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Current applications of electrocoagulation in water treatment: a review

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ABSTRACT

Electrocoagulation (EC) is known as an environmentally friendly technology for treatment of water or wastewater through a combination process of coagulation, oxidation and flotation. The rapid development of industry and agriculture, as well as the ineffective disposal of waste, may lead to a substantial increase in the loadings of water treatment. EC can be used for treatment of different types of water such as tannery and dyeing wastewater, organic wastewater, sewage, drinking water and heavy metal wastewater. An effective EC reactor system can show a good treatment efficiency but it requires a good design and operation of EC. Recently, the EC has been developed rapidly toward development of new electrodes and applicable operation modes, and thus more efficient EC systems for treatment of various water pollutants have emerged. In the present work, a brief overview of the recent research dealing with the application of electrodes and the coupling processes of EC with other technologies are presented.

Keywords: Electrocoagulation; Coagulation–flocculation; Water treatment; Electrodes

1. Introduction

Water pollution due to poor waste control in different agricultural industries has led to many pollutants including increased dissolved organic nitrogen [1]. Hexavalent chromium [Cr(VI)] and other carcinogenic pollutants are becoming more of a problem as industry waste products seep into groundwater [2]. With the rapid development of industry and agriculture, water pollution has become more serious. Thus, finding an efficient, economic and environmentally safe way to deal with water pollution has become a current focus of attention [1,2]. In the last few decades, many high-tech methods for the treatment of different kinds of polluted water have been developed [3–5], such as advanced oxidation, coagulation–flocculation, adsorption, biodegradation and filtration. Among them coagulation is one of the most important water treatment methods. Because it is easy-to-use, cost-effective and highly efficient, it has become an important pretreatment operation unit in both purification plants and sewage plants.

Electrocoagulation (EC) or electroflotation is an environmentally friendly technology [6]. EC uses the soluble anode and makes use of the electrochemical reaction during an integrated air flotation process, which creates the bubbles needed to capture pollutants and bring them to the surface. The pollutants are in the form of flocculant agglomerating suspended solids; moreover, a little oxidizing agent is also generated in the process to achieve the effect of removing

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partial organics [7]. The treatment process of EC is relatively complicated: Under the action of an electric field, soluble metal anodes produce cations into the water followed by various physical and chemical phenomena. In the process, from the generation of cations to the forming of flocs, three effects can be observed: (1) the flocculation effect [8,9], (2) the redox effect [9] and (3) the flotation effect [10]. The principle schematic diagram of EC reaction is as shown in Fig. 1, which was described by Holt et al. [11] in detail, who used Al as an anode and cathode.

Compared with traditional chemical flocculation, EC can remove pollutants without using chemical agents. Compared with biological treatment, cultivating microorganisms for EC is not necessary, which saves much performance time [12]. Compared with membrane treatment, EC is less affected by the environment, and the operation is easier. Therefore, EC is widely applied to the treatment of various kinds of polluted water. EC has the following advantages [13–15]: less secondary pollution occurs throughout the process; its equipment is simple and easy-to-use; it is efficient, convenient, universal and environmentally compatible in that EC can work under normal temperatures and pressure. Finally, EC can be combined with other treatment processes to increase biodegradation of wastewater. In a word, compared with traditional water treatment methods, EC has characteristics of high efficiency, low-energy consumption, easy operation and less pollution [10,16,17], making it a very effective water treatment method.

With the rapid growth of the economy, people's consumption level also increases. Water pollution has shown multiple complexity, and improving water quality and safety is a high priority for most people. Establishing efficient, environmentally sustainable, low-energy consumption in EC water treatment technology is currently one of the important research directions in the field of environmental science. EC has achieved significant progress with the development of relevant subjects. Currently, exploring highly efficient electrode material, match patterns and coupling applications of EC with other technologies are the key points to improving EC efficiency. This paper systematically summarizes the application effect of EC with different electrodes or EC coupling with other technologies in the treatment of different kinds of polluted water, and then proposes development in the direction of EC in the future.

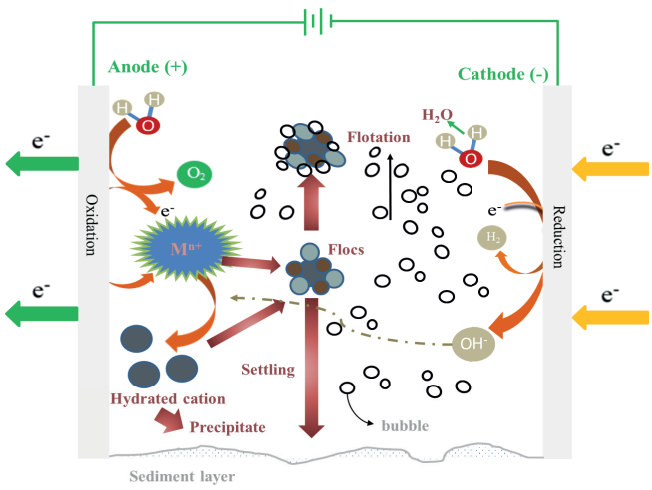

Fig. 1. Principle schematic diagram of EC reaction (M stands for the metal element).

2. EC reactor

According to the classification of operation mode, the EC reactor system (ERS) can be divided into two types: (1) a batch EC reactor system (BERS) and (2) a continuous flow EC reactor system (CFERS) [18]. For a simple ERS to do batch experiments as shown in Fig. 2(a), it only needs a power supply, digital magnetic stirrer, electrochemical cell, anode and cathode, while other auxiliary instruments such as a digital ampere meter and voltmeter, pH meter and conductimeter can also be added to observe the water quality parameters [19]. Fig. 2(b) shows a simple schematic diagram of an ERS, which was used for removal of hexavalent chromium in a batch experiment [20]. Monopolar electrodes can also be used. Fig. 2(c) shows an ERS for treatment of textile wastewater with the monopolar electrodes [21].

Also, a BERS could be constructed in a lab using Perspex with five stainless steel cathodes and four aluminum anodes for treatment of clay pollutants as shown in Fig. 2(d) [11,18]. For a BERS, the electrodes should be washed before each run and the solution with or without a certain pretreatment can be analyzed at the end of EC reaction.

The CFERS, as shown in Fig. 3 can be carried out by a continuously circulating process with a mechanical pump such as a peristaltic pump or a centrifugal pump. In practical engineering, the CFERS would be more helpful in a pilot-scale experiment because it can ensure the continuous operation of water treatment, and the operation is more convenient and even easy to implement in coupling with other water treatment processes. However, compared with the BESR, the CFERS would need higher voltage inputs to achieve the same electrocoagulation flotation (ECF) efficiency as found in the flowing fluid volumes taking less time via electrodes and less contact with metal ions [22]. Figs. 3(a) and (b) show a detailed CFERS, which was applied to the removal of natural organic matter (NOM) and arsenic from groundwater [23] and decolorization of textile dye wastewater [24], respectively. Compared with Fig. 3(a), Fig. 3(b) added a sludge treatment strategy. The sludge separation in chemical coagulation may be achieved through sedimentation while in the ERS, the sludge can be separated by sedimentation or by flotation, which is determined by the size of current density [25]. Therefore, the sludge can be moved to the second compartment through flotation. Overall, the basical composition is similar to that of BERS. Fig. 3(c) shows an ERS in a pilot-scale setup, which was prepared by Zodi et al. [26]. The operation flow and construction of the system can be clearly seen from the figure. CFERS can also be more easily combined with other processes to further clear wastewater. As shown in Fig. 3(d), a CFERS was constructed in the lab using a Perspex sheet [27]. After the EC reaction, the filltration process was carried out and the finished water quality parameters were then analyzed. In a CFERS, it was reported that the ECF efficiency, fluid flow rate, energy input and voltage inputs existed in a relationship, indicating that the ratio of

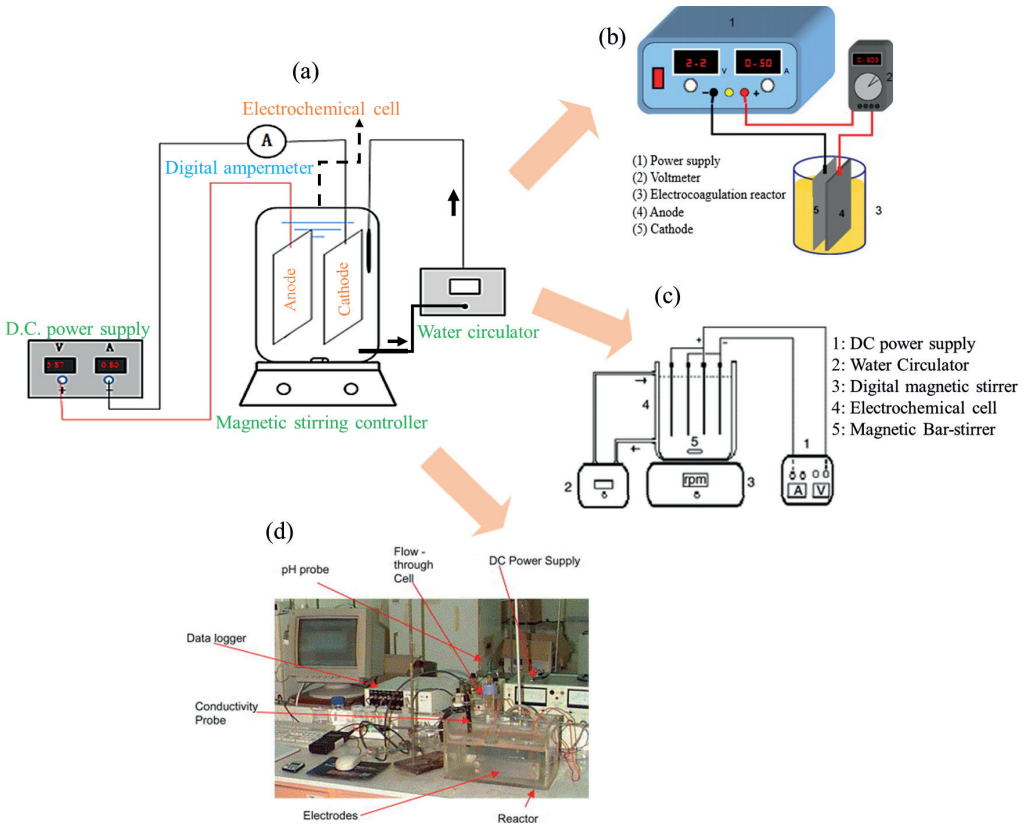

Fig. 2. Schematic diagram of EC experimental setup in a batch EC reactor system (BERS): (a) in-house BERS, (b) BERS [20], (c) BERS [21] and (d) BERS [11,18].

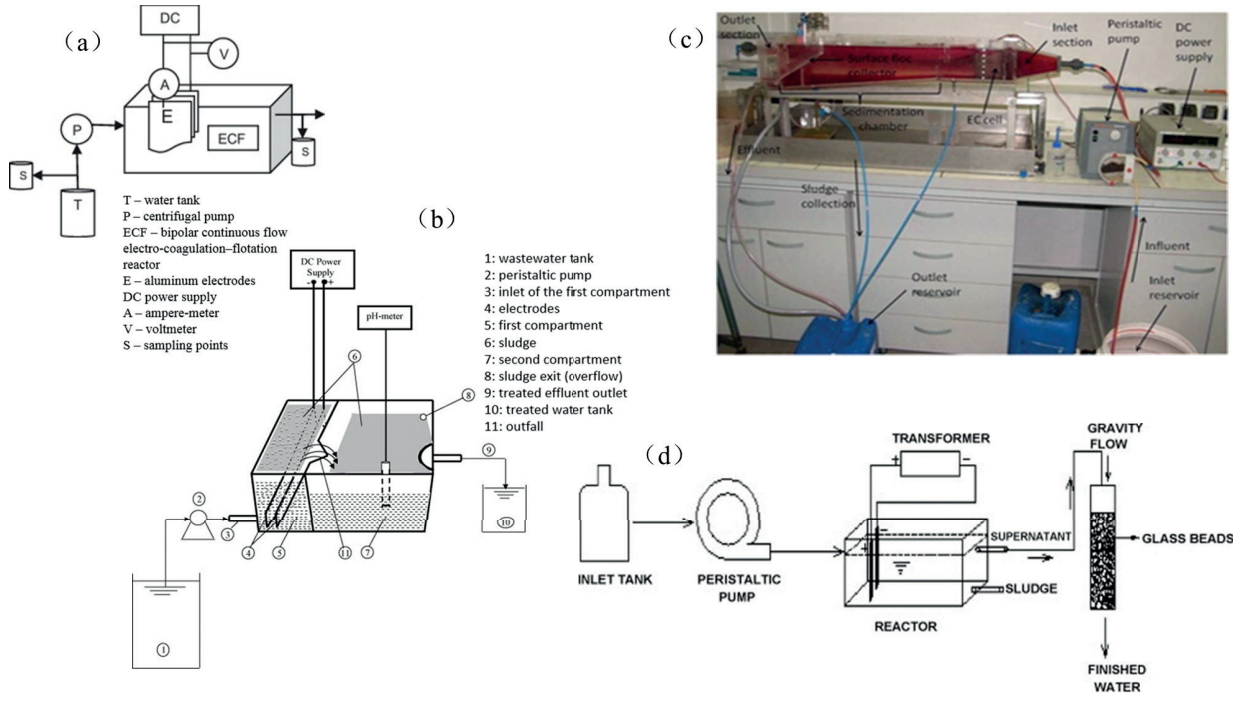

Fig. 3. Schematic diagram of EC experimental setup: (a) CFERS [23], (b) CFERS [24], (c) CFERS [26], and (d) CFERS [27].

ECF efficiency to energy input achieved the highest ECF efficiency for the lowest voltage inputs and highest flow rates, while higher voltage inputs and lower flow rates could result in higher ECF efficiencies [22]. Therefore, a rational design of CFERS is helpful to improve the efficiency of EC and reduce energy consumption.

3. Electrode

EC performance closely relates to electrode use. Traditional plate electrodes generally adopt Al and Fe electrodes. Taking Al or Fe as a sacrificial anode as an example, metal ions release from the sacrificial anode, which forms an ionic monomer and various kinds of hydrolysate. The principle of electrode reaction [25] is shown in Table 1.

Table 1 shows that metal ions formed by oxidation dissolution of soluble anodes form multinuclear hydrolysate [8]. Through charge neutralization, sweep flocculation and adsorption bridging action, the multinuclear hydrolysate reacts with impurities in water, and forms floc, and then removes the impurities by sedimentation and flotation [9]. The multinuclear hydrolysate combines with hydroxy and produces new hydroxide with features of stronger activity, and better sediment performance, which can be used as a good flocculant. Electron exchange happens directly on electrode. Soluble anodes lose electrons and dissolve into positively charged hydrolytic metal oxide. In addition, water generates O_2 through electrolysis; cathode gains electrons and gets hydrogen with oxidizability of water reduction. Second, under the action of electric field, N and P elements, part of the macromolecular organics and cyanide, will be changed into micromolecular organics and a harmless ingredient, even into N_2, CO_2 and H_2O. This process is called indirect redox titrimetry [6]. At last, oxidation of anodes can oxygenize chloride and make it lose electrons thereby transforming into chlorine or hypocholoride with sterilization effect [28]. In addition, when adopting Fe as the electrode at the dissolving place of the anode plate, the Fe^{2+} product is a strong reducing agent that can reduce high-valence heavy metal (such as Cr(VI)). In the course of EC, H_2 and O_2 are produced at both the anode and cathode by water electrolysis. When bubble size is relatively small but larger than the surface area, it adheres to suspended solids, colloids and other pollutants and rises to water surface by flotation, thus removing impurities in water [10]. Since the bubble created by EC is small, its flotation ability is stronger and the removing effect is better. In addition, EC also has functions of redox, sterilization, adjusting pH value and adsorption co-sedimentation, and it can remove various kinds of pollutants [29].

Electrodes are a consumable material, and their electrochemical properties show obvious differences. For example, Ulu et al. [30] studied the effect of using the EC method with different electrodes to remove NOM. The result showed that the dissolved organic carbon (DOC) removal rate of Al, Fe and dual electrodes (Al/Fe) were 71.1%, 59.8% and 68.6%, respectively. The Al electrode possessed better performance in removing NOM. Performance assessment required finding electrode material of lower energy consumption and higher efficiency, including various plate shapes and wider electrode material. For example, using metal with strong electrical conductivity like Ti as plate material increased the electrical conductivity of EC [31] or using a 3-D electrode [32,33] that added particles or fragment packing in a traditional 2-D electrode electrolytic tank to electrify 3-D electrode packing, forming a new working electrode on which electrochemical reaction can occur.

Table 1
The principle of electrode reaction

Item	Condition	Equation	
Al anode electrolytic reaction		$Al \rightarrow Al^{3+} + 3e$	(1)
	Alkaline condition	$Al^{3+} + 3OH^- \rightarrow Al(OH)_3$	(2)
	Acidic condition	$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$	(3)
Fe anode electrolytic reaction		$Fe \rightarrow Fe^{2+} + 2e$	(4)
	Alkaline condition	$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$	(5)
	Acidic condition	$4Fe^{2+} + O_2 + 2H_2O \rightarrow 4Fe^{3+} + 4OH^-$	(6)
H_2O electrolytic reaction of anode		$2H_2O \rightarrow O_2 + 4H^+ + 4e$	(7)
Reaction of anode containing Cl^-		$2Cl^- \rightarrow Cl_2 + 2e$	(8)
		$Cl_2 + H_2O \rightarrow HClO + H^+ + Cl^-$	(9)
		$HClO \rightarrow H^+ + ClO^-$	(10)
H_2O electrolytic reaction of cathode		$2H_2O + 2e \rightarrow H_2 + 2OH^-$	(11)

3.1. Al electrode

Tian et al. [34] with Al as the sacrificial anode used an activated carbon air cathode to process model wastewater to remove organic matter and nutrients in wastewater. This method could effectively remove N, P, chemical oxygen demand (COD) and total suspended solids (TSS). An experiment used a 1.5 cm plate space, a current density of 8 A/m^2, and an electrolysis time of 4 h at a removal rate of 99%, 99%, 72%–81% and 78%–89%, respectively. The results showed that activated carbon air cathode could remove nutrients with lower energy. Palahouane et al. [35] adopted the electrochemical method for the pretreatment of fluoride ions in photovoltaic wastewater. The experiment was conducted under the conditions of using an Al plate as the working electrode, a plate space of 1 cm, plate number 3, pH 7, a current density at 18.51 A/m^2, energy consumption was 0.32 kW h/m^3 and the removal rate was 95%. The results showed that EC could effectively remove fluoride ions in photovoltaic wastewater. Millar et al. [36] discussed EC performance in a coalbed water treatment. By imposing current density, current time and electrolysis time, they tried to promote the formation of calcium scale in the reverse osmosis device, and to realize a high removal rate of heavy metal ion. The removal rate of Ca, Mg, Sr, Ba and silicate were 100%, 87.9%, 99.3%, 100% and 98.3%, respectively. The experiment results showed that EC could make an effective pretreatment of coalbed water and remove the heavy metal ions inside. Liao et al. [37] separately used Al and iridium oxide as anodes to do a comparative experiment on processing municipal solid waste incineration (MSWI) fly ash and landfill leachate. It adopted an innovative EC technology to change fly ash ingredients into harmless material and stabilized the heavy metal content of fly ash. The results showed that iridium oxide anodes lacked coagulation effect while Al anodes could effectively process MSWI fly ash and landfill leachate, which proved to be a feasible method.

3.2. Fe electrode

Yazdanbakhsh et al. [38] explored method for removing COD in modeling wastewater using electrochemical oxidation process with Fe as anode. The experiment studied pH value, hydrogen peroxide amount, current density, electrolysis time and other factors' influence on COD removal efficiency to determine the optimal technique. The experiment results showed that the best conditions for removing COD were a current density of 20 mA/cm^2, a hydrogen peroxide concentration of 2 mg/L, an electrolysis time of 60 min, pH of 3 and a corresponding removal rate of 95.6%. Kobya et al. [39] used EC to remove As in underground water, and evaluated the removal efficiency when adopting Fe plate and Fe ball as anodes separately. The experiment determined the best operating conditions. When an Fe plate was used as anode, the best conditions were pH = 7.6 with current of 0.3 A, flow rate of 6 L/min, electrolysis time of 20 min and the removal rate of As was 99.3%. When an Fe ball was used as anode, the best conditions were the same as those of the Fe plate but the electrolysis time was 6 min and the removal rate of As was 96.9%. Lee and Gagnon [40] explored the growth of floc and particle size change when Fe was used as an anode in EC. The experiment analyzed floc structure by adopting scattering exponents as parameters and used a transmission electron microscope for the characterization method. The results showed that under high current operating conditions there would be a larger floc and a higher collision frequency of particles. Compared with Al as cathode, the floc produced by using stainless steel was larger by 15%. Kobya et al. [41] used Fe sacrificial anode to remove red mud slurry waste. The experiment determined the best operation conditions were pH of 8, a current density of 50 A/m^2 and electrolysis time of 45 min. With these conditions the removal rate of V, Si, Al, As, Mo and Ga was 97.68%, 82.65%, 98.22%, 99.44%, 99.69% and 99.95%, respectively.

3.3. Other metal electrode

Other metal material has proven competitive with Al or Fe electrodes for pollution removal from wastewater. Also, using new types of electrodes can effectively process polluted water. Wang et al. [42] studied the removal effect of perfluorooctanoate (PFOA) when using a Zn stick as an anode. They also separately used Al and stainless steel sticks as cathodes. The results showed that under current density of 0.5 mA/cm^2 and electrolysis time of 20 min with Zn as an anode and a stainless steel rod as a cathode, when Cl^-, NO_3^-, SO_4^{2+} and CO_3^{2+}/HCO_3^- were in water solution, the removal rate of PFOA was 99.7%, 98.1%, 96.2% and 4.1%, respectively. With Zn as an anode, Zn as a cathode and Cl^-, NO_3^-, SO_4^{2+} and CO_3^{2+}/HCO_3^- in water solution, the removal rate of PFOA was 98.9%, 97.3%, 7.4% and 4.6%, respectively. In addition, the hydroxide generated when using stainless steel as a cathode had better performance in removing PFOA compared with using Al as cathode.

Vasudevan et al. [43] separately used aluminum alloy and carbon steel as anodes and stainless steel as cathodes to remove phosphate in the water. The experiment studied parameters such as pH value, current density and material. The results showed that the maximum removal rate of phosphate was 99%, and the best experiment conditions used Al alloy as anode with a current density of 0.2 A/dm^2 and pH of 7; moreover, the experiment process followed second-order kinetics. Vasudevan et al. [44] studied removing heavy metal Cr in the EC process. The experiment used Al alloy as anode and galvanized iron as a cathode to study Na_2CO_3, B, silicate, fluoride and other anions' influence on Cr removal efficiency. At the same, the influence of some operating parameters including pH value, anode material and current density was also studied. Their experimental results showed that when current density was 0.2 A/dm^2 and pH 7, the removal efficiency of Cr reached the largest value of 98.2%, and the EC followed first-order kinetic model.

Al-Shannag et al. [45] used carbon steel as both anode and cathode to remove heavy metal ions such as Cu^{2+}, Cr^{3+}, Ni^{2+} and Zn^{2+} in electroplating wastewater. The experimental results showed that EC had a good effect on removing these heavy metal ions, and the best experimental conditions were a current density of 4 mA/cm^2, pH of 9.56 and electrolysis time of 45 min; under these conditions, the removal rate could reach 97%. This shows that it is an economical and feasible technique with a lower energy consumption. Kamaraj et al. [46] studied using Mg as a sacrificial anode and galvanized iron as a cathode to remove radioactive element in water. This experiment optimized each parameter and

allowed assessment of their influence on the removal of Sr and Cs. The results showed that when current density was 0.08 A/dm^2 and pH 7, it achieved the best removal rate with 97% to Sr and 96.8% to Cs; moreover, the process followed a second-order kinetics model and possessed good correlation.

Another study on the development of titanium as the electrode material in the electrochemical process has also received wide attention. Several electrodes prepared by coating titanium substrates, such as Ti/Pt [47] and Ti/Pt/Ir [48], Ti/Ir/Ru [49] and others [50,51] including Ti/TiRuO$_2$ and Ti/PbO$_2$ have been developed, which can improve electrochemical activity. It showed that these titanium-based materials are good candidates for practical applications. Coupled with Al or Fe as the reverse electrode, EC process can be added. Throughout the electrochemical process, the treatment efficiency of pollutants improved. Zhang et al. [52] used the Ti-based TiO$_2$ nanotube loading SnO$_2$ as an anode to process As in underground water instead of the Ti plate and using Fe as cathode. When experimental conditions included a current of 50 mA, a time of 60 min, 6.67 μM As(III) could be completely oxidized into As(V). The experiment results showed that EC could more effectively remove As(III) in underground water, and NaHCO$_3$ could restrain As(III) removal efficiency while NaCl increased it. Titanium salt (e.g., Ti(SO$_4$)$_2$) has also been reported as available in water purification [53]. A comparison of coagulation performance made between a titanium salt coagulant (TiCl$_4$) and the conventional coagulants (aluminum sulfate, polyaluminum chloride, iron chloride and polyferric sulfate) showed that the titanium salt coagulant had a higher pollutant removal efficiency (e.g., UV$_{254}$, DOC and turbidity) than conventional coagulants [54]. Recently, titanium salt as a coagulant used for water purification has also undergone rapid development. A new polymeric titanium-based coagulant was prepared by Xin et al. [55], who expect a similar coagulation function of hydrated Al and Fe; they indicated titanium can be an effective anode and its hydrated products can have a stronger coagulation effect [55].

3.4. Three-dimensional (3-D) electrode

Establishing a 3-D EC on the basis of 2-D EC is an important method to improve EC performance. Compared with 2-D system, 3-D electrode has higher capability of providing a large number of electrodes [56,57] in a reactor system. As shown in Fig. 4(B), in a 3-D electrode system many small particles is introduced into the 2-D reactor system and with the help of an electric field in the presence of appropriate voltage, the particles can be polarized thus forming the charged microelectrodes, which would reduce the transfer distance between the reactant and the electrode, enhancing the specific surface area of the working electrode [57,58]. As a result, more electrolytic efficiency can be obtained [59]. Chu et al. [60] prepared two kinds of 3-D electrodes to process paper-making wastewater, i.e., CTAB-bent (cetyltrimethylammonium bromide modified bentonite) and OH-Al-CTAB-bent (hydroxy-aluminum pillared organic bentonite) and

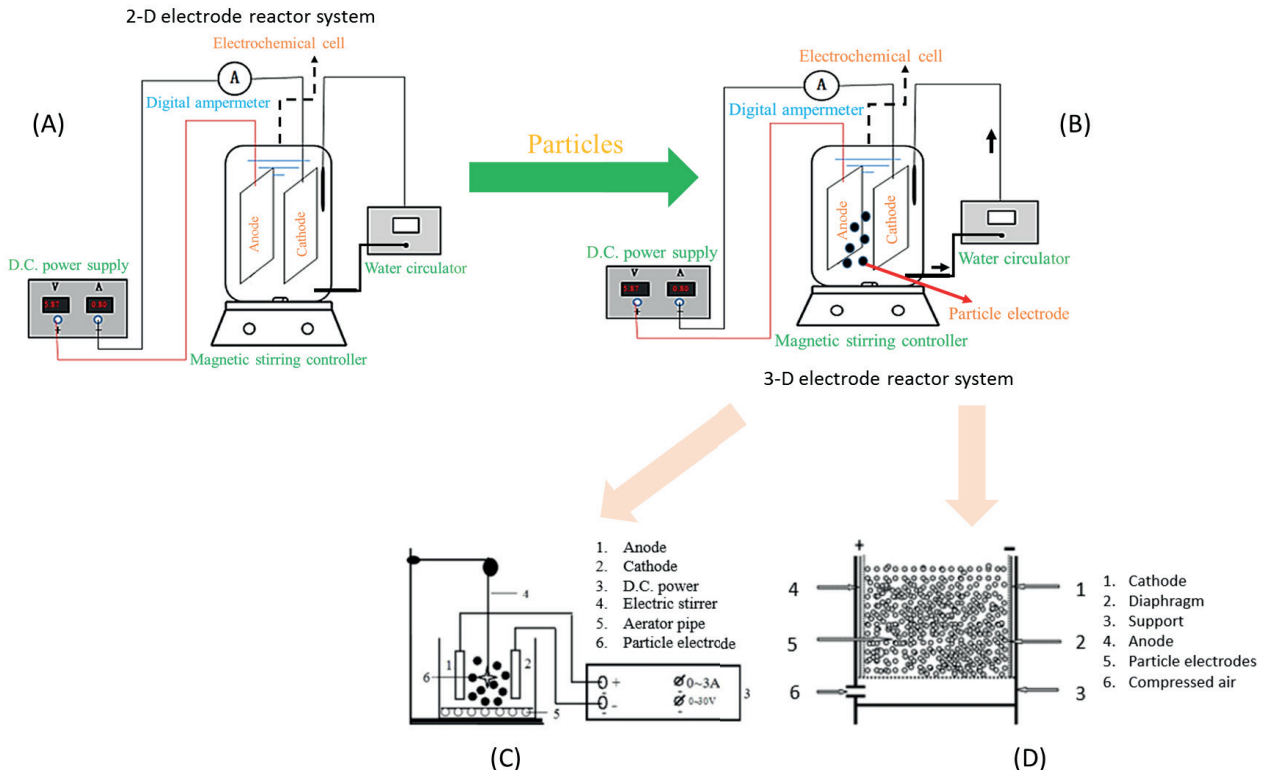

Fig. 4. Schematic diagram of: (A) in-house 2-D EC apparatus, (B) in-house 3-D EC apparatus, (C) 3-D EC apparatus [60], and (D) 3-D EC apparatus [61].

used in conjunction with general electrode plates as the EC apparatus shown in Fig. 4(C). This experiment compared the COD removal effect and color removal effect. The results showed that a 3-D electrode had a high COD removal and color removal efficiency and under the best conditions, it also had a high COD removal rate of 84.3% and color removal rate of 93%. Xiong et al. [61] constructed a 3-D electrode reactor system (see Fig. 4(D)), which was used for the treatment of simulated dye wastewater. Granular activated carbon (GAC) was chosen as the particle electrodes. The total efficiencies of color and COD reached a higher degree of 99% and 87%, respectively. This indicated the 3-D to be more promising process.

Jung et al. [62] used GAC as a 3-D electrode combining it with EC in wastewater treatment. Their experiment determined four main independent variables: (1) current, (2) activated carbon, (3) initial pH and (4) reaction time. The experiment optimized the parameters through response surface analysis and worked out best experiment conditions of a current of 354.3 mA, activated carbon of 47.1 g/L, initial pH of 5.4 and reaction time of 55 min. The COD removal rate was 98.56%. Jung et al. [63] used metal impregnated activated carbon in a particle electrode to process textile wastewater. The study showed that the adding of particle electrodes could significantly fasten color removal and COD removal rates. Through numerical optimization, the color removal efficiency could reach 99.13%, and the COD removal rate could reach 97.01%. Wang et al. [64] adopted the sol–gel method to load metallic oxides SnO_2 and TiO_2 thin films on surface of activated carbon particles and conducted X-ray diffractometer and a scanning electron microscope analysis. The result showed that SnO_2 and TiO_2 loaded on the surface of activated carbon particles experienced different forms and properties. Can et al. [65] used 3-D electrodes to process secondary industry wastewater. Their experimental results showed that when adopting a 3-D electrode, COD removal efficiency was about 50%; however, when they adopted a 2-D electrode the efficiency was 20%; what's more, 3-D electrodes consumed less energy than 2-D electrodes.

4. Typical polluted water treatment

EC has been widely used in the treatment of industry wastewater including heavy metals, phenols, dyeing and tannery pollutants, sanitary sewage, landfill leachate and feed water treatment [66,67], which contains removed organic pollutants, COD and F. Factors affecting EC performance include: current density, plate distance, pH value, electrolysis time and electrolyte concentration [25]. Current density is an important parameter affecting production of hydrolyzed metallic cation and bubble generation rates, and solution mixing and mass transfer at the electrodes [68]. In the previous research on cathodic dissolution in the EC using aluminium electrodes [69], the theoretical weight of hydrogen created in the EC system can be compared with the experimental amount, which was calculated using the Faraday's law as follows:

$$w = \frac{ItM}{FN_e} \tag{12}$$

where w is the weight of hydrogen created (g); I is the current intensity (A); t is the time (s); M is the molecular weight of hydrogen (g mol^{-1}); F is the Faraday constant (96,485.3 C mol^{-1}) and N_e is the number of electrons involved in reaction.

In a study on the removal of chromium from water [44], Faraday law was used to assess the average amount of adsorbent [$Al(OH)_3$], which was set as w value. The amount of chromium adsorption increases with the adsorbent concentration, indicating the chromium removal efficiency increased with the increase of current intensity. Also, the amount of electrode material dissolved (w) can also be assessed where M is the molecular weight of metals [68]. With the increase of current density, the number of soluble anodizing-dissolution metallic ions increases and the concentration of the new hydroxide matter produced by multinuclear hydrolysate combining with hydroxy increases too, which brings a better flocculation effect and higher rate of impurity particles removal [70]. Meanwhile, as current density increases, the effect of the electrolysis plate on water intensifies; then, the oxygen evolution effect and hydrogen evolution effect at the plate intensifies and accelerates macromolecule organics reducing them into micromolecule organics. Furthermore, with better effect, it accelerates the air flotation effect and thus optimizes the EC effect. However, if the current is excessively large, the polarization and passivation of electrodes increase, resulting in a voltage increase, electric energy loss and a sharp drop in current efficiency.

The change of plate distance also affects EC [71] such that the larger the distance, the smaller the current and current density between two plates. On the other hand, the smaller the distance between plates, the larger the treatment rate. The pH value affects the form of new hydroxide produced by multinuclear hydrolysate combined with hydroxy, and thus affects the mode and effect of EC removing pollutants [72]. Electrolyte concentration affects water conductivity and changes electron transmission rates in ways, such that the larger the transmission rate, the better EC can remove the impurity particles. When conductivity is low, current efficiency reduces, but energy consumption increases, which may cause excessive applied voltage that leads to polarization and passivation of plates [25]. Electrolysis time determines contact time between pollutants and new hydroxide and the forming efficiency of new hydroxide generated by multinuclear hydrolysate after combining with hydroxy; thus, EC performance is affected. In summary, EC effect is related to various factors, and the influence factors in treatment of different pollutant are also different, as shown in Table 2.

4.1. Tannery and dyeing wastewater

Since the adjustment of pollution and discharge regulations, the tannery industry is in the process of complete transformation. Deghles and Kurt [78] investigated the removal efficiency of COD, ammonia, N, Cr concentration and color in tannery wastewater. The study showed that when using Al electrodes in tannery wastewater treatment, after 45 min, the removal rate of COD, ammonia N, Cr concentration and color were 92%, 100%, 100% and 100%, respectively. At this moment the electrode transmission rate was 0.371 mS/cm. While using Fe electrodes, after 75 min,

Table 2
Removal of water contaminants by EC reactor system

Target pollutants		Current density/ conductivity	Electrolysis time (min)	pH	Removal efficiency (%)	References
BOD		4–8 mA/cm^2	10–60	4.57–8	71–95.5	[73–77]
COD		1–60 mA/cm^2	20–45	4.5–7	86.4–94	[78–84]
TOC		50–125 A/m^2	30–45	6–8.23	65–75	[85–88]
N	Ammonia N	1–50 mA/cm^2	60–120	5–7	90–99	[34,89–93]
	Nitrate N	40 V	40–60	7.34	85–93	[27,94–96]
	Nitrite N	–	40	<7	100	[97]
P		1–38 mA/cm^2	20–30	6–8	97	[98–101]
Color		4–14 mA/cm^2	30–50	4–7	>94	[82,102–105]
Turbidity		1.75 A	6	–	98	[106–109]
Heavy metals	Ag	–	5	11.5	99.5	[110]
	Cu	8–10 mA/cm^2	20–90	3–6	95–99.5	[111–114]
	Zn	6–8 mA/cm^2	30–90	5–8	95.5–100	[112,115–117]
	Cr	7–50 mA/cm^2	20	3–8	100	[111,118–120]
	Ni	10 mA/cm^2	20–60	3–8	70–100	[111,121,122]
	Mn	600 A/m^2	5–40	7–8	99.5	[115,123,124]
	Hg	2.5–3.2 A/dm^2	Fe: 15, Al: 25	7	99.95	[125]
Suspended solid		6–10 mA/cm^2	10–25	5–7	95–99	[126–128]
Bacteria		10 A/m^2	30	7.62	99.97	[129–131]
Virus		–	20	6.3	99	[132,133]
Organics	Phenols	1–20 mA/cm^2	10–20	2–4.57	92–99	[73,134,135]
	NOM	3 mA/cm^2	25–70	7.3	71.1	[30,136–138]
	BA	172.97 A/m^2	63.47	8.18	59.52	
	TPA	172.97 A/m^2	63.47	8.18	56.21	[139]
	p-TA	172.97 A/m^2	63.47	8.18	45.71	
	MBAS	–	10	5–9	>90	[140]
	SDS	1.0 mA/cm^2	10	6–7	>95	[141]

the removal rate of COD, ammonia N, Cr concentration and color were 87%, 100%, 100% and 100%, respectively, and at this moment the electrode transmission rate was 1.5 mS/cm. The discharge standards satisfy zero discharge standards. Kobya et al. [142] conducted continuous-flow EC in a study of dyeing wastewater treatment. Separately using Fe and Al electrode, under the conditions of inflow rate at 0.01 L/min, at an operating time of 80 min, a current density of 65 A/m^2, the removal rate of COD, TOC and turbidity was 85%, 76%, 95%, 77%, 72% and 95%, respectively.

Pajootan et al. [143] used Al electrodes (ECs) to remove Acid Black 52 and Acid Yellow 220 in dyeing wastewater. The experiment studied the influence of current density, initial dye concentration and pH value on EC and calculated energy consumption. Under conditions of current density at 40 A/m^2, pH 5, electrolyte concentration and 8 g/L, the removal rate of Acid Black 52 was 92% and Acid Yellow was 97%; therefore, EC could effectively remove color in dyeing wastewater. Zhuo et al. [144] used EC to remove azo dye in cobalt phosphomolybdate modified kaolin. The experiment results showed that this process could effectively remove Acid Red 3R with a removal rate of 98.3%. Merzouk et al. [145] made a comparison study on the removal effect of disperse red dye in textile wastewater by separately using the chemical coagulation method and EC method. The results showed that by using the chemical coagulation method, the color removal

rate could reach 90%. By using EC, the removal rate could be improved to 95%.

4.2. Organic wastewater

EC can be used to remove nutrient and organics in water. But its high energy consumption impedes its wide use in organic wastewater treatment [146]. Therefore, decreasing energy consumption is one of the key subjects faced by the application of EC in organic wastewater treatment. Tian et al. [34] made use of an activated carbon air cathode and Al as a sacrificial anode to explore the energy required by using EC to remove nutrients in model water. The study showed that under the conditions that the plate distance was 1.5 cm, with a current density of 8 A/m^2, an electrolysis time of 4 h, nitrogen and phosphorus's average removal rate was as high as 99%. The COD removal rate was 72%–81%; the TSS removal rate was 78%–89% and the energy required was 1.8 kWh/m^3 which was lower than the previously reported energy consumption of EC. The results proved that using activated carbon air as a cathode to remove nutrients could lower energy requirements.

Garg and Prasad [139] studied the EC process to degrade wastewater with purified terephthalic acid as main pollutant. Under the best working conditions and separately using Al and Fe as electrode, the respective removal rate to terephthalic acid (TPA), benzoic acid (BA), *para*-toluic acid (*p*-TA) and COD was 56.21, 59.52, 45.71 and 49.91; and 54.10, 53.84, 39.91 and 42.95. Fajardo et al. [147] adopted EC with a Zn anode and a stainless steel anode to remove phenol organics in organic wastewater. The experiment results showed that under optimal conditions where initial pH value is 3.2, current density is 250 A/m^2, plate distance is 1 cm and NaCl concentration is 1.5g/L, the total phenol content reduced by 84.2% and COD reduced by 40.3%. Ben-Sasson et al. [148] explored EC-microfiltration's removal efficiency to NOM. In this experiment, by combining EC with the end-microfiltration method and separately using Al and Fe as anode material, the results showed that both the Al electrode and Fe electrode could effectively improve removal efficiency of NOM and under the optimal conditions by combining EC- and end-microfiltration, increasing the efficiency by 20%.

4.3. Sewage

Barışçı and Turkay [149] tested eight different kinds of electrode combinations in EC treatment of sanitary sewage. The results showed that the optimal conditions for removing COD were using an Al–Fe–Al–Fe compounded electrode, current density 1 mA/cm^2, pH 7.62 and energy consumption 9.46 kWh/m^3. Pikaar et al. [150] used EC in which they used a compounded metallic oxide Ti electrode to remove sulfide in sanitary sewage. Through processing model water and real sanitary sewage, the experiment got the maximum removal rate of sulfide and determined that the final products of sulfide oxidization were sodium sulfate, sodium thiosulfate and S element. Chloride concentration and acetate concentration have no effect on the removal effect of sulfide. Therefore, removing sulfur by EC is a promising and feasible method. Rodrigo et al. [151] conducted an electrochemical study on municipal sewage reuse. The experiment applied a point diamond to do electrochemical study on three kinds of real municipal sewage. The results showed that EC could easily remove P, COD and colloid particles, and its energy consumption was less than 4.5 kWh/m^3. Therefore, regeneration technology was shown capable of replacing current water treatment methods. Tran et al. [99] used EC to process the wastewater of sewage plants. The results showed that under optimal current density conditions of 38.2 mA/cm^2 and a electrolysis time of 20 min, EC had good performance in removing total phosphorus in municipal sewage with a removal rate of 97%, what's more its cost was lower, about 0.24–0.35 $/m^3.

4.4. Drinking water

As and F are two key hazardous substance in drinking water [152]. EC can efficiently remove As and F content in the drinking water environments. Kobya et al. [153] explored the beat operating conditions for processing As content in drinking water through the batch process mode. With an Fe electrode and under the best experimental conditions (i.e., current density of 2.5 A/m^2, quantity of electric charge 50 C/L, surface-to-volume ratio 10 m^2/m^3, electrolysis time 7.5 min), the As removal rate exceeded 95%, and its operating cost was 0.00075 €/m^3. You and Han [154] studied the EC process as it relates to the influence of different ions and humic acids on the removal of trivalent arsenic in underground water. When Mg ion concentration was less than 10mg/L, As removal efficiency increased, but an excessive high content of Mg ions will impede the removal of As. When sulfate ion concentration was lower, it had no effect on As removal. However, if the concentration increased, As removal rate decreased. Moreover, phosphate ions and humic acid showed a negative correlation with As removal rate. Guzmán et al. [155] investigated using Al electrode continuous press filter EC to remove arsenide and fluoride compounds in underground water. With the underground water in the Bajío region, Mexico as the study object, the experiment indicated that arsenate content decreased by EC treatment, and the residual F content satisfied World Health Organization standards. Kobya et al. [156] studied the influence of Al and Fe electrodes connection modes (series or parallel) on removal efficiency of As in underground water. The experiment [148] showed that electrodes in series acquired maximum As removal efficiency, and as current density increased the removal efficiency also increased. The best As removal conditions were when electrodes connected in series with a current density of 2.5 A/m^2, an electrolysis time of 4 min, and at this moment a removal rate of the Fe anode at 94.1% and the Al anode at 93.5%.

4.5. Industry wastewater

The wastewater included higher COD, which could be effectively removed by EC. Liu et al. [126] studied processing particle matters in chemical polishing wastewater through EC and its dynamical behaviors. Fe was used as a sacrificial anode in this experiment, and with other parameters of pH between 5 and 7, a current density of 5.9 mA/cm^2 and an electrolysis time of 10 min, it achieved optimal experiment results with a removal rate of particle matter reaching 99%. Tsioptsias et al. [157] applied EC in syrup wastewater

treatment, and through the Box–Behnken response surface method it obtained the best operating conditions, which achieved a syrup wastewater content less than 45%, a current density of 33 mA/cm^2 and an electrolysis time of 3.5 h. Analysis showed the color removal rate to be 97%. The N and COD removal rate was larger than 50%, and the cost of COD removal was less than 2 €/kg. Kobya and Demirbas [158] used EC in production wastewater treatment and determined the best working conditions. Under the best working conditions, the removal rate of Al, Zr, P, COD and TOC were 99.41%, 99.38%, 99.8%, 72% and 37%, respectively. Pérez et al. [159] made use of the EC coupling biofilm method to process refinery wastewater. Experiment results showed that under the best working conditions for EC, it could process COD and total petroleum hydrocarbon (TPH) in refinery wastewater and the removal rate of each was 88% and 80%, respectively. Using the EC coupling biofilm method, the removal rate of COD and TPH could be as high as 98% and 95%. Zodi et al. [160] studied the effect of EC in paper-making wastewater treatment and with Fe- or Al-alloy plate, the DOC removal rate was 24%–46%, and the COD removal rate was 32%–68%. What's more, EC can efficiently remove lignin. The experiment results showed that the treatment performance of the Al plate was better than that of the Fe plate in general, and EC was very efficient in the paper-making wastewater treatment.

4.6. Heavy metal wastewater

El-Taweel et al. [161] used Fe as an anode and applied a fixed bed electrochemical batch reactor device to process the water solution with Cr(VI) to study EC performance. In this study [161], for treatment of Cr(VI) concentrations < 520 mg/L, the chemical reduction of hexavalent chromium into Cr^{3+} by iron (II) ions electrogenerated at the anode is described as follows:

$$HCrO^-_{4\,(aq)} + 3Fe^{2+}_{(aq)} + 7H^+_{(aq)} \rightarrow Cr^{3+}_{(aq)} + 3Fe^{3+}_{(aq)} + 4H_2O_{(1)} \quad (13)$$

$$0.9 < pH < 6.5$$

$$CrO^{2-}_{4\,(aq)} + 3Fe^{2+}_{(aq)} + 4H_2O_{(1)} \rightarrow 3Fe^{3+}_{(aq)} + Cr^{3+}_{(aq)} + 8OH_{(aq)}$$

$$6.5 < pH < 7.5 \quad (14)$$

$$CrO^{2-}_{4\,(aq)} + 3Fe(OH)_2 + 4H_2O_{(1)} \rightarrow Cr(OH)_3 + 3Fe(OH)_3 + 2OH_{(aq)}$$

$$7.5 < pH \quad (15)$$

For treatment of hexavalent chromium concentrations > 520 mg/L, the following reaction process also occurred:

$$Cr_2O^{2-}_{7\,(aq)} + 6Fe^{2+}_{(aq)} + 14H^+_{(aq)} \rightarrow 2Cr^{3+}_{(aq)} + 6Fe^{3+}_{(aq)} + 7H_2O_{(1)}$$

$$0.9 < pH < 6.5 \quad (16)$$

The results showed that in EC process different parameters (such as current intensity, sodium chloride concentration, initial pH) influenced the removal efficiency of Cr(VI) and the best working conditions were 1.5 g/L of sodium chloride, current 0.55A and pH 1 for the treatment of Cr(VI) ions at 100 mg/L, which considered the minimum residual hexavalent chromium concentration, energy consumption and operating cost. Overall, this EC system can effectively removed Cr(VI) ions from wastewater. Matias et al. [162] used EC to process silver nanoparticles which were synthesized AgNPs via four different routes by chemical reduction in aqueous solutions. This result showed that for treatment of the AgNPs solution containing citrate, it would consume more times to eliminate the pollutant. In contrary, it could present better floc formation occurred and treatment results. By conducting various experiments, they found that the silver nanoparticles removal rate could reach 98.6%–99.9%; therefore, EC was efficient in silver nanoparticle treatment. Mahmad et al. [163] in the EC treatment of chromium ions in landfill leachate compared the removal performance of different plates. The results showed that an Al plate could effectively remove turbidity and color of landfill leachate. However, to remove chromium ions, stainless steel plates had a better performance than the Al plate. Al Aji et al. [164] with Fe as an electrode made a batch study on the removal efficiency of Cu, Ni, Zn and Mn by EC. The result showed that first-order kinetic model could well fit the Cu, Ni and Zn removal, except to Mn removal. Through the changing of current density, pH value and initial metal concentration, the best experiment conditions were found. The result showed that high pH value was more suitable for metal removal, and at a current density of 25 mA/cm^2 with a total energy consumption of ~49 kWh/m^3, 96% removal rate was obtained for Ni, Cu and Zn while only 72.6 for Mn. In another study, Shafaei et al. [124] investigated the removal of Mn^{2+} ions from synthetic wastewater by EC, which indicated that using aluminium electrodes, the Mn^{2+} removal rate could also achieve high removal efficiency of 94.4% after 60 min at current density of 6.25 mA/cm^2 with pH 7.0 for treatment of Mn^{2+} concentration at 100 mg/L. Compared with the treatment of metal ions from synthetic wastewater, the treatment speed of some metals from those industrial wastewaters seem to be relatively slow. For example, Adhoum et al. [165] compared the removal of metals such as Cu^{2+}, Zn^{2+} and Cr(VI) which were from synthetic wastewater and industrial wastewater, respectively. The results showed that Cr(VI) removal rate was relatively slow as compared with the removal from synthetic wastewater, which would be attributed to that organic compounds competitively adsorb on $Al(OH)_3$ coagulant, resulting in a substantial reduction of metal ions removal. However, all results showed that EC can effectively reduce the metal ions to a very low level.

Finally, using statistical method to optimize the EC performance is one of good pathways in the EC process of heavy metal wastewater treatment. Searching an appropriate combination of parameters, such as pH, electric current, agitation velocity, electrolyte concentration and electrolysis time is needed. For example, Olmez [166] studied Cr(VI) removal by EC using response surface methodology (RSM), indicating that the combination of electric current, electrolyte concentration and application time after optimization with RSM could produce less amount of sludge compared with some chemical treatment by $FeSO_4{\cdot}7H_2O$ and non-hazardous in

nature. Also, the complete Cr(VI) removal was achieved at the optimum conditions. Using RSM for other metal removal optimization, such as arsenic [167], Ni, Cu and Zn [168] has also been highly concerned in EC process.

5. Improvement

To lower energy consumption of EC and improve its reaction efficiency, a few new methods and directions have been put forward in the experimental study processes of EC.

5.1. Selecting pulse power supply

Traditional EC mostly adopts DC power supply, which costs much energy, and plates which are consumed quickly. Currently, one study direction in EC uses a pulse power supply instead of a DC power supply. In the electrolytic pulse power supply process, the electrode produces electrons, and forms an electric field at the anode and cathode, and then the electrode transmission rate increases; while the power is off, it is good for water diffusion and reducing concentration difference; thus, preventing polarization and reducing energy consumption. Besides, the periodical change of polarity at two poles can effectively prevent electrode passivation. Eyvaz et al. [169] discussed alternating current's influence on removing dye in water solution by EC. With Al plates in bulk connection, the experiment processed two kinds of dye wastewater and compared DC power supply and pulse supply's influence on EC efficiency. The effect was assessed by the TOC removal rate and dye removal rate. Study results [157] showed that adopting pulse power supply had better performance in TOC removal and color removal; what's more, compared with DC, it cost less in treatment time; hence, using pulse AC could remove surface scaling of cathodes making pulse current better than DC on treatment efficiency. Lin et al. [170] explored using pulse power supply to eliminate plate passivation in the EC process. Experiment results showed that the pulse power supply could efficiently eliminate plate passivation and increase current efficiency; moreover, under the same removal conditions compared with DC EC, pulse current EC could save 30% energy consumption. Chen et al. [171] studied refractory dye wastewater by using pulse power EC with Al as the anode and discussed the influence of duty ratio and pulse frequency of pulse power supply on removal of color and COD in dye wastewater. The results showed that by using pulse power supply, energy consumption was reduced by more than 80%.

5.2. Developing new electrodes

Another new trend of EC is using new type electrodes or electrodes connection modes. Traditional electrode plate mostly uses Al, Fe electrode but they still produce higher quantities of sludge and cost [147]. Some new applications are to develop new electrode materials with lower energy consumption and higher efficiency including more diverse plate shape, and wider electrode material. With some new electrodes pairs, for example, EC system of Zn anode/stainless steel cathode pair was developed to treat phenolic wastewater, indicating the EC system of Zn anode/stainless steel cathode pair resulting in 84.2% and 40.3% of total phenolic (TPh) and COD removal, respectively, and Zn had a possible advantage of resulting in less quantities of sludge [147]. A new Fe/Al composite hydrogel anode electrode was prepared, which was used in an ERS with titanium plate as cathode. The EC process to treat alizarin red S with the Fe/Al composite hydrogel electrodes was found to be more effective than conventional electrode system in which the hydrogel was considered to have certain iron exchange capacity of eliminating residual metal irons [172]. In a 3-D electrode reactor system, developing new particles electrodes to improve EC efficiency is increasing rapidly. For example, a 3-D graphene aerogel material to treat dye wastewater was prepared by Sun et al. [173], which had high porosity, large surface area and high electrical conductivity, indicating a potential in the treatment of water and wastewater. Different electrode connection modes can also cause different EC effect on treatment of various pollutants [174]. The connection modes such as ponopolarparallel, monopolar series and bipolar series can be optimized to enhance EC performance.

Chen et al. [33] used 3-D electrode EC to remove COD and color in printing and dye wastewater. After 10 min, COD removal rate was 89.03% and color removal rate was 99.43%. Jung et al. [62] used activated carbon 3-D electrode packing to process reclaimed water and through response surface, they analyzed the effect of using different amounts of granular active carbon, initial pH values, reaction times and current on COD removal efficiency. The experiment came out with the best COD removal conditions of granular active carbon at 47.1 g/L, initial pH of 5.4, a reaction time of 55 min and under these conditions COD removal rate was 98.56%.

5.3. Enhancing coupling applications

EC is developing to the direction of coupling with other technologies. Research shows that by coupling with other technologies, EC performance can be dramatically improved. Current typical coupling technology has been widely used. For example, EC-membrane (ECM), EC-oxidation (ECO), ECF, EC-adsorption (ECA) and EC-catalysis (ECC) are all popular EC methods.

5.3.1. EC-membrane

Chellam and Sari [175] investigated drinking water treatment through EC coupling with microfiltration technology, and the results showed that the floc generated by EC could absorb NOM and disinfection byproduct precursors. It also could efficiently remove virus and silicate pollutants and reduce larger flocs that form in the microfiltration process and cause pollution by depositing on the film surface. Hakizimana et al. [176] conducted sea water desalination treatment by combining EC and reverse osmosis technology. The results showed that ECs high potential could reduce organic pollutants in water, and reverse osmosis film could effectively remove soluble organics and microorganisms in seawater. Hua et al. [177] explored ECs influence on membrane pollution of MBR and its sludge characteristics. The results showed that EC helps relieve membrane pollution. Han et al. [178] used EC to conduct pretreatment of a biogas digester at a pig farm and then achieved filtration through

nanofiltration membrane technology. The experiment indicated that through the response surface method, optimal working conditions could be obtained, and after EC pretreatment, the nanofiltration membrane pollution could be reduced by about 22.2%.

5.3.2. EC-oxidation

Aziz et al. [179] studied the effect of EC coupling advanced oxidation (ECO) on removing COD and color in alcohol-distillery wastewater. Their experimental results showed that the technology of ECO could completely remove COD and color in alcohol-distillery wastewater. Behin et al. [180] applied ozone oxidation assisted by EC to conduct decolorizing tests on synthetic azo acid dye wastewater. Under optimal conditions, they finished decoloration within 30 min and the energy consumption was only 7.4 kW/h. Their results [124] showed that, the combination of ozone and EC was more effective than traditional EC and ozone oxidization. Zhao et al. [181] combined EC and oxidation to process organic wastewater. The experiment showed that adding H_2O_2 in the EC process could increase COD removal rate up to 76%. The reason for the increase was that Fe^{2+} interacted with H_2O_2 and then generated hydroxyl radicals, which could effectively oxidize organics; however, excessive content of H_2O_2 would consume hydroxyl produced in the electric Fenton process, and consequently decrease COD removal rate.

5.3.3. EC-catalysis

Boroski et al. [182] studied the effect of EC coupling EC/TiO_2 heterogeneous photocatalysis (ECC) on turbidity and COD removal of pharmaceutical wastewater. The EC was conducted using an Fe plate, a current density of 763 A/m^2, pH of 6, and when the electrolysis time reached 90 min, the removal rate of turbidity and COD were 91% and 86%, respectively. Then, conducting photocatalysis under conditions of UV/TiO_2/H_2O_2 exposure for 4 h with mercury lamp at pH = 3, the residual COD after ECC treatment was 1,753 mg/L, and after EC and ECC treatment, it was only 160 mg/L and 50 mg, respectively. It showed that ECC was more effective on COD removal. Zhao et al. [183] combined electrochemical enzyme catalysis and EC to remove bisphenol A (BPA) in water containing humic acid. The experiment used Ti as the cathode and Al as the anode. Under experimental conditions with a current density of 2.3 mA/cm^2, electrolysis time was 20 min, BPA removal rate was 100% and TOC removal rate was 95.1%. After processing real wastewater, the removal rate of BPA and TOC were 94% and 52%, respectively.

5.3.4. EC-flotation

Adamovic et al. [184] discussed the practical feasibility of ECF in treatment of dyeing wastewater. They explored the best treatment conditions and analyzed the influence of operating variables through response surface analysis. In addition, they obtained balance parameters of pollutant removal efficiency. Liu et al. [185] studied removing non-steroid anti-inflammatory drugs through ECF, especially diclofenac, ibuprofen and ketoprofen. The experiment results showed that the removal efficiency of a single anti-inflammatory drug was good with a favorable removal rate. Zaidi et al. [186] used ECF to process doxycycline hyclate (DCH) in water solution. In this experiment, Al was used as anode and cathode. The experiment indicated that ECF was an effective treatment method, which showed significant effects under conditions of initial pH of 7.03 and a current of 5.39 mA/cm^2. In addition, adding NaCl was beneficial for increasing removal rate. The experiment results showed that DCH was in line with the dynamic model.

5.3.5. EC-adsorption

Secula et al. [187] used coupling EC and activated carbon (ECA) particles to remove indigo carmine dye in water solution. By dynamics, the experiment studied the influence of different adsorption material with various amounts on increasing dye removal rate. It also studied current density effect on the removal efficiency and running cost of coupling technology. The experiment results showed that adding activated carbon could improve dye removal efficiency and save much contacting time. The final removal rate of indigo carmine dye reached 99.5%. Bellebia et al. [188] studied removing COD content in paperboard plant wastewater by ECA coupling an activated carbon particles adsorption method. Through research, they obtained the best operation conditions and when pH = 3.21, the maximum COD removal rate by using Al electrode was 98.97%; while using Fe electrode, the rate was 93.37%. Linares-Hernández et al. [189] evaluated the ECA coupling biosorption process removing organics in industry wastewater. The experiment indicated that ECA could efficiently reduce organics and with the adding of the biosorption process, the removal efficiency improved. As a result, COD content decreased to 84% of the raw water, BOD removal rate was 78% and *Escherichia coli* removal rate was 99%.

6. Summary

In recent years, ERSs have proven effective in wastewater treatment. Compared with the chemical coagulation method, EC has many advantages. For example, it can reduce the complexity of the operation to adapt to a wider range of water environment conditions (such as low temperature, low turbidity and low pH), and no impurity ions are introduced into the water. As an eco-friendly, efficient and cost-effective method, EC integrates the advantages of chemical coagulation and electrochemistry. Recently, the design and operation of an EC reactor was developed. New electrode materials and coupling technologies have also been widely developed. In this article, we reviewed the application of EC in water or wastewater treatment. Our review shows that EC can efficiently remove many kinds of pollutants from water and new methods to improve EC efficiency have been proposed. However, there are also many limitations to the application of the EC, such as larger consumption of electric energy and metal as well as electrode reliability issues (such as passivation of electrodes). Therefore, obtaining a reliable and cost-effective EC process is of great practical significance. In order to solve these technical problems of EC, hard work is still needed.

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Symbols

EC	—	Electrocoagulation
NOM	—	Natural organic matter
MSWI	—	Municipal solid waste incineration
PFOA	—	Perfluorooctanoate
CTAB-bent	—	Cetyltrimethylammonium bromide modified bentonite
OH-Al-CTAB-bent	—	Hydroxy-aluminum pillared organic bentonite
ERS	—	EC reactor system
BERS	—	Batch EC reactor system
CFERS	—	Continuous flow EC reactor system
TSS	—	Total suspended solids
TPA	—	Terephthalic acid
BA	—	Benzoic acid
p-TA	—	*para*-Toluic acid
SDS	—	Sodium dodecyl sulphate
MBAS	—	Methylene blue active substances
ECM	—	Electrocoagulation-membrane
ECO	—	Electrocoagulation oxidation
ECF	—	Electrocoagulation flotation
ECA	—	Electrocoagulation absorption
ECC	—	Electrocoagulation catalysis
TPH	—	Total petroleum hydrocarbon

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