

Use of an Ultraviolet Light activated Persulfate Process to Degrade Humic Substances: Effects of Wavelength and Persulfate Dose

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Abstract

Natural organic matter (NOM), commonly found in surface and ground waters, form Disinfection by-products in drinking water. Generally, advanced oxidation processes (AOPs) featuring hydrogen peroxide are used to treat water, however, sulfate radical recently has been used to treat recalcitrant organics, because it is associated with a higher oxidation potential and more effective removal than hydroxyl radicals. Hence, in this research, we evaluated persulfate oxidation efficiency in terms of reductions in humic substances levels and investigated the degradation mechanism. The results showed that ultraviolet activated persulfate effectively treated humic substances compared with hydrogen peroxide and direct irradiation. Treatment was dose- and wavelength-dependent; higher persulfate concentrations or shorter UV wavelengths were more effective for treating humic substances as high concentration sulfate radicals were created. The degradation mechanism was similar to that of hydrogen peroxide. Aromatic and chromophore components were more susceptible to degradation than were lower molecular weight components, being initially decomposed into the latter, reducing UV_{254} absorbance and the $SUVA_{254}$. Lower molecular weight materials were eventually degraded to end products: NPOC levels fell. And we also treated the inflow of a drinking water treatment plant with persulfate, and humic substances were effectively removed.

Introduction

Natural organic matter (NOM), commonly found in surface and ground waters, is a complex matrix of organic compounds attributable to the many interactions between the hydrological cycle, the biosphere, and the geosphere (Sillanpää *et al.*, 2018). Aquatic natural organic matter is composed of large variety of compounds and derived from the breakdown of terrestrial plants as well as many bacterial, algal, and aquatic plant byproducts (Bhatnagar and Sillanpää, 2017, Rodríguez and Núñez, 2011). NOM may affect the odor, taste, and color of raw water: it forms halogenated organic disinfection byproducts (DBPs) including trihalomethanes (THMs) and haloacetic acids (HAAs), increases the chemical demand for oxidation coagulation and disinfection, fouls membranes, and promotes biological growth in water distribution systems (Bhatnagar and Sillanpää, 2017). Waples *et al.*, (2005) and Chin *et al.*, (1997) also found that NOM bound heavy metals and hydrophobic organic chemicals. Aquatic NOM features both hydrophobic and hydrophilic components; hydrophobic acids are often considered to be the major aquatic NOM fraction, containing more than half of the dissolved organic carbon (DOC) (Świetlik *et al.*, 2004). Of the various NOM components, hydrophobic acids are principally involved in disinfection by-products (Chang *et al.*, 2001). The hydrophobic acids (humic substances) are often separated into three components: (i) humin, insoluble in both alkali and acid; (ii) humic acid (HA), soluble in alkali but insoluble at $pH < 2$; and (iii) fulvic acid (FA), soluble in both alkali and acid (Pettit, 2006, Sillanpää *et al.*, 2011, Bhatnagar and Sillanpää, 2017). Because humin is not soluble in water at any pH, humic and fulvic acids are the principal humic substances. Karanfil *et al.*, (1999) found that the NOM fraction passing through a 0.45- μ m-pore-sized filter is the most difficult to treat, so we focused on this material.

In previous studies, either ozone or hydrogen peroxide (in combination with ultraviolet light) usually served as oxidants for NOM removal from, and minimization of DBPs formation in, drinking water. However, the sulfate radical is attracting increasing attention because some studies proved that it can degrade recalcitrant organics with greater efficiency than the hydroxyl radical or ozone (Gao *et al.* 2012, Huang *et al.*, 2005). Table 1 lists commonly used oxidants. Ozone and hydrogen peroxide are more expensive than persulfate. Also, although the hydroxyl radical effectively treats organic compounds given its high standard redox potential, the O-O bond-dissociation energy of H₂O₂ is higher than that of persulfate. On the other hand, the quantum yield of sulfate radical formation from persulfate photolysis within the 248-254 nm wavelength range is 1.4±0.3, much larger than that of hydroxyl radical formation from hydrogen peroxide photolysis (1.0) (Stefan, 2017). In other words, compared to the hydroxyl radical, a higher concentration of sulfate radicals will be produced under identical UV irradiation conditions. The sulfate radical may have a higher oxidation potential than the hydroxyl radical, ranging from 2.5–3.1 V, so persulfate treatment of organic compounds should be preferred. Previous studies have found that sulfate radicals produced on exposure to ultraviolet light and ultrasonic treatment reduced NOM levels (Tian *et al.*, 2018, Wang *et al.* 2015, An *et al.*, 2015). However, those studies focused principally on reduction efficiency. Here, we go further to understand the mechanisms in play: we seek the optimal ultraviolet wavelength, explore the structures of the compounds, and vary persulfate concentrations.

The usual sources of the sulfate radical are peroxodisulfate (PDS) and peroxymonosulfate (PMS). PDS forms very stable colorless-to-white crystals and is readily soluble in water. PDS is symmetrical in structure: the O-O bond distance is 1.497 Å. PMS is a white powder stable at pH values less than pH 6 and over pH 12. The stability is poorest at a pH of 9, where the concentration of and are equal (Saputra *et al.*). PMS also dissolves readily in water to form an acidic solution (Wang *et al.* 2018b). PMS is asymmetrical in structure: the O-O bond distance is 1.453 Å (Wang *et al.* 2018a). The common PDS is the sodium PDS (Na₂S₂O₈), and the common PMS is oxone (HSO₅·0.5KHSO₄·0.5K₂SO₄). Both PMS and PDS are strong oxidants, however they do not adequately remove organic pollutants directly; they must be activated to yield the more reactive sulfate radical (Wang *et al.* 2018b) PDS and PMS can be activated by UV, heat, ultrasound, and transition metals; the first three activators deliver energy to the persulfate anion, resulting in cleavage of the peroxide bond and formation of two sulfate radicals with high oxidation potentials (Matzek and Carter, 2016). However, compared to PDS, PMS features a shorter bond length, which translates to a higher bond dissociation energy (377 kJ mol⁻¹). In other words, to create the same concentration of the sulfate radical, PMS requires more energy than PDS for hemolytic peroxide cleavage. Therefore, we used PDS. Wang *et al.*, (2015) reported that sulfate radicals are likely attracted to particular chemical structures and then transferred to organics that become degraded to carbon dioxide and water; the sulfate radical cleaves the carbon bonds. Persulfate reacts directly with some organics to form sulfate radicals that propagate secondary reactions, or that create organic radicals (Matzek and Carter, 2016). Here, we used various persulfate concentrations and hydrophobic compounds differing in specific UV absorbance (SUVA₂₅₄) to explore the degradation of humic and fulvic acids via the UV/persulfate process. An *et al.*, 2015 found that UV at 185 nm (compared to 254 nm) enhanced hydrophobic NOM treatment; we tested both wavelengths. UV radiation is strongly absorbed by the conjugated bonds of

humic substances and by free electron pairs on heteroatoms (Corin *et al.*, 1996). When humic substances in water are UV-irradiated, photons are absorbed. Some of these interactions trigger direct photochemical transformations of humic molecules; these serve as precursors termed photoreactants, which are usually short-lived but extremely reactive (Corin *et al.*, 1996). Hence, as a control, organic compounds were treated with UV only. We compared the effects of hydrogen peroxide and persulfate under the same UV irradiation conditions to verify the oxidation efficiency.

Materials And Methods

2.1 Materials

All experimental solutions were prepared using Milli-Q water. Fulvic acid (FA) was purchased from IHSS. Two humic acids (HAs) differing in $SUVA_{254}$ were employed: one was from Sigma-Aldrich and the other from IHSS. Sodium persulfate was obtained from Sigma-Aldrich. Sulfuric acid (98%) was the product of Kanto Chemical and was used after dilution. Hydrogen peroxide was purchased from Kanto Chemical and sodium hydroxide was purchased from Wako Pure Chemical Industries; we prepared a 0.1 mol/L solution of the latter. UV lamps radiating at 185 nm (QGL8W-31) and 254 nm (QGL8W-21) were purchased from Iwasaki Electric. Input energy are 8 W for both lamps. The raw water sample was collected from the inflow of a drinking water treatment plant located in a sub-tropical region of Japan.

2.2 Stock solution

We dissolved 1 g of humic acid in 1 L of 0.1 M NaOH. After stirring for 2 h, the solution was passed through a series of GF-B and polytetrafluoroethylene (PTFE) membrane filters 0.45 μm in pore size. Such two-step filtration through descending mesh sizes allows filtration of the entire sample without clogging. Chloride ions react very rapidly with sulfate radicals, compromising degradation efficiency (Lutze *et al.*, 2015, Lou *et al.*, 2016). To reduce any effect of chloride, the pH of all samples was adjusted with sulfuric acid or NaOH and the samples were then diluted to their initial concentrations. The fulvic acid stock solution was similarly prepared, but the acid was dissolved in Milli-Q water rather than an NaOH solution.

2.3 Raw water

Raw water was taken from the inflow of a drinking water treatment plant located in a subtropical region of Japan. Previous research revealed that this water had a high DOC concentration and could not be efficiently treated via coagulation due to low $SUVA_{254}$ (Sakai *et al.*, 2016). Here, we utilized this water sample to investigate the treatment efficiency in real water environment. Water was taken from the reservoir and transported to our laboratory in the cold; it was immediately filtered through a 0.45- μm -pore-sized PTFE membrane, and subjected to the UV/persulfate process.

2.4 Experimental procedures

Batch experiments were performed to evaluate the effects of UV irradiation with and without persulfate. All photodegradation experiments were performed in a sealed cylindrical stainless steel reactor at room temperature as illustrated in supplementary information (Fig. S1); the cross indicates the UV lamp position.

First, 35 mL of stock solution was adjusted to neutral pH and diluted to 3.5 L with the addition of persulfate or hydrogen peroxide prior to UV irradiation. For raw water, persulfate was directly added, followed by irradiation. Samples (100 mL) were taken at 5 min intervals. Magnetic stirring (700 rpm) was employed to ensure that the entire solution was uniformly irradiated.

2.5 Analytical methods

2.5.1 DOC

We measured DOC concentrations to explore whether organic compounds were decomposed to end products. We used a TOC-VCSH analyzer (Shimadzu, Japan). Acid was automatically added to remove inorganic carbon (IC).

2.5.2 UV₂₅₄ absorbance and SUVA₂₅₄

Absorbance at 254 nm was measured with the aid of a UV-Vis spectrophotometer (model V-670; JASCO, Japan). The 254 nm region is that of π - π^* transitions in substituted benzenes and most polyenes. Aromatics typically exhibit more absorption at 254 nm than aliphatics (Kulovaara et al., 1996, Hua et al., 2015). Absorbance data at 254 nm thus reflect structural changes to some extent.

SUVA₂₅₄ has been reported to be proportional to both the apparent molecular weight and the aromaticity of humic substances (Uyguner and Bekbolet, 2005). We calculated SUVA₂₅₄ by reference to the DOC and UV₂₅₄ absorbance data: the SUVA₂₅₄ is the UV absorbance at 254 nm divided by the DOC concentration.

2.5.3 Excitation Emission Matrix (EEM) analysis

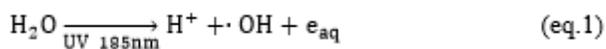
We used a fluorescence spectrophotometer (model FP-8200; JASCO, Japan) to explore the behaviors of humic substances at excitation wavelengths of 200–600 nm (in 5 nm increments) and emission wavelengths of 200–600 nm (also in 5 nm increments). In previous studies, the excitation and emission boundaries were used to divide spectra into five regions. The peaks at Ex_{250~280} and Em_{280~380} are referable to soluble, microbial byproduct-like materials (region IV). The region V peaks at Ex_{250~400} and Em_{380~600} are referable to humic acid-like organics. The region III peaks at Ex_{200~250} and Em_{380~600} are referable to fulvic acid-like materials. The regions I and II peaks at Em_{280~380} and Ex_{200~250} are referable to aromatic proteins (Chen *et al.*, 2003).

Results And Discussion

3.1 Reaction kinetics of humic substances undergoing persulfate oxidation

3.1.1 Degradation rates at different UV wavelengths

We delivered 185 nm and 254 nm UV irradiation in the presence or absence of persulfate, as shown in Figure 1. Under direct photolysis at 254 and 185 nm, the non-purgeable organic carbon (NPOC), UV_{254} absorbance, and $SUVA_{254}$ decreased continually; the reductions mediated by 254 nm UV were lower. Under 185 nm UV, the UV_{254} absorbance and $SUVA_{254}$ decreased more rapidly than did the NPOC, especially in the initial stages. UV at 185 nm was more effective. However, UV at 254 nm was chosen for further work, given its limited efficiency in terms of humic acid treatment. Similar results were obtained by Gao *et al.*, (2019) and Corin *et al.*, (1996). Gao *et al.*, (2019) found that the UV wavelength a compromise treatment, as follows affected the molar absorption coefficient of humic acid. UV at 185 nm better treated humic acid, because irradiation simultaneously created active intermediates including hydrogen atom, hydroxyl radical and other oxidative species such as hydrogen peroxide probably from water (Liu *et al.*, 2016, Han *et al.*, 2004); these efficiently decomposed humic acid:



When persulfate was added to 1 mM, the NPOC, UV_{254} absorbance, and $SUVA_{254}$ fell dramatically. After 30 min, the NPOC, UV_{254} absorbance, and $SUVA_{254}$ reductions were 82.4%, 99.0%, and 94.1% for 254 nm UV and 92.7%, 98.9%, and 84.9% for 185 nm UV, respectively. However, under UV irradiation only, the corresponding values were only 1.2%, 2.06%, and 0.86% (254 nm UV) and 28.1%, 58.1%, and 41.8% (185 nm UV), respectively. Therefore, the sulfate radical was taking the main role to effectively remove humic substances. After persulfate addition, UV at 185 nm was more effective than UV at 254 nm because the shorter wavelength delivered more energy, creating more sulfate radicals. However, when the water is irradiated by 185 nm lamp, hydroxyl radicals were created (eq.1) which makes it difficult to directly investigate sulfate radicals' treatment efficiency and mechanism. On the other hand, generally, 254 nm UV lamp was utilized in the water treatment plant. Hence, the following experiments were utilized 254 nm UV lamp instead of 185 nm lamp

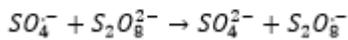
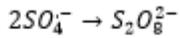
3.1.2 Dose-dependency of humic substances degradation by the UV/persulfate process

3.1.2.1 Dose-dependent degradation

Figure 2a and 2b presents the reductions in humic acid (Sigma) levels at persulfate concentrations of 0, 0.1, 1, and 10 mM. The removal rate was initially rapid and then slower. Figure 2c and 2d presents the fulvic acid data. With regard to humic acid, the reduction rate was greater at higher persulfate concentrations. At the end of the reaction, the reductions in UV_{254} absorbance and NPOC were 99.0%, 82.4% for humic acid and 98.5% and 83.1% for fulvic acid (1 mM persulfate), respectively. Although the final reductions were similar, the fulvic acid reaction was more rapid than the humic acid reaction; fulvic acid was more susceptible to persulfate treatment.

When humic and fulvic acids were treated with 10 mM persulfate, the NOM degradation rate increased. Higher sulfate radical concentrations increased degradation efficiency.

However, this does not mean that the higher the persulfate concentration, the better the treatment. On the contrary, a high persulfate concentration reduces efficiency because the sulfate radical can react with the persulfate anion or self-decay in the absence of an appropriate solute (Matzek and Carter., 2016). Hence, there is an optimum concentration of persulfate:



Given this reaction, even if persulfate is abundant, the sulfate radical will transform into non-toxic sulfate. Thus, sulfate radical-based advanced oxidation is environmentally friendly.

3.1.2.2 Mechanism of elimination of humic and fulvic acids

Persulfate at 1 mM reduced humic and fulvic acid levels (Fig. 2); the reductions in UV₂₅₄ absorbance and NPOC were similar. During humic acid degradation, the UV₂₅₄ absorbance decreased more rapidly from 0–5 min (24.3%); the NPOC fell more slowly (2.6%). This is because humic acid removal is a multi-step process. Humic acid and persulfate initially form an unstable adduct; aromatic portions are then degraded to smaller intermediate products via irradiation, reducing UV₂₅₄ absorbance, but reducing the NPOC level only minimally (Pedro *et al.*, 2008). Next, the sulfate radical oxidizes the intermediate products which are main low molecular weight products into end products, improving NPOC removal (Ahn *et al.*, 2017, Gao *et al.*, 2019). In other words, as aromatic organic matter is transformed, the UV₂₅₄ absorbance decrease rapidly from 0–5 min but the fall in NPOC level is limited during this interval.

For fulvic acid, the UV₂₅₄ absorbance also decreased more rapidly (74.1%) than did the NPOC level (30.4%) from 0-5 min. However, compared to humic acid, initial NPOC removal was more rapid can be considered that fulvic acid contains fewer aromatic portions and has small size than does humic acid. Sulfate radicals directly oxidize low molecular weight portion into end products, increasing initial NPOC removal.

3.1.3 Evaluation of humic acids of different SUVA₂₅₄

Due to the different structure of the humic acid and fulvic acid, it is hard to investigate the effect of the amount of aromatic compounds and molecular weight on treatment efficiency directly. Hence, we used two humic acids that differed in terms of the initial SUVA₂₅₄ and UV₂₅₄ absorbance (Fig. 3). From 0-10 min, 94.5% UV₂₅₄ absorbance, 48.2% NPOC, 89.4% SUVA₂₅₄ decreasing for HAs (IHSS) and 42.0% UV₂₅₄ absorbance, 16.6% NPOC, 30.6% SUVA₂₅₄ decreasing for HAs (Sigma) was investigated. Humic acid from

Sigma had a higher UV_{254} absorbance and $SUVA_{254}$ (0.179 cm^{-1} , $4.8 \text{ L mg}^{-1}\text{m}^{-1}$) than humic acid from IHSS (0.104 cm^{-1} , $2.8 \text{ L mg}^{-1}\text{m}^{-1}$). Thus, the former material contained more aromatic and chromophore portion than the latter, was degraded less efficiently. Aromatic and chromophore proportion are more susceptible to sulfate radicals. On the other hand, high $SUVA_{254}$ value indicated high molecular weight for humic substances which showed low treatment efficiency. And at initial stage, high $SUVA_{254}$ reduction was investigated for both two humic acids but low NPOC removal which indicated that most humic acid are not decomposed into final products. According to that, the oxidation mechanism can be considered that, aromatic and chromophore portion in humic acid was firstly decomposed into lower molecular intermediate products which lead to UV_{254} absorbance and $SUVA_{254}$ decreasing but limit NPOC removing. Then lower molecular intermediate products were finally oxidized into final products like water and carbon dioxide, resulting in NPOC reducing.

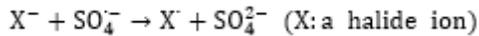
3.1.4 Efficiencies of various oxidants

Figure 4 presents the decomposition efficiencies of various oxidants. All of the NPOC level, UV_{254} absorbance, and $SUVA_{254}$ decreased continually. Hydrogen peroxide reduced the NPOC level, UV_{254} absorbance, and $SUVA_{254}$ by 47.2%, 19.8%, and 34.2%, respectively; the corresponding figures for persulfate were 99.0%, 82.4%, and 94.1%, thus significantly better. Sarathy and Mohseni, 2010 and Bazri *et al.*, (2012) reported that the $SUVA_{254}$ serves as an indicator of organic matter biodegradability and the potential for THMs and HAAs formation. Compared to persulfate, hydrogen peroxide did not effectively reduce the $SUVA_{254}$. In previous studies, organic compounds were not completely decomposed during oxidation, and were rather partially oxidized to toxic and assimilable transformation products (TPs) (Wang and Wang, 2018b). Hence, the UV/ H_2O_2 process may create new pollutants because NPOC removal is limited; persulfate provides cleaner water. The better treatment efficacy of persulfate is attributable to the fact that the O-O bond dissociation energy is lower than that of hydrogen peroxide (Table 1). This increases the sulfate radical concentration; that radical has a higher standard redox potential than the hydroxyl radical. Hence, persulfate was more effective than hydrogen peroxide when used to treat humic acid. Although humic substances can be completely eliminated using the UV/ H_2O_2 process, the oxidant concentration was greater and irradiation time was longer than those of the UV/persulfate system.

However, when hydrogen peroxide was added, the decreases in NPOC levels were similar to those afforded by persulfate, gradually increasing from 10 min; the reductions in UV_{254} absorbance and $SUVA_{254}$ were already rapid from 0–10 min. This is explained by fractional conversion of the aromatic and chromophoric components of humic acid, as reflected in the UV_{254} data (Bazri *et al.*, 2012). Aromatic and chromophoric components are initially transformed into lower molecular weight components, causing rapid reductions in UV_{254} absorbance and the $SUVA_{254}$, but only limited NPOC removal. This has been previously described; Ahn *et al.*, (2017) found that the levels of humic substances decreased, whereas the levels of low molecular weight acids increased, during the UV/ H_2O_2 process.

3.2 Degradation efficiency of raw water

Figures 5a, b present raw water purification via the UV/persulfate process. The reductions were 92% for UV_{254} absorbance, 56% for the NPOC level, and 82% for the $SUVA_{254}$; the sulfate radical effectively treated aquatic organic compounds. The limited NPOC removal was attributable to the high concentration of Br^- (0.302 mg/L). Lou *et al.*, (2016) reported that halide ions, especially Br^- , compromise treatment, as follows:



However, in raw water, NPOC features both hydrophobic and hydrophilic NOM. The treatment efficiencies of various NOMs vary: longer reaction times or higher persulfate concentrations enhance NPOC removal. Chen *et al.*, (2003) separated EEM data into five components containing specific NOMs. Figure 5b shows that the raw water contained humic acid-like compounds (region V), fulvic acid-like compounds (region III), and soluble microbial byproduct-like materials (region IV). All peaks eventually disappeared as reaction proceeded; all organic compounds were oxidized. The peaks of fulvic and humic acids were almost completely eliminated by 30 min.

Conclusion

We evaluated the utility of UV/persulfate treatment in terms of humic substances removal. Two principal factors were varied: the UV wavelength and the persulfate dosage. The reaction was both dose- and wavelength-dependent: higher levels of sulfate radicals accelerated NOM removal. Removal of high $SUVA_{254}$ humic acid required a higher persulfate concentration and longer irradiation time, given the abundant aromatic and chromophore proportion. Our evaluation of raw water revealed that persulfate optimally treated aquatic natural organic compounds but the process was inhibited by halide ions.

Compared to hydrogen peroxide, persulfate minimized humic acid and fulvic acid levels over a shorter time and at a lower concentration, given its lower O-O bond-dissociation energy. Both hydrogen peroxide and persulfate employ similar decomposition mechanisms: chromophore and aromatics portions are first transformed into intermediate materials of lower molecular weight (as indicated by the fall in UV_{254} absorbance and $SUVA_{254}$) and then further transformed into end products such as water and carbon dioxide. DOC was thus ultimately eliminated.

Declarations

Ethics approval and consent to participate

Not applicable to this manuscript

Consent for publication

Not applicable to this manuscript

Availability of data and materials

Not applicable to this manuscript.

Competing interests

The author declare that they have no competing interest

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Authors' contributions

Yiming FANG: Conceptualization, Methodology, Writing- Original draft preparation., Visualization, Investigation, Data curation

Hiroshi SAKAI: Writing- Reviewing and Editing, Funding Acquisition, Project Administration

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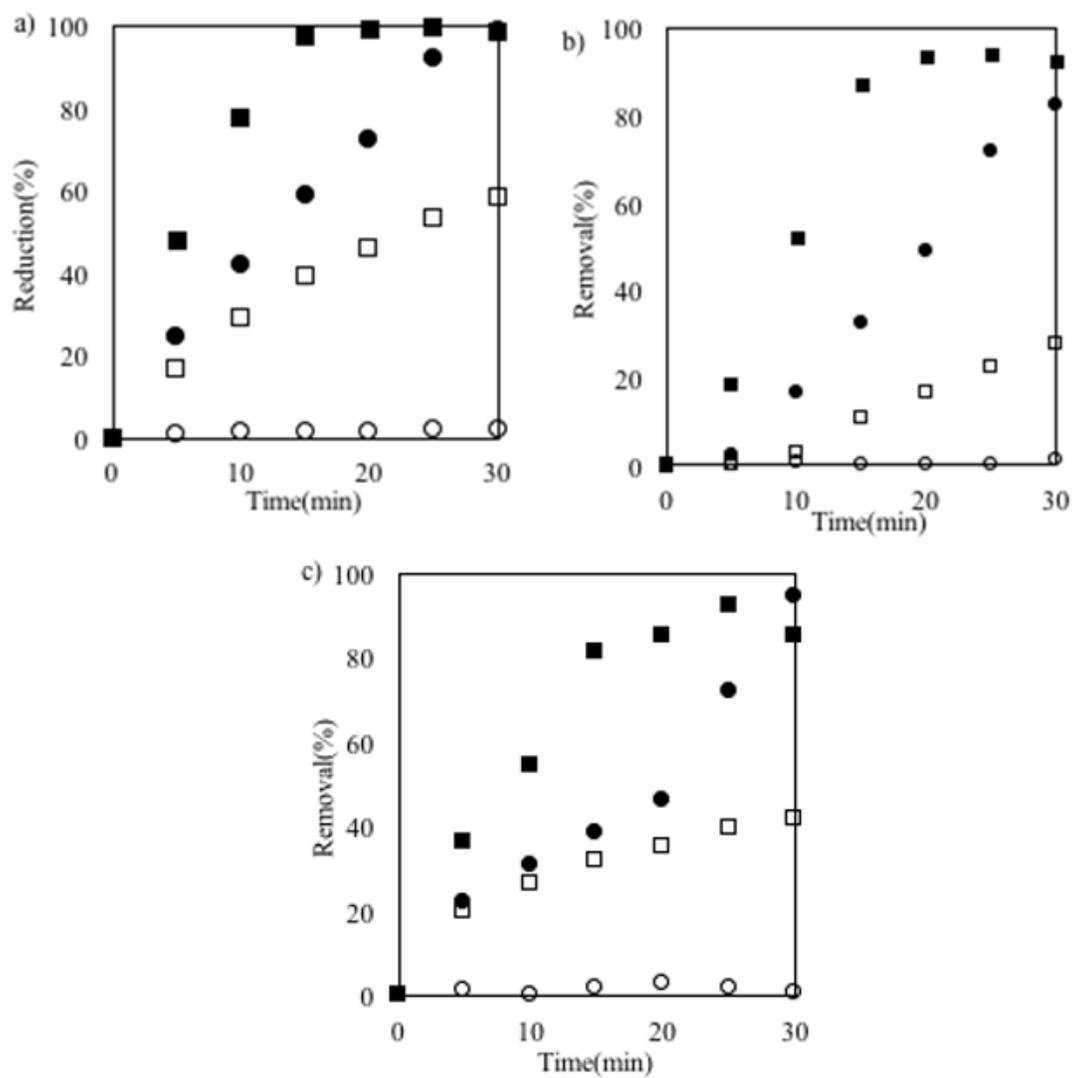
Tables

Table 1.

A comparison of various oxidants.

| Oxidant | O-O bond-dissociation energy [kJ mol ⁻¹] | Solubility in water at 25°C [g /L ⁻¹] | Average estimated lifetime in groundwater | Price [USD kg ⁻¹] | Standard redox potential (V) |
|--|--|---|---|-------------------------------|------------------------------|
| H ₂ O ₂ | 213 | soluble | hours to days | 1.5 | 2.80* |
| O ₃ | 364 | 0.1 | <1 h | 2.3 | 2.07 |
| Potassium ferrate | - | 0.7–3 | unstable in water at pH ≠ 9 | 2000 | - |
| PDS ¹ | 92 | 730 | >5 months | 0.74 | 2.5–3.1* |
| PMS ² | 377 | 298 | hours to days | 2.2 | 2.5–3.1* |
| <p>The remaining data were taken from Wacławek <i>et al.</i>, (2017), Kaneko <i>et al.</i>, (1996), and Zhou <i>et al.</i>, (2019).</p> <p>1. PDS: sodium persulfate. 2. PMS: 2KHSO₅·KHSO₄·K₂SO₄.</p> <p>*. The standard redox potential is that of the radical state.</p> | | | | | |

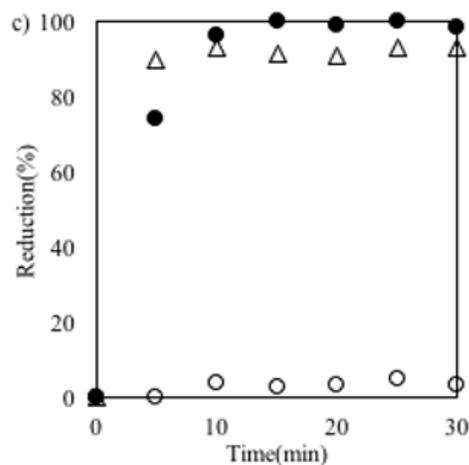
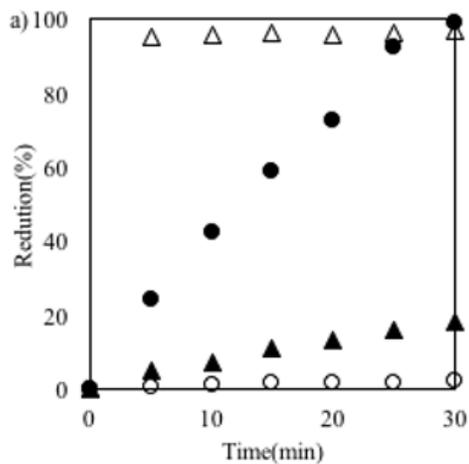
Figures



○254-nm UV only; ●254-nm UV with 1 mM PDS; □185-nm UV only; ■185-nm UV with 1 mM PDS.

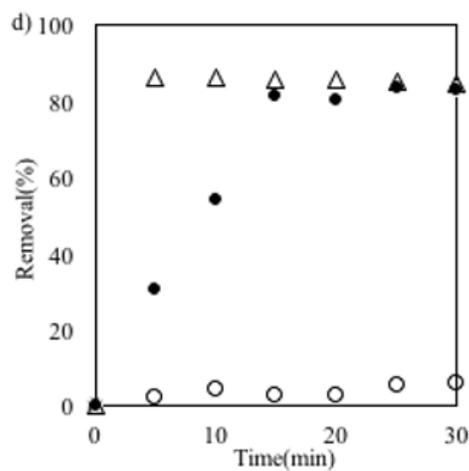
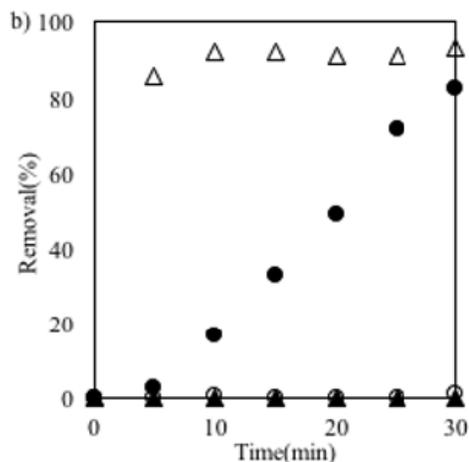
Figure 1

Effects of UV wavelength on humic acid (Sigma) removal: a). UV254 absorbance reduction, b). NPOC removal, c). SUVA decrease.



UV₂₅₄ absorbance reduction

UV₂₅₄ absorbance reduction



NPOC removal

NPOC removal

○ 254 nm UV only; ▲ 254 nm UV with 0.1 mM PDS; ● 254 nm UV with 1 mM PDS; △ 254 nm UV with 10 mM PDS

○ 254 nm UV only; ● 254 nm UV with 1 mM PDS; △ 254 nm UV with 10 mM PDS

Figure 2

Effects of initial persulfate level on humic acid (Sigma) and fulvic acid removal

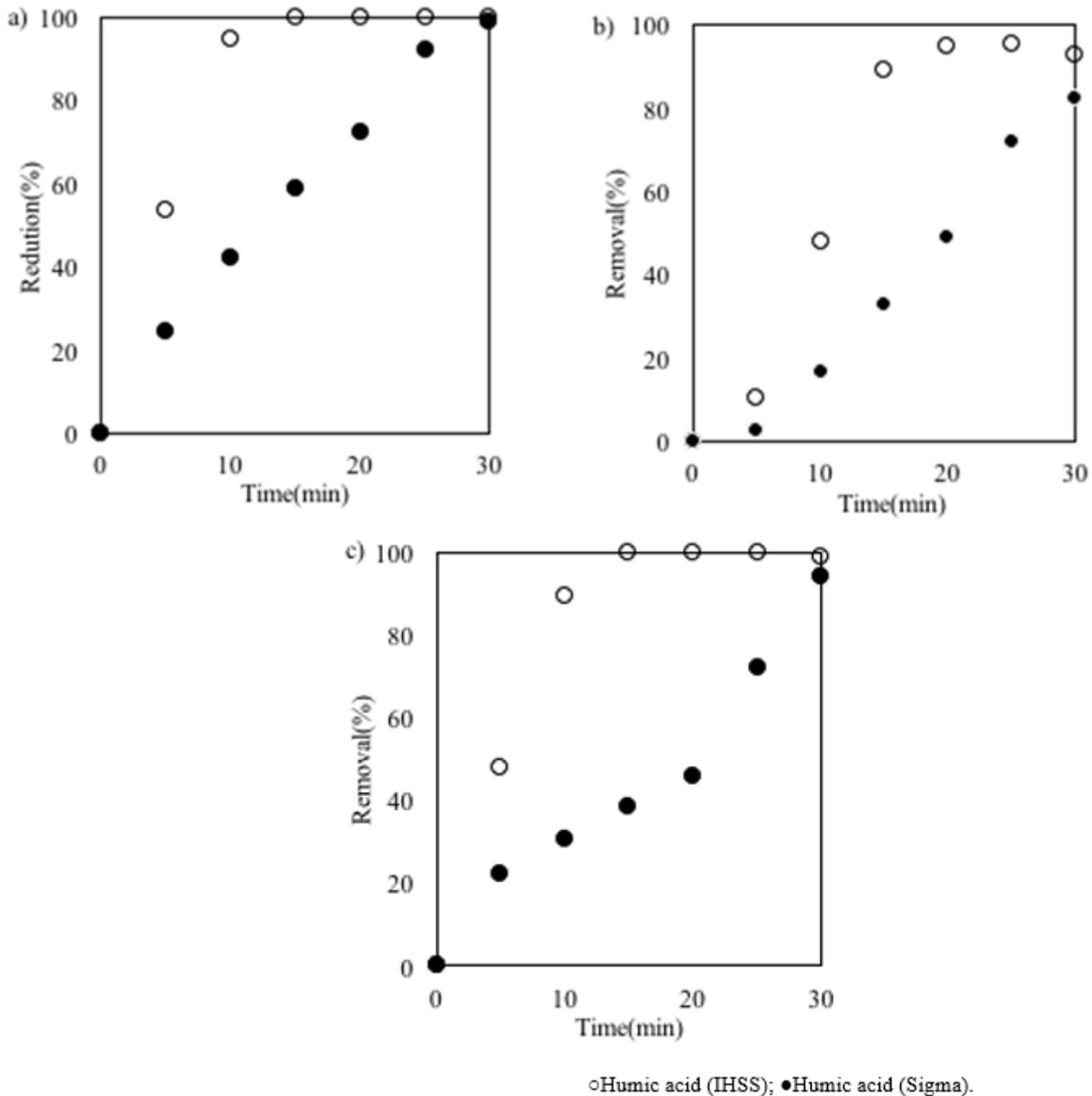


Figure 3

Decreases on different SUVA254 humic acid (initial persulfate level: 1 mM; UV wavelength: 254 nm; initial SUVA254 level: 2.8 L mg⁻¹m⁻¹ [IHSS]; 5.4 L mg⁻¹m⁻¹ [Sigma]): a). UV254 absorbance reduction; b). NPOC removal; c). SUVA254 decrease.

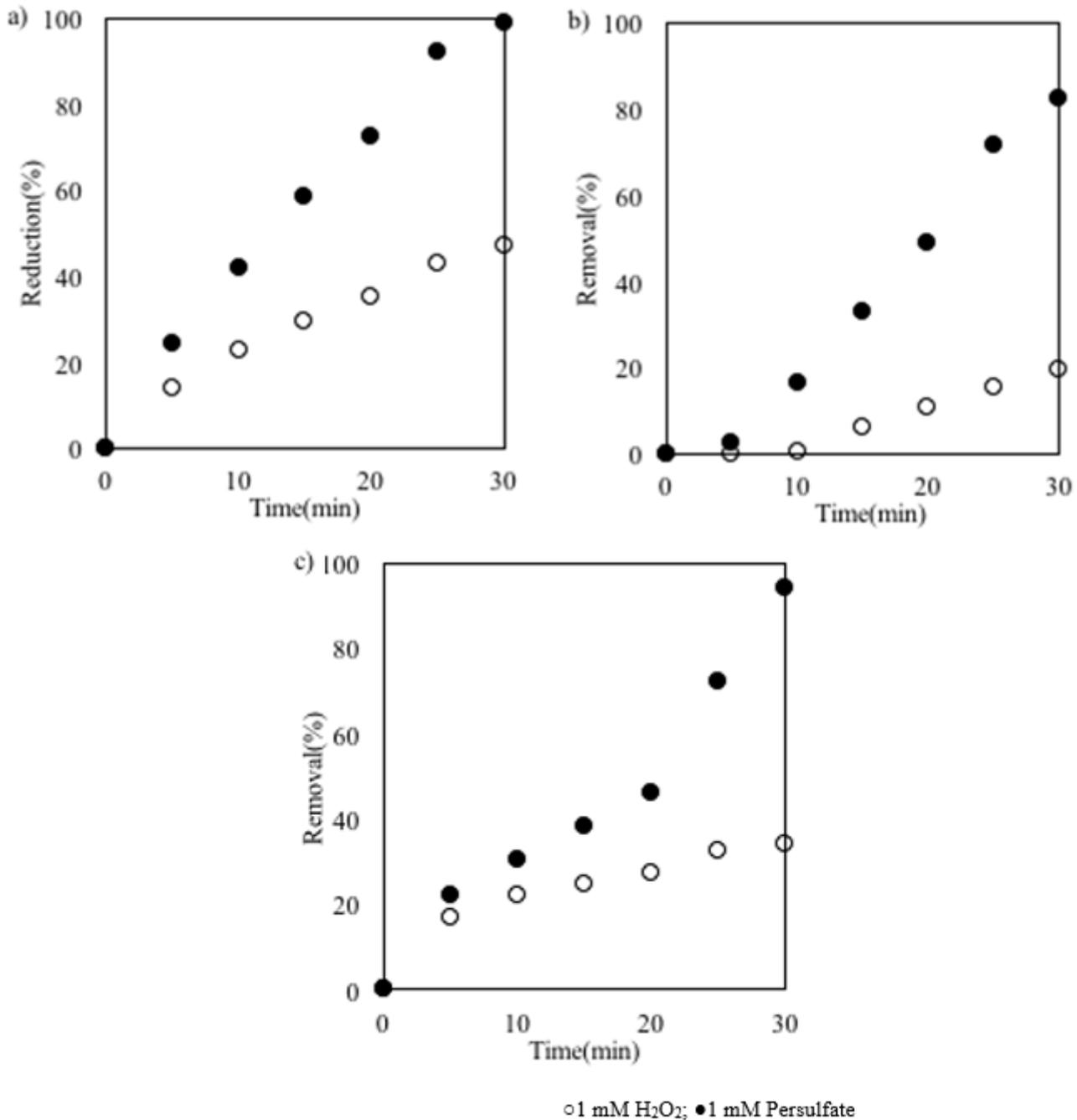
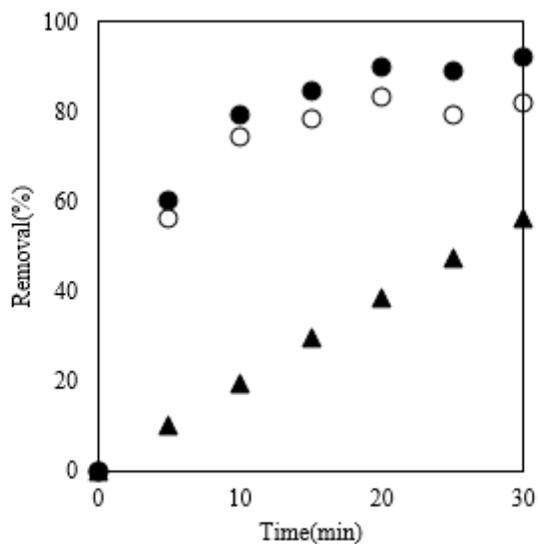


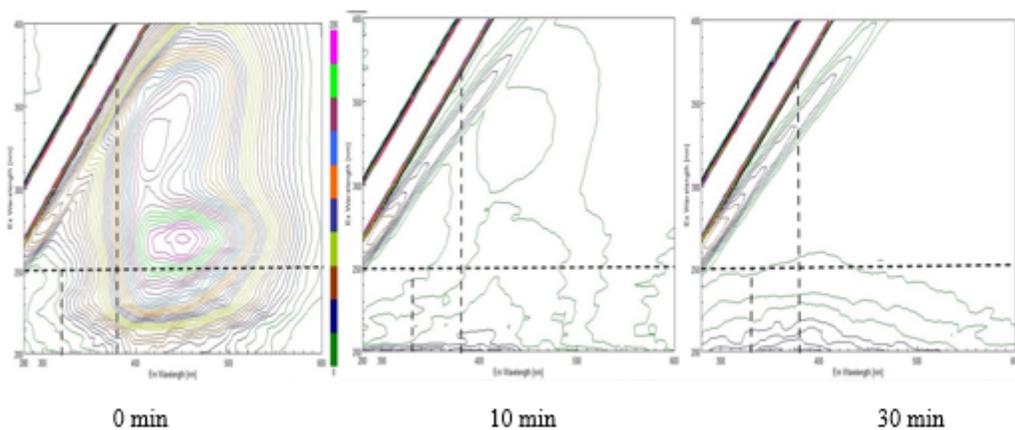
Figure 4

Decreases on humic acid (Sigma) by different oxidants (UV wavelength 254 nm): a). UV254 absorbance reduction; b). NPOC removal; c). SUVA254 decrease.



○SUVA decrease; ●Reductions in UV254 absorbance; △NPOC removal.

a



b

Figure 5

Decreases in raw water (initial persulfate level: 1 mM, initial SUVA₂₅₄ level: 1.1 mg-1m-1, initial NPOC level: 3.8 mg/L):

Supplementary Files

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