and c). Generally, the temperature rise is more pronounced
228 for incremental increases in applied current. The average temperature of sediments was in the range of 20 - 28 °C
229 (A0), 20 - 36 °C (B0), and 20 - 47 °C (C0). Calculating the change in dynamic water viscosity corresponding to
230 these temperature ranges and normalizing with its value at 20°C ($\eta(T)/\eta(20\text{ }^{\circ}\text{C})$). The corresponding decrease in
231 viscosity of 5% - 15% in the case of A0, 15% - 30% in the case of B0, and 30% - 45% in the case of C0. Thus,
232 the viscosity-reducing ohmic heating contribution results in a fundamental acceleration of the dehydration kinetics,
233 facilitating the removal of some of the ordinarily difficult remaining water. Hence, ohmic heating synergizes with
234 the electroosmotic flow in improving dewatering and its kinetics, consistent with [8]. Besides, the temperature
235 rises faster in the area near the cathode than in the area near the anode, which may be related to the resistance
236 changes. The flow of electric current through porous media is determined by the conductivity of the solid
237 (dispersed phase) and liquid phase (continuous phase). While several theories exist for current transport in
238 mixtures, they mostly assume regular lattice-type solid phases or completely random component distributions.
239 However, these models are not entirely applicable to filter cakes. Wyllie et al. developed a more realistic model
240 decades ago based on the "porous plug" model, which considers three different paths for electrical current flow
241 through the bed [38,39]. These include 1) alternating layers of interstitial solution and particles, 2) particles in
242 contact with each other, and 3) in the liquid phase channel. In most cases, path 1) dominates, but path 2) is
243 significant for low-conductivity liquids.

244 From the circuit point of view, the conductivity of porous media, k_b , which can be written as the sum of
245 contributions k_1 , k_2 and k_3 of the three conductance elements as Eq. (4):

$$246 \quad k_b = k_1 + k_2 + k_3 = \frac{ak\bar{k}}{ak+ek} + b\bar{k} + ck \quad (4)$$

247 Where k is the conductivity of the liquid phase; \bar{k} is the conductivity of the solid phase; the parameters
248 a , b , and c are the fractional section equivalents of the three elements as Eq. (5):

$$249 \quad a + b + c = 1 \quad (5)$$

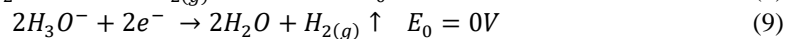
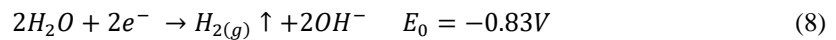
This ($dk + e\bar{k}$) term in Eq. (5) represents the contribution of the liquid with weight d and the solid with weight e in the first conduction process. The parameters d and e obey the following relationship as Eq. (6):

$$d + e = 1 \quad (6)$$

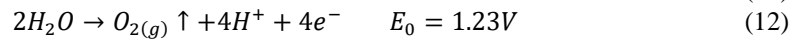
The relationship between the conductivity of the medium (k) and ohmic resistance (R) can be described as Eq. (7):

$$k = \frac{1}{R} \frac{L}{S} \quad (7)$$

Where L is the electrode gap, and S is the electrode area. For all the experimental groups, the L and S were the same. Thus, resistance is inversely proportional to conductivity. Fig. (d) shows the development of resistance in CO. Generally, the resistance increased with the continuous reduction of moisture content and formation of sediments cake. However, it rises faster in the area near the cathode than in the area near the anode, which is consistent with the temperature development tendency. According to Eq. (4), the conductivity of porous media k_b is related to the conductivities of the liquid and solid phases. During the electroosmotic dewatering process, the effect of the electrochemical reaction that occurs affects the conductivity of liquids and solids. The possible cathode reactions are:



The possible anode reactions are:



Where M represents any cationic species that can be reduced; E_0 is the standard electrode potential at a temperature of 298 K. Therefore, the dissolution of substances near the anode is beneficial to the maintenance of liquid and solid conductivity. Precipitation of species near the cathode exacerbates the decrease in conductivity and the increase in resistance. Besides, it is noticed that the resistance of the sample near the cathode area also showed a sudden short-term growth. This localized polarization phenomenon may be related to the generation of gas evolution that causes voids in the bed, creating an electrically insulating layer and significantly increasing the electrical resistance of the system. This can cause an increase in energy consumption and affect system stability. During electroosmotic dewatering, the negatively charged sediment particles move toward the anode under electrophoresis, increasing the compactness and strength of the sediments near the anode. Therefore, forming temporary holes near the cathode might be more conducive.

According to the changes in temperature, it is found that lower current leads to slower and more uniform temperature changes and water distribution in each region of the sample. A higher current causes faster and more uneven temperature changes and does not result in lower water content or more interstitial water release near the hotter cathode. This indicates that excessive ohmic heating may not be effective for moisture removal. Therefore, proper design to control the ohmic heating in each region within a specific range may reduce the electric energy loss and improve the energy efficiency of electroosmotic dewatering.

3.4 Cost estimates and overall assessment of the practical application

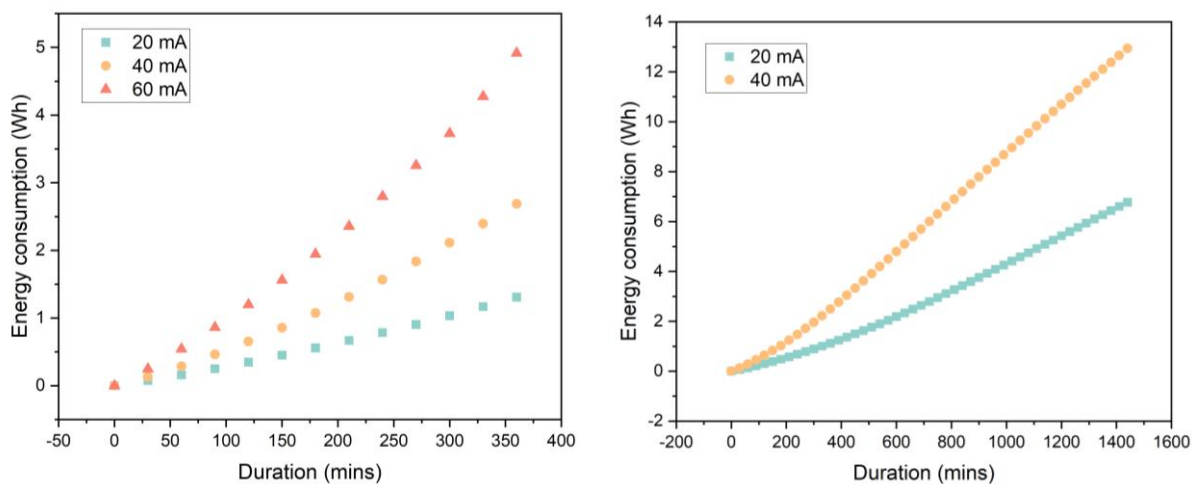


Figure 7. Energy consumption during the dewatering process

Electrochemical technology has been widely used for environmental management by many researchers. It can offer effective solutions for moisture removal, environmental protection, materials recycling, and clean synthesis by applying and improving existing methods or developing and implementing new ones [40–43].

293 However, some challenges remain for electrochemical-assisted technologies, such as electroosmotic dewatering,
294 to reach a high technology readiness level and become marketable processes [44]. One of these challenges is to
295 improve economic feasibility. Hence, the energy consumption of electroosmotic dewatering was analyzed to
296 propose possible strategies for reducing the operational costs of this technique. In general, the energy consumption
297 increases with time, as shown in Fig.7. At the beginning of electroosmotic dewatering, the energy consumption
298 increases slowly, and then the growth rate gradually accelerates. The higher the current used, the faster the growth
299 rate increased and the more energy consumed. It proves that the energy consumption in the electroosmotic
300 dewatering process is not constant but depends on the cake's dryness. The higher the cake's dryness, the higher
301 the energy consumption. This is attributed to the increased difficulty of removing the remaining water due to the
302 enhanced binding strength. Moreover, the cake drying and the gas generated near the electrodes may impair the
303 electrical contact between the cake and the electrode, resulting in increased contact resistance and reduced electric
304 field inside the cake, which consequently lowers the driving force. Precipitates generated near the cathodes may
305 cause an increase in resistance, thus also lowering the driving force. Therefore, when electroosmotic dewatering
306 is applied or combined with other techniques, a reasonable design should consider the better contact between the
307 cake and the electrodes, the sediments particles, and the efficient gas release generated by electrolysis. The
308 pretreatment of sediments (e.g., using flocculants) can also help reduce energy consumption by weakening the
309 bond between the remaining moisture and the sediments particles. Adding an acidic buffer near the cathode may
310 reduce the energy loss from higher ohmic heating near the cathode by alleviating precipitate generation. When
311 using electroosmotic dewatering, the control requirement of the final water content should also be fully considered.
312 For example, if the goal is to remove as much water as possible to reduce storage or transportation costs, the
313 duration can be controlled to end at the fast drain phase and before the transition phase appears (Fig.2) to
314 maintain high energy efficiency. On this basis, if the duration is further increased, some more water can be
315 removed, but it may significantly increase energy consumption. After the transition phase ends and enters the
316 termination phase, continuing to apply electric current will not significantly affect water removal. Still, longer
317 electrochemical reactions may increase the change of sediment characteristics and affect the suitable reuse
318 methods for treated sediments. Besides, it is found that using a higher current for a shorter period reduces the
319 water content of the sediments more effectively while consuming less power than using a lower current for a more
320 extended period.

321 Electroosmotic dewatering is a technique that uses an external electric field to extract water from semi-
322 solid materials placed between two electrodes, forming an electrochemical cell. Besides electroosmosis, other
323 electrokinetic phenomena involved in this process, such as electrode reactions, electrophoresis, and
324 electromigration, can affect the distribution of elements in the sediments and thus influence the reuse value of the
325 treated sediments. The effects of electroosmotic dewatering on the redistribution of elements such as heavy metals
326 and P were investigated. The results showed that most of these elements were not effectively removed by
327 electroosmotic dewatering. But around 1% - 15% of K and 20% - 45% of Na were extracted. The main components
328 of the removed water were K, Na, and trace amounts of Ca by electroosmotic dewatering. The water contained
329 negligible amounts of toxic heavy metals or essential elements of P. Therefore, the removed water could be used
330 as a Na and K supplement or disposed of directly. When a higher current is used for a shorter time, more liquid is
331 extracted in a shorter time, and the concentration of elements contained in the extracted solution is smaller. This
332 facilitates disposing of the extracted solution, such as directly returning it to the lake. Besides, Ca, Fe and Mg
333 concentrations decreased near the anode and increased near the cathode, while P concentration showed the
334 opposite trend. The pH values of the treated sediments also changed due to water electrolysis, with lower pH near
335 the anode and higher pH near the cathode. Longer durations result in more noticeable changes in elemental
336 composition and the pH values of the sediments. These variations in elemental distributions and pH suggest
337 different potential applications for the treated materials from different sections. For instance, the treated sediments
338 near the anode with higher P content, lower Ca, Fe, and Mg content, and lower pH could be suitable for P
339 extraction and recycling by methods such as electrodialysis. The extraction of P elements is usually more
340 accessible at lower pH levels. The content of the Ca element will affect the buffer capacity of sediments.
341 Mieczysław finds that Ca can form complexes with organic matter and clay minerals by replacing other cations
342 on the sorption complex and that these complexes can bond H^+ ions and neutralize acids [45]. The presence of Fe
343 and Mg elements may affect the P mineralogy and extraction efficiency [46]. The treated sediments near the
344 cathode with higher Ca content and pH could be suitable for producing building materials such as bricks and
345 cement [47].

346 347 **4. Conclusions and perspective**

348 The study explored the mechanism and potential of electroosmotic dewatering for dewatering and
349 valorizing phosphorus-rich lake sediments. Based on the analysis of the drying curve, the non-linear least-squares
350 minimization and curve fitting were applied to determine the different moisture content more accurately. Moisture
351 distribution analysis shows all four types of free, interstitial, surface, and bond water existed in raw sediments.
352 Applying an electric field (20 mA, 40 mA, and 60 mA) after gravity filtration can further reduce the mass of

353 sediments (7% - 20%) and lower transportation or storage costs. The electroosmotic removed water is mainly free
354 water and some released interstitial water. The fast drain phase, the transition phase, and the termination phase
355 occur during electroosmotic dewatering. The optimal duration of electric current application should be considered
356 to balance water removal and energy consumption. A higher current can enhance the dewatering efficiency with
357 lower energy consumption, where ohmic heating may help to decrease viscosity and release the water from the
358 capillary. However, it may result in excess ohmic heating, more precipitates, and gas generation (especially near
359 the cathode), thus decreasing energy efficiency and compromising the system's stability. The current conditions
360 do not significantly extract heavy metals or P from the sediments, which may facilitate the disposal of the removed
361 water. The notable changes in metals and P distribution and pH values imply that treated sediments from different
362 sections of setups could be reused for different purposes such as construction, P extraction, etc. Therefore, this
363 technology is easy to operate and suitable for the treatment of dredged sediments. Future work should aim to
364 improve the contact between the cake and the electrodes, the sediments particles, and the efficient release of gas.
365 It should also consider pretreatment to weaken the bond between the remaining moisture and the sediment
366 particles and alleviate the excess ohmic heating to improve the electric energy efficiency for commercial viability.
367

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