



## Review

# A Review of Research Progress in the Preparation and Application of Ferrate(VI)

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**Abstract:** Ferrate(VI) is a green and efficient water treatment agent for drinking and wastewater. It is widely used in water treatment because it has multi-functional uses such as oxidation, algae removal, disinfection, and adsorption flocculation. It does not cause secondary pollution to the environment. This paper compares ferrate(VI) with other water treatment agents and discusses three methods of preparing ferrate(VI). The removal, adsorption, and control of organic matter, algae, disinfection by-products, and heavy metal ions in water when ferrate(VI) was used as an oxidant, disinfectant, and coagulant were summarized. Ferrate(VI) has some advantages in removing toxic, harmful, and difficult-to-degrade substances from water. Due to the disadvantages of ferrate(VI) such as oxidation selectivity and instability, it is necessary to develop the hyphenated techniques of ferrate(VI). In this review, three hyphenated techniques of ferrate(VI) are summarized: ferrate(VI)–photocatalytic synergistic coupling, ferrate(VI)–PAA synergistic coupling, and ferrate(VI)–PMS synergistic coupling.

**Keywords:** ferrate(VI); water treatment; preparation; applications; hyphenated techniques



**Citation:** Yu, J.; Sumita, Z.; Zhang, K.; Zhu, Q.; Wu, C.; Huang, S.; Zhang, Y.; Yao, S.; Pang, W. A Review of Research Progress in the Preparation and Application of Ferrate(VI). *Water* **2023**, *15*, 699. <https://doi.org/10.3390/w15040699>

Academic Editor: Christos S. Akratos

Received: 1 January 2023

Revised: 20 January 2023

Accepted: 29 January 2023

Published: 10 February 2023



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## 1. Introduction

With the rapid development of urbanization and industrialization, the demand for commercial products has also increased dramatically. However, some unknown toxic pollutants and their usage cause environmental issues yearly [1,2]. For example, various micropollutants have been detected in surface water and certain new pollutants (such as toxic hormone chemicals, skin care products, and toxins) [3,4]. Although the levels of these pollutants in water are low, they can have a negative impact on human health, ecosystems, and biodiversity [5,6].

Recently, the most common methods for treating pollutants in the water environment are physical adsorption [7,8], biodegradation [9,10], and advanced oxidation [5,11]. The physical adsorption technique is mainly used to remove pollutants from the water due to the excellent adsorption ability of the adsorbent material, which may enrich the pollutants in the adsorbent. There are two organic and carbon-based adsorbents [12], mostly used in treating aqueous samples [13]. Although the adsorbed material has the advantages of low cost and good adsorption performance, the removal of pollutants by physical adsorption is based mainly on enrichment rather than degradation. Therefore, physical adsorption requires secondary treatment if it is not completely removed in treating pollutants. It is easy to cause recontamination problems, which hinders the wide application of adsorption materials. Compared to physical adsorption, biological treatment can completely remove contaminants. The biological treatment method is mainly based on the ability of microorganisms to use water pollutants as organic carbon sources, and realize the decomposition

and transformation of pollutants through the metabolism of the microorganisms themselves. However, the effect of biological treatment is easily affected by environmental factors, the environmental requirements are high, the treatment cycle is long, and the treatment of antibiotic-contaminated water bodies is prone to the production of resistant bacteria and genes; additionally, there is a risk of biosafety [14]. Compared with the first two, advanced oxidation methods produce hydroxyl radicals ( $\cdot\text{OH}$ ) with strong oxidizing capacity characteristics. Under certain reaction conditions, the pollutants are directly mineralized or improved by oxidation, so that macromolecular refractory organic matter is oxidized into low-toxicity or non-toxic small molecules, which has good application prospects [15,16]. However, the advanced oxidation technique has various disadvantages in the application of pollution removals, such as complex operation, high cost, and difficult operating parameters. Additionally, the treatment impact is easily influenced by several variables, and the effect is unstable [17].

Compared to the advanced oxidation method, the green chemical ferrate(VI) has several advantages in treating pollutants from wastewater [18–20]. Ferrate(VI) is a hexavalent iron salt with a high redox potential that exhibits high oxidation and bactericidal disinfection capabilities throughout the treatment process [21] and can also adsorb the particles and cause flocculation [22]; it does not cause secondary pollution and has been recognized as a green multi-functional water treatment agent.

This review summarizes the properties and applications of ferrate(VI), including the preparation method of ferrate(VI) and the removal, control, and adsorption of organic matter, algae, disinfection by-products, and heavy metal ions in water when ferrate(VI) is used as an oxidant, disinfectant, and coagulant. At the same time, the combination of ferrate(VI) and other substances is described, which can provide a reference for the further application of ferrate(VI).

## 2. Properties of Ferrate(VI)

### 2.1. Structure of Ferrate(VI)

The iron valence state in ferrate(VI) is positive hexavalent, which has strong oxidation. Among them, the UV-visible spectrum of potassium ferrate(VI) has a characteristic peak absorption at 510 nm and 800 nm. Its Infrared Spectroscopy (IR) also has a strong absorption peak at  $800\text{ cm}^{-1}$  and a shoulder peak at  $778\text{ cm}^{-1}$ , which is the characteristic peak of Fe–O bond telescopic vibration in potassium ferrite, so infrared spectroscopy can be used to qualitatively and quantitatively determine potassium ferrate(VI). Figure 1 shows the slightly distorted tetrahedral structure of  $\text{FeO}_4^{2-}$  in solid ferrate(VI), determined using X-ray photoelectron spectroscopy (XPS) and infrared spectroscopy (IR) [23,24].

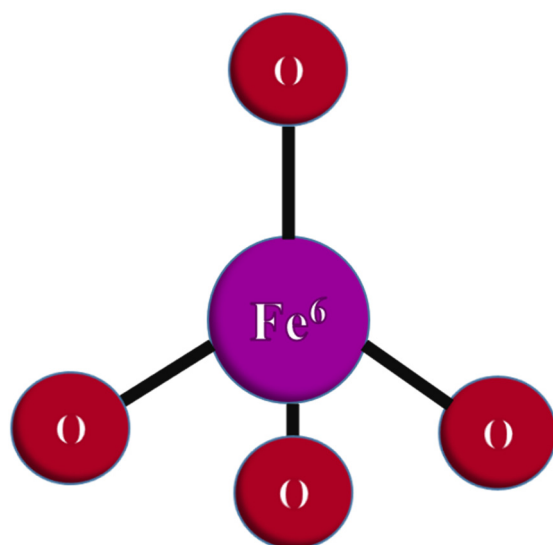
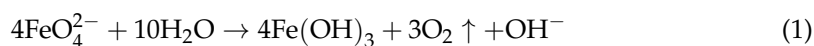


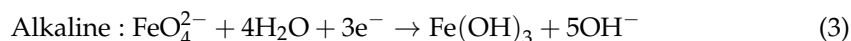
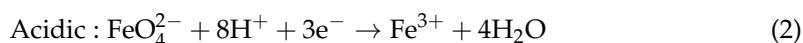
Figure 1.  $\text{FeO}_4^{2-}$  simulated structure diagram.

## 2.2. Stability of Ferrate(VI)

The stability of ferrate(VI) is one of the problems limiting its large-scale preparation and application. Because ferrate(VI) is poorly stable and difficult to store, most of the current applied research on ferrate(VI) is limited to the laboratory. The storage environment requirements for ferrate(VI) are more stringent and require low temperature and dry storage. Once removed from the dry environment, ferrate(VI) is highly susceptible to the influence of water molecules. Its stability will rapidly decrease and oxidative decomposition will occur, with the following reaction Equation (1).



The main factors affecting the stability of ferrate(VI) include the temperature of the solution, pH, and the coexistence of ions in the solution. The temperature has an important influence on the stability of ferrate(VI); the higher the temperature, the faster the decomposition rate of ferrate(VI) [25], so it is necessary to maintain a relatively low temperature in the process of electrolysis and oxidation preparation of ferrate(VI). Ferrate(VI) exists in four main forms, including  $\text{H}_3\text{FeO}_4^+$ ,  $\text{H}_2\text{FeO}_4$ ,  $\text{HFeO}_4^-$ , and  $\text{FeO}_4^{2-}$ . Under acidic conditions,  $\text{H}_3\text{FeO}_4^+$  and  $\text{H}_2\text{FeO}_4$  are the main forms, while  $\text{HFeO}_4^-$  and  $\text{FeO}_4^{2-}$  are the main forms under neutral or alkaline conditions.  $\text{FeO}_4^{2-}$  is extremely unstable and easy to decompose under an acidic environment, while  $\text{FeO}_4^{2-}$  has strong stability when pH is controlled at 9~10. The main reaction equations for  $\text{FeO}_4^{2-}$  under acid–base conditions are shown in Equations (2) and (3) below.



In addition to the above influencing factors, the components in the ferrate(VI) solution can also affect the rate of its decomposition. When the ferrate(VI) solution contains phosphate, it can hinder the decomposition rate of the ferrate(VI). At the same time, light also has a particular influence on the stability of ferrate(VI) [23]; ultraviolet light irradiation will accelerate the decomposition rate of ferrate(VI), so attention should be paid to avoiding light during storage.

## 2.3. Oxidation of Ferrate(VI)

Ferrate(VI) is strongly oxidizing and its redox potential under acidic conditions is 2.20 V, which is higher than some common oxidants such as ozone ( $\text{O}_3$ ), hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), chlorine ( $\text{Cl}_2$ ), chlorine dioxide ( $\text{ClO}_2$ ), and potassium permanganate ( $\text{KMnO}_4$ ) [26], and a comparison of redox potentials are shown in Table 1.

**Table 1.** Redox potentials of commonly used oxidants/disinfectants.

Oxidants/Disinfectants	Reaction Type	$E^0/\text{V}$
$\text{Cl}_2$	$\text{Cl}_2(\text{g}) + 2\text{e}^- \rightarrow 2\text{Cl}^-$	1.358
$\text{ClO}_2$	$\text{ClO}_2(\text{aq}) + \text{e}^- \rightarrow \text{ClO}_2^-$	0.854
$\text{O}_3$	$\text{O}_3 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{O}_2 + \text{H}_2\text{O}$	2.076
$\text{KMnO}_4$	$\text{MnO}_4^- + 4\text{H}^+ + 3\text{e}^- \rightarrow \text{MnO}_2 + 2\text{H}_2\text{O}$	1.679
	$\text{MnO}_4^- + 8\text{H}^+ + 5\text{e}^- \rightarrow \text{Mn}^{2+} + 4\text{H}_2\text{O}$	1.507
Ferrate(VI)	$\text{FeO}_4^{2-} + 8\text{H}^+ + 5\text{e}^- \rightarrow \text{Fe}^{3+} + 4\text{H}_2\text{O}$	2.20
	$\text{FeO}_4^{2-} + 4\text{H}_2\text{O} + 3\text{e}^- \rightarrow \text{Fe}(\text{OH})_3 + 5\text{OH}^-$	0.76

It was found that the strong oxidizing property of ferrate(VI) can effectively remove  $\text{NH}_3$ ,  $\text{CN}^-$ , and  $\text{SCN}^-$ , as well as carboxylic acid, phenol, amino acid, and organic nitrogen compounds from water [27]. Sailo et al. [28] used ferrate(VI) to remove Bisphenol A, and when the concentration ratio of ferrate(VI) to pollutants was increased to 3:1, the removal rate of Bisphenol A reached 100%, and the apparent rate constant was  $8.35 \times 10^2 \text{ M}^{-1} \text{ min}^{-1}$ .

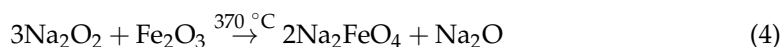
Additionally, with the increase in the amount of ferrate(VI) dosage, the removal effect will also increase. At the same time, the strong oxidation of ferrate(VI) can destroy the cell wall of bacteria and algae cells, and play a role in sterilization and algae. Zhou et al. [29] found that ferrate(VI) pre-oxidation can remove algae cells by destroying the protective organic layer. Therefore, ferrate(VI) is also an effective bactericidal disinfectant and algicide. At the same time, when used as a disinfectant, ferrate(VI) is not like disinfection by-products (DBPs) that are harmful to the human body and produced during chlorination treatment, such as trihalomethanes (THMs); on the contrary, ferrate(VI) can effectively control the formation of chlorination disinfection by-products [30].

### 3. Preparation of Ferrate(VI)

Based on the performance and application advantages of ferrate(VI), the efficient preparation of ferrate(VI) is also essential. At present, the preparation methods of ferrate(VI) mainly include the dry oxidation method [31], the wet oxidation method [32], and the electrochemical method [33]. Among them, the electrochemical method has a simple operation process, simple preparation, and high yield [31].

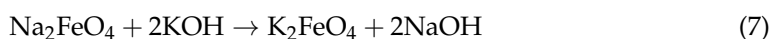
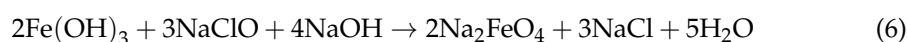
#### 3.1. Dry Oxidation

The dry oxidation method, also known as the solid-phase melting method, involves the formation of ferrate(VI) by combining iron filings or iron compounds with caustic alkali and peroxides (such as  $\text{Na}_2\text{O}_2$ ) in a high-temperature environment. E. Martinez-Tamayo et al. [34] used  $\text{Na}_2\text{O}_2$  and  $\text{FeSO}_4$  to prepare sodium ferrate(VI) and then mixed it with a saturated potassium hydroxide solution and purified it to obtain solid potassium ferrate(VI). Talaiekhosani et al. [31] improved the reaction conditions. They found that, in the absence of  $\text{O}_2$  and  $\text{CO}_2$ ,  $\text{Na}_2\text{O}_2$  reacts with iron oxide at a temperature of  $370^\circ\text{C}$  to form sodium ferrate(VI), as shown in Equation (4). The reaction under these conditions can reduce the possibility of explosion. L. Ninane et al. [35] reduced the cost of the preparation process to meet the needs in the actual water. Moreover, ferrous sulfate, potassium hydroxide, and calcium hypochlorite (or chlorine) are used as raw materials and the reaction time is shortened. The main raw material, ferrous sulfate, is a by-product of the titanium dioxide production process, so the cost of preparation can be reduced. The dry oxidation method can generate large quantities of high ferrate(VI), still, it is carried out under high temperature and high-pressure conditions, and most of the reaction processes are exothermic, which increases the risk of explosion. The reaction also has high requirements for the alkaline corrosion resistance of the equipment, resulting in high preparation costs and difficulty in achieving industrial production [36].



#### 3.2. Wet Oxidation

Wet oxidation is also known as hypochlorite oxidation. It is a process in which trivalent iron ions are oxidized to ferrate(VI) using hypochlorite in a concentrated alkali solution. To prepare a high concentration of sodium ferrate(VI) solution, a saturated KOH solution is poured into the solution, which precipitates potassium ferrate(VI) due to its lower solubility compared to sodium ferrate(VI). The reaction equation is shown in Equations (5)–(7) [37,38].

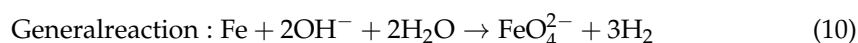
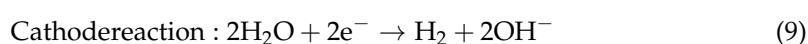
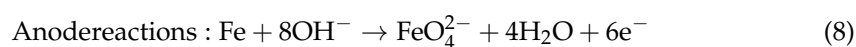


As early as 1950, the preparation of ferrate(VI) using the wet method was reported [39], and the purity also reached 96.9%, but the yield of ferrate(VI) was less than 15%. Wet oxidation is one of the commonly used methods for the preparation of ferrate(VI) because it uses easily available raw materials and has a simple process. However, the wet oxidation

method also has disadvantages such as: the need for large reactors for the reaction, high consumption of alkali, high preparation cost and low yield of ferrate(VI) [33], which makes it challenging to use on large-scale applications. To improve the product and reduce the cost of the preparation of ferrate(VI) by wet oxidation, further research is necessary. Tiwari et al. [40] used strong alkali solutions of potassium hydroxide to replace sodium hydroxide, simplifying the wet oxidation process and improving the yield and purity to 70% and 99%, respectively. Similarly, Tong et al. [32] designed a novel reactor that can control the time and temperature of the reaction, and the concentration of ferrate(VI) generated by the new device, which is  $7.6 \times 10^{-2}$  M compared to conventional reaction units, is twice as much as the old unit. The wet oxidation method requires the passage of chlorine gas into the reactor to prepare a saturated hypochlorite solution, which presents specific safety hazards in the preparation process. To address this problem, some scholars have turned their attention to the use of persulfate ions instead of hypochlorite ions to oxidize Fe(III) to ferrate(VI) using the free radicals generated by persulfate activation [41]. Although the purity of ferrate(VI) prepared by the wet oxidation method reaches 96%, there are still problems of low yield and high preparation cost, so a green and efficient preparation method is urgently needed.

### 3.3. Electrochemical Method

Compared with the preparation of dry and wet oxidation methods, electrochemical methods have attracted much attention because of their simple operation, simple process, and high product purity. The principle of this method is that under the solution condition of strong alkali, the anode material (pure iron, cast iron, and wrought iron) is consumed, causing the anode to undergo oxidation in the superpassivation potential region and dissolve to form ferrate(VI). The main reaction formula in the electrolysis process is shown in Equations (8)–(10) [42,43].



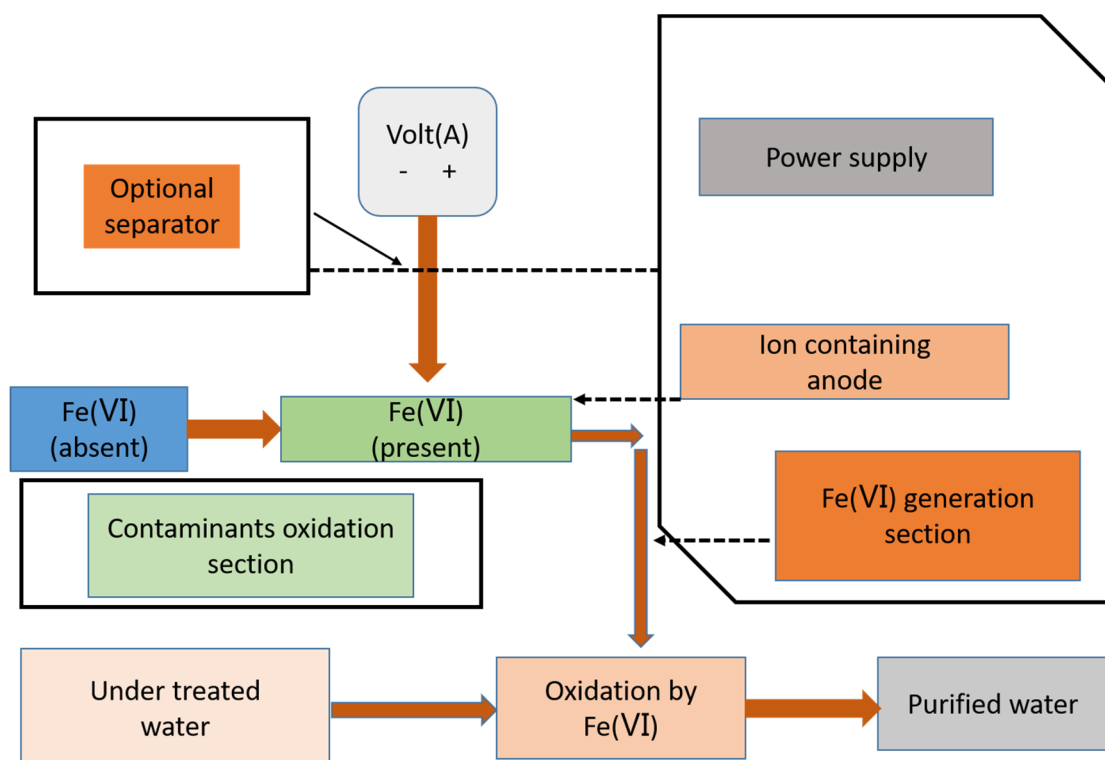
During the electrolytic preparation of ferrate(VI), the anode loses electrons and generates ferrate(VI). Therefore, the anode material's composition can affect ferrate preparation (VI). Talaiekhosani et al. [31] found that by increasing the iron anode material's carbon content, the prepared ferrate's concentration and electrolytic efficiency (VI) improved. By using iron rods with 0.9% carbon content as anodes, they achieved an electrolysis efficiency of 70%, which was six times higher than iron rods, with only 0.08% carbon content. By increasing the carbon content of the iron anode, small holes in the electrode are formed, which promotes iron precipitation. In addition to the anode material's effect on the efficiency of ferrate(VI) generation, the anode morphology also affects the concentration of ferrate(VI) generated [44]. Ding et al. [45] used a porous magnetic iron electrode as the anode, and the results showed that the electrolysis efficiency was as high as 52.3% under the same conditions. This porous magnetic iron electrode not only has a high carbon content, but also contains a large number of small iron electrode pores, which are more conducive to the precipitation of iron and help to slow down the passivation of the electrode. This promotes the generation of high ferrate(VI). In addition, when the anode material contains some non-metallic elements, the preparation effect can be improved. Diaz et al. [46] found that the presence of silicon in cast iron slowed down the anodic passivation process when studying the effect of different electrode materials on the formation of the passivation layer during the generation of ferrate(VI). The concentration of lye is also very important for the production of ferrate(VI) [47]. Sibel et al. [48] explored the effect of lye concentration on electrolytic preparation and experimented with different concentrations of NaOH, and the ferrate(VI) concentration increased with the increase of lye concentration. However, the optimal concentration was 16 mol/L, and the resulting ferrate(VI) concentration was 1.98 mM. Although the higher concentration of lye can increase the concentration

of ferrate(VI), at the same time, the increase in lye concentration will increase the viscosity of the electrolyte, causing the electrons to overcome the resistance of the electrolyte, which increases energy consumption, reduces the transfer efficiency, and inhibits the formation of ferrate(VI), thereby increasing the preparation cost.

In the process of electrolysis, it is necessary to reduce costs and energy consumption. Yang et al. [49] used a gas diffusion electrode (GDE) for cathodic electrolysis to prepare ferrate(VI), which can increase the cathode potential and reduce the tank pressure, thereby reducing the energy consumption in production, which is 31.96–56.67% compared to the traditional electrolysis method. However, as the electrolysis time increases, a passivation layer is formed on the surface of the anode, which hinders the formation of ferrate(VI) [50]. The use of periodic intermittent reverse current electrolysis instead of conventional continuous electrolysis with a DC power supply can slow down passivation. Pi et al. [51] used periodic reverse current to prepare sodium ferrate(VI), which increased the rate of ferrate(VI) synthesis and the concentration of the prepared sodium ferrate(VI) by 75.0%.

#### 4. Application of Ferrate(VI) in Water Treatment

As a water treatment agent, ferrate(VI) is widely used, and Figure 2 shows a schematic diagram of the treatment of wastewater by electrochemically prepared high ferrate [18]. Ferrate(VI) is a hexavalent iron salt with strong oxidation, and redox potential up to 2.20 V under acidic conditions, and its oxidation performance is higher than other common strong oxidants (such as ozone, chlorine, and potassium permanganate). The redox product of ferrate(VI) is a non-toxic and harmless ferric iron salt that can be used as a flocculant to improve the removal of pollutants [52], and does not produce toxic by-products compared to chlorine and ozone treatment [53], so it also has good potential for use in pollutant degradation and removal. Ferrate(VI) is often used as an oxidizing agent to remove pharmaceuticals and personal care products, phenolic compounds, and algae.



**Figure 2.** Electrochemical preparation of ferrate(VI) treatment of wastewater.

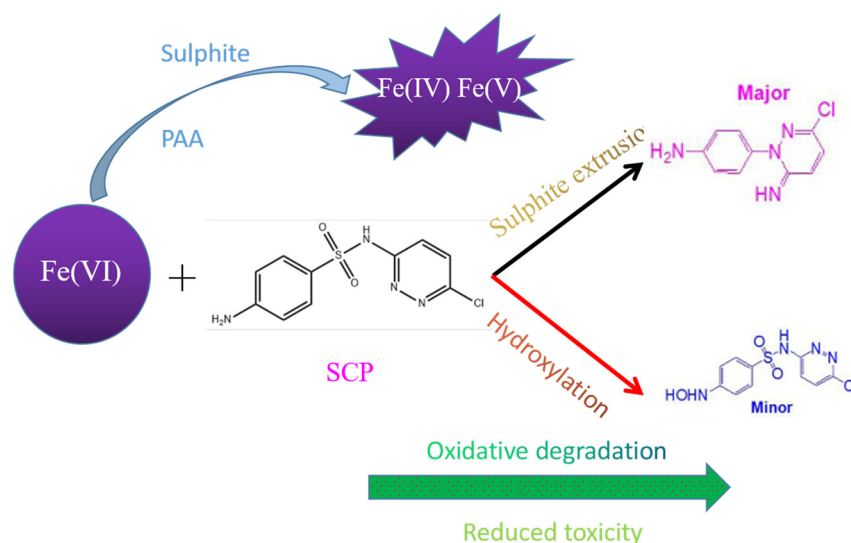


#### 4.1. Ferrate(VI) as an Oxidant

##### 4.1.1. PPCPs

Pharmaceuticals and personal care products (PPCPs) are an emerging class of pollutants that include drugs such as antibiotics,  $\beta$ -blockers, antiepileptic drugs, and daily care products such as skincare, cosmetics, hairspray, and hair dyes [54]. Although the concentration of PPCPs in the environment is low, there are significant safety risks. When PPCPs enter the human body through the food chain, they can cause harm to human health, such as carcinogenic, teratogenic and mutagenic [55]. Ferrate(VI) is commonly used to remove PPCPs from water. It has been shown to have a good removal effect on contaminants such as theophylline [56], metoprolol [57], carbamazepine (CBZ) [58], and sulfachloropyridazine (SCP) [32] from water.

SCP belongs to the sulfonamide class of antibiotics (SA), and ferrate(VI) has also been effective in removing sulfonamide antibiotics [32]. SA is composed of heterocyclic N aromatic rings linked by aniline and sulfa groups. Acosta-Rangel et al. [59] found that SA can be completely removed within 5 min when the molar ratio of ferrate(VI) to SA is 6:1 and the pH is 3. Similarly, Pi et al. [51] used the ferrate(VI) to remove SCP, and at a molar ratio of 15:1, the removal rate of SCP was as high as 90% under neutral conditions. The degradation of SCP by ferrate(VI) is divided into two pathways: first, the  $\text{SO}_2$  in the sulfonamide group is converted to  $\text{SO}_4^{2-}$ , and the intermediate products of ferrate(VI), Fe(IV), and Fe(V) can also convert  $\text{SO}_2^{3-}$  to  $\text{SO}_4^{2-}$ ; second, the  $-\text{NH}_2$  in the aniline group is oxidized to  $-\text{NHOH}$  and  $-\text{NO}$ , and finally to  $-\text{NO}_2$  [60]. Additionally, the oxidation of sulfonamide groups in SCP by ferrate(VI) can reduce the toxicity of SCP, and the degradation schematic is shown in Figure 3.



**Figure 3.** The degradation of SCP by ferrate(VI).

Ferrate(VI) has a high removal rate for electron-rich pollutants in PPCPs, such as phenol, olefins, amines, and aniline moieties. It has been found that roxithromycin and oleandomycin in macrolide antibiotics contain amine groups, which are easily oxidized by ferrate(VI) compared to other antibiotics. Therefore, ferrate(VI) has a better removal rate for antibiotics containing amine structures [61]. Similarly, tetracyclines, chlortetracycline, and oxytetracycline have phenol and olefin groups and are therefore easily removed by ferrate(VI) oxidation [62].

However, the removal of pollutants by ferrate(VI) is susceptible to the pH. Ma et al. [63] found that, in the degradation of tetracycline hydrochloride (TCH) using ferrate(VI), the pH of the reaction solution had a large effect on the removal of TCH, and lowering the pH of the reaction solution could improve the removal rate of TCH with an optimal pH of 9–10 and a molar ratio of ferrate(VI) to TCH of 1:10, resulting in the removal rate of

TCH being 98.57%. Similarly, when ferrate(VI) is used to degrade PPCPs, the removal rate can be improved by reducing the pH from 12 to 7 [28]. This is because the redox potential of ferrate(VI) gradually increases as the pH decreases, and therefore the reactivity also increases as the pH decreases. However, the pH value also affects the stability of ferrate(VI); ferrate(VI) is unstable in an acidic environment and is prone to decomposition. The higher the pH value, the more stable ferrate(VI) is. At pH 9–10,  $\text{FeO}_4^{2-}$  is highly stable and this is the best condition for removing TCH. Similarly, when chemical oxidation is used to degrade pollutants, active species make a significant contribution to the removal of pollutants. It has been found that when ferrate(VI) degrades pollutants, intermediate iron species [Fe(IV) and Fe(V)] are involved in the reaction [64–66]. The activity of intermediate iron species is several orders of magnitude higher than that of ferrate(VI), which facilitates the degradation and removal of organic pollutants.

#### 4.1.2. Phenolic Compounds

Phenolic compounds are widely used in the chemical industry, but they can be harmful if they remain in the environment for an extended period. Ferrate(VI) has a good removal effect on phenolic compounds and can effectively degrade phenolic compounds in a short time [67]. When using ferrate(VI) to degrade phenolic pollutants, the dosage of ferrate(VI) is an important influencing factor. Zheng et al. [20] found that a molar ratio of ferrate(VI) to 4-Tert-Butylphenol (4-tBP) greater than 10 can achieve complete degradation of 4-tBP within 5 min. Similarly, Li et al. [68] found that when the content of ferrate(VI) increased, the removal rate of Bisphenol A (BPA) also increased, and BPA could be completely degraded within 5 min under the optimal molar ratio of ferrate(VI):BPA = 5:1. Similarly, Widhiastuti et al. [69] found that when the molar ratio of ferrate(VI):BPA in a composite reverse osmosis concentrate is 50, the degradation rate of BPA exceeds 90%. In addition to the dosage, pH is also an important factor that influences the effectiveness of ferrate(VI) in removing phenolic compounds. Delaude et al. [43] found that when ferrate(VI) alone is used to remove phenol from water, the effect is not significant. However, when sodium hypochlorite reagent is added to the reaction solution, the removal rate of phenol can be significantly improved. This is because the sodium hypochlorite solution is weakly alkaline, the ferrate(VI) is more stable in the alkaline environment, and the rate of self-decomposition is inhibited, allowing most of the ferrate(VI) to be used to oxidize phenol. Similarly, Sun et al. [70] once again proved that ferrate(VI) is the most effective method for the removal of BPA under alkaline conditions; in addition, the study also found that  $\text{Fe}(\text{OH})_3$  is also conducive to the removal of BPA.  $\text{Fe}(\text{OH})_3$  is an effective coagulant, thus demonstrating that ferrate(VI) is effective at removing phenolic compounds.

Most phenolic compounds contain benzene rings and hydroxyl groups, and ferrate(VI) tends to react with these substances, so rapid degradation of phenolic compounds can be achieved. Ferrate(VI) can gradually break down phenolic compounds into low-molecular compounds, reducing the antibacterial properties of the decomposition products. As a result, the toxicity of phenolic compounds after oxidation of ferrate(VI) can be reduced [71].

#### 4.1.3. Algae

Reservoir eutrophication and algal bloom outbreaks in drinking water sources have become significant threats to the current water ecological environment [72,73]. The overgrowth of algae can easily cause a series of problems such as foul odor and deterioration in water quality. At the same time, algae itself is also a precursor of DBPs, so removing algae is of great benefit for the control of DBPs.

Numerous studies have shown that ferrate(VI) is more effective at removing algae than other methods. For example, Ma et al. [74] compared the effectiveness of potassium ferrate(VI) ( $\text{K}_2\text{FeO}_4$ ), polyferric chloride (PFC), and potassium permanganate ( $\text{KMnO}_4$ ) in removing algae in water. The results showed that the removal effect of  $\text{K}_2\text{FeO}_4$  on algae was better than that of PFC and  $\text{KMnO}_4$ , and the removal rate was as high as 92.4%. Similarly, Emilia et al. [73] used ferrate(VI) to remove chlorella, and when 8.34 micromole



of ferrate(VI) was added, the removal rate of chlorella was 89%. The mechanism by which ferrate(VI) removes algae is mainly through oxidation, which destroys the surface structure of algae cells, this causes the extracellular sheath to crack and the intracellular substances to discharge, which leads to the death of the algae [75]. Additionally, the reduction product  $\text{Fe}(\text{OH})_3$  of ferrate(VI) has a flocculation effect, which can further adsorb and remove algal cells. Therefore, based on the advantages of ferrate(VI) algae removal, ferrate(VI) pre-oxidation is usually used to remove algae [76]. He et al. [77] found that after the oxidation treatment with ferrate(VI), not only was the structure of the algae cells destroyed, but the particle size and zeta potential of the algae also increased by 20% and 55%, respectively, which promotes the aggregation of algae and improves algae removal efficiency. Increasing the dosage of ferrate(VI) or the reaction time can also improve the algae removal rate. Dong et al. [78] used ferrate(VI) to remove cyanobacteria, and the dosage of ferrate(VI) was increased or the oxidation time was prolonged; consequently, the removal of algal cells and algal organic matter (AOM) by ferrate(VI) increased. Ferrate(VI) can effectively inhibit algae growth, enhance the flocculation effect of water bodies, and increase the purification capacity of a water body. At the same time, ferrate(VI) also reduces the concentration of DBPs produced during subsequent chlorination. An amount of 32% of TCM, 33% BDCM, 43% TCP, and 82% TCNM were controlled by  $\text{Fe}(\text{VI})$  (0.03 mM) pre-oxidation, respectively [77].

#### 4.1.4. Reduction Products of Ferrate(VI)

The reduction product  $\text{Fe}(\text{III})$  or iron hydroxide of ferrate(VI) has a strong coagulating effect that can adsorb particles in water and reduce turbidity. Therefore, the reduced product of ferrate(VI) can also be used as a coagulant. It has the following advantages when used as a coagulant: (1) It produces low amounts of sludge and is low cost. In removing turbidity, potassium ferrate(VI) produces much less sludge than other coagulants ( $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ ), iron nitrate [ $\text{Fe}(\text{NO}_3)_3$ ], iron chloride ( $\text{FeCl}_3$ ), and aluminum sulfate [ $\text{Al}_2(\text{SO}_4)_3$ ]. (2) It can rapidly reduce colloidal stability. The ferrate(VI) can destabilize the colloid within 1 min, while it takes 30 min to achieve the same effect using iron and ferrous salts [79].

Based on the strong oxidizing and reducing capabilities of ferrate(VI), it can be used in the pre-oxidation, conventional, and deep treatment stages of water treatment processes. In addition to removing trace pollutants from water, it can also save on the use of flocculants and reduce costs. Ferrate(VI) is often used to remove sewage that is rich in heavy metals. Tiwari et al. [80] found that, at a lower dosage, the use of ferrate(VI) was able to reduce many metallic elements as well as toxic heavy metals in treated water. Similarly, Lan et al. [81] added ferrate(VI) to wastewater containing arsenic and antimony, and the removal of antimony increased with a longer contact time. This is because the addition of ferrate(VI) decomposes itself over time, and the decomposition product,  $\text{Fe}(\text{III})$ , can effectively adsorb and remove arsenic and antimony from the water. At the same time, pH is also one of the factors affecting the removal of heavy metals. Pruce et al. [82] found that when the pH rises from 5 to 10, the removal rate of  $\text{Cd}(\text{II})$  is increased; when the pH is 10,  $\text{Cd}(\text{II})$  is completely adsorbed and removed. Similarly, M.R et al. [83] found that at high pH values, heavy metals condense, promoting the adsorption of heavy metals by ferrate(VI). This is because, under alkaline conditions,  $\text{Fe}(\text{III})$ , a product of ferrate(VI) decomposition, can combine with  $\text{OH}^-$  ions in solution to form  $\text{Fe}(\text{OH})_3$  with coagulability. The amount of ferrate(VI) dosing is proportional to the removal rate of heavy metals [84]. Prucek et al. [85] increased the ratio of ferrate(VI) to antimony to 10:1, and after some time, the removal rate of antimony reached 80%. In addition to heavy metals, ferrate(VI) can remove radionuclides from water as a coagulant [62,86,87]. Petrov et al. [88] removed  $\alpha$  and  $\beta$  radionuclides from wastewater using potassium ferrate(VI). There are also indications that when used as a scavenger, ferrate(VI) can remove almost all radionuclides except cesium [31]. With its superior performance, ferrate(VI) can remove colloidal particles and adsorb heavy metal ions in water without causing secondary pollution, making it a green and efficient water treatment agent.

Table 2 summarizes the oxidative removal conditions and removal rates of various organic pollutants by ferrate(VI).

**Table 2.** Ferrate(VI) removal capacity of common pollutants in water.

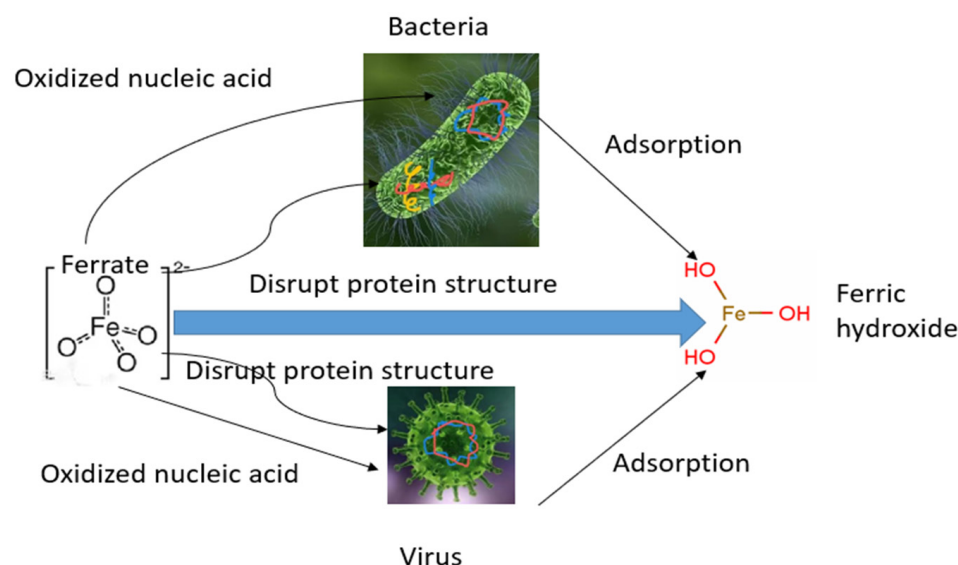
Type of Pollutant	Name of Pollutant	pH	Molar Ratio of Ferrate(VI) to Pollutants	Time/min	Removal Rate/%	References
Medicine	SMZ:	5–9	20:1	—	100	[89]
	Mycin	4–9	5:1	—	80	[90]
	SDZ	7	20:1	—	75	
	Sulfonamide	3	6:1	15	100	[59]
	Cotinine	6.5	—	—	90	
	Sulfachloropyridazine	7	10:1	40	90	[51]
	Atrazine	7	25:1	—	100	[32]
Phenolic compounds	4-tBP	—	10:1	5	100	[20]
	p-Nitrophenol	5	3:1	50	80	[91]
	Pentachlorophenol	9	—	—	—	[92]
	BPA	8	—	60	99	[69]
	Tetrabromobisphenol A	7	4:1	3	99.06	[93]
	Bisphenol F	7.5–10	3.33:1	5	94	[94]
Alcohols	Ethanol	6	15:1	30	80	[95]
Chain hydrocarbon derivatives	Iminodiacetic acid	8–10	—	—	90	[80]
Organophosphorus pesticides	Clorpyrifos	7	100:1	5	100	[47]
Aldehydes	Benzaldehyde	—	—	—	96	[96]
Dye wastewater	Rhodamine B	7	—	8	100	
	Congo Red	9.2	5:1	20	98.2	[97]
	Methyl Orange	6	—	60	99.2	[98]
Algae	Aeruginosa suspension	7	7:15	—	70.25	[99]
	<i>Chlorella</i> sp.	8–9	3:1	—	46.2	
	<i>P. limnetica</i>	8–9	3:1	—	58.1	[78]

#### 4.2. Ferrate(VI) as a Disinfectant

##### 4.2.1. Water Disinfection

Disinfection in the water treatment system is essential for removing bacteria and viruses. During the treatment process, disinfectants are added to inhibit the growth of microorganisms. Ferrate(VI) can be used as a strong oxidant and disinfectant for water sterilization and disinfection. Compared with traditional chlorine disinfection, ferrate(VI) effectively removes microorganisms, and reduces the precursors of disinfection by-products. The schematic diagram in Figure 4 [100] illustrates the disinfection of microorganisms such as bacteria by ferrate(VI). Furthermore, ferrate(VI) kills microorganisms by oxidizing their nucleic acids and destroying their protein structures: on the one hand, ferrate(VI) kills microorganisms by oxidizing the nucleic acids of bacteria and viruses and destroying their protein structures; on the other hand, the iron hydroxide colloids obtained by ferrate(VI) reduction can adsorb bacteria and viruses and cause microorganisms to aggregate and precipitate.

Ferrate(VI) has advantages over other disinfection when used as a disinfectant, and the process is safer. Table 3 summarizes the advantages and disadvantages of ferrate(VI) and other disinfectants.



**Figure 4.** Schematic diagram of ferrate(VI) disinfection.

**Table 3.** Advantages and disadvantages of different disinfectants.

Disinfectant Name	Advantages	Disadvantages
Chlorine	Low cost Strong disinfection ability Raw materials are readily available Long-term preservation	Produces toxic DBPs Dechlorination is required Harm to health
Ozone	The by-product is oxygen, which is non-toxic and harmless Strong disinfection capacity and fast rate Remove odors	High cost A small amount of virus is produced Harmful to the human body Corrosive equipment
Ferrate(VI)	Strong disinfection ability No disinfection by-products The reaction product has a coagulation effect The process is simple, the footprint is small, and the cost is low	Ferrate(VI) yields are low Ferrate(VI) has poor stability and is difficult to store for a long time

When ferrate(VI) is used to disinfect wastewater, not only can it remove organic matter from the wastewater, but it can also sterilize it. Ferrate(VI) mainly kills microorganisms in two ways: 1. By using strong oxidation, it oxidizes the cell wall, DNA, and other important microbial structures, thereby inactivating them; 2. The ferrate(VI) reaction product is ferric iron, which has a strong coagulating effect under alkaline conditions, and can remove colloidal substances such as microorganisms. Talaiekhosani et al. [101] conducted research using ferrate(VI) as a disinfectant and showed that a ferrate(VI) concentration controlled at 0–50 ppm can kill all microorganisms in water. Ferrate(VI) can destroy the surface structure of bacteria with its strong oxidation, and can rapidly inactivate *Escherichia coli*, total coliform, *Bacillus subtilis*, etc. [31]. When using ferrate(VI) for disinfection, pH is an important influencing factor. When the pH was 8.2, 6 mg/L of ferrate(VI) eliminated 99% of *E. coli* from the water. However, when the pH decreased to 7, the disinfection effect of ferrate(VI) increased, eliminating 99.9% of *E. coli* flora and 97% of bacteria in the water [31]. This is because ferrate(VI) becomes more active at lower pH levels. This shows that ferrate(VI) is highly effective at removing microorganisms such as bacteria from the

water. Li et al. [102] compared ferrate(VI)-treated water with chlorinated treated water to study the bacterial communities in each. In the chlorinated samples, the number of viable bacteria increased with the increase in chlorine dosage, while in the ferrate(VI)-treated samples, the trend decreased with the increasing ferrate(VI) dose. This suggests that ferrate(VI) is more effective at removing microorganisms such as bacteria more significantly than chlorine, and can reduce the formation of DBPs.

#### 4.2.2. Control Application of Disinfection By-Products

Chlorine is a commonly used disinfectant in wastewater treatment plants, due to its low cost and high disinfection efficiency. However, during the disinfection process, it reacts with natural organic matter (NOM) in water to form volatile trihalomethanes (THMs) and refractory halogenacetic acids (HAAs) [103,104], as well as haloacetonitriles (HANs) and haloaldehydes (HKs). It has been shown that the use of ferrate(VI) (0.03 mM) in pre-oxidation can reduce the amounts of TCM and BDCM by 32% and 33%, respectively [77]. The mechanism by which ferrate(VI) can inhibit the formation of chlorine disinfection by-products is through the transfer of amines, alcohols, and amino acids from NOM to carbonyl compounds, which are then further oxidized to acids that are highly resistant to chlorine, thereby hindering the production of THMs.

When ferrate(VI) is used as a disinfectant, it can effectively control the formation of disinfection by-products. Ferrate(VI) removes total organic carbon (TOC) better than chlorine and produces relatively small amounts of THMs. Li et al. [105] studied the effect of ferrate(VI) on the formation of DBPs in sewage plants. The contents of trichloromethane (TCM), dichlorobromomethane (DCBM), dibromochloromethane (DBCM), and tribromomethane (TBM) in water samples decreased with the addition of ferrate(VI) concentration, and ferrate(VI) pre-treatment could effectively reduce the amount of THMs generated during chlorination. The control mechanism of ferrate(VI) on DBPs is mainly the oxidation of its precursors to achieve removal. The control mechanism of ferrate(VI) on disinfection by-products is summarized in Table 4. The effect of ferrate(VI) on the control of DBP production is mainly influenced by the amount and pH of the ferrate(VI) dosing. Similarly, Li et al. [105] found that the levels of TCM, DCBM, DBCM, and TBM decreased with increasing ferrate(VI) concentration when ferrate(VI) was added to the water samples. The pH of the solution also affected the production of DBPs. Dong et al. [78] found in their experiments that the yield of DBPs in *Chlorella* solution gradually decreased when the pH was increased from 7 to 9. However, Ding et al. [45] found that the best removal of dichloroacetonitrile (DCAN) by ferrate(VI) was achieved at pH 6.5. The control of DBPs by ferrate(VI) varies under different pH conditions. Under acidic conditions, the pre-oxidation of ferrate(VI) was effective in reducing the generation of THMs; on the contrary, for HANs, a lesser amount was generated under alkaline conditions. This is related to the fact that the precursors of HANs, tryptophan or kynurenine, are more active under acidic conditions [106]. Therefore, when using ferrate(VI) to control DBPs, the pH should be determined according to the properties of the DBPs.

**Table 4.** Control mechanism of ferrate(VI) on DBPs.

Disinfection Method	Type of DBPs	Name of DBPs	Precursors	Mechanism of Action	References
Chlorine disinfection	THMs	Chloroform	NOM, AOM, Phenols, Benzene, Amino acids	The action of ferrate(VI) completely removes hydrophobic organic molecules and partially removes hydrophilic organic molecules, and reduces the formation potential of THMs, thus controlling the amount of THMs produced	<a href="#">[107]</a>
		Bromodichloromethane			
		Bromomimetic			
	HAAs	Chloroacetic acid		Ferrate(VI) reduces the amount of DBPs produced by chlorine disinfection by oxidizing organic matter in the water to acids that are highly tolerant to chlorine	<a href="#">[108]</a>
		Dichloroacetic acid			
	HANs	Chloroacetonitrile		Ferrate(VI) oxidizes organic matter in water to acids that are highly resistant to chlorine, thereby reducing the amount of DBPs produced by chlorine disinfection	<a href="#">[109]</a>
		Bromoacetonitrile			
Ozone disinfection	Bromate	Sodium bromate	Bromide ( $\text{Br}^-$ )	Ferrate(VI) has no reaction properties against $\text{Br}^-$ under medium-alkaline conditions, so controlling the pH of the reaction is a crucial condition for ferrate(VI) control of bromate	<a href="#">[30]</a>
Chloramine disinfection	Iodine-substituted DBPs	Dichloriodomethane	Iodide ( $\text{I}^-$ )	High doses of ferrate(VI) oxidize iodide directly to iodate, which does not react with chlorine, thereby reducing the amount of iodosterilization by-products	<a href="#">[110]</a>
		Dibromiodomethane			
		Iodoform			

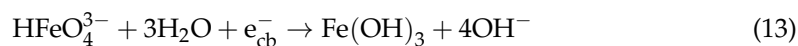
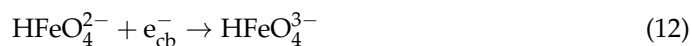
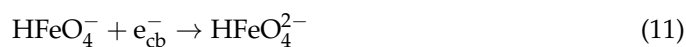


## 5. Hyphenated Techniques of Ferrate(VI)

Although ferrate(VI) is an effective tool for removing refractory pollutants in water, its application still has some challenges. Ferrate(VI) has strong selectivity for removal, and different pollutants have different removal rates [111]. Ferrate(VI) reacts quickly with organic pollutants containing an electron-rich organic fraction first, and reacts slowly with other organic substances (e.g., ibuprofen and meprobamate) [112,113]. Ferrate(VI) is added to help the solution decompose rapidly. Therefore, to overcome these problems, the hyphenated technique of ferrate(VI) has been developed. Shao et al. [27] observed that when compared to ferrate(VI) treatment alone,  $\text{CaSO}_3$  can promote the conversion of ferrate(VI) to phases Fe(IV) and Fe(V) and increase the removal rate of organic pollutants by 6.1 times. At present, the hyphenated techniques of ferrate(VI) include ferrate(VI) and photocatalysis, which uses light energy to convert ferrate(VI) into Fe(IV) and Fe(V) with a stronger oxidation capacity [114]. The removal rate of pollutants by the combination of ferrate(VI) and peroxymonosulfate (PMS) is significantly higher than that of ferrate(VI) or PMS alone. Ferrate(VI) is combined with PAA, and PAA will also promote the decomposition of ferrate(VI) into Fe(IV) and Fe(V) with strong oxidizing ability, thereby improving the removal rate of organic pollutants. Table 5 summarizes the hyphenated techniques for ferrate(VI).

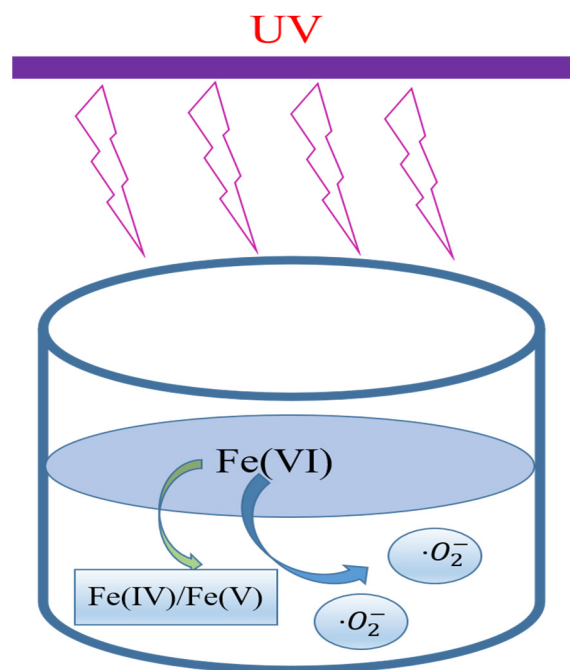
### 5.1. Ferrate(VI)–Photocatalysis

To further overcome the selectivity of ferrate(VI) for the scavengers, the removal of organics can be enhanced by ferrate(VI) activation or catalysis [115]. It was found that ferrate(VI) can act as an electron acceptor in the UV/TiO<sub>2</sub> system, and the decomposition of ferrate(VI) to Fe(IV), Fe(V), and Fe(III), shown in Equations (11)–(13) [116]. In addition, the researchers also found that under UV irradiation, it is accompanied by the production of superoxide free radicals, as shown in Figure 5 [116]. The combined system can effectively degrade organic matter in water, and photocatalysis uses sunlight as the light source, which can reduce costs and will not produce secondary pollutants. The principle of ferrate(VI) and photocatalysis is mainly based on the catalyst TiO<sub>2</sub> under ultraviolet irradiation, which causes electron transition on the valence band to form electron-hole pairs, while electrons are negatively charged, have reduction, holes and undergo oxidation, ferrate(VI) can be used as an electron trap, and can effectively prevent electrons and holes from combining, while electron-hole pairs can reduce ferrate(VI) to Fe(IV) and Fe(V) with stronger oxidation capacity. Tian et al. [114] also proved that Fe(IV) and Fe(V) are stronger than ferrate(VI), about 1000 times more, so the degradation of the target pollutant by ferrate(VI)–photocatalysis is more thorough.



For example, Wu et al. [116] found a method that can effectively degrade 2,4-DCP in water; the activation of ferrate(VI) by ultraviolet light can significantly increase the degradation rate of 2,4-DCP by ferrate(VI), which is 6.9 times and 9.2 times higher than that of ultraviolet irradiation alone and ferrate(VI) oxidation alone, respectively. Similarly, Yuan et al. [117] studied the degradation of dimethyl phthalate (DMP) by K<sub>2</sub>FeO<sub>4</sub> and TiO<sub>2</sub> photocatalysis, and found that the ferrate(VI)–TiO<sub>2</sub>–UV system had the best degradation effect on DMP, which was significantly higher than the degradation rate under potassium ferrate(VI) and UV irradiation alone. Similarly, Heng et al. [91] also used ferrate(VI)/ultraviolet light to synergistically degrade p-nitrophenol in water, and the removal rate of ferrate(VI)/ultraviolet light system was significantly higher than that of ferrate(VI) alone, and the COD<sub>Cr</sub> degradation rate of p-nitrophenol reached 85.71%. It can be seen from the data that ferrate(VI) and photocatalytic technology can significantly

improve the removal rate of organic pollutants. In addition, ferrate(VI)–photocatalytic technology effectively removes algae and other substances in water. Xia et al. [118] used ferrate(VI)–photocatalysis to remove algal toxins from water. When the dosage of ferrate(VI) was 10 mg/L, the removal rate of algal toxin by the combination of ferrate(VI) and photocatalytic technology increased from 63% to 100%, which could quickly remove the algal toxin. Combined with several studies, it can be seen that the effect of ferrate(VI) and photocatalytic technology is significantly higher than that of ferrate(VI) alone, and has a good application prospect.



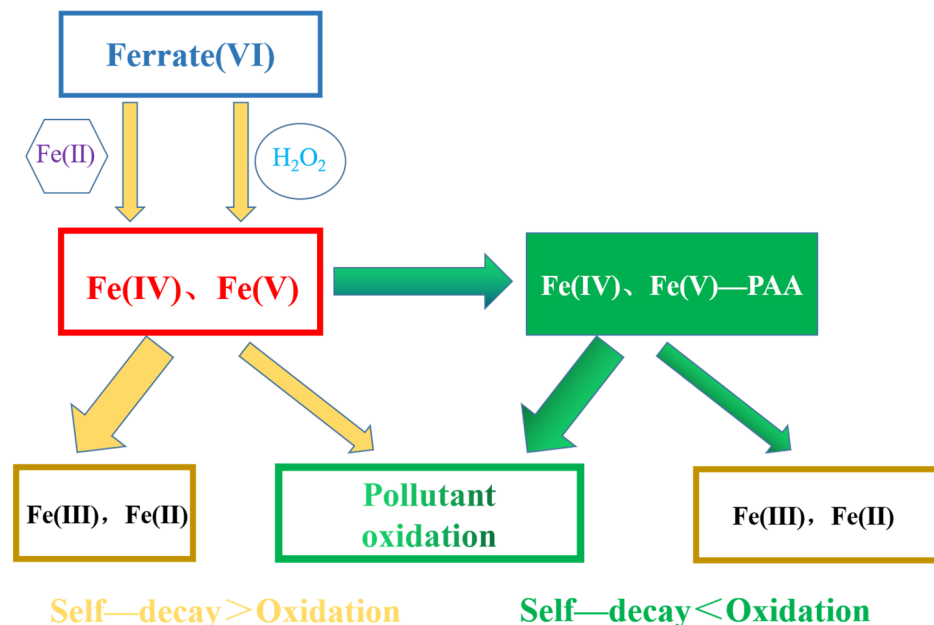
**Figure 5.** Free radicals produced by UV/ferrate(VI) systems.

### 5.2. Ferrate(VI)–PAA

Peracetic acid (PAA  $\text{CH}_3\text{COOOH}$ ) is a volatile and easily decomposable chemical with strong oxidation properties, and the decomposition products  $\text{CH}_3\text{COOH}$ ,  $\text{CH}_3\text{OH}$ , and  $\text{O}_2$  are harmless. In addition, PAA, like ferrate(VI), can be used as a disinfectant, and the DBPs produced are less harmful than halogenated disinfection by-products [16,119]. It is an effective method to activate ferrate(VI) by transferring single or double electrons to reducing agents ( $\text{SO}_3^{2-}$  and  $\text{S}_2\text{O}_3^{2-}$ ) [120] and solid materials (carbonaceous materials and silica gels) [121,122] to improve the removal rate of pollutants. PAA combined with ferrate(VI) is a new area of research. Kim et al. [123] used Fe(II) to activate PAA, promoting the transformation of ferrate(VI) into higher oxidizing capacity Fe(IV) and Fe(V) that can effectively remove pollutants from water.

Wang et al. [124] found that when ferrate(VI) is combined with PAA, the removal effect of ferrate(VI) on micropollutants is improved by promoting electron transfer efficiency. At pH 7.3 and 8, the addition of PAA to the ferrate(VI) system has a better effect on the removal of CBZ than ferrate(VI) alone. Similarly, Manoli et al. [125] found that when ferrate(VI) (200  $\mu\text{M}$ ) and PAA (100  $\mu\text{M}$ ) combined at pH 9, they could remove 80–90% of PPCPs in 1 min. PAA can enhance the removal rate of ferrate(VI) from organic matter by decomposing into Fe(IV) and Fe(V) through electron transfer, which greatly improves the oxidation performance of Fe(IV) and Fe(V) compared to ferrate(VI) [27], and at the same time, PAA will also decompose to produce strong oxidizing organic radicals ( $\text{CH}_3\text{C}(\text{O})\text{O}\cdot$ ), making the degradation of organic matter more thorough and more rapid. Manoli [125] also demonstrated that the main cause of the degradation of organic matter in the ferrate(VI)–PAA system is Fe(V)/Fe(IV). When ferrate(VI) is used in combination with PAA, most

of Fe(IV) and Fe(V) in the system are used for organic degradation, which is in contrast to using ferrate(VI) alone, as shown in Figure 6. The ferrate(VI)–PAA oxidation system has great potential for the degradation of pollutants in water, and also reduces the cost of removing pollutants, making it a promising application.



**Figure 6.** Difference between ferrate(VI)–PAA system and ferrate(VI) alone.

### 5.3. Ferrate(VI)–PMS

As ferrate(VI) is in an aqueous solution, it is extremely unstable and will decompose rapidly under acidic and neutral conditions. Therefore, a solution is needed to increase the oxidation time of ferrate(VI) in order to improve the efficiency of the reaction [126]. Shao [127] and Yang [128] et al. combined ferrate(VI) with various chemicals to improve the removal of contaminants. For example, the application of ferrate(VI)/sulfite can degrade enrofloxacin and phenol has a better degradation effect than ferrate(VI) alone. However, Wu et al. [113,114] found that the ferrate(VI)/PMS process was more effective than that of atrazine in the degradation of atrazine, and hydroxyl radicals and sulfate radicals were detected in the process of ferrate(VI)/PMS for the degradation of atrazine. It has been reported that ferrate(VI) can be used in combination with PMS, since PMS is also an oxidant, which can act as an electron acceptor or donor to improve degradation efficiency against contaminants [129]. The self-decomposition of ferrate(VI) produces Fe<sup>3+</sup> and Fe<sup>2+</sup>, which can activate PMS and form sulfate radicals (SO<sub>4</sub><sup>•−</sup>) [130].

However, ferrate(VI)/PMS systems are affected by various factors when degrading contaminants. The pH of the initial solution has a certain effect on the degradation effect. He [131] et al. found that the removal rates of the ferrate(VI)/PMS system at pH 4, 5, 6, 7, and 8 were 74.7%, 81.9%, 68.1%, 53.2%, and 44.8%, respectively. This is because, between pH 4 and 7, the main type of ferrate(VI) is HFeO<sub>4</sub><sup>−</sup>, which is higher in activity but easily decomposes [132]. When the pH is higher than 7, FeO<sub>4</sub><sup>2−</sup> becomes the main species, although the stability is improved, the activity is reduced, the activation of PMS is weakened, and the removal rate of diclofenac(DCF) is reduced. Excess H<sup>+</sup> will form hydrogen bonds with the main substance of PMS (HSO<sub>5</sub><sup>−</sup>) in an acidic environment, inhibiting the synergistic effect of ferrate(VI) and PMS and reducing the removal rate of DCF. In addition, the dose of ferrate(VI) and PMS also affects the removal rate. When Feng [133] et al. used ferrate(VI) and PMS to degrade flumequine (FLU), the solubility of ferrate(VI) remained unchanged, and the molar ratio of PMS:FLU was increased from 10 to 200, and the removal rate of FLU was also increased from 21% to 61%. Since both substances

are oxidants, have an oxidizing effect, and have a synergistic effect, the removal rate will be increased by increasing the dose. This is because reactive sulfur species (RSS) (e.g.,  $\text{SO}_4^{\cdot-}$ ) are generated during the reaction. Reactive oxygen radicals (ROS) ( $\text{OH}^{\cdot}$ ) and high-valent iron ( $\text{Fe}^{\text{IV}}$  and  $\text{Fe}^{\text{V}}$ ), iron oxide/iron hydroxide, a reduction product of ferrate(VI), also accelerate the formation of  $\text{SO}_4^{\cdot-}$  in PMS [134]. N ria et al. [135] activated PMS in sunlight to enhance the disinfection and decontamination capacity of ferrate(VI) under neutral conditions. When using ferrate(VI)/PMS/solar to degrade sulfamethoxazole (SMX), within one hour, SMX degradation was nearly 80%, and the effect was much higher than the removal rate of ferrate(VI) alone or ferrate(VI)/PMS. The combination of ferrate(VI) and suitable agents can not only enhance the stability of ferrate(VI), but also improve the removal rate of ferrate(VI) to target pollutants, which has broad research and development prospects.

**Table 5.** Removal of pollutants by ferrate(VI)-combined technology.

Combined Technology	pH	Pollutants	Removal Rate/%	Active Species	References
Ferrate(VI)–UV	6	2,4-DCP	75.8	$\text{Fe(IV)}$ , $\text{Fe(V)}$ and $\cdot\text{O}_2^-$	[116]
	6	BPA	79.2	$\text{Fe(IV)}$ , $\text{Fe(V)}$ and $\cdot\text{O}_2^-$	
	2	Formaldehyde	100	$\text{Fe(IV)}$ , $\text{Fe(V)}$ and $\cdot\text{O}_2^-$	[136]
	9	DMP	40	$\text{Fe(IV)}$ , $\text{Fe(V)}$ and $\cdot\text{O}_2^-$	[117]
	711	P-nitrophenol	62.6576.31	$\text{Fe(IV)}$ , $\text{Fe(V)}$ and $\cdot\text{O}_2^-$	[91]
Ferrate(VI)–PAA	8	CBZ	100	$\text{Fe(IV)}$ , $\text{Fe(V)}$ and $\text{CH}_3\text{C(O)O}\cdot$	[124]
	6–9	CBZ	100	$\text{Fe(IV)}$ , $\text{Fe(V)}$ and $\text{CH}_3\text{C(O)O}\cdot$	[125]
Ferrate(VI)–aluminum salt	—	$\text{COD}_{\text{Mn}}$ UV254	4060	—	[29]
	—	DOC UV254/Protein	35.933.771.8	$\text{Fe(IV)}$ , $\text{Fe(V)}$	[137]
	—	Microcystic aeruginosa	59.3	$\text{Fe(IV)}$ , $\text{Fe(V)}$	[138]
	—	Thallium	92	—	
Ferrate(VI)–PMS	6	Atrazine	100	$\text{Fe(IV)}$ , $\text{Fe(V)}$ , $\cdot\text{OH}$ and $\text{SO}_4^{\cdot-}$	[113]
	5	SMX	80		[139]

## 6. Conclusions

Ferrate(VI) is a highly efficient water treatment agent that combines the functions of oxidation, disinfection, and adsorption flocculation. The application prospect of ferrate(VI) is also extensive. According to this paper, the following conclusions are drawn: (1) Ferrate(VI) is very widely used in the field of water treatment. Due to its strong oxidizing properties, it can remove most organic pollutants and algae from the water. As a disinfectant, it can quickly inactivate bacteria and viruses, and has a control effect on the disinfection by-products produced during chlorine disinfection, which is a non-toxic and harmless disinfectant. As a coagulant, it can adsorb most of the particles in water and has a certain adsorption effect on heavy metals, reducing water turbidity. (2) The disadvantage of ferrate(VI) is that it is unstable, so how to obtain high-purity ferrate(VI) in the process of preparation is one of the following research hotspots. Among the existing methods for the preparation of ferrate(VI), electrolysis is the most promising green method; at the same time, the influencing factors in the preparation process are solution temperature, pH, current density, alkali concentration, etc. The influence of these factors on the results from continuous experiments must be controlled. Ferrate(VI) is also very harsh on preservation conditions, which is unfavorable for its storage and transportation. Developing the in situ preparation process and improving its preservation requirements will, to some extent, promote its application. (3) Ferrate(VI) has strong oxidizing properties and is effective at pollutant removal. However, ferrate(VI) is highly selective of the removables and the removal rate varies for different pollutants. Combining ferrate(VI) with other technologies can improve the removal rate of target pollutants. The hyphenated techniques of ferrate(VI) coupling mainly include ferrate(VI)–PMS, ferrate(VI)–PAA, ferrate(VI)–photocatalytic coupling, etc. In recent years, ferrate(VI)-coupling technology has also been the hotspot and application direction of research on ferrate(VI). Therefore, the combination of ferrate(VI)

and other water treatment agents is a new research direction to promote the application of ferrate(VI).

**Author Contributions:** Writing—original draft preparation, J.Y. and S.H.; writing—review and editing, J.Y., K.Z., Q.Z. and S.; visualization, J.Y., C.W., and S.Y.; and supervision, W.P. and Y.Z. project administration, W.P. and Y.Z.; funding acquisition, Y.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Natural Science Foundation of Shanghai (Grant No. 20ZR1438200) and the National Key Research and Development Project of China (Grant No. 2021YFC3200805).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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