Synergetic effects of iron-carbon micro-electrolysis integrating with other technologies

S M Zheng¹,²,³, X Y Wang¹, C H Chen²,³ and H Kong¹

¹College of Chemistry and Chemical and Environmental Engineering, Weifang University, Weifang 261061, China
²Key Laboratory of Pollution Processes and Environmental Criteria (Ministry of Education), Tianjin Key Laboratory of Environmental Remediation and Pollution Control, College of Environmental Science and Engineering, Nankai University, Tianjin 300071, China

E-mail: zhengshimei12@163.com; chencuih@nankai.edu.cn

Abstract. The combination of iron-carbon micro-electrolysis (ICME) technology and other technologies is an important development direction for the treatment of refractory wastewater, which could overcome the disadvantages of each technology and combine the advantages of each technology. The synergetic effects of ICME combined with Fenton process not only save the cost of adding reagents, but also significantly improve the efficiency of the combination treatment. The advantage from the combination of ICME with ozone is due to plenty of hydroxyl radicals coming from ozone decomposition, which enhances the complex contaminants removal. The synergetic effects of ICME integrated with biological process include mainly two respects. One is that the galvanic cells produced around the ICME could readily convert complex organic compounds to biodegradable substrates, which is conducive to the degradation of pollutants by microbes. Another one is that the iron ions released from ICME possess great capability to promote the performance of the microbes to treat wastewater, for instance, mineral nutrients for microbes, electron transfer mediator, and vital components of enzymes. Accordingly, the integration of ICME with other technologies has great application prospect for refractory wastewater.

1. Introduction

At present, industrial wastewater accounts for a large proportion of the wastewater produced in China, owing to the rapid development in economy and industry. Most industrial wastewater, such as printing and dyeing wastewater, pesticide wastewater, textile wastewater, and pharmaceutical wastewater and so on, has the characteristics of high color, high concentration of refractory organic substances, complex composition, low biodegradability, and even biological toxicity, which bring difficulties to direct biochemical treatment [1]. Because of these intractable characteristics, the industrial wastewater should be taken seriously, otherwise the balance and the safety of ecology will be in threat. Therefore, the efficient treatment of industrial wastewater is of great significance to protect water resource.

Because the biochemical treatment usually can do nothing to directly treat refractory industrial wastewater, the chemical and physiochemical methods are employed to pretreat it, such as Fenton oxidation, photochemical oxidation method, catalytic ozonation, iron-carbon micro-electrolysis (ICME), sonolysis oxidation, flocculation, resin adsorption, and so on [1]. These technologies could overcome the difficulties for biochemical process, for example, poor biodegradability and biological
toxicity. Compared with several physiochemical methods to treat the ultra-high concentration organic wastewater, including flocculation, salt-containing distillation, resin adsorption, ICME, and Fenton, the study of Zhu et al. [2] evidenced ICME process with better COD removal efficiency, at the same time it possessed feature of simple operation, which is fit for pilot scale study. ICME technology, also known as internal micro-electrolysis, is a cost-effective and eco-friendly treatment method and has been extensively applied as the pretreatment of bio-recalcitrant wastewater. Because of its high efficiency, simple operation, and long life span [3,4], it is considered as an attractive technology for industrial wastewater.

The mechanism of ICME technology resembles the electrochemical fundamental, and the apparent difference is that without the external power supply, the corrosion of micro-scale iron acts as anodes to supply the electrons. Its essence is to make use of the electrode potential difference between iron and carbon to form innumerable micro-batteries in the wastewater with certain conductivity. The removal of pollutants in the wastewater is achieved through the electrode reaction together with a series of physicochemical reactions initiated by the electrode reaction. The series of physicochemical reactions include redox reaction, flocculation precipitation, electrochemical adhesion and physical adsorption. The reactions in ICME system are present as follows.

First, the electrode reaction. Numerous galvanic cells are spontaneously created between the iron (anode) and carbon (cathode), and the potential difference between iron and carbon electrode is 0.44V, which is high enough to promote the structural transformation of the bio-refractory organic matters [2]. The removal and transformation of pollutants in the electrode reaction process mainly depends on the electrode reaction process shown in the equations (1)-(4) [1], through the high conductivity of carbon, the electrons of the zero valence iron are transferred to the pollutant molecules, thus the complex pollutants are transformed to easily biodegradable substances.

Anode:

\[ Fe - 2e \rightarrow Fe^{2+} \quad E_0(Fe^{2+}/Fe) = -0.44V \]  \hspace{1cm} (1)

Cathode:

Under the acid condition \[ 2H^+ + 2e \rightarrow 2[H] \rightarrow H_2 \quad E_0(H^+/H_2) = 0.00V \] \hspace{1cm} (2)

Oxygen present under the acid condition \[ O_2 + 4H^+ + 4e \rightarrow 2H_2O \quad E_0(O_2/H_2O) = 1.22V \] \hspace{1cm} (3)

Oxygen present under Neutral condition \[ O_2 + 4H_2O + 4e \rightarrow 4OH^- \quad E_0(O_2/OH^-) = 0.41V \] \hspace{1cm} (4)

| Wastewater type          | CODCr (mg/L) | Influent B/C | Effluent B/C | Scale | Reference |
|-------------------------|--------------|--------------|--------------|------|-----------|
| ABS Resin               | 1100-1300    | 0.385        |              | Lab  | [5]       |
| Landfill Leachate       | 538          | 0.071        | 0.21         | Pilot| [6,7]     |
| Bromoamine Acid         | 3707         | 0.04         | 0.237        | Lab  | [3]       |
| Chemical Industrial     | 328-353      | 0.043        | 0.609        | Lab  | [8]       |
| Caprolactam             | 32800        | 0.091        |              | lab  | [9]       |
| Oilfield produced Water | 258-290      | 0.069        | 0.17         | lab  | [10]      |

Second, the oxidation-reduction reaction. In the process of electrode reaction, the Fe^{2+} produced by the anode and the atomic hydrogen [H] produced by the cathode in the acidic environment are both reducible and have high chemical reactivity [5], which can react with a variety of pollutants. The nitro-containing in organic matter can be reduced to amino group, the azo bond and the chain structure of the macromolecular organic matter can be broken down, and the ring of the organic substance can
be opened, therefore the toxicity of the pollutants in wastewater could be reduced and the biodegradability of the raw water could be improved. The ratio of biological oxygen demand (BOD) and chemical oxygen demand (COD) (B/C ratio) before and after wastewater treated by ICME is shown in table 1.

Third, the flocculation precipitation. In the process of micro-electrolysis, the ferrous ion Fe$^{2+}$ produced by anodic reaction and the ferric ion Fe$^{3+}$ formed by partial oxidation of Fe$^{2+}$ are easy to form iron hydroxide (including Fe(OH)$_2$ and Fe(OH)$_3$) flocculating precipitates under alkaline conditions. They can adsorb and flocculate the original suspended substance and the insoluble substance produced by the micro-electrolysis reaction. The adsorption and flocculation ability of the newborn colloid flocculant ferric hydroxide Fe(OH)$_3$ in the micro-electric field is higher than that of the ferric hydroxide obtained from the hydrolysis of the common coagulant in the wastewater. In addition, ferrous ion Fe$^{2+}$ and ferric ion Fe$^{3+}$ can react with PO$_4^{3-}$, S$^{2-}$, CN$^-$ and other inorganic ions in wastewater to form precipitate and remove them, thus reducing their toxicity to the subsequent biochemical systems.

Fourth, the electrochemical attachment. Charged colloids and charged particles in wastewater are subjected to the action of micro-electric field to form electrophoresis [11], which moves toward the electrode which is opposite to its own charge. Finally, under the action of electrostatic gravity and surface energy, the charged colloid and charged particles will accumulate and deposit on the electrode.

Fifth, the physical adsorption. Iron scrap and coke or activated carbon are usually used as electrode materials of ICME, which all have strong surface activity and can adsorb organic pollutants in wastewater [3]. Cast iron is porous in weak acidic solution and has strong surface activity, so it can effectively adsorb organic pollutants and various metal ions in wastewater.

As we know, any single treatment usually has its own limitations, for example, long retention time, high cost, and poor removal. In recent years, the high-strength industrial wastewater is usually treated by the combination of methods, such as physical-chemical methods coupled with physicochemical methods or biological processes [12-15], which would integrate the advantage of each treatment to achieve effective treatment efficiency of organics, metals, toxicity, and color. The combination between the physicochemical methods can enhance the chemical and physicochemical reactions, which could improve the biodegradable extent of refractory compounds. Through the pretreatment of physicochemical unit coupled with biological process, the purpose is to reduce the pollution load, such as high organic matter, to meet the water quality requirement of the subsequent biochemical treatment unit, and to ensure the high efficiency and stable operation of the whole treatment process system. There are several combination processes between ICME and other technologies demonstrating better performances, such as Fenton technology and biological processes. The synergistic effects, advantages and possible mechanisms of ICME integrating with other technologies are discussed in the following part.

2. Integration of ICME with other technologies

2.1. Integration of ICME with Fenton process
The mechanism of Fenton reaction is the hydroxyl radical (·OH) theory. The redox potential of hydroxyl radical is second only to fluorine in nature, which is as high as 2.80 V, its oxidation ability is very strong, and the organic matter can be oxidized into carbon dioxide and water without selectivity [6,7]. Under the catalysis of ferrous ion Fe$^{2+}$, H$_2$O$_2$ produces hydroxyl radical, which leads to a series of chain reactions. The whole reaction process is very complicated. The primary Fenton reactions are shown in formulas (5)-(8).

\[
Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + HO^\cdot 
\]  \hspace{1cm} (5)

\[
Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + H_2O + HO^\cdot 
\]  \hspace{1cm} (6)
\( \text{Fe}^{3+} + \text{H}_2\text{O}_2 \rightarrow \text{Fe}^{2+} + \text{H}^+ + \text{HO}_2 \cdot \) (7)

\( \text{HO}_2 \cdot + \text{H}_2\text{O}_2 \rightarrow \text{H}_2\text{O} + \text{O}_2 + \text{HO} \cdot \) (8)

However, the apparent shortcoming of the traditional Fenton method is that a large amount of extra hydrogen peroxide and ferrous ion are needed to keep the production of hydroxyl radicals, which is cost of reagents. The ferrous ion (Fe\(^{2+}\)) produced in situ by ICME reaction could act as reactant and can trigger Fenton reaction with the addition of H\(_2\)O\(_2\), so ICME can provide ferrous ions that Fenton reaction needs. Thus, the integration of ICME with Fenton oxidation process not only saves the cost of adding ferrous ions, but also enhances the oxidation, because of the high reactivity of the newborn ferrous ions from ICME reaction. Many studies have reported that when under aerated condition, the H\(_2\)O\(_2\) could be generated in situ in internal micro-electrolysis reactor since oxygen may compete as an electron acceptor [6,7,16,17], therefore no extra H\(_2\)O\(_2\) are needed to add. There are two type integrations for ICME-Fenton advanced oxidation. One type is to enhance the removal rate of organic pollutants and improve the removal effect of ICME by adding H\(_2\)O\(_2\) into the effluent of ICME reaction to produce Fenton effect. Zhang et al [18] found that the efficiency of COD removal was improved by the addition of H\(_2\)O\(_2\) at the end of internal micro-electrolysis. Another type is the direct addition of H\(_2\)O\(_2\) in the ICME reactor, whereas micro-electrolysis and Fenton oxidation are carried out at the same time. Wang et al [12] reported that the landfill leachate was treated by the integration of ICME and Fenton process. The results showed that the COD removal and the B/C ratio were up to 74.59% and 0.50, respectively, and the combination of micro-electrolysis and Fenton effectively oxidized and finally destroyed the fractions of high molecular weight in leachate, such as refractory fulvic-like pollutants. So, the pretreatment of industrial wastewater by ICME-Fenton advanced oxidation process can effectively reduce the concentration of COD in the water body and improve the biodegradability of the water body. Thereby, it is found that the integration of ICME and Fenton process can not only save the cost of medicament, but also have a significant improvement on the treatment of ICME and Fenton process.

Compared with ICME alone, ICME-Fenton advanced oxidation could combine both advantages, and the refractory organic compounds and toxic substances could be converted into small molecular substances. The combination of ICME with Fenton oxidation could increase the COD removal rate by about 10%-25% in the pretreatment of refractory industrial wastewater, and the biodegradability of wastewater can be effectively improved [12]. Combining ICME with H\(_2\)O\(_2\) to produce Fenton reagent can not only realize the recovery and utilization of waste iron scrap, but also reduce the addition of H\(_2\)O\(_2\), and enhance the oxidation ability of ICME, so it would be a potentially promising technology to pretreat the refractory industrial wastewater.

2.2. Integration with ozone process

As a well-known mighty oxidant, ozone can attack the bonds related with color, like conjugated double bonds [13], therefore it is very powerful in decolorizing textile effluents and converts bio-refractory dyes into biodegradable species [19]. It not only can be used alone, but also can be combined with other processes, such as one unit for the disinfection in drinking water and for the treatment in the wastewater [20]. There are two distinguished ways in the reactions of ozone with organic matters in water: at low pH molecular ozone highly selectively attacks on the organic molecules, whereas the decomposition of ozone forms free radicals, which non-selectively react with the organic substances [21].

Ruan et al reported the integration of ozone with internal micro-electrolysis to electrochemically degrade reactive red X-3B [22]. The removal rate of color was up to 99%, and the removal rates of COD, TOC and absorbable organic halides were improved in varying degrees, 85%, 59%, and 74%, respectively. The reason for degrading reactive red X-3B was dominantly attributed to the formation of the radicals, hydroxyl radicals \( \cdot \text{OH} \), whose production were enhanced in the presence of ozone. Thus, the hydroxyl radicals were the primary contributory factor to degrade the reactive red X-3B and its
intermediates in the combined system of ICME and ozone.

So, for ICME system, the existence of ozone enhances the production of hydroxyl radicals, therefore the synergetic effect is established in the combination of ICME and ozone process.

2.3. Integration with biological process

In the galvanic cell reaction of ICME, the electric field forming between iron and carbon creates microelectron flow, where the growth of microbe and the activity of metabolic enzyme are effectually stimulated by the electron transfer, which will further promote the biodegradation ability of microorganism [1]. Furthermore, after the biodegradability of wastewater is improved by the ICME process, consequently it will provide a great foundation for the biological treatment [14]. Hu et al reported that the organic compounds could be converted into easily biodegradable substrates, but hardly oxidized to CO2 by ICME, and the removal of organic substances was mainly by the adsorption by activated carbon [23]. So under some conditions or for some contaminants, the removal of COD still depends on the degradation of organic compounds by microbes or the adsorption by activated carbon. Hence the enhanced effect coming from the integration of ICME with biological process could effectively contribute to the improvement on the degradation efficiency of refractory substances by biological effect. Consequently, the underlying mechanism for the synergistic effect of the degradation property by micro-electrolysis combined with biological process is of great importance and great interest.

First, the galvanic cells produced from the ICME could readily convert complex organic compounds to biodegradable substrates, resulting in the enhanced effect of converting the complex organic substances to simple and easily biodegradable substances [24]. Wang et al [15] investigated the integration of UASB and ICME to treat Fischere-Tropsch wastewater. It was shown that the number of macroscopic galvanic cells formed around ICME was larger than that of microscopic galvanic cells produced in zero-valent iron (ZVI) group, which accelerated the electrons transfer from anodic iron to cathodic carbon. Accordingly, the hydrogen transfer among species was enhanced. Therefore, higher efficiency of COD removal, more production of methane, and the less accumulation of low molecular weight organic acids were for ICME group than those of groups with granular activated carbon (GAC) addition and ZVI addition. Ma et al [1] showed that the B/C ratio in the effluent was only 0.27 in the treatment of single biological process, while drastically increased from 0.21 to 0.46 in the combination of ICME with biological reactor. Compared with only biological process, the integrated process showed significant synergetic effect and greater capability to increase the degradation of organic compounds and the biodegradability of wastewater. The presence of ICME was a key factor to dramatically decrease the phenolic composites in the wastewater, suggesting that the organic compounds were oxidized and the benzene ring structures and the side chain bonds were destroyed by the radicals and oxidants, which were produced in the micro-electrolysis process [11]. Correspondingly, the bio-refractory and even toxic pollutants were converted into easily biodegradable and less toxic intermediates. Furthermore, [H] generated from the galvanic cell reaction could be utilized by microorganisms to further enhance the redox reaction, which also could effectually reduce some substances, such as iron oxides, precipitated on the surface of ICME, thereby deferring the passivation occurrence on the surface of the ICME [1]. Apparently, the integrated process manifested greater efficiency of COD removal, endured relatively higher influent loading and longer retention time.

Second, the presence of iron could act as a promoter for several processes in the wastewater treatment. The presence of iron could substantially alter the fraction of iron within the sludge, and it is found that the enhanced efficiency of COD removal and the elevated production of methane were more likely associated with predominant reducible iron fraction [15]. Iron ions released from ICME are vital mineral nutrients for microbes and its enzymes and also act as mediators for the electron transferring in the electron transfer chain happening in the cell interior, which thereby stimulate the growth and metabolism of microbes [25]. For the anaerobic treatment, oxidation-reduction potential could be reduced by iron, creating a favorable micro-environment for methanogens [26]. Meantime,
the iron could act as the exogenous electron donor for converting CO$_2$ to produce methane displayed in the equation (9) [27]. For anaerobic digestion, the trace element dosage was added following the sequence of ferrous, cobaltous and nickelous, and whether the ferrous dosage was adequate played an important role on the final activation effect of nickelousto methanogenesis [15]. Some studies have shown that ferrous ions released from iron corrosion could act as a cytochrome in the energy metabolism and ferredoxin in the methyloptrophic methanogens [27,28]. In the presence of ICME process, the formation of electric field among iron, carbon and wastewater could induce the electrochemical reactions, which further optimize reducing condition in the anaerobic system and simultaneously promotethe biotransformation of organic substances that facilitate the final methanogenesis.

$$8H^+ + 4Fe + CO_2 \rightarrow CH_4 + 4Fe^{2+} + 2H_2O$$ \hspace{1cm} (9)

The ZVI can serve as a reductant (electron donor) to chemically reduce nitrate following the equation (10). And the primary product of iron reducing nitrate is ammonia [29]. Due to its high efficiency for nitrate removal without the expense of organic carbon sources, it has been widely studied [29,30]. Besides, the residual Fe$^{2+}$ at the anode can also act as a reducing agent for nitrate reduction under acidic conditions, as equation (11) shows [23]. Simultaneously, there exists another microbial route for iron to reduce nitrate. Fe(II) oxidation bacteria could utilize the ferrous ions to reduce nitrate, and the production is nitrogen, as the equation (12) shows. In the presence of ferrous ions, Schaedler et al found that the expression levels of genes coding for nitrate reduction enzymes were stimulated, including periplasmic nitrate reductase napA and membrane-bound nitrate reductase narG [31]. So in theory, the application of ICME could dramatically improve the efficiency of ZVI-based nitrate reduction. It is shown that ICME can happen when ZVI is attached to activated carbon, even in neutral or alkali solutions [26,32]. In the presence of ZVI and activated carbon at an influent pH of 6.5-7.0, Hu et al found that the reduction rate of nitrate improved from 23 g nitrate to 81 g nitrate (m$^3$·d)$^{-1}$, and the reaction rate constant was increased from 0.11 $\times$ 10$^{-4}$ to 0.39 $\times$ 10$^{-4}$ [23].

$$NO_3^- + 4Fe(0) + 7H_2O \rightarrow NH_4^+ + 4Fe^{2+} + 10OH^-$$ \hspace{1cm} (10)

$$NO_3^- + (8 - 6n)Fe^{2+} + 6H^+ \rightarrow nN_2 + (1 - 2n)NH_4^+ + (8 - 6n)Fe^{3+} + 3H_2O$$ \hspace{1cm} (11)

$$2NO_3^- + 10Fe^{2+} + 2AH_2O \rightarrow N_2 + 10Fe(OH)_3 + 18H^+$$ \hspace{1cm} (12)

The ferrous ions Fe$^{2+}$ could improve the performance of the activated sludge to treat the wastewater. Wang et al found that the ferrous ions Fe$^{2+}$ from iron corrosion effectively stimulated the protein secreted from microbes, which increased the protein proportion in the tightly bound extracellular polymeric substances (EPS) and promoted better bioflocculation [15]. The portion of ferrous ions Fe$^{2+}$ leaching may be conducive to promote the formation of total EPS. The reason is that a divalent ion (such as Fe$^{2+}$) usually combines with protein in bacterial attachment to a surface, and creates crucial ionic cross-bonding effect for the bacterial polysaccharide with negative charge, and eventually the three dimensional structure forms more stably [33]. Additionally, the enhanced EPS with metallic ions involved could form gel networks on the surface of sludge and contribute more to microbial adhesion and attachment by means of chemical bonding or physical cementation aggregation [34]. Furthermore, ferric oxides (α-FeOOH or α-Fe$_2$O$_3$) generated from micro-electrolysis reaction could involve in the special function bacteria, such as electrochemically active bacteria or extracellular respiratory bacteria, consequently the degradation of organic substances is accelerated by the extracellular electron transfer [35]. Meanwhile, the iron ions released from ICME have strong adsorption, flocculation and interparticle bridging effect to form stable activated sludge, which is helpful to enhance the metabolic activity of microorganisms and improve the biodegradation rate of organic substances [11].

Obviously, the combination of ICME and biological process is expected to explore the common
advantages of ICME process and biological process and to exhibit synergic effect on wastewater treatment, which will be conducive to accelerate the biodegradation of complex organic compounds by microbes. From the above analysis, it is concluded that the integrative effect of micro-electrolysis reaction with biological processes far more than additive effect, and the synergic effect displayed between them is impressive, which plays an important role on obtaining striking COD removal.

3. Perspectives
ICME, as one of the electrochemical oxidation methods, possesses characteristics of little or no harm on the environment, because of the use of harmless reagents and no extra energy needed [10]. Seen from the summary and analysis of the above literatures, the application of ICME could not only be as pretreatment process for refractory industrial wastewater, but also as post-treatment of the biological treatment wastewater, so it has flexibility according to actual requirement. Its integrations with Fenton, ozone, and biological process show many respects of synergetic effect and great advantage. Not only can organic substances be removed efficiently, but also can the removal of inorganic substances (such as nitrogen, phosphorus, and metals) be greatly improved [32,36]. However, it is a long way off perfect. There are still some problems to be solved in the mechanism research and practical application of ICME technology.

- Micro-electrolysis has a complex mechanism of action, including reduction reaction, oxidation reaction, adsorption, flocculation and precipitation, electric field effect, and so on. At present, there is no quantitative analysis on the primary and secondary relationship about the mechanism of pollutant removal by the micro-electrolysis, as well as the coupling relationship. The each mechanism of micro-electrolysis process could be macroscopically divided, and then the effect of treatment can be compared and studied. Microscopically, the degradation path of specific pollutants and electron transfer routes should be investigated to find out their mutual relationship with the mechanism of each action, which will help to determine the primary and secondary relationship and coupling relationship of each mechanism in micro-electrolysis.

- Due to the strong processing capacity of micro-electrolysis in only lower pH condition, how to improve the pH range applicability of the micro-electrolysis process is an important problem that needs to be solved in the application process. On the one hand, it can be initiatory from the modification on the ICME material. On the other hand, the micro-electrolysis reactor is also a significant factor for treatment effectiveness, so it can make modification on the reactor, for example, external electric field applied for the micro-electrolysis reactor or ozone adopted to improve pH application of micro-electrolysis.

- The materials of ICME have the problems of clotting and passivation with the prolongation of the treatment time. The resolution can be found from the improvement on the synthesis of materials, such as the application of high-temperature calcining technology, the addition of catalyst, or new nano micro-electrolysis technology. For example, Deng et al. (2017) [32] utilized manganese (Mn) and nickel (Ni) to improve ICME-based phosphonate adsorption and found that the addition of Mn and Ni both notably accelerated the dissolution of ferric ions from iron scraps. The application of catalyzed iron scrap-GAC removed the pH reliance of ZVI and inhibits the generation of ammonia [23]. The nano particle ZVI (nZVI) can drive autotrophic denitrification process [37,38]. The immobilization of nZVI onto GAC can form an ICME micro-electrolysis system. It has been reported that GAC/nZVI micro-electrolysis can degrade organics (iminobispropanenitrile) [24] and inorganics (Cr (VI), the removal rate up to 99.5%) [39]. The reaction rate was ten times higher than that of traditional adsorption reaction, and the GAC/nZVI micro-electrolysis was confirmed to possess large specific surface area and distinguished reducibility [39]. Or the resolution can also be found from the modification on the micro-electrolysis reactor, such as using internal circulation or fluidized bed micro-electrolysis reactor to solve the problems.

- Based on the fact that the synergetic effects are obviously dominant for the integration of
ICME with other technologies, so the combination of micro-electrolysis with other technologies is an important development direction for refractory wastewater treatment. Except the above mentioned combinations of ICME with Fenton process, biological process, and ozone aeration, there are still several technologies which can combine with ICME to greatly improve the treatment efficiency, for example, microwave discharge electrodeless lamp and coagulation. Furthermore, the mechanisms underlying the synergetic effects are still not well established, thereby more effects need to investigate the synergetic effects of the integration of ICME with other technologies.

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