Chapter 13
Field Study IV: Arsenic Removal from Groundwater by Ferrate with the Concurrent Disinfecting Effect: Semi-Pilot On-site Application

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Abstract The effect of ferrates on arsenic removal from groundwater was initially observed using laboratory tests. Two different sources of groundwater containing an elevated concentration of As (ca 100 µg/L) were used for the semi-pilot scale testing, both possessing the potential for drinking water production. Groundwater treated by ferrates under laboratory conditions proved to meet the requirements for As limits in drinking water, i.e., 10 µg/L (according to Czech legislation—Public notice No. 252/2004 Sb.). A prototype of a portable technological unit for an on-site ferrate application (Fe(IV), Fe(V)) has been constructed to prove on a semi-pilot scale that ferrates are applicable for production of drinking water. Water flow of 100 L/h, two sources of groundwater containing arsenic in concentrations ten times exceeding the limit for drinking water, and ferrates (in the form of commercial ferrate, dosed in different amounts—5 mg/L, 10 mg/L, 15 mg/L, and 20 mg/L) were used. The quality of the treated water from both sites was in compliance with the requirements for drinking water. The minimal dose of commercial ferrates to reach the As limit for potable water was set to 10 mg/L for the first water source and 15 mg/L for the second one. Elimination of microbial organisms was achieved even with a lower dose of commercial ferrates—10 mg/L. The main advantages of the tested

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technology over the existing ones are minimal reagent consumption, minimal sludge production with As (hazardous waste), and disinfecting effect.

Keywords Ferrates · Arsenic removal · Drinking water treatment · Groundwater · Disinfecting effect · Disinfecting agents

13.1 Introduction

Ferrates have been described in the literature for the past two decades as a new type of substance enabling versatile employment in environmental applications. Laboratory tests on the level of fundamental research proved their significant potential applicable for water remediation (e.g., removal of metals, triazine pesticides, endocrine disruptors, cyanides, chemical warfare agents, etc., disinfecting effects (Filip et al. 2011; Zboril et al. 2012; Prucek et al. 2013, 2015; Yates et al. 2014). Ferrates show strong oxidation effect; their final products after the reaction—ferric oxides and oxyhydroxides—are considered nontoxic, and, moreover, they can act as coagulants. Chemical properties of ferrates such as fast reaction with contaminants or low reagent consumption and the resulting lower waste footprint represent an advantage for their application compared with other commonly used technologies.

High-quality resources of drinking water have been disappearing in the Czech Republic, hence the need to begin deploying resources of lower quality. On account of that, research into the disinfecting effect of ferrates has been included within the treatment scheme for arsenic removal. From a microbiological point of view, the remediated water met the requirements for drinking water. Such a promising effect may have been caused by the combination of several factors: disinfecting effect of ferrates reacting in water environment, sorption of microorganisms on the formed nanoparticles of iron oxide/oxyhydroxide, and ultrafiltration with the pore size of 0.45 μm.

13.2 Characterization of Ferrates Used for the Testing

For the purpose of laboratory tests aimed at arsenic removal from groundwater, we used commercial ferrates. In this case, these were commercial ferrates from NANO IRON company (Czech Republic) containing about 33 wt.% of K_2FeO_4 in aqueous solution (UV–VIS measurement done by spectrophotometry at 510 nm and subsequent calculation according to Bielski and Thomas (1987). Detailed characterization of the commercial ferrate is provided in Tables 13.1 and 13.2.

The commercial ferrate is formed by coarse-grained aggregates of a black-violet or almost black color containing crystals of ferrates Fe(V) and Fe(VI). When it is dissolved in water, ferrate Fe(V) disproportionates to Fe(VI) and Fe(III) in the ratio about 2:1. Ferrates in aqueous solution exist mainly in the form of Fe(VI). Fe(VI) is unstable in aqueous solution, after 24 h the concentration reaches only about 10% of

Table 13.1 Concentration of ferrate in the commercial product (solid product)—characterized by Mössbauer and atomic absorption spectroscopy

ENVIFER batch 019, solid product	
Compound	Concentration (%)
$KFe(III)O_2$	29 ± 3
$K_3Fe(V)O_4$	50 ± 5
$K_2Fe(VI)O_4$	6 ± 2
K_2O	<3

The difference of up to 100% is due to the content of oxide impurities (approx. 5–10%), the accumulation of measurement errors and the content of unidentified components with different stoichiometry

Table 13.2 Concentration of ferrate in the commercial product (aqueous solution)—characterized by UV–VIS spectrometry, 510 nm

| ENVIFER batch 019, aqueous solution 0.5 g/L		
Time after dissolving	Absorbance	Concentration of $K_2Fe(VI)O_4$ (%)
1 min	0.98	33.35
24 h	0.1	3.40

With regard to practical use, checking the current content of ferrates in the aqueous solution in the form of Fe(VI) using UV–VIS spectrometry is sufficient and accessible to most of the laboratories

the original concentration in the solution (with the commercial ferrate, it is only 3.4%; see Table 13.2). In industrial practice, ferrates could be processed in a solid form on plants enabling dry storage and dosing. Another option being considered is dosing ferrates in the form of tablets (Czölderová et al. 2018).

13.3 The Principle of the Method for Arsenic Separation by Ferrates

Reaction of ferrates with water leads to the formation of nanoparticles in the form of amorphous γ-Fe_2O_3 and γ-FeOOH (Kolařík et al. 2018). Arsenic is adsorbed, and partly incorporated, within 3–4 min into the structure of the nanoparticles. Subsequently, the microflakes formed during the process containing Fe hydroxides and As have to be thoroughly separated from the water (Prucek et al. 2013).

Initially, we carried out a series of laboratory tests with two different sources of groundwater having a naturally elevated arsenic concentration (ca 100 μg/L), both of which could be used for drinking water production. Following the application of ferrates, the groundwater met the requirements for arsenic limits in drinking water (ca 10 μg/L) in both of the tested sources. On the basis of the experience with the laboratory tests, the prototype of a mobile device for a ferrate application (Fe (IV) and Fe(V)) on-site with the flow of 100 L/h has been designed. This device has been constructed to prove on a semi-pilot scale that ferrates are applicable for production of drinking water.
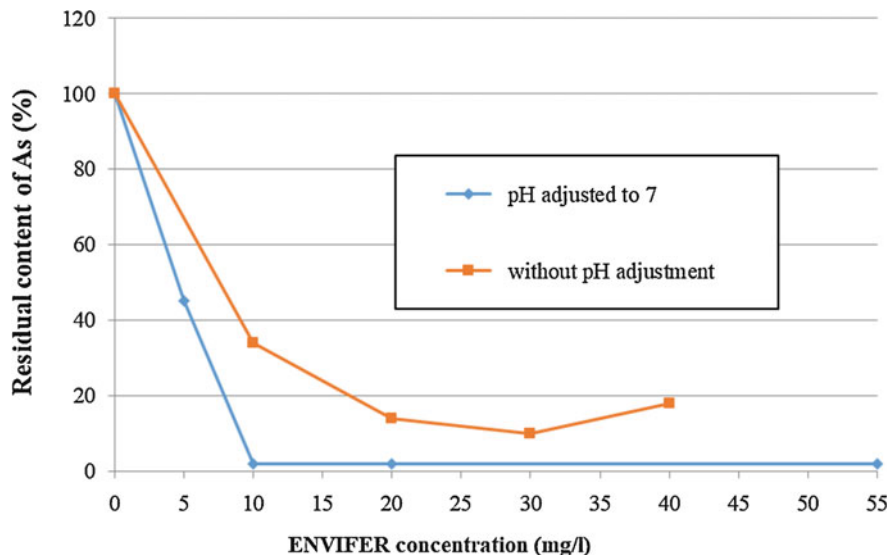
Fig. 13.1 pH optimization for dosing of commercial ferrate to get a maximal As removal in water KLU (see below)—a laboratory test

13.4 Optimal Conditions for Arsenic Separation Set under Laboratory Conditions for the Target Groundwater

Ferrates exhibit alkali reaction with water. Therefore, the pH rises as the amount of ferrate increases. pH values, oxidation–reduction potential (ORP), and temperature were continuously measured during the reaction of groundwater with ferrate. Laboratory tests confirmed the optimal pH value for As removal to be 7.0 (see Fig. 13.1). Further decrease in the pH value leads to lower ferrate stability.

Maximal oxidation–reduction potential E_h measured during the reaction reached 850 mV. This value confirms strong oxidizing environment. Optimal reaction time was set to 20 min, including adding the ferrate, adjusting the pH, and adding a polymeric flocculant. It was followed by 10-min ageing enabling possible sedimentation and by another 15 min of three-phase filtration.

13.4.1 Laboratory-Verified Conditions for as Removal from Groundwater Using Ferrates

- *pH*: after adding the ferrate, adjust the pH to 7 with HCl
- *Redox potential*: ORP E_h maximum 850 mV; max measured ORP on AgCl electrode 630 mV
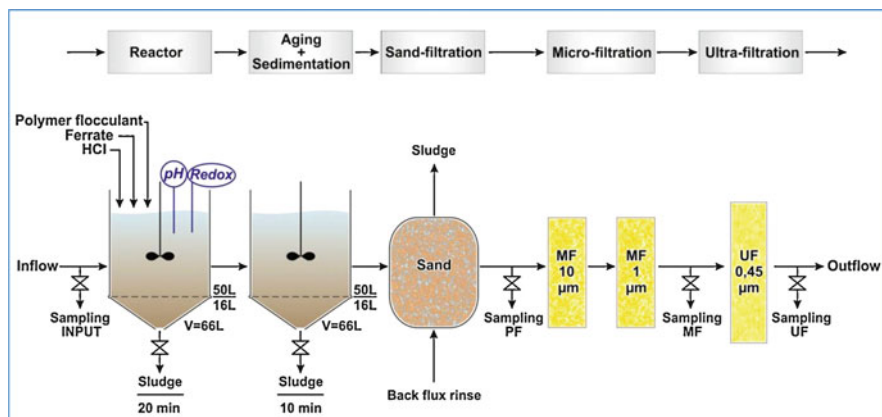
Fig. 13.2 Scheme of technological unit for arsenic removal from groundwater by ferrates. (Capacity approx. 100 L/h)

- *Larger particles formation support*: application of polymeric flocculant solution increases efficiency in separation of the Fe-As complex by filtration
- *Reaction time*: 20 min (1 min ferrate addition, 5–7 min acid addition, 12–15 min flocculant addition)
- *Microflakes separation time*: 10 min sedimentation (negligible sludge formation), 15 min three-step filtration (sand filtration + microfiltration + ultrafiltration)

13.5   Description of a Mobile Semi-Pilot Plant for Ferrate Application

On the basis of the laboratory tests results, a prototype of a mobile technological unit for ferrate (Fe(IV), Fe(V)) application has been designed. This mobile device is aimed at on-site application operating at the flow rate of 100 L/h (see Fig. 13.2).

The aim was to verify the applicability of ferrate for drinking water production on a semi-pilot scale.

The whole line is placed in a transportable container that can be fixed to a tow bar of a car (see Fig. 13.3). The size of the container is 2 m × 2 m × 3 m (width, height, length). The container runs on electrical power 380 V.

The line configuration (see Fig. 13.4)

- mixing reactor with ferrate dosing, diluted HCl, and a solution of polymeric flocculant
- tank for ageing of the reaction and possible sedimentation
- sand filtration
- microfiltration—10 μm and 1 μm
- ultrafiltration—0.45 μm

Fig. 13.3 Transport of mobile technological unit to a site

Fig. 13.4 (**a**) The overall view of the semi-pilot plant—mixing reactor, tank for ageing, sand filtration (the black container), two-phase microfiltration (in the top right-hand corner), ultrafiltration (the silver container below the microfiltration). (**b**) Detailed picture of microfiltration (at the top) and ultrafiltration (silver container below)
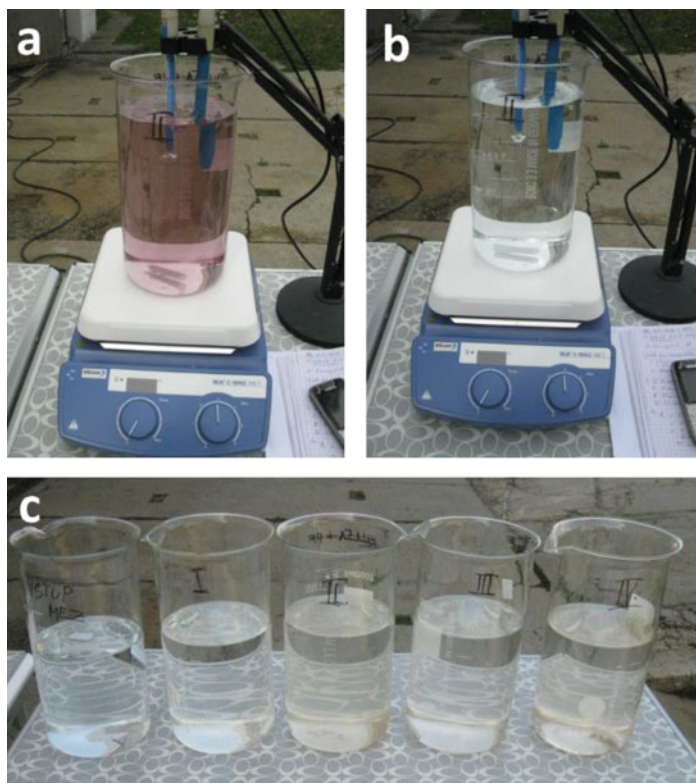
Fig. 13.5 (**a**) Sample of water right after ferrates were added. Commercial ferrate dose—10 mg/L. (**b**) The same sample after 30 min of ferrate addition. (**c**) Verifying on-site tests: progress in the change of the color monitored from the beginning—(INPUT, see "VSTUP MEZ") until the end of the process (left to right). The numbers refer to different doses of the commercial ferrate—5 mg/L (I), 10 mg/L (II), 15 mg/L (III), and 20 mg/L (IV)

13.6 Test Results of the Mobile Line on Site

13.6.1 *Arsenic Separation*

The proposed technology was tested using actual groundwater with a naturally elevated concentration of As in two different localities being 12 km far away from each other (unspecified localities in the Czech Republic labeled MEZ and KLU). The water from MEZ contained about 90 µg/L As, the water from KLU contained about 100 µg/L, while the limit for concentration of As in drinking water is 10 µg/L. The dose and timing of the reagents was adjusted on site by technological laboratories to suit the conditions of the water being currently treated (see Fig. 13.5).

Subsequently, the target water was treated on a semi-pilot plant using different doses of commercial ferrates (5 mg/L, 10 mg/L, 15 mg/L, 20 mg/L). The operating

Table 13.3 Arsenic removal using ferrates, semi-pilot plant, duplicate testing of each dose of commercial ferrate

As separation Semi-pilot tests	INPUT As (µg/L)	OUTPUT As (µg/L)							
		ENVIFER 5 mg/L		ENVIFER 10 mg/L		ENVIFER 15 mg/L		ENVIFER 20 mg/L	
		A	B	A	B	A	B	A	B
Water MEZ	89	11	17	<5	<5	<5	<5	<5	<5
Water KLU	102	–	–	13	17	12	<5	<5	5

Table 13.4 The effect of ferrates on the water in KLU locality after using 15 mg/L of commercial ferrate, duplicate test (A, B)

Sample	As µg/L	Fe mg/L	K mg/L	pH –
Detection limit	0.0050	0.0020	0.0150	1
A – INPUT	102	0.0035	2.5	7.44
A – After PF	69	1.26	9.03	6.59
A – After MF	24.9	0.252	8.73	7.35
A – After UF	12.5	0.0814	8.75	7.22
B – INPUT	102	0.0035	2.5	7.44
B – After PF	62.5	1.3	9.26	7.39
B – After MF	43.2	0.784	9.37	7.37
B – After UF	<0.005	0.0746	9.85	7.25

50 L Water KLU + 750 mg Commercial Ferrate +0.5 mL Flocculant +4.0 mL 10% HCl

volume of the mixing reactor for a semi-continuous process is 50 L; the reaction lasted for ca 30 min including the time for emptying the reactor. 100 L of raw water could be processed within 1 h. The pH values, the oxidation–reduction potential, and temperature were measured continually. The maximum value of E_h during the reaction was 850 mV. Each dose of ferrate was verified in duplicate on the semi-pilot plant. In order to evaluate the effectivity of the As separation on the semi-pilot plant, four different samples were collected—raw water (input), water after sand filter (PF), water after microfiltration 1 µm (MF), and water after ultrafiltration (UF), i.e., the treated water. The chemical analysis of the samples was carried out in an accredited commercial laboratory (ALS). The final concentrations of As after applying the target doses of commercial ferrates in each locality are shown in Table 13.3.

Arsenic concentrations in the treated water from both localities were below the set limit for drinking water (max. 10 µg/L). The optimum dose of a commercial ferrate for MEZ water was 10 mg/L, for KLU water 15 mg/L. It is highly likely that the 12.5 µg/L value achieved in the first test (A) was due to the previous test with a lower dose of a commercial ferrate (10 mg/L), which was proved to be insufficient for arsenic removal from KLU locality (Filip et al. 2017).

The agents used for arsenic removal from groundwater obviously affect the quality of the remediated water. Ferrates (K_2FeO_4) raise the concentration of K, Fe, and the pH. Table 13.4 shows the example of such changes. Specifically, herein we present the results of a duplicate test on KLU water after applying a 15 mg/L dose

Table 13.5 Comparison of the effect of arsenic removal using particular filtration steps for the test water employing the optimum dose of commercial ferrate

	MEZ water (commercial ferrate 10 mg/L)		KLU water (commercial ferrate 15 mg/L)	
	As concentration in water (%)	Ratio of As removed by a particular filtration phase (%)	As concentration in water (%)	Ratio of As removed by a particular filtration phase (%)
INPUT	100	0	100	0
Sand filtration	49.5	50.5	61.3	38.7
Microfiltration	11.9	37.6	42.4	18.9
Ultrafiltration	0	11.9	0	42.4

of a commercial ferrate. Such a dose guarantees that the limit for arsenic concentration in drinking water will be met.

If we focus on the test B performance and its results, i.e., the output after ultrafiltration, it is clear that the final concentrations—Fe 0.0746 mg/L (limit 0.2 mg/L), K 9.85 mg/L (limit is not set; potassium is an essential element in humans and is seldom, if ever, found in drinking water at levels that could be a concern for healthy humans and the recommended daily requirement is greater than 3000 mg), and pH 7.25 (limit for pH 6–8)—comply with the requirements for drinking water. Adding ferrates has only a minimum impact on the original water content.

The effect of arsenic separation using different filtration steps for the optimal dose of commercial ferrates in KLU water and MEZ water is different—see Table 13.5.

With MEZ water, the highest proportion of arsenic was already removed during the sand filtration phase (50%); with KLU water the highest proportion of arsenic was removed only during the last filtration phase—ultrafiltration (42.4%). It is clear that the water chemistry has a considerable impact on the reaction of the water with the ferrate and on forming Fe microflakes for arsenic separation. As a result, the operating costs of the treatment will be different for the two localities even if the initial concentration of arsenic is almost the same in each one. It has been confirmed repeatedly that proposing a technology and reagent doses only according to laboratory tests based on spiked water is inaccurate. Results that are to be reliable must be achieved with real water that has been remediated. The results of the semi-pilot unit tests showed that the proposed technology is sufficiently robust and it reliably achieves the removal of Fe-As microflakes regardless of their size, so that the arsenic concentration in the remediated water complies with the limit for drinking water.

13.6.2 *Microbiological Analysis*

The results of the microbiological analysis of KLU water carried out on a semi-pilot unit are presented in Table 13.6. We monitored the microbiological rejuvenation of the input and output water from the testing line after ultrafiltration for each tested dose of the commercial ferrate.

Table 13.6 Results of the microbiological analysis of KLU water—input and output water from the tested technology for each dose of the commercial ferrate (sampling point—after UF)

Bacterial microflora	Unit	KLU INPUT	KLU ENVIFER 10 mg/L without flocculant	KLU ENVIFER 10 mg/L	KLU ENVIFER 15 mg/L	KLU ENVIFER 20 mg/L
Clostridium perfringens	CFU/ 100 mL	0	0	0	0	0
Coliform bacteria	CFU/ 100 mL	100	0	0	0	0
Enterococci	CFU/ 100 mL	57	0	0	0	0
Escherichia coli	CFU/ 100 mL	0	0	0	0	0
Microorganisms cultivated at 22 °C	CFU/ mL	3300	18	0	3	0
Microorganisms cultivated at 36 °C	CFU/ mL	2900	10	0	0	0

Table 13.6 clearly shows that the water coming out from the tested technology complies with the requirements for drinking water from the microbiological point of view. The disinfecting effect of ferrates has already been described in the literature. Nevertheless, such results have been achieved owing to the combination of different factors—disinfecting effect caused by ferrates reacting in water, sorption of microorganisms into the formed iron hydroxides microflakes, the impact of ultrafiltration with the pore size of 0.45 μm, and disinfecting the line before the test. However, the reliability of the disinfecting effect of the tested technology has yet to be confirmed under operating conditions in the long run.

13.6.3 Economic Point of View

The price of commercial ferrates for industrial applications is currently (2018) about EUR 80 per kilo. As the dose of ferrate ensuring the effectiveness of the arsenic removal from the tested groundwaters is 10–15 mg/L, i.e., 10–15 g/m^3, the price of the amount sufficient to treat 1 m^3 of water could range between 1.0–1.1 EUR/m^3.

In 2017 the following ferrate-based products were available on the market for the purpose of laboratory tests (see Table 13.7).

Since the production of ferrates is demanding, batches from individual producers may vary. Therefore, it is recommended that the quality of the particular batch should be checked in the following steps:

1. Verify the presence of Fe in a ferrate aqueous solution by fundamental analysis.

**Table 13.7** List of ferrates available on the market

Producer/Supplier	Price and comment
Santa Cruz Biotechnology, Inc. (USA)	104 EUR/g
	Purity $\geq$92% according to the producer
Sigma Aldrich	200 EUR/g
	Purity $\geq$95% according to the producer
NANO IRON (CZ)	0.08 EUR/g
	Content of K_2FeO_4 30–40%

2. Measure the absorbance of the aqueous solution at 510 nm (or 505 nm). In the literature, it is recommended that both of these wavelengths should be used for measuring the concertation of Fe(VI) in aqueous solution. The Fe(VI) spectrum has a broader peak in this area, i.e., both variants are correct. When comparing UV–VIS spectra of ferrates and permanganate, it is clear that measuring at 510 nm is not sufficient for distinguishing a ferrate solution from permanganate (see Fig. 13.6a, b).
3. Ferrates can contain traces of heavy metals (Cr, Ni, V, Cu, etc.). Although, it is convenient to use ferrates at very low concentrations even from economic point of view (dozens of mg/L), it is still recommended that the final content of heavy metals in the remediated water in which ferrates were applied should be checked.
4. When in solutions with demineralized water, ferrates will show greater efficiency. Nevertheless, such a ferrate is unstable and requires fast processing. When in solutions with drinking water, ferrates will be more stable (1–2 h), but their reaction will take more time.

13.6.4 Waste Products

The amount of waste products was evaluated after completing the test in KLU locality. Within this testing, 516 L of water containing 0.1 mg/L of arsenic was processed under different technological conditions, meaning different ENVIFER doses.

Sand filter, microfiltration (2 pcs), and ultrafiltration separated out ferrate-reaction products containing arsenic from the water having been treated. Filtration units from microfiltration and ultrafiltration showed only slightly yellowish color; neither of them showed any fall in pressure (indication of pore clogging), i.e., they were preserved for the following tests. The sand filter was cleaned using a standard method, i.e., by counter-current flushing with five units of drinking water equalling five units of the sand filter content. The filling volume of the sand filter was 35 L, the total volume of the cleaning water was 175 L (5 × 35 L). The cleaning water was collected in a container. After the process of cleaning the filter had been finished, samples were collected for chemical analysis in an accredited laboratory ALS.
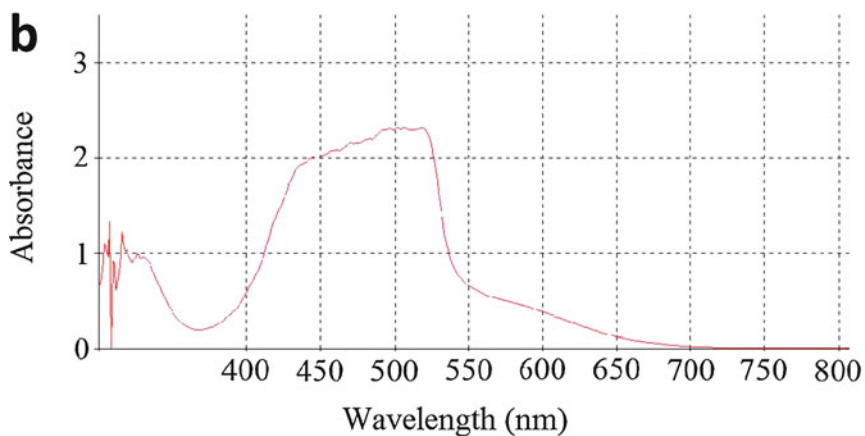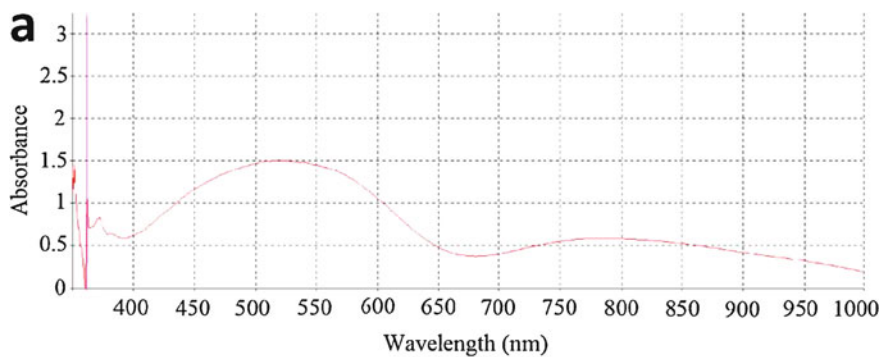
Fig. 13.6 (**a**) UV–VIS spectrum of ENVIFER 036 in aqueous solution at concentration 0.5 g/L. (**b**) UV–VIS spectrum of $KMnO_4$ in aqueous solution at concentration 0.5 g/L. **c** Differently colored aqueous solutions at concentration 0.5 g/L—commercial ferrate (on the left—pinker and lighter) and potassium permanganate (on the right—purpler and darker)

Table 13.8 Results of chemical analysis of the cleaning water from the sand filter

	SUM (mg/L)
Parameter	Cleaning water from the sand filter
CHSKMn	1.11
NL (105 °C)	10.2
As total	0.119
Fe total	2.74
As dissolved	0.0105
Fe dissolved	0.0125

The results of the laboratory analysis of the cleaning water from the sand filter are presented in Table 13.8.

Table 13.8 suggests the following facts:

- Cleaning water: standard volume of cleaning water equaling five volumes of the sand filter filling is sufficient for flushing the filter. The concentration of the dissolved As (0.0105 mg/L) and the dissolved Fe (0.0125 mg/L) used in the cleaning water meet the requirements for drinking water (Table 13.8), i.e., both arsenic and iron are strongly bonded to the microflakes in the form of undissolved substances remaining in the sludge, and being released into the cleaning water only minimally. After the sludge from the filtration has been removed, the cleaning water does not represent hazardous waste.
- Sludge: any measurable amount of sludge was detected on the sand filter after having treating 516 L of water.
- The used filters from filtration and microfiltration will be disposed of according to the Waste Regulations. If a low number of filters (dozens or hundreds per year) are disposed of, they could be treated as hazardous waste. In case of a larger-scale technology, the possibility of recategorizing the filters as other type of waste should be considered on the basis of evaluating their hazardous properties.

13.6.5 Limitations of the Method

It has been found out that higher concentrations of phosphorus in water can decrease the efficiency of the method employing ferrates for arsenic removal (Kolařík et al. 2018). The cause of such decrease consists in the geochemical relation of the two elements. This fact has been proved with contaminated groundwater (labeled SFA) containing 988 mg/L of phosphorus and 2.5 mg/L of arsenic. The highest efficiency in laboratory tests was achieved with a commercial ferrate dosed at 60 mg/L. The efficiency in arsenic removal was only 30%. 1.73 mg/L of arsenic and 823 mg/L of phosphorus were detected in the output water. Comparing the quality of raw water from SFA locality and raw water from KLU locality is provided in Table 13.9.

The limit for drinking water was not achieved with SFA sample even after employing other methods commonly used in the water industry. Employing

Table 13.9 Phosphorus—effect on arsenic removal from water

ALS laboratory chemical analysis		Phosphorus limits		As removal	
		Site SFA		Site KLU	
Parameter	Unit	SFA INPUT	SFA OUTPUT UF 60 mg/L	KLU INPUT	KLU OUTPUT UF 15 mg/L
Dissolved solids dried at 105 °C	mg/L	4570	–	428	437
Chemical oxygen demand (COD-Mn)	mg/L	4.10	–	0.71	0.84
Chloride	mg/L	114	–	23.0	31.3
Fluoride	mg/L	23.4	–	<0.200	<0.200
Hydrogen carbonates HCO_3^-	mg/L	615	–	96.2	86.3
Nitrates	mg/L	35.3	–	88.8	88.1
Orthophosphate	**mg/L**	**1590**	**–**	**0.157**	**<0.040**
Sulfate as SO_4^{2-}	mg/L	423	–	53.4	53.5
Electrical conductivity at 25 °C	mS/m	423	–	50.6	51.9
pH value	**–**	**6.54**	**6.56**	**7.44**	**7.25**
Arsenic	**mg/L**	**2.5**	**1.73**	**0.102**	**<0.0050**
Calcium	mg/L	36.1	–	56.8	61.2
Iron	mg/L	<0.0200	0.234	0.0035	0.0746
Magnesium	mg/L	25.9	–	13.8	14.9
Manganese	mg/L	0.184	–	0.00631	0.00780
Phosphorus	**mg/L**	**988**	**823**	**0.098**	**<0.040**
Potassium	mg/L	27.2	–	2.50	9.85
Sodium	mg/L	1450	–	15.0	16.4

The bold entries mark the key parameters influencing the efficiency of ferrates in arsenic removal

commercial sorbent GEH, we achieved as low arsenic concentration in the remediated water as with ferrates—1.7 mg/L. By means of coagulation tests, we achieved the lowest concentration of As in the output water for coagulant $FeCl_3$ and the dose of Fe 190 mg/L (1.2 mg/L and pH 9.5); Al (PAX-18)-based coagulant achieved only minimal efficiency (As in the output water 1.9 mg/L).

13.7 Conclusion

- The efficiency of the proposed technology for arsenic separation employing ferrates was proved on a mobile technological unit with a flow of 100 L/h with two different sources of groundwater ten times exceeding the allowed limit of arsenic concentration in drinking water. In both cases the final concentration of arsenic in the remediated water was lower than the detection limit of the analytical method (<5 μg/L). The optimal dose of ferrate (ENVIFER from NANO IRON, Czech Republic) for MEZ water was 10 mg/L, for KLU water was 15 mg/L.
- It has been found that the different chemistry of the tested water in MEZ locality and KLU locality had a major impact on the reaction of ferrates with arsenic, although the initial concentration of arsenic was the same. With MEZ water, the most part of arsenic removal was achieved during the first filtration stage; with KLU water, it was during the last stage. The operating costs for the treatment will then differ. As a result, proposing a method and the reagent doses only on the basis of laboratory tests with distilled water cannot prove efficient.
- The water remediated with the proposed technology meets the limits for drinking water from the microbiological point of view.
- When working with commercial ferrates, it is recommended that Fe(VI) content as well as presence of heavy metals in the tested products should be checked.
- The presence of phosphates in higher concentrations could be a limitation in removing arsenic from water.

References

Bielski BHJ, Thomas MJ (1987) Studies of hypervalent iron in aqueous solutions. 1. Radiation-induced reduction of iron(VI) to iron(V) by $CO_2{}^-$. J Am Chem Soc 109(25):7761–7764. https://doi.org/10.1021/ja00259a026

Czölderová M, Behúl M, Filip J, Zajíček P, Grabic R, Vojs-Staňová A, Gál M, Kerekeš M, Híveš J, Ryba J, Rybanská M, Brandeburová P, Mackuľak T (2018) 3D printed polyvinyl alcohol ferrate (VI) capsules: Effective means for the removal of pharmaceuticals and illicit drugs from wastewater. Chem Eng J 349:269–275. https://doi.org/10.1016/j.cej.2018.05.089

Filip J, Yngard RA, Siskova K, Marusak Z, Ettler V, Sajdl P, Sharma VK, Zboril R (2011) Mechanisms and efficiency of the simultaneous removal of metals and cyanides by using ferrate(VI): Crucial roles of nanocrystalline iron(III) oxyhydroxides and metal carbonates. Chem Eur J 17(36):10097–10105. https://doi.org/10.1002/chem.201100711

Filip J, Kolařík J, Zajíček P, Maršálek B, Stavělová M, Matysíková J, Mackuľak T, Slunský J (2017) Experiences with ferrate (FeV and FeIV) application: Results from pilot-scale treatment of drinking surface and waste waters. In: 10th world congress on chemical engineering, Barcelona, Spain

Kolařík J, Prucek R, Tuček J, Filip J, Sharma VK, Zbořil R (2018) Impact of inorganic ions and natural organic matter on arsenates removal by ferrate(VI): Understanding a complex effect of phosphates ions. Water Res 141:357–365. https://doi.org/10.1016/j.watres.2018.05.024

Prucek R, Tuček J, Kolařík J, Filip J, Marušák Z, Sharma VK, Zbořil R (2013) Ferrate(VI)-induced arsenite and arsenate removal by in situ structural incorporation into magnetic iron(III) oxide nanoparticles. Environ Sci Technol 47(7):3283–3292. https://doi.org/10.1021/es3042719

Prucek R, Tuček J, Kolařík J, Hušková I, Filip J, Varma RS, Sharma VK, Zbořil R (2015) Ferrate (VI)-prompted removal of metals in aqueous media: Mechanistic delineation of enhanced efficiency via metal entrenchment in magnetic oxides. Environ Sci Technol 49(4):2319–2327. https://doi.org/10.1021/es5048683

Yates BJ, Zboril R, Sharma VK (2014) Engineering aspects of ferrate in water and wastewater treatment – a review. J Environ Sci Health, Part A 49(14):1603–1614. https://doi.org/10.1080/10934529.2014.950924

Zboril R, Andrle M, Oplustil F, Machala L, Tucek J, Filip J, Marusak Z, Sharma VK (2012) Treatment of chemical warfare agents by zero-valent iron nanoparticles and ferrate(VI)/(III) composite. J Hazard Mater 211–212:126–130. https://doi.org/10.1016/j.jhazmat.2011.10.094