Effects of water matrix on virus inactivation using common virucidal techniques for condensate urine disinfection

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Abstract

Three common virucidal techniques (chlorine, UV and UV/TiO₂) were applied to inactivate virus (MS2 and Phi X174) in condensate water after the evaporation of source-separated urine for reclaimed water. The inactivation efficiencies were compared with the results of previous studies, with the emphasis on the analysis of water matrix effects. Results showed that all virus inactivation in condensate water were lower than the control (in sterilized DI water). As for UV/TiO₂ disinfection, both nitrate and ammonia nitrogen could promote slightly viral inactivation, while the inhibition by urea was dominant. Similarly, ammonia nitrogen had greater impacts on chlorine disinfection than urea and nitrate. In contrast, all water matrices (urea, nitrate and ammonia nitrogen) had little influence on UV disinfection. Based on the findings in this study, UV disinfection could be recommended for disinfecting the reclaimed water from the evaporation of source-separated urine.

Keywords

Human urine; Evaporation; Disinfection; Urea; Ammonia nitrogen; Nitrate

1. Introduction

Since 1990s, numerous studies on separating urine at source have been conducted by various groups on different aspects, such as the promotion of sustainable wastewater management (Kirchmann and Pettersson, 1995; Wilsenach and van Loosdrecht, 2003) and the recovery of nutrients (Antonini et al., 2012; Udert and Wachter, 2012). These studies were based on the fact that urine contains high concentrations of nutrients in a relatively small volume. In other words, majority of these studies focused on the reduction and/or recovery of nutrients, and only limited attention was paid on water in source-separated urine until now.

It was reported that humans produced about 1.4 L of urine per person per day (Larsen et al., 2009). If properly collected and treated, human urine could be a promising and rich source of the reclaimed water to meet various needs, especially in areas with dense population but shortage of water. However, pharmaceuticals and personal care products were unfavorably found in human urine (Koch et al., 2014; Magiera and Baranowsica, 2014), which posed potential health risks for water reuse from source-separated urine. On the other hand, although urine from healthy humans does not generally contain pathogens, it is still a challenge that source-separated urine may involve pathogens due to the faecal contamination (Hoglund et al., 1998), such as enteric bacteria and coliphage MS2 (Chandran et al., 2009), rhesus rotavirus and Salmonella typhimurium phage 28B (Hoglund et al. 2002). In particular, the presence of viruses could increase the safety risk of using

reclaimed water from source-separated urine, which indicates that suitable disinfection techniques should be applied to remove pathogens from source-separated urine before reuse.

Evaporation was an effective method to collect water from urine (Maurer et al., 2006). There can hardly be any chromaticity in the reclaimed water from urine when the evaporation was conducted under a condition of less than 100 °C (boiling), because urochrome could not be evaporated below temperature of boiling (Drabkin, 1930). However, energy consumption followed by the increase of operational cost is one of the major challenges for the application of evaporation to source-separated urine. Recently, Antonini et al. (2012) introduced solar thermal evaporation into human urine for nitrogen and phosphorus recovery, which provided a feasible solution for the application of evaporation technique to human urine with a much lower cost. However, it was a pity that discussions were sparsely found on the feasibility of the collected condensate water as the reclaimed water in their study. Another study (Yildiz and Unluturk, 2009) implied that pharmaceuticals and personal care products may not exist in condensate urine by solar thermal evaporation. Thus, there are two major challenges for the condensate water reuse from source-separated urine: (i) high nitrogen content and high pH, and (ii) potential pathogens. High nitrogen content and high pH are both contributed by ammonia (Jonsson and Vinneras, 2007), which could be significantly removed along the evaporation based on the mentioned study (Antonini et al., 2012). The potential pathogens (e.g. bacteria and viruses), however, may not be removed as easily as ammonia due to the inadequate heat from sunlight irradiation. In particular, viruses are usually more resistant to thermal disinfection than bacteria. Bertrand et al. (2012) reported that the inactivation of enteric viruses by thermal disinfection was not evident under temperature lower than 50 °C. Furthermore, resistant fractions of viruses might still remain infectious in thermal inactivation processes (Tuladhar et al., 2012), even if virus thermal inactivation was considered to be caused by nucleic acid degradation or protein denaturation (Delrue et al., 2012). To sum up, viral contamination of the condensate urine water from the solar thermal evaporation shall deserve close attention.

To date, many studies have reported viral inactivation by various virucidal techniques such as chlorine (Beck et al., 2013), UV (Hijnen et al., 2006) and UV/TiO₂ (Misstear and Gill, 2012). However, to our best knowledge, there was limited information available on the application of these virucidal techniques to the condensate water from source-separated urine. In this study, MS2 (ssRNA) and Phi X174 (ssDNA) coliphages were both used as surrogates for human viral pathogens in condensate water from source-separated urine. Three virucidal techniques (chlorine, UV and UV/TiO₂) were applied to remove the aforementioned viruses. The inactivation efficiencies were compared to previous studies with the emphasis on the analysis of water matrix effects. The aim of this work was to find out the desirable disinfection strategy for the reuse of reclaimed water from source-separated urine.

2. Materials and methods

2.1 Chemicals

The chemicals were mainly obtained from Sigma-Aldrich, US including non-porous titanium dioxide (TiO₂, Degussa-P25, purity >99.5%), urea (powder, d 1,335 g L⁻¹), ammonium chloride (NH₄Cl, purity >99%), sodium nitrate (NaNO₃, 99%), sodium hypochlorite solution (NaOCl, ACS reagent, d 1,206 g L⁻¹, available chlorine 10-15%), sodium thiosulfate pentahydrate (Na₂S₂O₃·5H₂O, ACS reagent, 99.5%). The stock solutions of chemicals were respectively prepared by dissolving the corresponding compound into DI-water (autoclaved for 15 min at 121 °C) to yield the initial concentrations of 100 mg L⁻¹ for Urea, ammonia nitrogen (NH₃-N), nitrate (NO₃⁻). Moreover, 12.060 mg L⁻¹ NaOCl solution was freshly prepared before experiment, as well as 30 g L⁻¹ Na₂S₂O₃ solution and 30 g L⁻¹ TiO₂ solution.

2.2 Viruses

The two viruses used in the experiments - MS2 (ssRNA coliphage, ATCC 15597- B1) and Phi X174 (ssDNA coliphage, ATCC 13706-B1) - were supplied by ATCC in freeze-dried form. After hydration in suitable broths, the viruses were stored at 4 °C. The host of MS2 was *E. coli* (ATCC 15597), while the host of Phi X174 was *E. coli* (ATCC 13706). Overnight cultures (18-20 h) of *E. coli* host cells (1 mL) were transferred to 30 mL of freshly sterilized tryptic soy broth (TSB) and incubated for 4 h (log phase) at 37 °C in an orbital shaker set at 150 rpm. Stock cultures of bacteriophages (1 mL) were transferred to the TSB containing log phase *E. coli*, and incubated overnight at 37 °C, 150 rpm. The culture was then centrifuged at 3,600 rpm for 10 min (Eppendorf Centrifuge 5810, Germany), and the liquid fraction was obtained through a 0.22-µm PES sterile filter paper (Nalgene, Rochester, USA). The filtrate was stored at 4 °C for future use. The bacteriophage Phi X174 was propagated and stored under the same conditions as that of MS2, with the only difference in the hosts as mentioned earlier.

2.3 Preparation of solutions

Three different solutions were prepared including the sterilized DI-water (autoclaved for 15 min at 121 °C, as a control), the real condensate water and the simulated water. Human urine samples (5 L) were collected from ten healthy volunteers in National University of Singapore, Singapore. To simulate solar thermal evaporation, the rotary evaporator (IKA RV10, Singapore) with a chiller (CCA-1111CE, China) was used to evaporate the collected urine at 60 °C (1.0 bar) for the real condensate water. Three stock solutions of chemicals (Urea, NH₃-N and NO₃⁻) were respectively added into the sterilized DI-water to form the simulated water based on the pre-determined ratios. All prepared solutions were stored at 4 °C, and spiked to obtain a final concentration of 10¹⁰-10¹¹ PFU mL⁻¹ for MS2 or 10⁶-10⁷ PFU mL⁻¹ for Phi X174 prior to disinfection experiments.

2.4 Water matrix analysis

Table 1 showed the water matrix of the real condensate water from sourced-separated urine before and after the treatment.

Concentration of urea was measured colorimetrically using the diacetyl monoxime method (Cozzi, 2004). Concentration of nitrate ion was determined by ion chromatography (ICS-1600, DIONEX). Ammonia nitrogen was detected according to the Salicylate method (Nitrogen, Ammonia, High Range, Test 'N tube) with a detection range of 0-50 mg L⁻¹ measured at 425 nm wavelength. Free chlorine was detected colorimetrically at 520 nm by the Palintest N, N-diethyl-p-phenylenediamine method (Greenberg et al., 1992).

(Table 1)

2.5 Disinfection experiments

For chlorine disinfection, the mixed samples (30 mL) comprised of NaOCl solution (12.060 mg L⁻¹, 1.2 mL) and the prepared solutions were kept at pre-determined time intervals, and then 0.3 mL Na₂S₂O₃ solution (30 g L⁻¹) was added and kept for 10 min to remove the residual chlorine.

For UV disinfection, a Rayox UV collimated beam unit (Calgon Carbon Corporation, US) was used with the monochromatic 10 W low pressure mercury lamp emitting UV light at 253.7 nm. Incident UV irradiance was measured using a radiometer (International Light IL1400A, USA). During experiments, the sterile polystyrene Petri dish (Aldrich, O.D. ×H 60 mm × 15 mm) containing the prepared solutions (10 mL) was placed on a magnetic stirrer. The average germicidal irradiance value on water surface was approximately 66 µW cm⁻². The prepared solutions were irradiated using pre-determined UV fluence. Based on a previous study (Guo et al. 2010), the Petri factors were accounted for prior to UV fluence (mJ cm⁻²) computation, using the product of the incident radiation and time based on the Microsoft excel spreadsheet provided by the manufacturer.

For UV/TiO₂ disinfection, two Philips TL 6 W black light lamps were applied to provide UV light at 365 nm. Before the experiment, the prepared solutions (29 mL) were poured into the 9-cm diameter sterile Pyrex[®] crystallizing dishes (Aldrich, capacity 270 mL, O.D. ×H 90 mm × 50 mm), where 1 mL TiO₂ solution (30 g L⁻¹) was added according to the reference (Maness et al., 1999). Then, the Pyrex[®] crystallizing dishes with the prepared solutions were placed on magnetic stirrers, and the irradiance value at the centre of water surface was about 1260 μW cm⁻². The mixed solutions were exposed to UV radiation for pre-determined exposure durations. During irradiation, samples were continuously stirred at a speed of 150 rpm for proper mixing. The irradiated sample (1 mL) was extracted for the determination of virus concentration at pre-determined intervals. After collection, the sample was filtered through 0.22-μm PES sterile filter paper (Nalgene, Rochester, USA).

After disinfection experiments, phages MS2 and Phi X174 in water samples were both immediately enumerated using the double-layer agar method (USEPA Manual of Methods for Virology, EPA 600/4-84/013 (N16), June 2001).

2.6 Data analysis

All experiments were done in triplicates, and the average of three replicate experiments was calculated and used for data interpretation. Data analysis graph was obtained by ORIGIN (version 8) and MINITAB (version 15).

3. Results and Discussion

3.1 Inactivation efficiencies

3.1.1 Chlorination

Chlorine is a widely used chemical disinfectant for the treatment of wastewater discharges (usually after secondary treatment) as well as surface and well water, due to its low cost, high efficiency, and residual biocidal effect (Rodriguez and Serodes, 2001). However, the data of inactivation by chlorination varied with different water matrices. Lykins et al. (1994) reported that more than 4.1 log reduction of MS2 in treated river water through pressure sand filtration were achieved after 17-min chlorination (free chlorine residual: 0.7 mg L⁻¹). In contrast, higher sodium hypochlorite dosages (8, 16 and 30 mg L⁻¹ free chlorine residual) added into the primary sewage effluent could only achieve relatively poor inactivation (1.0 log reduction) of MS2 after 30 min (Tree et al., 2003). Although many studies have reported the disinfection by chlorination in real waters, there was still limited information on condensate water evaporated from source-separated urine.

In this study, there were about 1.1 log reduction of MS2 at 480 mg L⁻¹ initial sodium hypochlorite dose (available chlorine: approximately 50 mg L⁻¹) for 10 min, while the obtained inactivation (1.03±0.05 log) of MS2 in peptone water only needed 18 mg L⁻¹ initial sodium hypochlorite dose for the same contact time (Koivunen and Heinonen-Tanski, 2005). D'Souza and Su (2010) reported that greater than 6 log reduction of MS2 in phosphate-buffered saline with 5% trisodium phosphate were obtained with contact time of only 1 min, which was similar to the case of 10% household bleach (0.6% sodium hypochlorite, 5000 mg L⁻¹ available chlorine). Similarly, Beck et al. (2013) claimed greater than 5 log reduction of MS2 in the filtered gray water were achieved after 90 min of contact (free chlorine residual: 1 mg L⁻¹). However, MS2 inactivation curve in condensate water tended to be flat (~3 log inactivation) after 70 min of contact (Fig. 1B), which implied that it might be impossible to increase log reduction of MS2 even further through prolonging contact time with low chlorine dose in the condensate water.

Particularly, in the presence of ammonia nitrogen, free chlorine could be combined to form chloramine, which mitigates the disinfection capacity of chlorine (Lykins et al., 1994). In this

study, there was not free chlorine found in condensate water (Table 1), which suggested that the inactivation of viruses was determined by the formed chloramines. This can well explain the fact that the inactivation rates for both MS2 and Phi X174 in real condensate water were lower than that in sterilized DI-water (Fig. 1).

(Figure 1)

3.1.2 UV disinfection

Previous studies have shown that UV irradiation was very effective against the pathogens (e.g. bacteria and virus) found in drinking water and wastewater (Oppenheimer et al., 1997; Park et al., 2011). However, the data on inactivation of the used viruses by UV varied with different water matrices listed in S1, from which it can be seen that water with less water matrices tended to require the lower UV fluence given the same level of virus inactivation. To date, virus inactivation by UV irradiation in condensate water evaporated from source-separated urine was still unclear.

More than 4 log reduction of phi X174 were achieved at 10 mJ cm⁻² of UV fluence, while more UV fluence (about 60 mJ cm⁻²) was required for MS2 to obtain the same inactivation efficiency in this study, which was within the range of the data reported by the literature (Hijnen et al., 2006). However, to achieve the same virus inactivation efficiency, UV fluence required in this study was far less than that required in real water (e.g. groundwater and filtered water from river) shown in S1, which indicated that the interference in condensate water evaporated from source-separated urine should be less than that in real water listed in S1. It can also be reflected by the results in Fig. 2 that the inactivation rate of MS2 by UV in sterilized DI-water was slightly greater than that in real condensate water. This was also applicable to phi X174.

(Figure 2)

3.1.3 UV/TiO₂ photocatalysis

It was well accepted that photocatalytic technique was a desirable process for disinfection of bacteria in drinking water and wastewater, due to its high efficiency and environmental friendliness (Maness et al., 1999; Alrousan et al., 2012). However, limited information was available about virus inactivation by this technique, especially in the real water matrices. Therefore, UV/TiO₂, a typical photocatalytic process, was applied to virus inactivation in condensate water in this study. It can be seen from Fig. 3 that the inactivation rates for both MS2 and phi X174 by UV/TiO₂ were obviously higher in sterilized DI-water than that in real condensate water. About 20-min exposure was able to achieve 4 log reduction of MS2, which was greatly faster than reported by Lee and Ko (2013), in which 4 log reduction of MS2 in the 0.22 µm filtered groundwater were achieved at 120 min. It indicated that water matrix in this study was an important factor in terms of UV/TiO₂ disinfection performance.

(Figure 3)

3.2 Effects of water matrix on virus inactivation

The effects of water matrix can be reflected by the difference of the above virus inactivation between sterilized DI-water and real condensate water. In this study, the effect of urea on virus inactivation was analysed using the simulated water, as well as that of nitrate and ammonia nitrogen. Moreover, the definition of ratio (K) was given as the equation (1) to reflect the change of virus inactivation in different levels of the simulated water, and to further evaluate the impact of water matrices on virus inactivation in real condensate water.

$$K = a/b \quad (1)$$

Where a is the virus inactivation efficiencies in different levels of the simulated water, b is the virus inactivation efficiencies in the sterilized DI-water, $K < 1$ inhibition, $K \approx 1$ no effects, $K > 1$ promotion.

Based on Fig. 4, virus inactivation through chlorine and UV were both unchanged with the increase of urea concentration with $K \approx 1$ for MS2 and Phi X174. This indicated that there were little impacts of urea on the virus inactivation using chlorine and UV. De Laat et al. (2011) claimed that urea could be decayed by free chlorine with slow decomposition rate ($\sim 1\%$ per hour in the presence of $1.6\text{--}1.8\text{ mg L}^{-1}$ of free chlorine). Although there was around $48\text{--}72\text{ mg L}^{-1}$ of available chlorine in this study, the contact time given to inactivate the viruses was very short, which might mask the effect of urea on virus inactivation. In practice, contact time could be longer for the reaction between chlorine and urea in condensate water, which may produce some chemicals. However, these chemicals were proved to be CO_2 and NO_3^- (De Laat et al., 2011), which was not likely to cause any impact on virus inactivation in aqueous solution. It was, however, a different case for UV/ TiO_2 treatment, where virus inactivation decreased moderately with the increase of urea concentration (Fig. 4). Meanwhile, K values of MS2 and Phi X174 were in the range of $0.42\text{--}0.58$ and $0.6\text{--}0.72$, respectively. It implied that the urea could inhibit UV/ TiO_2 disinfection. This might be due to the reaction between $\text{OH}^\cdot$ and urea, which can be reflected by the data in Table 1.

(Figure 4)

Results from Fig. 5 indicated that the impact of nitrate on virus inactivation by chlorine was not evident due to $K \approx 1$ for MS2 and Phi X174, while it slightly enhance virus inactivation by UV ($1 < K < 1.1$). The previous study reported that $\text{OH}^\cdot$ could be formed from nitrate exposed to UV lamps (Mark et al., 1996), which implied that the virus inactivation could be enhanced when nitrate exists in water and is irradiated by UV. However, the concentration of nitrate was low in this study (Table 1), which may only result in small amount of $\text{OH}^\cdot$. Similarly, the virus inactivation by UV/ TiO_2 increased slightly with the increase of nitrate levels ($1 < K < 1.15$ for MS2 and Phi X174), which indicated that nitrate promoted the virus inactivation by UV/ TiO_2 to some extent, although Keen et al. (2012) claimed that nitrate underwent photolysis when irradiated with ultraviolet (UV) light only in the $200\text{--}240$ and $300\text{--}325\text{ nm}$ wavelength range. There must be some other reasons responsible for the effect of nitrate, such as the potential reaction of nitrate with electron (e^-) formed from UV/ TiO_2 photocatalysis (Kudo et al., 1987).

(Figure 5)

The profile of virus inactivation by chlorine had a great change with the increase of ammonia nitrogen concentrations (Fig. 6), with $K < 0.11$ for MS2 and Phi X174, which indicated that ammonia nitrogen considerably inhibited the virus inactivation by chlorine. It can be explained that the chloramine formed from the reaction of ammonia nitrogen with free chlorine has slow disinfection action. In contrast, the virus inactivation by UV was not enhanced with increased ammonia nitrogen concentration ($K \approx 1$), which indicated that ammonia nitrogen had no impact on the virus inactivation by UV.

(Figure 6)

In terms of UV/ TiO_2 disinfection, K was in the range of $1.1\text{--}1.3$ for MS2 and $1.1\text{--}1.4$ for Phi X174. It showed that ammonia nitrogen promoted slightly virus inactivation by UV/ TiO_2 . Emerson et al. (1975) claimed ammonia nitrogen comprised of dissolved un-ionized ammonia (NH_3) and ionized ammonia (NH_4^+). Thereinto, dissolved NH_3 was the proposed agent for pathogen inactivation with the slow inactivation kinetics (Vinneras et al., 2008). It implied that the effect of dissolved NH_3 could not be shown probably because of the short contact time in this study. Therefore, the effect of ammoniac nitrogen on virus inactivation might be related to the ionized ammonia (NH_4^+) in this study. In addition, according to the comparison of K values, it can be deduced that the inhibition of urea to virus inactivation was more significant than the promotion of both nitrate and ammonia nitrogen.

The relationship of water matrix with virus inactivation were further evaluated by Cluster analysis. Cluster analysis could determine the correlation among different factors. And correlation degree

was obtained by identifying the distance across variables using a tree-shape figure (Pitt et al. 2004). Fig. 7 shows the cluster analysis of virus inactivation by three common virucidal techniques with different water matrix. Based on the Fig. 7, it can be seen that the correlation of urea with Phi X174 inactivation by chlorine was the most significant, as well as that of NO_3^- and $\text{NH}_3\text{-N}$ with Phi X174 inactivation by UV/ TiO_2 , respectively. Through synthetical thinking of K values and Cluster analysis, UVC disinfection is considered for disinfecting the reclaimed water from the evaporation of source-separated urine.

(Figure 7)

4. Conclusions

All virus in activations in condensate water from source-separated urine were inhibited compared to the control under the same conditions. Both nitrate and ammonia nitrogen promoted slightly the virus inactivation through UVA/ TiO_2 , but the inhibition of urea was more significant in the inactivation. Similarly, the ammonia nitrogen had greater impacts on chlorine disinfection than urea and nitrate. In contrast, all water matrices (urea, nitrate and ammonia nitrogen) hardly had any influence on UVC disinfection. Based on the inactivation efficiencies and the effect of water matrices, UVC disinfection can be considered for disinfecting the reclaimed water from the evaporation of source-separated urine.

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Table 1 Water quality of the real condensate water

Treatment	Urea mg L ⁻¹	NO ₃ ⁻ ion mg L ⁻¹	NH ₃ -N mg L ⁻¹	Free chlorine mg L ⁻¹
Initial	12.1 (0.22)	0.31 (0.04)	56 (2.49)	ND
NaClO solution	11.6 (0.12)	0.35 (0.06)	47 (3.56)	ND
UV	12.0 (0.29)	0.30 (0.05)	52 (3.40)	ND
UV/TiO ₂	8.7 (0.16)	9.06 (0.29)	28 (2.02)	ND

Note: To obtain the treated water samples, the NaOCl solution (12.060 mg L⁻¹, 1.2 mL) was added into the condensed samples (30 mL) and kept for 1 min; UVC (60 mJ cm⁻²) was provided to irradiate the condensed samples (10 mL); the condensed samples (30 mL) with 1g L⁻¹ TiO₂ was exposed to UVA light for 10 min; 'ND' means not detectable; standard deviation (SD) were in brackets.

Fig. 1 Inactivation of viruses by sodium hypochlorite (approximately 480 mg L⁻¹)

Note: A - the disinfection in sterilized DI-water, B - the disinfection in real condensed water. Error bars denoted standard deviation (SD).

Fig. 2 Inactivation of viruses by UV. Note: Error bars denoted standard deviation (SD).

Fig. 3 Inactivation of viruses by UV/TiO₂. Note: Error bars denoted standard deviation (SD).

Fig. 4 The relationship of virus inactivation with different urea concentration

Note: Inactivation of MS2 by NaOCl ($\sim 480 \text{ mg L}^{-1}$) for 15 s (■); Inactivation of Phi X174 by NaOCl ($\sim 480 \text{ mg L}^{-1}$) for 45 s (□); Inactivation of MS2 by UV at 60 mJ cm^{-2} (●); Inactivation of Phi X174 by UV at 8 mJ cm^{-2} (○); Inactivation of MS2 by UV/TiO₂ for 1 min (▲); Inactivation of Phi X174 by UV/TiO₂ for 5 min (△); Error bars denoted standard deviation (SD).

Fig. 5 Inactivation of virus under different nitrate concentration

Note: the inactivation of MS2 by NaOCl ($\sim 480 \text{ mg L}^{-1}$) for 10 s (■); the inactivation of Phi X174 by NaOCl ($\sim 480 \text{ mg L}^{-1}$) for 30 s (□); the inactivation of MS2 by UV at 60 mJ cm^{-2} (●); the disinfection of Phi X174 by UV at 8 mJ cm^{-2} (○); the disinfection of MS2 by UV/TiO₂ for 1 min (▲); the disinfection of Phi X174 by UV/TiO₂ for 5 min (△); Error bars denoted standard deviation (SD).

Fig. 6 Inactivation of virus with different ammonia nitrogen concentration

Note: Inactivation of MS2 by NaOCl ($\sim 480 \text{ mg L}^{-1}$) for 5 min (■); Inactivation of Phi X174 by NaOCl ($\sim 480 \text{ mg L}^{-1}$) for 1 min (□); Inactivation of MS2 by UV at 60 mJ cm^{-2} (●); Inactivation of Phi X174 by UV at 8 mJ cm^{-2} (○); Inactivation of MS2 by UV/TiO₂ for 1 min (▲); Inactivation of Phi X174 by UV/TiO₂ for 5 min (Δ); Error bars denoted standard deviation (SD).

Fig. 7 The dendrogram of virus inactivation with different water matrix

Note: A means MS2 inactivation by Chlorine, B means Phi X174 inactivation by Chlorine, C means MS2 inactivation by UVC, D means Phi X174 inactivation by UV, E means MS2 inactivation by UV/TiO₂, F means Phi X174 inactivation by UV/TiO₂.