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A review on the recent advances in electrochemical treatment technologies for sludge dewatering and alternative uses

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ABSTRACT

Municipal wastewater treatment plants generate enormous quantities of sludge as a byproduct, which not only contains a significant amount of water and harmful pathogens but also serves as a repository for a variety of essential materials and nutrients. The recovery of water and other valuable substances is highly dependent on the employed treatment methods. In recent years, electrochemical processes have attracted a great deal of interest as an efficient technique for sludge dewatering and resource recovery. By separating free and bound water from the sludge matrix, electro-dewatering can substantially reduce the volume of sludge, making it a more cost effective and sustainable method of sludge management. Furthermore, the resulting sludge cake is more manageable and transportable, making it a viable option for further disposal or resource recovery. By considering the beneficial aspects of sludge electro-dewatering, this paper aims to critically review the mechanism underlying electrochemical methods of sludge dewatering as well as modified development strategies for scal-up potentials.

Introduction

In response to the rising demand for public health and environmental protection, the installation of wastewater treatment plants (WWTPs) is increasing rapidly around the world. The complete process of wastewater treatment encompasses various stages of cleaning and purification steps, including preliminary large solid and girt removal by screening, settling of solids followed by oil and grease separation in a primary settling tank, removal of dissolved organic matter and toxic metals by means of chemical or biological methods (designed and engineered depending on the types of wastewater), and a final polishing step prior to discharging the water to the environment. In each stage of the wastewater treatment process, sludge is produced as a byproduct and flows into the sludge settling vessel as waste sludge for further thickening, dewatering, and disposal. The global production of sewage sludge is estimated at 45 million tons of dry matter per year, so we need to consider this vast volume of sludge management by different processes. (Demirbas et al., 2017; Solé-Bundó et al., 2019).

The composition of sludge can vary based on several parameters such as the type of treated wastewater, the treatment process employed and the location of the treatment facility. In general, however, the sludge contains all of the undesirable and toxic components of the wastewater, including a variety of organic compounds, pathogens, heavy metals, microplastics and nutrients (Edwards et al., 2017; Q. Zhang et al., 2017). As a result, improper disposal of sludge can adversely impact the environment and public health. For example, the decomposition of organic matter in sewage sludge can emit unpleasant odors and greenhouse gasses like methane and carbon dioxide, which contribute to climate change (Chang et al., 2023). Nutrients in the sludge can cause nutrients overload in soil and water system, triggering algal blooms and other environmental problems. Harmful pathogens in the sludge, including bacteria, viruses and parasites, can pose a risk to public health if not properly treated or disposed of. High levels of heavy metals, such as lead, cadmium and mercury, can be toxic to humans, animals and plants and can accumulate over time in soil and water systems. In addition, microplastics in the discarded sludge can cause harm to the aquatic and terrestrial ecosystems (Corradini et al., 2019). Therefore, an effective sludge treatment system can reduce the risks associated with sewage sludge disposal.

Treatment of sludge can be an integral part of a circular economy because it offers the chance to recover valuable resources such as energy, nutrients and water. For instance, anaerobic digestion of sewage sludge can generate biogas, which can be used to generate heat and electricity (Usack et al., 2019). This can help in reducing our dependency on non-

Abbreviations: AD, anaerobic digestion; WWTP, wastewater treatment; EDW, electro-dewatering; AS, activated sludge; ADS, anaerobically digested sludge; SCOD, soluble chemical oxygen demand; DS, dry solid; VSS, volatile suspended solid; CST, capillary suction timer; US, ultrasonication; EPS, extracellular polymeric substances; LB-EPS, loosely bound extracellular polymeric substances; TB-EPS, tightly bound extracellular polymeric substances; EF, electro-Fenton; AOPs, advanced oxidation processes; AT, acid treatment; AO, anodic oxidation, SRF, specific resistance to filtration.

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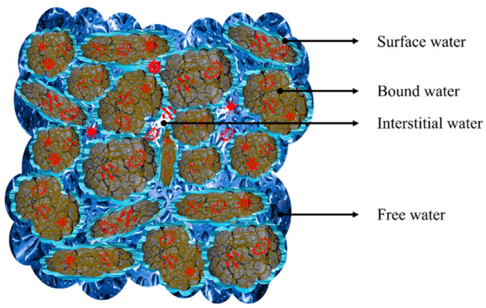

Fig. 1. Sludge flocs with different types of water.

renewable energy sources and greenhouse gas emissions. Apart from that, sewage sludge contains nutrients such as nitrogen and phosphorous that can be recovered and used as fertilizers in agriculture, promoting a closed-loop approach to resource management (Sichler et al., 2022). More importantly, sludge contains a substantial quantity of water, which may be rich in dissolved metals and nutrients. Using an appropriate dewatering technique, it is possible to recover these resources, thereby reducing the demand for virgin resources and minimizing waste.

Dewatering is an essential part of sludge management system and plays an important role in reducing the volume and weight of sludge by removing various types of water from the sludge (Shi et al., 2015). Based on the binding energies between water and solid sludge particles, sludge water may be divided into four different types (Vaxelaire and Cézac, 2004), as shown in Fig. 1. The first type is free water, which is less difficult to separate because it is not directly bonded to solid particles. Approximately 65–85% of total sludge water is free water and can be eliminated through simple thickening or light mechanical stresses (Chen et al., 2015; Vaxelaire and Cézac, 2004). The second type is interstitial water, which is confined by capillary forces and held in the crevices and interstitial spaces of flocs and microorganisms. It accounts for 10–25% of the total water content in the sludge and can be released by breaking up the sludge flocs and disrupting the microbial cells (Mikkelsen and Keiding, 2002; Ruiz-Hernando et al., 2014). The third form of water is surface water, which sticks to solid particles through adsorption and adhesion. Surface water is not free to move because it adheres to solid surfaces, whereas interstitial water is free to move once physical confinement is removed (Wei et al., 2018). The last one is bound water which is chemically bonded to solid particles and EPS matrix. It also includes intracellular water and accounts for approximately 10% of total water content of the sludge. Due to strong chemical bonds, this type of water can be recovered by destroying cells and the EPS matrix, followed by thermal dehydration (Cao et al., 2021; Vaxelaire and Cézac, 2004).

To dewater, the most straightforward method is to use sludge drying beds. In this case, sludge is left to dry on an open bed of sandy soil until the sludge is completely dried (Gikas, 2017; Stefanakis et al., 2014). After six weeks of drying, the sludge cake, as it is known, may contain about 40% solids. The main drawback of this system is that a large area is required, and odor problem may appear. To overcome these problems, several other techniques, such as rotary drum vacuum filtration, centrifugation, and the belt filter press have been used for sludge dewatering. These mechanical systems require less space than sludge-drying beds, and they offer a greater degree of operational control. The odor drawback has been solved by performing these mechanical systems in a closed areas (He et al., 2017). However, due to the colloidal and compressible nature of sludge, the optimum efficiency of these mechanical systems remained constrained to 35% dry solid contents. Consequently, several physical and chemical conditioning methods have been adopted prior to mechanical dewatering to improve the efficiency of pressurized mechanical dewatering system. The addition of skeleton builders (Wu et al., 2016), the freeze thaw approach (Hu et al., 2011), use of microwaves (Cai et al., 2017), and ultrasonic conditioning (Lambert et al., 2022; J. Li et al., 2016) are among the physical preconditioning techniques that have been evaluated for enhanced dewatering efficiency. Chemical conditioning represents the addition of alkalis (Li et al., 2005), surfactants (Chen et al., 2001), oxidants (W. Zhang et al., 2015), and coagulants/flocculants (Mowla et al., 2013).

Recently, electric field assisted sludge dewatering has gained increased attention due to several benefits, such as simple equipment design, ease of operation, and reduced need of chemicals (Mahmoud et al., 2018; Zhen et al., 2013). Complex electrochemical operations (ohomic heating effect, redox reactions, electrokinetic phenomena and pH gradient effect) in the electro-dewatering process can reduce the water content of sludge from about 80% to less than 40% while removing sludge malodor and pathogens (Rumky et al., 2020). Until now, comprehensive summary on electrochemical technology for sludge dewatering has not been published. Therefore, this review highlights the potential electro-chemical processes for sludge treatment with emphasis on, (a) the main mechanism and advantages of electrochemical processes for sludge treatment, (b) the feasibility of different pre-treatments (vacuum, ultrasonic, heating etc,) with EDW and different alternative usage of sludge materials. This review may increase the attention given to the electrochemical methods for sludge treatment and help people expand knowledge in this field.

Electrochemical methods for sludge treatment

Electro-dewatering

Electrochemical treatment of sludge is clean and robust process to decrease the amount of biosolid waste and remove pathogens. The fundamental principles are to disintegrate the sludge structure by direct electric force and indirect oxidation. Electro-dewatering (EDW) of waste sludge has recently gained significant attention due to its high sludge dewatering efficiency and energy savings as compared to conventional mechanical dewatering and thermal drying. It has been reported that the highest attainable solid content of mechanically dewatered sludge is approximately 30–35% (wt/wt) (Gronchi et al., 2017; Mahmoud et al., 2018). To further improve the solid content, thermal drying is required, which results in much higher energy consumption and operational expenses for sludge dewatering. EDW, on the other hand, may reach 60% (wt/wt) solid content while utilizing less than a quarter of the energy necessary for thermal drying (Huang et al., 2022; Lv et al., 2019; Olivier et al., 2015).

EDW systems are simply electrochemical cells integrated with a mechanical pressure system and are occasionally referred to as electro-mechanical dewatering system. When an electric field is applied using inert electrode through the sludge slurries, water electrolysis and other electro-kinetic phenomena such as electrophoresis, electro-osmosis and electromigration take place (Mahmoud et al., 2013, 2010; Pham-Anh et al., 2012). These electrochemical reactions and electro-kinetic phenomena significantly enhance the dewatering degree and solid content of the sludge cake. A schematic of the key electrochemical reactions and transport processes in an electro-dewatering system is presented in Fig. 2 and described in the following subsections.

Water electrolysis

Water electrolysis is the primary process that occurs in the sludge suspension when an electric field is introduced. Water oxidation occurs at the anode, creating oxygen gas and releasing protons into the surrounding environment. As a result, a decrease in pH is detected at the anode surroundings. The reduction of water, on the other hand, produces hydrogen gas and hydroxide ions at the cathode. The *in-situ* generated hydroxide ions raises the pH near the cathode (Mahmoud et al., 2010; Pham-Anh et al., 2012).

Electrolysis also induces extracellular polymeric substance (EPS) layer deterioration and microbial cell lysis, which reduces the stabil-

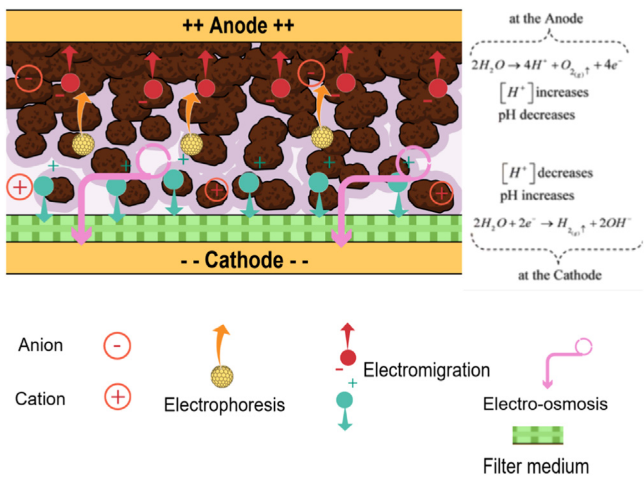

Fig. 2. Schematic representation of electro-dewatering process (modified from *Mahmoud* et al.*, 2011*).

ity of sludge flocs. Additionally, the evolution of gasses (hydrogen and oxygen) at both electrodes causes the formation of void spaces within the sludge bed and raises the system's electrical resistance. As a result the sludge temperature rises which may aid dewatering by decreasing water viscosity and increasing evaporation (Navab-Daneshmand et al., 2015; Pham-Anh et al., 2012).

Electromigration

Electromigration is the self-diffusion of charged species or ions toward the oppositely charged electrodes, which takes place in response to an applied electric potential in an electrochemical system. During electrolysis, the pH of the anode decreases, which aids in the acidification of the sludge suspension. As a result, phosphorous and other heavy metals are liberated into the water phase from the sludge matrix. These liberated metal ions are further transported and concentrated into the cathode compartment via electromigration. Therefore, electromigration plays a key role in the recovery of nutrients and other metal ions during sludge electro-dewatering (Mahmoud et al., 2010; Pham-Anh et al., 2012).

Electrophoresis

Transport process electrophoresis refers to the migration of charged particles towards the oppositely charged electrodes relative to a stationary liquid phase. Sludge flocs are negatively charged particles and therefore, during electro-dewatering process the movement of sludge particles occur towards the anode due to the electrophoresis effect. (Mahmoud et al., 2011, 2010; Pham-Anh et al., 2012)

Electro-osmosis

Electro-osmosis process, on the other hand, refers to the transport of aqueous phase through the porous solid phase under the action of applied electric potential. In sludge EDW process, electro-osmosis plays the most crucial role in displacing extra water from the sludge cake. Water in sludge exists as cationic hydrates by interacting with other cations. These cationic hydrate clung to the sludge surface due to the negatively charged nature of the sludge particle, generating an electric double layer. When an electric field is provided to a sludge section using electrodes, the ensuing Coulomb force induces the net charge in the electric double layer to shift, and the cationic hydrate migrates to the cathode via electro-osmotic action. Several factors affect the electro-osmosis mechanism in EDW process, including sludge physical and chemical properties, applied voltage gradient, sludge cake thickness, mechanical pressure, and dehydration period. Therefore, currently researchers are focusing on the improvement of electro-osmosis mechanism of sludge EDW by integrating it with other processes (Mahmoud et al., 2010; Martin et al., 2019; Shen et al., 2016).

Electro-dewatering integrated with vacuum pressure

Electro-osmosis is integrated with a constant negative pressure (i.e., vacuum) is termed as vacuum electro-osmosis dewatering (VEOD), significantly decreasing dewatering time and, thus, energy consumption. Water in sludge comprises cationic hydrate and therefore, it can adhere to the negatively charged sludge particles. When exposed to an electric field, cationic hydrate migrates to the cathode; however, due to the electrophoresis effect, large sludge particles impede this migration, making it more difficult to recover than free water. Squeezing the sludge floc framework with a high vacuum reduces porosity and transforms pore water to free water, which can be quickly separated. (Shen et al., 2016; Xu and Ding, 2016)

Electro-dewatering integrated with ultrasonication

An electric field applied to the sludge suspension causes the liquid phase to flow to the cathode direction and the solid phase to flow to the anode direction. However, as time passes, the liquid phase in the sludge cake near the anode becomes discontinuous, increasing the resistance to current flow through the sludge bed and resulting in the disruption of electro-osmotic dehydration. In that case, the electro-osmosis rate can be increased further by using an ultrasonic method. The application of an ultrasonic process accelerates the disruption of sludge flocs and the release of bound water through shockwaves produced by ultrasonic cavitation. As a result, the liquid phase passing through the sludge bed speeds up and increases the interaction between the liquid phase and the electrode, improving the sludge dewaterability (Dey et al., 2022; Ma et al., 2018).

Electro –Fenton

The Electro-Fenton (EF) process is a promising electrochemical advanced oxidation process (EAOP) in which the organic pollutants are oxidized by an indirect electrochemical oxidation by hydroxyl radicals produced by the Fenton reaction. Hydroxyl radical (·OH), the second most powerful oxidizing specie after fluorine, is formed electrochemically by the reaction of H_2O_2 and Fe^{2+} ion according to the following Eq. (1):

$$H_2O_2 + Fe^{2+} \rightarrow Fe^{3+} + OH^- + OH \quad (1)$$

In EF process, Fenton reagents, H_2O_2 and Fe^{2+}, can be electrogenerated according to the following 4 different strategies:

i Electro-generation of H_2O_2 and Fe^{2+} simultaneously by an oxygen sparging cathode and sacrificial anode, respectively.
ii External injection of H_2O_2 and electro-generation of Fe^{2+} using a sacrificial iron anode
iii External injection of Fe^{2+} and electro-generation of H_2O_2 using an oxygen sparged cathode
iv External injection of H_2O_2 and Fe^{2+} in an electrolytic cell for ·OH generation and regeneration of Fe^{2+} at the cathode (Burgos-Castillo et al., 2018; Chen et al., 2019).

Bio-electro–Fenton

Zhu and Ni published the first MFC-Electro-Fenton system for POPs degradation in the cathode chamber in 2009 (Zhu and Ni, 2009). Following that, the process was renamed bio-electro-Fenton, and it has gotten a lot of attention in recent years, resulting in the rapid development of a number of bio-electro-Fenton systems. The MFC-based bio-electro-Fenton, which uses anodic electrogenic microbe, is one of the most used systems. The MFC-based bio-electro-Fenton system uses anodic electrogenic bacteria to create electrical power from biodegradable organics to

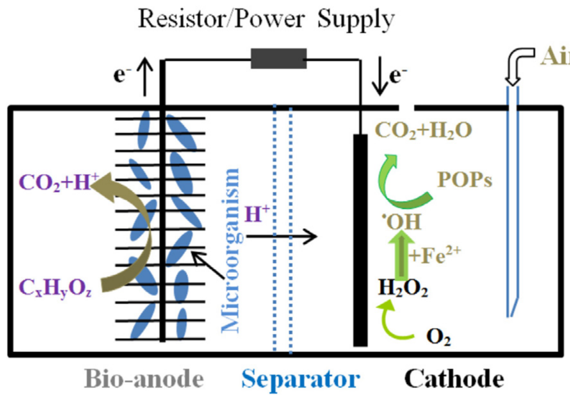

Fig. 3. Bio-electro-Fenton working principle (copied with permission (X. *Li* et al., *2018*)).

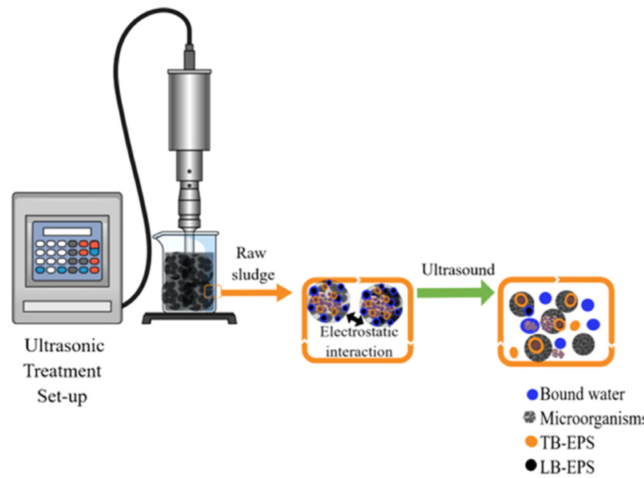

Fig. 4. Ultrasonic and ohmic heating affects on sludge materials.

drive the Fenton process in the cathode chamber, which allows POPs in wastewater to be oxidized (Y. Zhang et al., 2015). Bio-electro-Feton process is considered as low toxic process with energy saving and it can be powered by wastewater-derived renewable energy (Asghar et al., 2014).

In general, bio-electro-Fenton systems are made up of two chambers separated by a membrane (for example, a proton-exchange membrane, a cation-exchange membrane, or a bipolar membrane), as shown in Fig. 3. The anaerobic anode chamber is filled with biodegradable organic matter-containing wastewater, whereas the aerobic cathode chamber is filled with POP-containing wastewater. In the anode chamber, biodegradable organic matter is oxidized by microorganisms, which is a common principle in nearly all bio-electro-Fenton systems. The anode's oxidation activities release electrons, which are then delivered to the cathode through an external connection. The idea is similar to that of traditional bio electrochemical systems (where electrodic reactions are directly or indirectly linked to the metabolic activity of microorganisms), and also, all of the anode materials and microorganisms can be employed in bio-electro-Fenton systems. In the cathode chamber, electro-Fenton processes are primarily seen. The electro-Fenton process' reaction mechanism has received a lot of attention (Feng et al., 2010).

For pollutants oxidation, the two-electron reduction of oxygen on the cathode produces H_2O_2 (Eq. (2)), which subsequently combines with Fe^{2+} to create radical •OH (Eq. (3)). High H_2O_2 production rate and concentration are required to achieve high pollutant degradation performance in bio-electro-Fenton systems.

$$C_xH_yO_z + (2x - z)H_2O \rightarrow {}_xCO_2 + (4x + y - 2z)H^+ + (4x + y - 2z)\,e^- \quad (2)$$

$$O^2 + 2H^+ + 2e^- \rightarrow H^2O^2 \quad (3)$$

$$H^2O^2 + Fe^{2+} \rightarrow Fe^{3+} + OH^- + OH \quad (4)$$

Application of different electrochemical processes in sludge treatment

Turning the sludge into valuable resource by alternative usage provides a new sustainable path for sludge management beyond treatment and safe disposal. The electrochemical process draws scientific attention to sludge resources recovery, removing bound water and proposing sludge materials in different alternative areas (e.g, adsorbent, fertilizer, catalyst etc.) (Chowdhury et al., 2022; Rumky et al., 2023). However, research on the different electro-chemical processes for sludge treatment is limited and electro-chemical processes in bigger scale, very rarely found. This section focuses on different electrochemical treatment processes, their setup, the characteristics of sludge materials, and the quality of the final sludge after different electrochemical treatment processes.

In Table 1, different sludge characteristics are collected from the already published literatures. Different electrochemical set-ups with various electrodes have been checked by researchers to achieve more efficient processes for sludge treatment. Vacuum electro-osmosis was studied for sludge treatment where perforated steel anode and cathode were used by Shen et al., (2016) and titanium electrodes were used by Ding et al.,(2016). Citeau et al., (2012) obtained 58% dry solid for digested sludge and 78% for AS by mechanical dewatering with electrical assistance. Moreover, Feng, Wang and Ji., (2014) improved bound water content 0.25 g/g dry solid after pressurized electro-osmosis of AS with perforated cathode. Electrode material and structure is considered as vital point in electrochemical processes, so the information in Table 1 will help readers to choose electrodes for their own developed methods after considering the process efficiency (e.g., dry solid content after treatment). Further, characterzation is used to evaluate the sludge's physical, chemical and biological properties which is valuable point in sludge management.

Electro-dewatering (EDW) is one of the most promising methods for sludge treatment, but its performance depends on the sludge's characteristics. Although the traditional drying process can achieve a high level of sludge dryness and contamination destruction, EDW is considered more effective because of the lower capital and operating costs (Mahmoud et al., 2018).

Several conditioning (ultrasonic, heating, chemical, vacuum) are proposed by researchers to enhance the electro-dewatering of sludge (Tables 2 and 3). Energy from ultrasonic methods show an important role for sludge disinfection, disruption or the dewatering performance improvement. Ultrasonic can produce a kind of sponge effect in sludge and helps the migration of moisture through natural channels or artificial channels created by ultrasound wave circulation. The changed sludge structure and properties influenced the electro-dewatering and Riera-Franco De Sarabia et al., (2000) studied a high power (10 or 20 kHz) acoustic treatment for sludge solid-liquid separation by accelerating the bound water separation. Shock waves created during ultrasonication can destroy the extracellular polymeric substances and sludge flocs, which improved the dewaterability by changing bound water to free water (Fig. 4). Capillary suction time (CST) decreased depending on the ultrasonic duration for sludge treatment and in general lower ultrasound frequency, 10 to 20 kHz may improve dewaterability performance with CST reduction (Chu et al., 2001; Mason, 2007).

Besides, ultrasonication can destroy the bacteria in the sludge which reduces the water content and odd smell from wastewater sludge (Table 3). The treatment was found to improve the sludge combustion value and therefore contributed to the sludge incineration (Zhang et al., 2020). Ma et al., (2018), on the other hand, tested ultrasonication

Table 1
Sludge characteristics for different electrochemical treatment.

Type of sludge	Experimental Setup	Raw sludge characteristics						References
		pH	SCOD (mg/L)	SS (g/L)	VSS (g/L)	SRF ($\times10^{11}$ m/kg)	Zeta Potential (mV)	
Activated sludge (AS)	Total volume of 960 mL made of polymethyl methacrylate. Anodic oxidation: RuO2-coated titanium electrode (anode) and Ti mesh (cathode). RuO2-coated titanium and active carbon fiber (ACF) used as anode and cathode in electro-Fenton system.	6.82 ± 0.15	136.46 ± 13.19	24.23 ± 0.34	13.34 ± 0.47	7.62 ± 0.39	-30.15 ± 1.80	(Chen et al., 2019)
AS Municipal WWTP	Ti/RuO2-IrO2 and Ti meshes used as the anode and cathode	6.83 ± 0.10	-	36.8 ± 0.78	-	2.38 ± 0.09	-13.60 ± 1.00	(Y. Li et al., 2016)
AS Refining, cyclohexanone, etc. production industrial WWTP		6.72±0.34	-	36.9±0.56	-	2.32±0.08	-9.9±0.83	
AS Caprolactum production industrial WWTP	Ti/RuO2-IrO2 and Ti meshes used as the anode and cathode	6.73±0.07	-	15.9±0.05	-	10.88±0.11	-15.10±0.94	(Y. Li et al., 2016)
AS		6.95±0.15	-	16.14±0.07	9.57±0.06	-	-	(Zhen et al., 2012)
AS	Electro-osmotic dewatering which comprises filter-press cell, a DC power supply, a thermometer, and two precision balance.	6.9	-	-	-	-	-15.2	(Cao et al., 2018)
Pre-dewatered sludge	Vacuum electro-osmosis dewatering apparatus Cuboid sludge tank, a perforated stainless-steel anode and cathode, a DC power supply, and two cylindrical vacuum tanks	8.54- 8.75	-	-	-	-	-14.3 to -15.6	(Shen et al., 2016)
Sludge collected from horizontal sedimentation tank	Vacuum electro-osmosis dewatering apparatus which comprises a DC power supply, a sludge tank, three titanium cathodes and anodes, and two cylindrical vacuum tanks	7.73±0.15	-	-	-	-	-12.6±1.1	(Xu et al., 2016)
Anaerobically digested sludge	a DC power supply, titanium cathode and anode electrodes, and cloth filter	7.16- 7.38	-	-	15.3 to 17.0	-	-14.0 to-15.9	(Tuan and Sillanpää, 2010)
AS	Pressurized electro-osmotic dewatering apparatus which comprises a cylindrical laboratory filter-press cell, a DC power supply, a multimetre FLUKE 45, and two precision balances	7.7	-	-	78% (dry solid)	-	-20	(Citeau et al., 2012)
Digested sludge		7.6	-	-	58% (dry solid)	-	-26	
AS	Electro-dewatering unit comprising hydraulic piston, titanium anode, and stainless-steel perforated cathode, filter belt, and electronic balance	7.1- 7.5	-	-	70–90% w/w	-	-	(Navab Danesh-mand et al., 2012)
AS	Pressurized electro-osmotic dewatering apparatus comprising a DC power supply, a beaker, a precision balance, anode fixed on the bottom of the piston, and a perforated disk cathode	7.12±0.02	1800±290	8.34±0.08	Free water = 0.24 g/g dry solid and bound water = 0.25 g/g dry solid	-	-	(Feng et al., 2014)

(*continued on next page*)

Table 1 (*continued*)

Type of sludge	Experimental Setup	Raw sludge characteristics						References
		pH	SCOD (mg/L)	SS (g/L)	VSS (g/L)	SRF ($\times 10^{11}$ m/kg)	Zeta Potential (mV)	
AS Response surface methodology optimization of Mn (III) conditioning (C) -horizontal electro dewatering (HED) process	Electroosmotic dewatering apparatus opened to the atmosphere and no pressure difference between two electrodes which were Ta_2O_5 coated metal oxide IrO_2.	6.90±0.01	-	13.5±0.01	8.6±0.01	-	-9.47±0.85	(X. Guo et al., 2017)
AS Characterization during Mn (III) C - HED process	Electroosmotic dewatering apparatus opened to the atmosphere and no pressure difference between two electrodes which were Ta_2O_5 coated metal oxide IrO_2.	6.87±0.01	-	13.8±0.01	9.1±0.01	-	-9.72±0.85	(X. Guo et al., 2017)
AS	HED apparatus made of plexiglass comprising two IrO2 Ta2O5 electrodes (distance 65 mm) and filter chamber covered with a polypropylene filter cloth	6.71±0.04	-	16.32±1.30	10.6±0.30	-	-8.52±0.35	(H. Li et al., 2018)
AS	Electro-dewatering system comprising a DC power supply, a IrO2-Ta2O5-coated titanium anode, a stainless steel cathode, filter medium, and pressure supply equipment	6.1- 7.5	-	-	55.3–61.5% w/w	-	-19.2 to -14.3	(S. Zhang et al., 2017)
AS	Magnetic micro-particle conditioning-magnetic field conditioning-drainage under gravity-HED.	6.58±0.04	-	5.53±0.30	4.46±0.21	-	-	(Qian et al., 2016)
Mechanical dewatered sewage sludge	Electro-dewatering pretreatment on nitrous oxide emission using 40 L of composter	7.22	-	-	85.01%	-	-	(Wang et al., 2018)
Electro-dewatering sewage sludge		8.47	-	-	67.53%			
Anaerobic sludge	Electrolytic reactor (0.5 L) comprising HAMEG 7042–5 power supply and Fe electrodes (distance 4 cm) for electrocoagulation and electrochemical peroxidation	7.8–8.2	-	31,333.3±2494.1	-	-	-	(Olvera-Vargas et al., 2019)

Table 2
Sludge dewaterability characteristics after electrochemical treatment.

Name of the process	Specialization of process	Sludge type	Optimal operating parameter	Dewaterability of sludge				References
				EPS	CST, SRF	Wc of sludge (%)	Others	
Advanced oxidation process: Electro-Fenton (EF)	Advanced oxidation process	Activated sludge	Power density 40 mA/cm2 and lower pH (≤3) was determined as optimum condition for enhancement of sludge dewatering.	EF able to compress more EPS than anodic or acid treatment and can accelerate more tightly bound EPS redistribution to soluble EPS.	SRF reduction 18.77% by AT[1], 30.17% by AO[2] and 64.57% by EF after 60 min of treatment.	97%	Dewaterability can enhance within 40–60 min of EF, sludge flocs decreased, and floc became coarser with bigger holes	(Chen et al., 2019)
Hybrid process of Electrolysis/electrocoagulation (with zero valent iron activated persulfate oxidation)	Voltage 40 V of electric field	Waste activated sludge (WAS)	4.15 g/L $Na_2S_2O_8$ and voltage 40 V considered after zero valent iron electrode applied	EZP can able to disrupt EPS, degrade protein substances and bound water released.	CST decreased by 49.1% and SRT decreased by 87.4%		EZP was economically feasible after preliminary economic analysis	(Y. Li et al., 2016)
Electrochemical pretreatment (EPT) with input of 10 V/800mA	Voltage 10 V of electric field	Primary treatment sludge – after chemical treatment (CEPT)	EPT 5–15 min with titanium electrodes (titanium-EPT)	limited dewaterability improvement			EPT-Ti: less sulfide control	(Zeng et al., 2020)
			EPT 15 min with carbon electrodes (carbon-EPT)	Sludge dewaterability enhanced	CST and SRF decreased > 80%		Carbon-EPT: disintegrate sludge flocs about 70% reduction	(Zeng et al., 2020)
Bio-electro-Fenton		Waste activated sludge		The anode treatment and Fenton can enhance sludge walls breaking and hydrolysis			COD increased by 41.0% for CS[3], 25.8% for AS[4], and 42.0% for CAS[5]	(Yu et al., 2018)
Electro-osmosis + weak ultrasonic	Ultrasonic and 60 V of electric field	Sewage sludge	Voltage: 60 V (5 min), 0.1 MPa mechanical pressure (5.5 min); Ultrasonic 0.510 W/cm2 (3.5 min) for pre-treatment and 20 W (0.255 W/cm2) and 3.5 min for the coupling method.	Dehydration rate improved: 34.71% (with electro-osmosis+ultrasonic), Dehydration rate: 17.40% (with electro-osmosis only)			Electro-osmosis with ultrasonic coupling can enhance dehydration, change of current stable and energy consumption is less.	(Ma et al., 2018)
Electro-osmotic dewatering or Electro-dewatering (EDW)	Voltage and pH	Activated sludge	Voltage, pH and ionic strength considered as EDW parameters	EPS totally depends on the alkalization, while oxidation and acidification responsible for EPS (At anode). At anode, avg. EDW R^2 >0.79, p<0.02 and cathode R^2 >0.87, p<0.03. Moreover, dissolved organic matter is negatively correlated with cathodic EDW and positively with anodic EDW.			EDW improved by raising operating voltage and decreasing pH; even EDW increases with decreasing ionic strength and decreasing with the opposite condition.	(Cao et al., 2018)
Vacuum electro-osmosis dewatering (VEOD)	Vaccume	Drinking water treatment sludge (DWTS)	Electro-osmosis process: 0.05 MPa, 2.5 V/cm	Vacuum filtration: Sludge moisture content decreased 79%; VEOD: removes all free water and pore water reduced by 60.2% and surface adhesion 15.9%		Moisture content at pH 3.3 was 63.7% (potential gradient 1.25) and 58% (potential gradient 7.5)	Energy consumption: at pH 3.3, 0.37 kWh/kg and at pH 10.6, 0.48 kWh/kg (gradient potential 1.25); At pH 3.3, 0.52 kWh/kg and at pH 10.6, 0.55 kWh/kg (gradient potential 7.5)	(Shen et al., 2016)

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Table 2 (*continued*)

Name of the process	Specialization of process	Sludge type	Optimal operating parameter	Dewaterability of sludge				References
				EPS	CST, SRF	Wc of sludge (%)	Others	
Electro-osmosis (with Fenton like process)	Fenton process	Drinking water treatment sludge (DWTS)	According to 3D response surface of the water, Fe^{3+} dosage of 54 mg/g sludge, H_2O_2 dosage of 87 mg/g sludge and pH of 6.3	Dewaterability enhanced by different treatment processes like Fenton treatment decreased the internal combined water (9 mgH_2O/mg sludge) and increased (19 mgH_2O/mg sludge) the free water in sludge; H_2SO_4 + Fenton improved free water 28 mgH_2O/mg sludge and decreased internal combined water 4 mgH_2O/mg sludge; whereas untreated sludge has free water 12.5 mgH_2O/mg sludge and internal combined water 4 mgH_2O/mg sludge.		Moisture content decreased to 63%	Vaccum elctro-osmosis showed lower dewaterability whereas 63% improvement achieved by combination with Fenton like process or acidification	(Xu et al., 2016)
Pressure driven electro-dewatering (with freeze/thaw and polyelectrolyte conditioning)	Pressure driven and 20 V of electric field	Anaerobically digested sludge	Power supply: 20 V Permeability factor: 7.62	CST (natural freezing) enhanced after 1,2,3 months was 69,54 and 38 sec. CST (polymer dosage): after 5 kg/ton CST became 39.3 sec and after 10 kg/ton CST became 13sec		Dry solid content increased 39.3–41.5% after the treatment from initial 3%.	Freeze/thaw conditioning reduced the CST significantly which can not be done by EDW alone, so sludge conditioning is necessary for solid-liquid separation.	(Tuan and Sillanpää, 2010)
Electro-osmosis	10 to 20 V of electric field	Activated sludge	10, 15, and 20 V/cm electric field studied			Dry solid content increased 40–45%	Dimensionally stable anodes (DSA) considered as most suitable material than stainless steel coated by PVD technique with TiN, AlTiN, and DLC	(Gronchi et al., 2017)
Electro-Fenton (EF) treatment		Anaerobically digested sludge	Fenton reagent and 15 mM H_2O_2	Dewaterability enhancement: 97% Leached 16.0% Cr, 42.6% Fe and 56.0% Pb under Fenton and 15 mM H_2O_2. Phosphorus recovery was about 74%–79% for all EF processes			Conventional Fenton/all EF can able to recover phosphorus 74~79% but RuO_2 anode based EF can be better than conventional.	(Burgos-Castillo et al., 2018)
Vacuum electro-osmosis dewatering (VEOD)	Vacuum	Drinking water treatment sludge (DWTS)	From statistical analysis: vacuum pressure -0.06 MPa, pH 6.2 and potential gradient 2.5 V/cm	Moisture content reduced from 97% to 57% at optimized point with energy consumption 0.35 kW.h/kg.				(Xu and Ding, 2016)
Electro-osmotic dewatering or Electro-dewatering (EDW)	Max. 20 V of electric field	Anaerobically and aerobically stabilized sludge	20 V for higher dry solid content and 15 V for better energy consumption. So 15 V considered as optimum point.	20 V can enhance dry solid content about 37.5% for aerobically digested sludge and 42.9% for anaerobically digested sludge.			Biological process is also studied here but did not evidence any influence on EDW	(Visigalli et al., 2017)
Pressurised electro-osmotic dewatering (PEOD)	Max 50 V of electric field	Activated sludge and anaerobically digested sludge	40 and 80 A/m^2, 20, 30, and 50 V for both sludges	Dry solid content improved to 47% w/w (activated sludge) and 31.7% w/w (anaerobically digested sludge) by PEOD.			Constant current and voltage can enhance ohmic effect, but dewatering does not affected much by filter cloth presence but 69% less energy consumption found by thin filter cloth for 45% w/w of DS content.	(Citeau et al., 2012)

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Table 2 (*continued*)

Name of the process	Specialization of process	Sludge type	Optimal operating parameter	Dewaterability of sludge				References
				EPS	CST, SRF	Wc of sludge (%)	Others	
Electro-dewatering (EDW)		Activated sludge	Constant electric density 80A/m^2 and pressure 5 bar in two-sided filter press.	EDW can improve dry matter 40% w/w with 0.025 kWh/kg energy consumption in 2 h. Without electric field, only compression at 5 bar took 11 h to get 22% w/w dry matter. Best performance found with 12 g/kg DS by cationic polyelectrolyte, conc. of electrolyte about 10^{-3} M salt and acidic pH.			Higher current application can increase higher dry solid content.	(Olivier et al., 2015)
Electro-conditioning in a membrane electro-bioreactor	Membrane bioreactor	Activated sludge	Batch reactors ranging 5 and 35 A/m^2 of current density with three conc. from 3000 mg/l to 15,000 mg/l	Current density significantly improves the SRF by extracting bound water through electro-osmosis.	Compared to sludge control reactor, filterability enhanced and SRF decreased to 200 times.		One cubic meter of sludge consumes 2.5 kWh of electricity and 80 g of electrode.	(Hua et al., 2015)
Pressurized electro-osmotic dewatering (PEOD)	Pressurized process	Activated sludge	401 kPa pressure and 50 V voltage considered as optimum fact from response surface methodology	50 V electrical compression enhance dewatering to get dry solid content 0.25 g/g		Dry solid content 41.90% and energy consumption 0. 153 kWh at optimum point	Humic acid formed and organic matter filtrate increased during electrical compression and after EC stage, the rupture bacteria cells with parallel slits became visible in AS.	(Feng et al., 2014)
Permanganate/bisulfite (PM/BS) conditioning horizontal electro-dewatering (HED)	Conditioning and 20V	Activated sludge	20 V for 120 min with KMnO4 0.01 mol/L activated sludge and NaHSO3 0.05 mol/L activated sludge	At anode side, 51.68% free water and 87.62% bound water removed. At cathode side, 36.55% free water and 85.08% bound water removed. EPS was solubilized and TB-EPS, LB-EPS converted to outer EPS by increasing sludge dewaterability.			Mn^{2+} and MnO_2 as skeleton builders can enhance flocculation effect and sludge dewatering.	(X. Guo et al., 2017)
Zero valence iron (ZVI)/persulfate (ps) integrated electro-dewatering (ZVI/ps-HED)	40 V at optimum	Activated sludge	0.35 g ZVI/g DS and 0.15 g ps/g DS	96.32% free water content and 79.78% bound water content removed by ZVI/ps -HED process.		Lowest water content 83.675 found after HED at 40 V with 120 min (from response surface methodology)	Proteins and polysaccharides decreased from solid and liquid part due to oxidative degradation. ZVI/ps decreased proteins of slime 57.22% and polysaccharides of EPS 68.50%.	(H. Li et al., 2018)
Electro-dewatering (EDW)		Activated sludge	Voltage 0 to 55 V and Ionic strength 0.13 to 4.29 g/L applied here	In anode, dewatering rate ($R^2 > 0.79$, $p < 0.02$) and cathode ($R^2 > 0.87$, $p < 0.03$) correlated with the pore volume of the sludge cake. Anodic oxidation covert EPS to small molecules and there is no correlation with anodic DOM and electro-osmotic dewatering whereas cathodic DM has negative correlation with dewatering rate.			Depending on stronger electro-osmotic effect, cathodic cake's porous structure became more plentiful than anode due to sludge flocs migration towards anode.	(Cao et al., 2018)

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Table 2 (*continued*)

Name of the process	Specialization of process	Sludge type	Optimal operating parameter	Dewaterability of sludge				References
				EPS	CST, SRF	Wc of sludge (%)	Others	
Electro-osmosis (using Fenton like process)	Fenton process	Drinking water treatment sludge	Fe^{3+} dosage 54 mg/g sludge, and H_2O_2 dosage 87 mg/g sludge (pH 6.3)	Final moisture content reached to 63% and proved that dewaterability enhancement by EPS destruction after Fenton like treatment.			Vacuum electro-osmosis showed low dewatering which can be enhanced by 63% by adding Fenton process with acidification.	(Xu et al., 2016)
Electro-dewatering (EDW) (influence of Na_2SO_4)		Waste activated sludge	Na_2SO_4 dosage of 12.5 g/kg DS (constant voltage 20 V)	EDW curve follow the S curve: first stage showed electro-osmosis very low; second stage EDW efficiency increased via electro-osmosis and in the third stage dewatering efficiency became constant by showing constant water removal and dry solid content.		Water removal efficiency 42.5% at optimum Na_2SO_4 dose	The pH gradient was intensified after adding Na_2SO_4 in EDW process and organic content migration increased from cathode to anode in comparison with raw WAS.	(Xiao et al., 2017)
Pressurized electro-osmotic dewatering (PEOD) (with bio-drying)	Pressurized process	Sewage sludge	7.5 min (at PEOD optimum condition)	Moisture content decreased from 83.41% to 60.0% at optimum PEOD process.			Accumulation of moisture content also tested and removal slightly less for T1 (41.49%) than T2 (44.60%). 68.1°C obtained for T2 and 3.6°C higher than T1.	(Q. Li et al., 2018)
Temperature variation on electro-dewatering	Temperature	Mechanically dewatered sludge	50°C temperature with voltage 35V	Proteins and polysaccharides in the EPS denatured when the temp. was >50 °C, so dried sludge cracked and electrical conductivity elevated.			When voltage switched from 35 V to 15 V at 50°C, energy consumption reduced to 108.23 KWh/ton of sludge material.	(Lv et al., 2019)
High apparent electrical resistivity (AER) in EDW		Activated sludge	Variation in the AER checked for EDW set-up	Sludge AER was less than 5000 Ω/m before the moisture content was decreased to 60%. As moisture content continued to decrease, AER increase from bottom to top layers. Gas accumulation and pH decreased in top layer, which increase sludge AER.			Dewaterability limit reached when free water near anode removed.	(Sha et al., 2020)
Pressurized electro-dewatering	Pressurized process	Municipal sludge	Constant voltage gradient mode with less energy consumption	Moisture content after constant voltage gradient mode was 28.41% and after constant voltage mode was 27.33%			Energy consumption was 189.62 Wh/kg_{H2O} of constant voltage gradient mode, much lower than constant voltage mode.	(Rao et al., 2021)

[1] Acid treatment (AT)
[2] Anodic oxidation treatment (AO)
[3] Cathode treated sludge
[4] Anode treated sludge
[5] Cathode-anode treated sludge

Table 3
Mechanisms and corresponding effects of various pretreatments before electrochemical treatment of sludge.

Type of pretreatment	Mechanism	Brief description of function	Limitation and end use	Ref
Mechanical compression	Water distribution	The bound water content of sludge was determined as a function of the sludge's mechanical dewatering strain. Depending on its behavior during mechanical dewatering, it was possible to classify water into distinct categories (free water, bound water separable by moderate mechanical strain, bound water removable by maximal mechanical strain, bound water not removable mechanically).	Bound water cannot be removed fully.	(Colin and Gazbar, 1995)
Ultrasonic	Degradation	The sludge flocs and cell walls are destroyed by ultrasonic waves, which liberate EPS, which speeds up the hydrolysis process. Ultrasonic waves create a sponge effect in the sludge, allowing water to flow more freely through the channel from the wave surface.	This process is not yet fully studied for sludge and have some limitation. Energy consumption for ultrasonic is relatively high.	(Xu et al., 2019)
Vacuum	Vacuum filtration	Free water is first removed by vacuum filtration, as the adhesion strength of free water with sludge is weak		(Xu and Ding, 2016)
Temperature	Microbial cell rupture	The influence of the hydrothermal process on excess sludge dewatering performance at 150–210 °C, and found that increasing the temperature caused sludge floc size to shrink and damaged the binding of extracellular polymeric substances (EPS) with water.	Not energy efficient	(Lv et al., 2019)

with electro-osmosis and found that suitable ultrasonic energy enhanced electro-osmosis dehydration. In addition, lower energy consumption was obtained suggesting that the coupling (ultrasonic + electro-osmosis) is better than only ultrasonic pretreatment for EDW. However, appropriate action time with ultrasonic process development is required as the electric potential of 60 V was needed in this study. 40 W and 3.5 min are optimum conditions but more scale-up is needed for future consideration. If the final aim is to produce biogas, the ultrasonic treatment of sludge is an excellent option. Ultrasonication can break down the interstitial water from the sludge flocs and therefore even moderate sonication will enhance the sludge dewatering and release organic content. After ultrasonic treatment, addition of polyacrylamide (PAM) polymer can be used to agglomerate the sludge and improve its dewaterability further. As ultrasonic energy consumption is high, further research is needed to find out the optimum ultrasonic duration to get the best result for sludge conditioning.

On the contrary, negative vacuum pressure combined with electro-dewatering (VEOD) can remove pore and surface adhesion water from sludge. It works gradually by reducing dewatering time and energy. In this process, floc structure is disrupted with pH difference and porosity reduction happens due to high vacuum pressure in sludge. Vacuum pressure of 0.03 or more 0.1 MPa was found to increase the sludge dewatering by reducing the process time. Xu and Ding., (2016) studied the VEOD and found that pH 6.2 and potential gradient of 2.5 V/cm resulted 0.35 $kWh/kg_{\text{removed water}}$ energy consumption using optimum dewatering parameters (Shen et al., 2016; Xu and Ding, 2016).

Water in sludge contains cationic hydrates that adhere to negative sludge particles making sludge dewatering more difficult. Under this methodology, cationic hydrates drift to cathode but this migration is hampered by sludge (Fig. 5). Sludge particles' surface charge changes by the different pH and zeta potential, which reduces the binding force among particles with surface water and it has been finally concluded that the high voltage may be able to remove final moisture from the sludge (Mahmoud et al., 2010; Shen et al., 2016; Yin et al., 2006). However, higher voltage will increase the process cost. In addition, protein content plays an important role in tightly bound EPS (TB-EPS) and removing protein will improve the sludge dewaterability.

Thermal pretreatment for EDW was studied by Lv et al.,(2019) and temperature threshold value for sludge electro-dewatering was evaluated. 15 V was tested for EDW and peak temperature maximum of 30 °C was found as a good choice for sludge pretreatment. However, the current trend was continuously decreasing with EDW progress. However, for the sludge pre-treated at 50 °C, 60 °C and 70 °C the subsequent current got higher than initial 1.9A. In the meantime, EDW reached to a

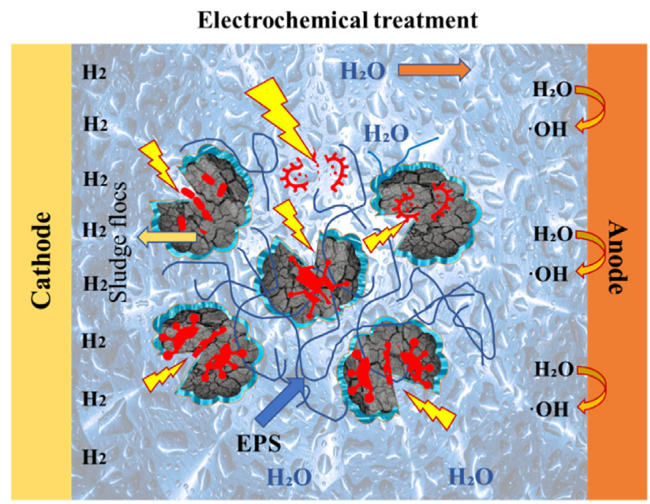

Fig. 5. Electro-chemical treatment for treating sludge materials.

steady state with dewatering limit of 25.2 g. After considering these results, it is suggested that the dewatering performance significantly increases when the temperature is >50 °C and within 40 °C to 50 °C there is a temperature threshold and sludge characteristics (EPS and biological composition) might be related to that. Different types of pathogens are available in different sludge sources, so various microbial communities exhibit having different tolerance temperature; therefore, temperature threshold exhibits a certain range of fluctuation (within 50 °C).

Recently, three different dewatering modes i.e. ultrahigh-pressure MDW, pressurized EDW with constant voltage and constant voltage gradient mode were performed for municipal sludge treatment by Rao et al.,(2021). Based on the filtrate flow rate, moisture distribution, constant voltage gradient mode has higher dewatering efficiency with less energy consumption than other modes. So, this possibility might be another option for sludge treatment in larger scale.

In terms of particular resistance to filtration, volatile suspended solids removal, and soluble organics release, Electro-Fenton (EF) was investigated as a pretreatment tool for improving activated sludge dewatering and disintegration by Chen et al., (2019). To understand better the involved pathways, researchers looked at the morphology of sludge flocs and the properties of EPS. The outcomes revealed that EF could increase the dewaterability of activated sludge effectively in 40–60 min.

The sludge disintegration performance with acid treatment (AT) and anodic oxidation (AO) as a controller was studied. Specific resistance to filtration (SRF) showed 18.77% reduction for AT, 30.17% reduction for AO but 64.57% for EF which displayed the efficiency of EF over others after 60 min.

Disintegration and reduction of sludge solid using EF showed volatile suspended solid reducing by 36.89%; higher than 6.77% using AT and 18.42% using AO. Moreover, tightly bound EPS (TB-EPS) contributed to water retention and lightly bound EPS (LB-EPS) to sludge dewaterability (Chen et al., 2015). EF treatment significantly decreased the TB-EPS, but LB-EPS and soluble EPS increased indicating the TB-EPS conversion to loosely and soluble EPS. One sequential EC process studied by Olvera-Vargas et al., (2019) contained electrochemical peroxidation (ECP) with EF for sludge treatment for the first time. In this research EF was at first used as a conditioning and stabilizing process and Fenton reaction caused 75.4% reduction of the total organic carbon under pH 5 and Fenton dosing ratio of 5:1 within 2 h of treatment. Moreover, all coliforms died after 1 h, and organic contents were mineralized achieving 91.6% of COD and 87.2% TOC removal.

Fenton oxidation has some drawbacks that prevent it from being used on a large scale. Excess supply of iron sludge is one such example, which is difficult to remove and may lead to secondary pollution. Due to a limited operating pH range and high chemical inputs, other limitations arise (S. Guo et al., 2017). Fe rich sludge could be an option to use as sludge based electrode. As we know, Fe based electrode are used in electro-coagulation; so it would be an option for further research area considering the conversion of waste to electrode materials. Moreover, it is also possible to overcome Fenton process's limitations by employing heterogeneous Fenton oxidation and fluidized-bed Fenton processes (Bello et al., 2017; Dias et al., 2016). So, these two would be possible future research paths for sludge treatment.

By considering Fenton's costly H_2O_2 usage; few researchers are suggesting to use bio-electro-Fenton (BEF). It is a combination of electro-Fenton and microbial electrolysis and recently it has been also reported that BEF can decompose sludge flocs as well. Protein and polysaccharide, a major part of COD, are used to study the disintegration of sludge. As per Yu, Jin and Zhang., (2018), cathode treated sludge' (CTS) soluble protein increased by 70% but only 26.8% increased for cathode-anode treated sludge (CATS) compared original raw sludge. On the other hand, for anode treated sludge' (ATS) soluble protein decreased 36.8% compared to original sludge. Soluble polysaccharides of CTS, ATS, and CATS increased by 154.9%, 11.9% and 53.4%, whereas soluble COD increased 41%, 25.8% and 42%, respectively. The value of soluble protein, polysaccharide, and COD increased, indicating that both cathode and anode promoted sludge hydrolysis, but only soluble protein decreased in anode compartment. Soluble proteins' faster utilization due to anaerobic bacteria might be the reason of soluble protein lower value in anode chamber. Both gram-positive and gram-negative bacteria were investigated with anode digestion. Results showed the higher efficiency of hydroxyl radicals in lipid-containing membrane to induce radical chain reaction. Besides, for macromolecules destruction, anode is considered more efficient with the enzyme secretion; a significant technique for cell disruption (Yu et al., 2018).

In practical applications, a full-scale sludge disposal system is complicated due to costly chemicals and tedious operating procedures with various pH reaction conditions. A few researchers studied the pilot scale sludge treatment e.g. Fenton's treatment with lime neutralization received 60% reduced water content, which is considered a significant sludge volume reduction by Liang et al.,(2015). Moreover, the lab-scale electro-Fenton system considered the sludge conditioning cost, chemical and electrical cost. In contrast, future pilot-scale electro-Fenton conditioning experiments will be used to estimate overall costs, including fixed costs and energy usage, for incineration of dewatered sludge (Cai et al., 2019). H_2O_2 -oxidation was also studied by Neyens et al., (2003) for pilot-scale sludge treatment based on the optimal conditions (25 g H_2O_2 kg^{-1} dry solid, 1.67 g Fe^{2+}-ions kg^{-1} dry solid at pH 3) where dry solid content improved 47% which is only 20% by traditional sludge dewatering system.

In the pilot-scale experiments, a novel spring pressure filtration was also used to simulate the actual industrial conditions and achieve better performance. The ultrahigh pressure filtration system was able to reach pressures of up to 40 MPa, which increased the sludge dewatering rate and efficiency even further. 70 L of sludge materials was investigated by ultrahigh pressure filtration system and Fenton's reagent + lime + pressure filtration was found as economically feasible for sludge dewatering (Liang et al., 2015).

Various lab-scale electro-dewatering set-ups have been developed for sludge EDW but pilot-scale processes are rarely found. Lv et al., 2019 studied the lab scale sludge dewatering electrolyser to optimize sludge operational cost by reducing energy consumption. One pressure-driven EDW lab-scale set-up (Fig. 6a) for sludge electrodewatering by 5, 15 and 25 V in order to condition the sludge for agricultural use was studied with special focus on the removal of heavy metals and pathogens and evaluation of the nutrient content by (Rumky et al., 2020). Two-sided lab-scale device (Fig. 6b) was used for sludge EDW and conditioned digested sludge dewatered more efficiently than activated sludge. Specific resistance of activated sludge was 28% higher than that of digested one and activated sludge's solid fraction increased by up to 20 percent at 40 A/m^2. Filter cloth's different position was also assessed for digested sludge at 5 bar and 40 A/m^2 but the configuration did not affect much EDW performance (Mahmoud et al., 2018). There is a limitation of set-up presented in Fig. 6a, where excess water is collected after passing through the cathode area. This makes pH highly alkaline in cathode area when cations precipitate as hydroxides slowing down the electromigration. Thus, this set-up has less metal removal efficiency compared to two sided lab-scale device. As two sided lab-scale device has possibility of water collection from both anode and cathode side, metal removal will be enhanced.

Revitalizing sludge materials: exploring energy consumption in electrochemical processes and alternative utilization methods

The energy consumption of electrochemical processes for sludge treatment depends on various factors. These include the choice of electrode material and configuration, the applied voltage, the electrolyte composition, the characteristics of the sludge, the process duration, and the system efficiency. Optimizing these factors is crucial to minimize energy consumption, but optimization contributes to more sustainable and environmentally friendly sludge management practices. According to a study on dewaterability limit and energy consumption in sludge electro-dewatering process, the energy consumption in sludge electro-dewatering process was directly explored using linear sweep voltammetry (LSV) analysis by a high-voltage electrochemical workstation instead of a traditional DC power source (Yu et al., 2017). Another study found that the energy consumption (EC) and the costs of sludge treatment increase sharply with the increase of the production of high moisture content (MC) activated sludge in the process of industrialization (Sha et al., 2021). In terms of the energy saving and reduction of the water content, the pressure mode process (i.e., electro-osmotic dewatering) has performed better than the non-pressure mode process (i.e., electrochemical pretreatment) (Zeng et al., 2022). The cost of electrochemical processes are considered by few reserachers and according to the research, the total cost of transport and disposal of sludge is $50 per wet ton and 80€/ton by considering 4.5 kWh/t centrifuge energy and 67.49 kWh/t electro-dewatering (Rumky, 2022; Zeng et al., 2022).

After treatment, sludge can be used alternatively by considering as an organic and nutrient source or as a waste materials to be disposed of (Fig. 7). Due to improper disposal, numerous organic contaminants in raw and stabilized sewage sludge will cause secondary environmental contamination and have a negative impact on human health (Report, 2010). As a result of the complications associated with the desire to recycle the useful constituents of sludge, land application as a

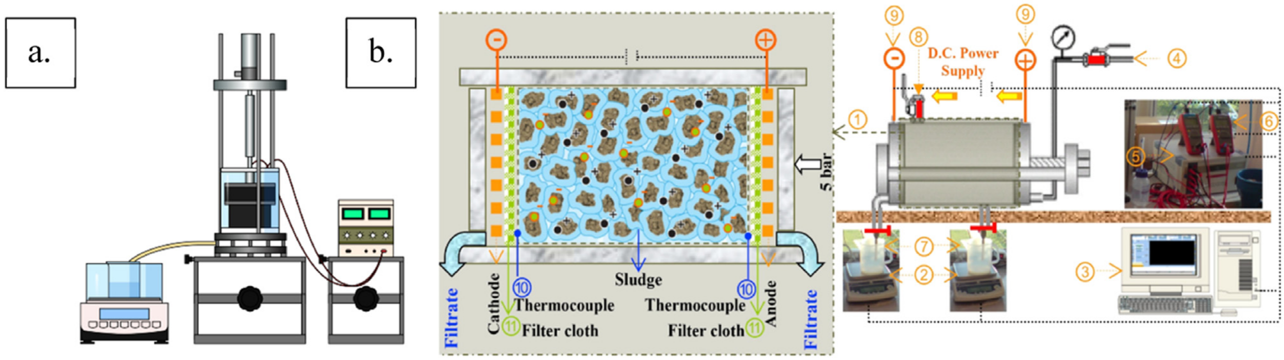

Fig. 6. Two different laboratory electro-dewatering set-up of sludge materials from two different research groups (a) consists of electronic scale with beaker, compression and electro-dewatering cell; (b) (1) Filtration/compression cell, (2) Electronic scale, (3) Computer and data acquisition software, (4) Movement sensor, (5) DC power supply, (6) Digital multimeter, (7) Filtrate collector, (8) Teflon piston (9) Electrodes (copied with permission from (*Mahmoud* et al.*, 2018*; *Rumky* et al.*, 2020*)).

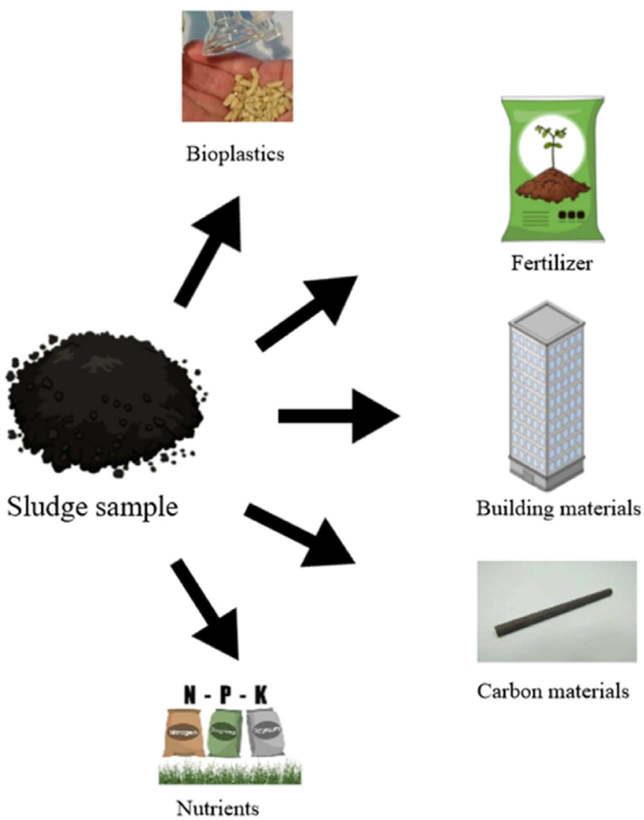

Fig. 7. Possible path for alternative usage of sludge materials.

form of efficiently reusing sludge has come into focus. However, the pollutants should be considered as they can enter soil by sludge disposal (Corradini et al., 2019).

On the other hand, sludge contains lots of nutrients especially phosphorus that should be recovered to be used as fertilizer. As we know, earth's phosphrous is being depleted at an alarming rate and price of the fertilizers has increased dramatically due to current political situation. At current consumption levels, we will run out of our reserve phosphorus, so phosphorus recovery from sludge is highly important. Many recovery technologies have been developed from sewage sludge or ash, but only a few have been implemented on a wide scale. Sludge in agriculture is a low-cost alternative for recycling phosphate, but must be sterilized before being applied to soil. Phosphate water solubility in biosolids is reduced by iron in waste sludge. This is considered to be a positive outcome in some cases because it prevents phosphorus from being lost in surface runoff (Lambert et al., 2022; Lu et al., 2012; Zeng et al., 2022).

Bulk phosphate, on the other hand, should be solubilized at very high and low pH. High acidification, for example, dissolves iron oxides and iron phosphate minerals and releases phosphate and Fe (III). Heavy metals and other metals, on the other hand, can dissolve at low pH. To increase the amount of phosphate available for recovery, phosphate has been leached from sludge in a number of ways. Alkaline treatment is another method for releasing phosphate from iron-containing sludge. It dissolves less metals than an acidic treatment but the phosphate in the liquid may be precipitated. Phosphate may be precipitated from the liquid process after solid-liquid separation to obtain calcium phosphate, a valuable recovery product that can be used directly in the fertilizer industry (Ohtake and Tsuneda, 2018). The ferrous iron phosphate mineral vivianite $Fe_2(PO_4)_3 \times 8H_2O$ can be directly precipitated from the solution at circumneutral pH if iron and phosphate are present. Even though vivianite can be found in dried sludge, at room temperature and usually above 700^0C, it transforms into amorphous iron phosphate in a matter of hours (Čermáková et al., 2015).

Besides, biodegradable plastic production from sludge as polyhydroxyalkanoate (PHA), is another promising way of sludge potentiality. Due to harmful effects of conventional plastics on the environment, biodegradable plastic preparation has became an important research area. Bioplastics can also be extracted from sludge and the process optimized by various parameters (duration, temperature & sludge solid conc.) (Kumar et al., 2018). PHA became alternative for petroleum-based plastics as the rapid depletion of petroleum reserves, as well as the prevalence of traditional synthetic plastics in the atmosphere are responsible for major environmental issues. The main barrier to the growth of the bioplastic market is the high cost of production, lack of recycling facilities, and inadequate waste management technology but Kumar et al., (2018) successfully optimized the extraction process by response surface methodology. Even the study clearly shows that "waste" should not be regarded as "waste," especially in light of its potential for extracting high-value products such as bioplastics (Brockhaus et al., 2016; Kumar et al., 2018).

To develop additional usage of sludge, sludge-based catalysts are widely accepted. To make this, sludge drying between 110 to 130^0C was considered as the best pretreatment and calcination happened at 300^0C for C1 (fresh mine tailings) & C2 (aged mine tailings), 500^0C for C3 (wastewater sludge from steel industry) and 450^0C for C4 (bottom sludge from petroleum storage) where higher organic content requires higher temperature. The synthesis of catalysts from sludge improved the thermal and energetic stability of the waste materials. C1 and C2 catalysts from the mining industry had a higher specific capacity and thermal stability than other catalysts, making them the best option for high-temperature processes. The production of catalysts from waste sludge will be a viable alternative for the recovery of waste from the mining and steel industries, as well as the storage of hydrocarbons, with a low E-factor that ensures the process's long-term viability. This process encouraged Ecuador to adopt a circular economy focused on the recycling of hazardous industrial waste (Castro-León et al., 2020). Even Rumky et al., (2023) studied the catalytic behavior of sludge for tetracycline removal after potitianium sulfate treatment and suggesting a new research avenue for future development. Mian and Liu, (2020) also studied the sludge biochar by different chemical/thermal treatment and the catalyst efficiently degraded the organic pollutant by peroxymonosulfate (PMS) activation. Moreover, Fe-rich sludge from the electro-Fenton is considered as a limitation of the process, but it could be used to make 3D electrodes by using a commercial 3D printer. As we know, this commercial electrode preparation will open the path for different applications of sludge based electrode materials (Arenas et al., 2017; Zhang et al., 2022).

Moreover, a basic pressing and carbonization process was used to transform waste sludge into bifunctional electrode materials. The poor conductivity of sewage sludge (SS) - derived biochar as an electrode material is the primary limitation due to the low carbon content of the SS. Fortunately, by combining waste biomass with SS prior to carbonization, this issue can be easily solved and 969 ± 28 mW m^{-2} power density was achieved from the microbial fuel cell of SS-derived carbon monoliths. Other electrochemical devices, such as other fuel cells, batteries, and energy storage, are expected to use SS as an electrode material, which could open up new opportunities for practical value-added applications of SS-derived biochar (Lambert et al., 2022; Yuan et al., 2015).

The possibility of using 10% sewage sludge by weight in concrete base layers was proposed by de Figueirêdo Lopes Lucena et al., 2014. To meet the minimum criteria for road bases, the soil stabilization technique was used to boost the residue properties. This stabilization technique intended to use common additives including cement, lime, and emulsion. The primary goal was to assess the changed soil's strength activity. For testing, sludge-soil mixtures with various additive contents (2, 4, 6, and 8%) were prepared. According to the results, the stabilization of soil mixtures with sewage sludge has the ability to be used in the pavement industry (de Figueirêdo Lopes Lucena et al., 2014).

In above sections, the possible uses for sludge materials after various treatment processes are taken into consideration. The use of sludge as a fertilizer has been restricted in some countries for a long time. Furthermore, pathogens can be found in sludge, so we must be extremely vigilant. Researchers are also investigating the use of sludge in a variety of other ways, including as a catalyst, electrode material, structural component, and the extraction of PHA. As a result, all of these possibilities give a sense of sludge that goes beyond waste.

Exploring the pros, cons, and future potential of electrochemical sludge treatment processes

Electrochemical processes offer efficient removal of pollutants from sludge, including heavy metals and organic compounds, with high selectivity for targeted contaminant removal. Methods such as electrocoagulation, electrooxidation effectively treat sludge and enhance its quality. Moreover, electrochemical treatment enables the recovery of valuable resources from sludge, such as phosphorus-rich compounds, reducing reliance on chemical fertilizers and generating renewable energy through microbial fuel cells or anaerobic digestion. Electrochemical disinfection methods like electrochlorination and electrooxidation effectively inactivate pathogens in sludge, ensuring safe disposal or reuse. These versatile processes can be applied to various sludge types, encompassing wastewater treatment, industrial, and agricultural sludge, and can be adapted to different scales and configurations, accommodating centralized and decentralized treatment systems (Qasem et al., 2021; Zeng et al., 2022).

However, there are several factors that need to be considered for their successful implementation of electro-chemical treatment of sludge. Cost-effectiveness can be improved with further research but the scaling up the processes for large-scale treatment may require additional optimization. Factors such as electrode configuration, power requirements, and hydraulic design must be carefully considered to ensure uniform treatment and effective contact with the electrodes. Managing operating conditions, including pH levels and current densities, becomes critical, requiring robust monitoring and control systems. Tailoring the processes to specific sludge types can ensure optimal performance but may increase complexity. Careful design, monitoring, and control are necessary for stable and efficient operation. Regulatory constraints and approval processes must be considered during implementation. Addressing these aspects will contribute to the successful integration of electrochemical processes in sludge treatment. While electrochemical processes show great promise for sludge treatment, it's important to address these limitations through ongoing research, development, and practical implementation. Continued innovation and optimization will contribute to their wider adoption and integration into sustainable sludge management practices (Feijoo et al., 2023).

Exploring the future applications of electrochemically treated sludge and concluding observation

The electrochemical treatment of sludge offers significant potential for improving dewaterability and the versatility of sludge materials. Different electrochemical processes can be applied depending on the desired outcome, such as nutrient recovery or sludge dewatering. Challenges, such as the pH limitations of certain processes and the high operating costs, need to be addressed for wider industrial-scale implementation. The development of new electrode materials and the utilization of 3D printed materials from sludge show promise for enhancing electrochemical processes in sludge treatment. Further research and exploration of pre-treatment methods, such as ultrasonic or vacuum techniques, can enhance the effectiveness and efficiency of electrochemical treatment. Despite the challenges, the future application of electrochemical processes in sludge treatment and resource recovery holds potential, with advancements in electrode materials and system stability contributing to their broader adoption.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Arenas, L.F., Ponce de León, C., Walsh, F.C., 2017. 3D-printed porous electrodes for advanced electrochemical flow reactors: A Ni/stainless steel electrode and its mass transport characteristics. Electrochem. Commun. 77, 133–137. doi:10.1016/j.elecom.2017.03.009.
Asghar, A., Abdul Raman, A.A., Daud, W.M.A.W., 2014. Recent advances, challenges and prospects of in situ production of hydrogen peroxide for textile wastewater treatment in microbial fuel cells. J. Chem. Technol. Biotechnol. doi:10.1002/jctb.4460.
Bello, M.M., Abdul Raman, A.A., Purushothaman, M., 2017. Applications of fluidized bed reactors in wastewater treatment – A review of the major design and operational parameters. J. Clean. Prod. doi:10.1016/j.jclepro.2016.09.148.
Brockhaus, S., Petersen, M., Kersten, W., 2016. A crossroads for bioplastics: exploring product developers' challenges to move beyond petroleum-based plastics. J. Clean. Prod. doi:10.1016/j.jclepro.2016.04.003.
Burgos-Castillo, R., Sillanpää, M., Brillas, E., Sirés, I., 2018. Removal of metals and phosphorus recovery from urban anaerobically digested sludge by electro-Fenton treatment. Sci. Total Environ. 644, 173–182. doi:10.1016/j.scitotenv.2018.06.337.

Cai, C., Liu, H., Wang, M., 2017. Characterization of antibiotic mycelial residue (AMR) dewatering performance with microwave treatment. Chemosphere 174, 20–27. doi:10.1016/j.chemosphere.2017.01.121.

Cai, M., Wang, Q., Wells, G., Dionysiou, D.D., Song, Z., Jin, M., Hu, J., Ho, S.H., Xiao, R., Wei, Z., 2019. Improving dewaterability and filterability of waste activated sludge by electrochemical Fenton pretreatment. Chem. Eng. J. 362, 525–536. doi:10.1016/j.cej.2019.01.047.

Cao, B., Zhang, T., Zhang, W., Wang, D., 2021. Enhanced technology based for sewage sludge deep dewatering: A critical review. Water Res. 189, 116650. doi:10.1016/j.watres.2020.116650.

Cao, B., Zhang, W., Du, Y., Wang, R., Usher, S.P., Scales, P.J., Wang, D., 2018. Compartmentalization of extracellular polymeric substances (EPS) solubilization and cake microstructure in relation to wastewater sludge dewatering behavior assisted by horizontal electric field: Effect of operating conditions. Water Res. 130, 363–375. doi:10.1016/j.watres.2017.11.060.

Castro-León, G., Baquero-Quinteros, E., Loor, B.G., Alvear, J., Montesdeoca Espín, D.E., Rosa, A.D.La, Montero-Calderón, C., 2020. Waste to catalyst: Synthesis of catalysts from sewage sludge of the mining, steel, and petroleum industries. Sustain 12, 1–16. doi:10.3390/su12239849.

Čermáková, Z., Švarcová, S., Hradilová, J., Bezdička, P., Lančok, A., Vašutová, V., Blažek, J., Hradil, D., 2015. Temperature-related degradation and colour changes of historic paintings containing vivianite. Spectrochim. Acta Part A Mol. Biomol. Spectrosc. doi:10.1016/j.saa.2014.12.082.

Chang, H., Zhao, Y., Bisinella, V., Damgaard, A., Christensen, T.H., 2023. Climate change impacts of conventional sewage sludge treatment and disposal. Water Res 240, 120109. doi:10.1016/j.watres.2023.120109.

Chen, Y., Chen, H., Li, J., Xiao, L., 2019. Rapid and efficient activated sludge treatment by electro-Fenton oxidation. Water Res. 152, 181–190. doi:10.1016/j.watres.2018.12.035.

Chen, Y., Yang, H., Gu, G., 2001. Effect of acid and surfactant treatment on activated sludge dewatering and settling. Water Res. 35, 2615–2620. doi:10.1016/S0043-1354(00)00565-0.

Chen, Z., Zhang, W., Wang, D., Ma, T., Bai, R., 2015. Enhancement of activated sludge dewatering performance by combined composite enzymatic lysis and chemical re-flocculation with inorganic coagulants: Kinetics of enzymatic reaction and re-flocculation morphology. Water Res. 83, 367–376. doi:10.1016/j.watres.2015.06.026.

Chowdhury, S.D., Bandyopadhyay, R., Bhunia, P., 2022. Reutilization of sludge as fertilizer, in: Clean Energy and Resource Recovery. Elsevier 423–434. doi:10.1016/B978-0-323-90178-9.00060-3.

Chu, C.P., Chang, B.V., Liao, G.S., Jean, D.S., Lee, D.J., 2001. Observations on changes in ultrasonically treated waste-activated sludge. Water Res. doi:10.1016/S0043-1354(00)00338-9.

Citeau, M., Olivier, J., Mahmoud, A., Vaxelaire, J., Larue, O., Vorobiev, E., 2012. Pressurised electro-osmotic dewatering of activated and anaerobically digested sludges: Electrical variables analysis. Water Res. 46, 4405–4416. doi:10.1016/j.watres.2012.05.053.

Colin, F., Gazbar, S., 1995. Distribution of water in sludges in relation to their mechanical dewatering. Water Res. doi:10.1016/0043-1354(94)00274-B.

Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E., Geissen, V., 2019. Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. Sci. Total Environ. doi:10.1016/j.scitotenv.2019.03.368.

de Figueirêdo Lopes Lucena, L.C., Thomé Juca, J.F., Soares, J.B., Portela, M., 2014. Potential Uses of Sewage Sludge in Highway Construction. J. Mater. Civ. Eng. 26, 04014051.

Demirbas, A., Edris, G., Alalayah, W.M., 2017. Sludge production from municipal wastewater treatment in sewage treatment plant. Energy Sources, Part A Recover. Util. Environ. Eff. doi:10.1080/15567036.2017.1283551.

Dey, A.R., Nekrasevits, A., Semken, R.S., Mikkola, A., Sihvonen, T., 2022. Applying ultrasound plus electrokinetics to enhance sludge dewatering. Dry. Technol. 40, 2990–3002. doi:10.1080/07373937.2021.1989460.

Dias, F.F., Oliveira, A.A.S., Arcanjo, A.P., Moura, F.C.C., Pacheco, J.G.A., 2016. Residue-based iron catalyst for the degradation of textile dye via heterogeneous photo-Fenton. Appl. Catal. B Environ. 186, 136–142. doi:10.1016/j.apcatb.2015.12.049.

Edwards, J., Othman, M., Crossin, E., Burn, S., 2017. Anaerobic co-digestion of municipal food waste and sewage sludge: A comparative life cycle assessment in the context of a waste service provision. Bioresour. Technol. 223, 237–249. doi:10.1016/j.biortech.2016.10.044.

Feijoo, S., Estévez, S., Kamali, M., Dewil, R., Moreira, M.T., 2023. Scale-up modelling and life cycle assessment of electrochemical oxidation in wastewater treatment. Chem. Eng. J. 455, 140627. doi:10.1016/j.cej.2022.140627.

Feng, C.H., Li, F.B., Mai, H.J., Li, X.Z., 2010. Bio-electro-fenton process driven by microbial fuel cell for wastewater treatment. Environ. Sci. Technol. doi:10.1021/es9032925.

Feng, J., Wang, Y.L., Ji, X.Y., 2014. Dynamic changes in the characteristics and components of activated sludge and filtrate during the pressurized electro-osmotic dewatering process. Sep. Purif. Technol. 134, 1–11. doi:10.1016/j.seppur.2014.07.019.

Gikas, P., 2017. Towards energy positive wastewater treatment plants. J. Environ. Manage. 203, 621–629. doi:10.1016/j.jenvman.2016.05.061.

Gronchi, P., Canziani, R., Brenna, A., Visigalli, S., Colominas, C., Montalà, F., Cot, V., Stradi, A., Ferrari, G., Diaz, C., Fuentes, G.G., Georgiadis, A., 2017. Electrode surface treatments in sludge electro-osmosis dewatering. Mater. Manuf. Process. doi:10.1080/10426914.2017.1279313.

Guo, S., Yuan, N., Zhang, G., Yu, J.C., 2017a. Graphene modified iron sludge derived from homogeneous Fenton process as an efficient heterogeneous Fenton catalyst for degradation of organic pollutants. Microporous Mesoporous Mater. 238, 62–68. doi:10.1016/j.micromeso.2016.02.033.

Guo, X., Wang, Y., Wang, D., 2017b. Permanganate/bisulfite (PM/BS) conditioning–horizontal electro-dewatering (HED) of activated sludge: Effect of reactive Mn(III) species. Water Res. 124, 584–594. doi:10.1016/j.watres.2017.08.027.

He, J., Yang, P., Zhang, W., Cao, B., Xia, H., Luo, X., Wang, D., 2017. Characterization of changes in floc morphology, extracellular polymeric substances and heavy metals speciation of anaerobically digested biosolid under treatment with a novel chelated-Fe2+ catalyzed Fenton process. Bioresour. Technol. 243, 641–651. doi:10.1016/j.biortech.2017.06.180.

Hu, K., Jiang, J.Q., Zhao, Q.L., Lee, D.J., Wang, K., Qiu, W., 2011. Conditioning of wastewater sludge using freezing and thawing: Role of curing. Water Res. 45, 5969–5976. doi:10.1016/j.watres.2011.08.064.

Hua, L.C., Huang, C., Su, Y.C., Nguyen, T.N.P., Chen, P.C., 2015. Effects of electro-coagulation on fouling mitigation and sludge characteristics in a coagulation-assisted membrane bioreactor. J. Memb. Sci. 495, 29–36. doi:10.1016/j.memsci.2015.07.062.

Huang, S., Zhou, X., Zhou, L., Huang, Z., Shen, J., 2022. Constant-current electro-dewatering of sewage sludge: Effect of anthracite modification on dehydration performance and economic benefit. J. Environ. Chem. Eng. 10, 107087. doi:10.1016/j.jece.2021.107087.

Kumar, M., Ghosh, P., Khosla, K., Thakur, I.S., 2018. Recovery of polyhydroxyalkanoates from municipal secondary wastewater sludge. Bioresour. Technol. doi:10.1016/j.biortech.2018.01.031.

Lambert, N., Van Aken, P., Smets, I., Appels, L., Dewil, R., 2022. Performance assessment of ultrasonic sludge disintegration in activated sludge wastewater treatment plants under nutrient-deficient conditions. Chem. Eng. J. 431, 133979. doi:10.1016/j.cej.2021.133979.

Li, C.W., Lin, J.L., Kang, S.F., Liang, C.L., 2005. Acidification and alkalization of textile chemical sludge: Volume/solid reduction, dewaterability, and Al(III) recovery. Sep. Purif. Technol. 42, 31–37. doi:10.1016/j.seppur.2004.06.001.

Li, H., Wang, Y., Zheng, H., 2018a. Variations of moisture and organics in activated sludge during Fe0/S2O82−conditioning–horizontal electro-dewatering process. Water Res. 129, 83–93. doi:10.1016/j.watres.2017.11.006.

Li, J., Liu, Y., Li, H., Chen, C., 2016a. Fabrication of g-C 3 N 4 /TiO 2 composite photocatalyst with extended absorption wavelength range and enhanced photocatalytic performance. J. Photochem. Photobiol. A Chem. 317, 151–160. doi:10.1016/j.jphotochem.2015.11.008.

Li, Q., Lu, X., Guo, H., Yang, Z., Li, Y., Zhi, S., Zhang, K., 2018b. Sewage sludge drying method combining pressurized electro-osmotic dewatering with subsequent bio-drying. Bioresour. Technol. 263, 94–102. doi:10.1016/j.biortech.2018.04.110.

Li, X., Chen, S., Angelidaki, I., Zhang, Y., 2018c. Bio-electro-Fenton processes for wastewater treatment: Advances and prospects. Chem. Eng. J. 354, 492–506. doi:10.1016/j.cej.2018.08.052.

Li, Y., Yuan, X., Wu, Z., Wang, H., Xiao, Z., Wu, Y., Chen, X., Zeng, G., 2016b. Enhancing the sludge dewaterability by electrolysis/electrocoagulation combined with zero-valent iron activated persulfate process. Chem. Eng. J. doi:10.1016/j.cej.2016.06.041.

Liang, J., Huang, S., Dai, Y., Li, L., Sun, S., 2015. Dewaterability of five sewage sludges in Guangzhou conditioned with Fenton's reagent/lime and pilot-scale experiments using ultrahigh pressure filtration system. Water Res. doi:10.1016/j.watres.2015.07.041.

Lu, Q., He, Z.L., Stoffella, P.J., 2012. Land application of biosolids in the USA: A review. Appl. Environ. Soil Sci. doi:10.1155/2012/201462.

Lv, H., Liu, D., Zhang, Y., Yuan, D., Wang, F., Yang, J., Wu, X., Zhang, W., Dai, X., 2019. Effects of temperature variation on wastewater sludge electro-dewatering. J. Clean. Prod. 214, 873–880. doi:10.1016/j.jclepro.2019.01.033.

Ma, D., Lin, S., Cui, C., Zhai, J., 2018. Application of weak ultrasonic treatment on sludge electro-osmosis dewatering. Environ. Technol. (U.K.) doi:10.1080/21622515.2017.1329351.

Mahmoud, A., Hoadley, A.F.A., Citeau, M., Sorbet, J.M., Olivier, G., Vaxelaire, J., Olivier, J., 2018. A comparative study of electro-dewatering process performance for activated and digested wastewater sludge. Water Res. 129, 66–82. doi:10.1016/j.watres.2017.10.063.

Mahmoud, A., Olivier, J., Vaxelaire, J., Hoadley, A.F.A., 2013. Advances in mechanical dewatering of wastewater sludge treatment. Wastewater Reuse and Management 253–303. doi:10.1007/978-94-007-4942-9_9.

Mahmoud, A., Olivier, J., Vaxelaire, J., Hoadley, A.F.A., 2011. Electro-dewatering of wastewater sludge: Influence of the operating conditions and their interactions effects. Water Res. 45, 2795–2810. doi:10.1016/j.watres.2011.02.029.

Mahmoud, A., Olivier, J., Vaxelaire, J., Hoadley, A.F.A., 2010. Electrical field: A historical review of its application and contributions in wastewater sludge dewatering. Water Res. 44, 2381–2407. doi:10.1016/j.watres.2010.01.033.

Martin, L., Alizadeh, V., Meegoda, J., 2019. Electro-osmosis treatment techniques and their effect on dewatering of soils, sediments, and sludge: A review. Soils Found doi:10.1016/j.sandf.2018.12.015.

Mason, T.J., 2007. Sonochemistry and the environment - Providing a "green" link between chemistry, physics and engineering. Ultrason. Sonochem. doi:10.1016/j.ultsonch.2006.10.008.

Mian, M.M., Liu, G., 2020. Activation of peroxymonosulfate by chemically modified sludge biochar for the removal of organic pollutants: Understanding the role of active sites and mechanism. Chem. Eng. J. doi:10.1016/j.cej.2019.123681.

Mikkelsen, L.H., Keiding, K., 2002. Physico-chemical characteristics of full scale sewage sludges with implications to dewatering. Water Res. 36, 2451–2462. doi:10.1016/S0043-1354(01)00477-8.

Mowla, D., Tran, H.N., Allen, D.G., 2013. A review of the properties of biosludge and its relevance to enhanced dewatering processes. Biomass and Bioenergy 58, 365–378. doi:10.1016/j.biombioe.2013.09.002.

Navab-Daneshmand, T., Beton, R., Hill, R.J., Frigon, D., 2015. Impact of Joule Heating and pH on Biosolids Electro-Dewatering. Environ. Sci. Technol. 49, 5417–5424. doi:10.1021/es5048254.

Navab Daneshmand, T., Beton, R., Hill, R.J., Gehr, R., Frigon, D., 2012. Inactivation mechanisms of bacterial pathogen indicators during electro-dewatering of activated sludge biosolids. Water Res. doi:10.1016/j.watres.2012.05.009.

Neyens, E., Baeyens, J., 2003. A review of thermal sludge pre-treatment processes to improve dewaterability. J. Hazard. Mater. 98, 51–67. doi:10.1016/S0304-3894(02)00320-5.

Ohtake, H., Tsuneda, S., 2018. Phosphorus Recovery and Recycling, Phosphorus Recovery and Recycling. https://doi.org/10.1007/978-981-10-8031-9

Olivier, J., Conrardy, J.B., Mahmoud, A., Vaxelaire, J., 2015. Electro-dewatering of wastewater sludge: An investigation of the relationship between filtrate flow rate and electric current. Water Res. 82, 66–77. doi:10.1016/j.watres.2015.04.006.

Olvera-Vargas, H., Zheng, X., Garcia-Rodriguez, O., Lefebvre, O., 2019. Sequential "electrochemical peroxidation – Electro-Fenton" process for anaerobic sludge treatment. Water Res. 154, 277–286. doi:10.1016/j.watres.2019.01.063.

Pham-Anh, T., Sillanpää, M., Isosaari, P., 2012. Sewage Sludge Electro-Dewatering Treatment—A Review. Dry. Technol. 30, 691–706. doi:10.1080/07373937.2012.654874.

Qasem, N.A.A., Mohammed, R.H., Lawal, D.U., 2021. Removal of heavy metal ions from wastewater: a comprehensive and critical review. NPJ Clean Water 4, 36. doi:10.1038/s41545-021-00127-0.

Qian, X., Wang, Y., Zheng, H., 2016. Migration and distribution of water and organic matter for activated sludge during coupling magnetic conditioning-horizontal electro-dewatering (CM-HED). Water Res. 88, 93–103. doi:10.1016/j.watres.2015.10.001.

Rao, B., Pang, H., Fan, F., Zhang, J., Xu, P., Qiu, S., Wu, X., Lu, X., Zhu, J., Wang, G., Su, J., 2021. Pore-scale model and dewatering performance of municipal sludge by ultrahigh pressurized electro-dewatering with constant voltage gradient. Water Res. doi:10.1016/j.watres.2020.116611.

Report, C., 2010. Environmental, economic and social impacts of the use of sewage sludge on land. Consult. Rep. Opt. Impact 1–32.

Riera-Franco De Sarabia, E., Gallego-Juárez, J.A., Rodríguez-Corral, G., Elvira-Segura, L., González-Gómez, I., 2000. Application of high-power ultrasound to enhance fluid/solid particle separation processes. Ultrasonics doi:10.1016/S0041-624X(99)00129-8.

Ruiz-Hernando, M., Simón, F.X., Labanda, J., Llorens, J., 2014. Effect of ultrasound, thermal and alkali treatments on the rheological profile and water distribution of waste activated sludge. Chem. Eng. J. doi:10.1016/j.cej.2014.06.036.

Rumky, J., 2022. Sludge Valorization by Chemical and Electrochemical Processes. LUT University. https://urn.fi/URN:ISBN:978-952-335-871-3.

Rumky, J., Bandina, E., Repo, E., 2023. Behavior of Sludge Dewaterability and Nutrient Contents after Treatment with Cellulose-Based Flocculants with Combined PTS and Catalytic Behavior of Sludge towards Tetracycline Degradation. Resources 12, 17. doi:10.3390/resources12020017.

Rumky, J., Visigalli, S., Turolla, A., Gelmi, E., Necibi, C., Gronchi, P., Sillanpää, M., Canziani, R., 2020. Electro-dewatering treatment of sludge: Assessment of the influence on relevant indicators for disposal in agriculture. J. Environ. Manage. 268, 110689. doi:10.1016/j.jenvman.2020.110689.

Sha, L., Wu, Z., Ling, Z., Liu, X., Yu, X., Zhang, S., 2021. Dewaterability and energy consumption of electro-dewatered sludge near the anode and the cathode during electro-dewatering process. J. Environ. Chem. Eng. 9, 105729. doi:10.1016/j.jece.2021.105729.

Sha, L., Yu, X., Wu, Z., Liu, X., Wang, H., Jiang, Q., Zhang, S., 2020. Study of the variations in apparent electrical resistivity of activated sludge during the electro-dewatering process. Environ. Res. doi:10.1016/j.envres.2020.110453.

Shen, K., Xu, H., Ding, M., Cui, J., 2016. Dewatering of drinking water treatment sludge by vacuum electro-osmosis. Sep. Sci. Technol. doi:10.1080/01496395.2016.1201111.

Shi, Y., Yang, J., Yu, W., Zhang, S., Liang, S., Song, J., Xu, Q., Ye, N., He, S., Yang, C., Hu, J., 2015. Synergetic conditioning of sewage sludge via Fe2+/persulfate and skeleton builder: Effect on sludge characteristics and dewaterability. Chem. Eng. J. 270, 572–581. doi:10.1016/j.cej.2015.01.122.

Sichler, T.C., Adam, C., Montag, D., Barjenbruch, M., 2022. Future nutrient recovery from sewage sludge regarding three different scenarios - German case study. J. Clean. Prod. 333, 130130. doi:10.1016/j.jclepro.2021.130130.

Solé-Bundó, M., Garfí, M., Matamoros, V., Ferrer, I., 2019. Co-digestion of microalgae and primary sludge: Effect on biogas production and microcontaminants removal. Sci. Total Environ. 660, 974–981. doi:10.1016/j.scitotenv.2019.01.011.

Stefanakis, A., Akratos, C.S., Tsihrintzis, V.A., 2014. Vertical Flow Constructed Wetlands: Eco-engineering Systems for Wastewater and Sludge Treatment, Vertical Flow Constructed Wetlands: Eco-engineering Systems for Wastewater and Sludge Treatment. Elsevier doi:10.1016/C2012-0-01288-4.

Tuan, P.A., Sillanpää, M., 2010. Effect of freeze/thaw conditions, polyelectrolyte addition, and sludge loading on sludge electro-dewatering process. Chem. Eng. J. doi:10.1016/j.cej.2010.08.028.

Usack, J.G., Van Doren, L.G., Posmanik, R., Tester, J.W., Angenent, L.T., 2019. Harnessing anaerobic digestion for combined cooling, heat, and power on dairy farms: An environmental life cycle and techno-economic assessment of added cooling pathways. J. Dairy Sci. 102, 3630–3645. doi:10.3168/jds.2018-15518.

Vaxelaire, J., Cézac, P., 2004. Moisture distribution in activated sludges: A review. Water Res. doi:10.1016/j.watres.2004.02.021.

Visigalli, S., Turolla, A., Gronchi, P., Canziani, R., 2017. Performance of electro-osmotic dewatering on different types of sewage sludge. Environ. Res. 157, 30–36. doi:10.1016/j.envres.2017.05.015.

Wang, K., Wu, Y., Wang, Z., Wang, W., Ren, N., 2018. Insight into effects of electro-dewatering pretreatment on nitrous oxide emission involved in related functional genes in sewage sludge composting. Bioresour. Technol. 265, 25–32. doi:10.1016/j.biortech.2018.05.089.

Wei, H., Gao, B., Ren, J., Li, A., Yang, H., 2018. Coagulation/flocculation in dewatering of sludge: A review. Water Res. 143, 608–631. doi:10.1016/j.watres.2018.07.029.

Wu, Y., Zhang, P., Zhang, H., Zeng, G., Liu, J., Ye, J., Fang, W., Gou, X., 2016. Possibility of sludge conditioning and dewatering with rice husk biochar modified by ferric chloride. Bioresour. Technol. 205, 258–263. doi:10.1016/j.biortech.2016.01.020.

Xiao, J., Wu, X., Yu, W., Liang, S., Yu, J., Gu, Y., Deng, H., Hu, J., Xiao, K., Yang, J., 2017. Migration and distribution of sodium ions and organic matters during electro-dewatering of waste activated sludge at different dosages of sodium sulfate. Chemosphere 189, 67–75. doi:10.1016/j.chemosphere.2017.09.034.

Xu, H., Ding, T., 2016. Influence of vacuum pressure, pH, and potential gradient on the vacuum electro-osmosis dewatering of drinking water treatment sludge. Dry. Technol. doi:10.1080/07373937.2015.1095203.

Xu, H., Shen, K., Ding, T., Cui, J., Ding, M., Lu, C., 2016. Dewatering of drinking water treatment sludge using the Fenton-like process induced by electro-osmosis. Chem. Eng. J. 293, 207–215. doi:10.1016/j.cej.2016.02.025.

Xu, X., Cao, D., Wang, Zonghua, Liu, J., Gao, J., Sanchuan, M., Wang, Zhenjun, 2019. Study on ultrasonic treatment for municipal sludge. Ultrason. Sonochem. doi:10.1016/j.ultsonch.2019.05.008.

Yin, X., Lu, X., Han, P., Wang, Y., 2006. Ultrasonic treatment on activated sewage sludge from petro-plant for reduction. Ultrasonics. doi:10.1016/j.ultras.2006.05.187.

Yu, Q., Jin, X., Zhang, Y., 2018. Sequential pretreatment for cell disintegration of municipal sludge in a neutral Bio-electro-Fenton system. Water Res. 135, 44–56. doi:10.1016/j.watres.2018.02.012.

Yu, W., Yang, J., Wu, X., Gu, Y., Xiao, J., Yu, J., Shi, Y., Wang, J., Liang, S., Liu, B., Hou, H., Hu, J., 2017. Study on dewaterability limit and energy consumption in sewage sludge electro-dewatering by in-situ linear sweep voltammetry analysis. Chem. Eng. J. 317, 980–987. doi:10.1016/j.cej.2017.02.137.

Yuan, Y., Liu, T., Fu, P., Tang, J., Zhou, S., 2015. Conversion of sewage sludge into high-performance bifunctional electrode materials for microbial energy harvesting. J. Mater. Chem. A 3, 8475–8482. doi:10.1039/c5ta00458f.

Zeng, Q., Hao, T., Yuan, Z., Chen, G., 2020. Dewaterability enhancement and sulfide mitigation of CEPT sludge by electrochemical pretreatment. Water Res. doi:10.1016/j.watres.2020.115727.

Zeng, Q., Huang, H., Tan, Y., Chen, G., Hao, T., 2022. Emerging electrochemistry-based process for sludge treatment and resources recovery: A review. Water Res. 209, 117939. doi:10.1016/j.watres.2021.117939.

Zhang, D., Hou, R., Wang, W., Zhao, H., 2022. Recovery and reuse of floc sludge for high-performance capacitors. Front. Environ. Sci. Eng. 16, 78. doi:10.1007/s11783-021-1512-5.

Zhang, M., Zhang, Z., Liu, S., Peng, Y., Chen, J., Yoo Ki, S., 2020. Ultrasound-assisted electrochemical treatment for phenolic wastewater. Ultrason. Sonochem. 65. doi:10.1016/j.ultsonch.2020.105058.

Zhang, Q., Hu, J., Lee, D.J., Chang, Y., Lee, Y.J., 2017a. Sludge treatment: Current research trends. Bioresour. Technol. 243, 1159–1172. doi:10.1016/j.biortech.2017.07.070.

Zhang, S., Yang, Z., Lv, X., Zhi, S., Wang, Y., Li, Q., Zhang, K., 2017b. Novel electro-dewatering system for activated sludge biosolids in bench-scale, pilot-scale and industrial-scale applications. Chem. Eng. Res. Des. 121, 44–56. doi:10.1016/j.cherd.2017.02.035.

Zhang, W., Yang, P., Yang, X., Chen, Z., Wang, D., 2015a. Insights into the respective role of acidification and oxidation for enhancing anaerobic digested sludge dewatering performance with Fenton process. Bioresour. Technol. 181, 247–253. doi:10.1016/j.biortech.2015.01.003.

Zhang, Y., Wang, Y., Angelidaki, I., 2015b. Alternate switching between microbial fuel cell and microbial electrolysis cell operation as a new method to control H2O2 level in Bioelectro-Fenton system. J. Power Sources doi:10.1016/j.jpowsour.2015.05.020.

Zhen, G., Lu, X., Zhao, Y., Chai, X., Niu, D., 2012. Enhanced dewaterability of sewage sludge in the presence of Fe(II)-activated persulfate oxidation. Bioresour. Technol. doi:10.1016/j.biortech.2012.01.170.

Zhen, G.Y., Lu, X.Q., Li, Y.Y., Zhao, Y.C., 2013. Innovative combination of electrolysis and Fe(II)-activated persulfate oxidation for improving the dewaterability of waste activated sludge. Bioresour. Technol. 136, 654–663. doi:10.1016/j.biortech.2013.03.007.

Zhu, X., Ni, J., 2009. Simultaneous processes of electricity generation and p-nitrophenol degradation in a microbial fuel cell. Electrochem. Commun. doi:10.1016/j.elecom.2008.11.023.