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The virus removal in UV irradiation, ozonation and chlorination

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A B S T R A C T

The COVID-19 pandemic draws much attention to virus inactivation since the SARS-CoV-2 was detected in miscellaneous environments and the wastewater can be a potential transmitting pathway. UV irradiation, ozonation and chlorination are widely used disinfection processes in water treatment. In this review, the mechanisms and applications of three disinfection processes are introduced, and their inactivation effects on virus as well as other microorganisms are compared and discussed. The resistance of viruses to UV irradiation is generally stronger than that of bacteria. 4-log inactivation of bacteria can be easily obtained within a UV dose of 10 mJ/cm². However, the doses to reach the same virus removal rate vary greatly from 10 to 140 mJ/cm². The coronaviruses have even stronger UV resistance. Comparatively, ozonation and chlorination are effective methods to inactivate viruses, and the CT values of 4-log removal for most viruses concerned are lower than 1 mg·min/L and 10 mg·min/L, respectively. Protozoa, fungal spores and bacterial spores are more resistant to disinfection. Temperature, pH, organic matters, turbidity and other parameters all have influences on the disinfection. With a 10 °C decrease in temperature, the CT value required for certain removal rates doubles. Generally low pH promotes disinfection and high pH is against it. In drinking water and wastewater treatment process, the resistance properties of microorganisms and other influence parameters should be taken into consideration when choosing disinfection technologies.

1. Introduction

Virus is a class of ultra-microscopic, non-cellular, absolutely intracellular parasitic organisms with no metabolic capacity. Based on the structure of virus particles, virus can be divided into two categories, enveloped virus and non-enveloped virus (Fig. 1). Non-enveloped virus particles consist of a dense protein capsid and nucleic acid. The nucleic acid generally binds to nuclear proteins. The vast majority of enteroviruses in sewage fall in the category of non-enveloped viruses, such as poliovirus, rotavirus, norovirus, coxsackievirus, echovirus, adenovirus, etc. [1]. Enveloped virus has an extra membrane obtained from the host cell outside the protein capsid, which contains spike proteins critical for cell infection. The membranous envelope can be easily damaged by a variety of chemical agents, such as detergents, organic solvents, oxidants, etc. and is prone to be affected by environmental factors, such as high temperature, drying, and the presence of other microorganisms. Therefore, in the absence of outbreaks, enveloped viruses, such as influenza virus, HIV, coronavirus, etc. cannot be detected in urban sewage [1]. It is widely believed that enveloped viruses cannot be transmitted through wastewater. However recent studies have shown that the SARS-CoV-2 mRNA was detected in wastewater from various sources [2–4]. The transmission pathway of wastewater cannot be ruled out since coronavirus can survive for a relatively long time in wastewater. For example, SARS coronavirus can survive for 2 days at 20 °C in wastewater and 3 days in feces [5]. Murine coronavirus and porcine coronavirus can survive for 3–4 days at 25 °C in wastewater after pasteurization, and their survival time can be increased by 5-fold and 11-fold at 4 °C, respectively [6]. Considering that during an outbreak, the amount of enveloped virus in sewage will increase greatly, the wastewater may also become a means of virus transmission.

Disinfection is one of the methods to control pathogenic microorganisms in wastewater treatment plants. At present, common disinfection processes include ultraviolet disinfection, ozone disinfection, chlorination disinfection (chlorine, sodium hypochlorite or chlorine dioxide), etc. The efficiencies of inactivating virus and other pathogens vary among different processes. This paper will introduce different disinfection processes and their abilities to remove various virus.

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2. Virus inactivation by UV irradiation

Lights of wavelengths between UV200 and UV280 jeopardize the stability of C–C bonds in some molecules such as pyrimidines, purines, and flavins. The main mechanism of UV disinfection concerns the formation of pyrimidine dimers (thymine and cytosine in DNA, uracil and cytosine in RNA) after absorbing the UV energy, thus affecting a series of biochemical processes such as DNA replication, RNA transcription and protein translation [7].

There are hundreds of studies on the UV inactivation of microorganisms. Generally, the logarithmic inactivation rate has a linear relationship with UV dose:

$$\log_{10}(C_0/C_t) = \frac{k}{C_2} F$$

Where, $C_0$ is the initial concentration of a microorganism. $C_t$ is the concentration of survived organism after $t$ time of UV irradiation. $k$ is the inactivation constant (cm$^2$/mJ), and $F$ is the UV dose (mJ/cm$^2$).

The constant $k$ differs among species (Table 1). It reflects the UV sensitivity of microorganisms and most viruses conform to the above rule. Some microorganisms, mainly bacteria and spores cannot be inactivated at low UV doses. Their inactivation curves can be fitted by Shoulder Model [8]:

$$\log_{10}(C_t/C_0) = -k \times F - b$$

Where, $b$ is the y-intercept.

The inactivation constants of different microorganisms are summarized in Table 1. The UV sensitivities of different species were found to be: bacteria > non-enveloped virus ≈ protozoa. The sensitivity of enveloped virus varies greatly (Fig. 1). In addition, the inactivation effect of medium-pressure mercury lamps (MPMLs) is always better than that of low-pressure mercury lamps (LPMLs). This is probably because MPMLs produce UV wavelengths of 200–380 nm, which damage other molecules such as proteins as well as nucleic acids, whereas LPMLs only produce UV wavelength of 254 nm. Nevertheless, LPMLs have better photodissociation efficiency than MPMLs [9]. In recent years, the UV-light emitting diode (LED) has drawn increasing attention for its several promising advantages over the mercury lamp including environmental friendliness, durable construction, no warm-up time and ability to turn on and off frequently [10,11]. By controlling the proportions of aluminum nitride (AIN) and gallium nitride (GaN) which are the materials of the semiconductor, UV-LEDs can emit light of wavelengths from 210 nm to 365 nm. However, applications of UV-LEDs on water disinfection are relatively scarce (Table 1).

There are limited reports on the UV inactivation of coronavirus. Most of the studies focused on the LPMLs disinfection of SARS coronavirus (SARS-CoV), but the results showed great discrepancies. It was reported that SARS-CoV was completely inactivated at 162 mJ/cm$^2$ [14]. In the mass production of the inactivated SARS vaccine, 600 mJ/cm$^2$ could kill the virus for sure [15]. However, another study found that there was only about a 1.36-log removal at 241 mJ/cm$^2$ [16]. According to formula (1), the inactivation constant $k$ of SARS-CoV calculated from the data in this literature was approximately 0.0034, which means the SARS-CoV has lower UV resistance than adenovirus. In addition to SARS-CoV, Pratelli [17] conducted UV inactivation research on canine coronavirus (UVC band, unknown wavelength), and found that the UV dose of 2341 mJ/cm$^2$ could only result in a 1.75-log removal. The inactivation constant was 0.0007, which ranked the highest UV resistance retrieved at present. Such high resistance might be due to the low power (0.0271 mW/cm$^2$) of the UV lamp used in this study. It is unclear whether the law of virus inactivation still conforms to formula (1) at such a low power. Recently, a study on SARS-CoV-2 showed an UVA dose of 292 mJ/cm$^2$ can only achieve a 1-log reduction and an UVC dose of 1048 mJ/cm$^2$ achieves complete inactivation [18]. Another study applying UVC found that a dose of 37.5 mJ/cm$^2$ was capable to bring a more than 3-log
Table 1
Inactivation constant \( k \) (cm\(^2\)/mJ) of different microorganisms. Notes: a Average values from different literatures.

| Microorganisms          | LPMLs | MPMLs | UV-LEDs |
|-------------------------|-------|-------|---------|
|                         | \( (95% \text{ Cl}; r^2) \) | \( (95\% \text{ Cl}; r^2) \) | (Wavelength, nm) |
| **Virus**               |       |       |         |
| Non-enveloped virus     |       |       |         |
| Poliovirus 1 [8]        | 0.135 | (0.007; 0.79) |         |
| Adenovirus [8, 12,13]   | 0.033* | 0.111* |         |
| Rotavirus [8]           | 0.102 | 0.154 | (0.006; 0.011; 0.78; 0.92) |
| Feline calicivirus [8]  | 0.106 |       |         |
| Bovine calicivirus [8]  | 0.190 | 0.293 | (0.008; 0.96; 0.97) |
| Cowpoxivirus [7]        | 0.119 |       |         |
| SARS coronavirus [8]    | 0.006 |       |         |
| Hepatitis virus [8]     | 0.181 |       |         |
| A [8]                   | 0.028; 0.70 | | |
| Phage MS2 [8, 10]       | 0.055 | 0.122 | 0.078 (255); 0.93 (0.92) |
| Phage qX174 [8,10]      | 0.396 | 0.578 | 0.360 (280) |
| Phage T7 [8,10]         | 0.232 | 0.195 | 0.235 (275) |
| Phage P22 [8,10]        | 0.084 | 0.080 | 0.035 (280) |
| Enveloped virus         |       |       |         |
| HIN1 [12]               | 1     |       |         |
| Vesicular stomatitis virus [12] | 2.3 | | |
| Phage Φ6 [10]           | 0.067 |       |         |
| **Bacteria**            |       |       |         |
| Escherichia coli [6,10] | 0.506 | 0.539 | 0.300 (255); 0.422 (275) |
| Salmonella typhi [8]    | 0.515 |       |         |
| Yersinia pseudotuberculosis [8] | 0.899 | | |
| Vibrio cholera [8]      | 1.341 |       |         |
| Campylobacter jejuni [8] | 0.880 | | |
| Shigella dysenteriae [8] | 1.308 | | |
| Shigella sonnei [8]     | 0.468 |       |         |
| Legionella pneumophila [8] | 0.739* | | |
| Bacillus subtilis [8,10] | 0.059 | 0.051 (250); 0.120 (282) |
| **Protozoa**            |       |       |         |
| C. parvum [8]           | 0.225 | 0.243 | (0.07; 0.29; 0.37; 0.49) |
| Giardia muris [8]       | 0.122 | (0.178; 0.81) | | |
| Acanthamoeba spp [8]    | 0.021 |       |         |

In any case, coronaviruses are generally more resistant to UV than other viruses.

One mechanism of UV resistance of virus, suggested by some researchers, is that dsDNA virus like adenovirus is still capable to infect cells even the DNA is damaged, and the damaged DNA is then recognized and repaired by host cells, resulting in a low inactivation rate. Evidence for this theory is that when MPMLs were used for disinfection instead of LPMLs, the resistance of adenovirus was significantly reduced [13] because the MPMLs have a wider wavelength band and can also damage proteins. However, coronavirus and influenza are both enveloped ssRNA viruses. The reason for their huge differences in UV resistance remains unclear.

In the practical application of water treatment, UV disinfection of virus in drinking water requires a 4-log inactivation rate [20]. Considering that most enterprises still use LPMLs as their main light source, the UV doses required by different pathogenic microorganisms to reach 4-log inactivation using LPMLs disinfection are summarized in Fig. 1. The sensitivity of different microorganisms to UV disinfection is revealed. All pathogenic bacteria can achieve a 4-log removal at a dose of 10 mJ/cm\(^2\), which can be defined as UV hypersensitive microorganisms. Enteroviruses are UV high-sensitive or sensitive microorganisms. 80 mJ/cm\(^2\) can inactivate 4-log of most microorganisms, but adenovirus and Acanthamoeba spp. require higher doses. SARS coronavirus and canine coronavirus need 1176 and 5714 mJ/cm\(^2\) respectively according to the UV-LEDs studies incomparable sometimes [10]. For standardized methodology for obtaining the UV dose, which makes results comparable sometimes [10]. For mercury lamps, the inactivation protocol is well established and the laser collimator is usually used for research. Its calculation method is as follows [21]:

\[ E_{avg} = E_0 \times \text{Petri Factor} \times \text{Reflection Factor} \times \text{Water Factor} \times \text{Divergence Factor} \]

Where, \( E_{avg} \) is the average UV intensity, mW/cm\(^2\). \( E_0 \) is the UV intensity of the center of the water sample surface, mW/cm\(^2\). Petri Factor is the average ratio of the UV intensity in the range of the sample plate to \( E_0 \), which is used to evaluate the state of the UV reactor. Water Factor = \((1 - \alpha^{-l})/\alpha l \) (10), where \( \alpha \) is the absorption coefficient (cm\(^{-1}\)), and \( l \) is the vertical depth of water sample (cm). Divergence Factor = \( L/(L + 1) \), where \( L \) is the vertical distance of the UV lamp to the water surface.

For the UV reactor used in engineering, it is very difficult to measure the average UV dose. The hydraulic retention time and UV light intensity are different at different positions in the reactor. To solve this problem, one solution is the fluid dynamics simulation [22,23], but the accuracy still needs to be improved especially for wastewater which is rich in dissolved organic carbon (DOC) and suspended solids (SS). The other is biodosimetry. Biodosimetry is the measurement of the UV reactor by using microorganisms the dose-inactivation relationships of which have been calibrated on the laser collimator, so as to obtain the reduction equivalent fluence (REF) [24].

3. The virus removal by ozonation

Ozone was first applied to water treatment in France in 1886 [25]. Due to its good properties including strong oxidation ability, producing less disinfection by-products than other chemical disinfectants and removing the color and odor in water, ozone expanded its influence from Europe to the whole world. At the beginning, some European countries like Germany, England and Netherland used ozone for its taste and color removal ability with the disinfection purpose being less important. Ozone

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reacts with water rapidly and generates several kinds of free radicals and ions including HO·, HO2·, O2, O3, etc., but the ozone molecules play the main role in disinfection. The oxidative reaction is very quick. Generally, the concentration of residual ozone is halved in the first 30 s [26–28] and reaches at least a 1-log inactivation [29]. It is reported that oxidation of proteins by ozone mainly occurs at the tyrosine, tryptophan, histidine, cysteine, and methionine residues, resulting in the abnormal folding ability and changed higher order structures [30]. As for nucleic acids, the predominant radical reactions happen on the bases of dCMP, dTMP and dGMP, attacking the carbon-nitrogen double bonds [31], although one study found the predominant reactions seemed to be with the sugar component for dAMP [32].

As mentioned above, enveloped viruses have membranous envelopes that surround their capsids. Since the invasion of enveloped viruses into host cells relies on the specific proteins on their envelope, destruction of the envelope structure is able to inactivate viruses. A study using ozonized water to disinfect SARS-CoV-2 found that the virus was no longer viable after the envelope destruction, although the nucleic acids could still be detected [33]. For non-enveloped viruses, the structure of capsid proteins is much more stable than that of envelope proteins, while the nucleic acids become more sensitive in some cases. Roy and colleagues [34] found that the capsid protein of poliovirus 1 (PV1) was altered but the binding ability of virus to host cells remained unaffected after a low dose of ozone treatment. However, the virus was actually inactivated because of the RNA destruction. A recent study [35] has further revealed that the 1–124 nt region of the 5′-non-coding region of PV1 genome, which is necessary for viral replication, is more vulnerable to ozone attack. Based on these findings, it can be concluded that the resistance of viral components to ozone is capsid protein > nucleic acid > envelope (if any).

Since factors like temperature and pH can affect ozone disinfection, the following part discusses the details.

3.1. The effect of temperature on ozone disinfection

High temperature reduces the solubility of ozone in water, accelerates the decomposition of ozone but also the disinfection process. In common temperature range between 5 and 30 °C, a rise in temperature increases the efficiency of ozone disinfection and decreases the CT value [25,26,36]. The temperature coefficient Q10 is applied to describe the fold reduction of CT values induced by a 10 °C decrease. The calculation formula of Q10 is as follows:

$$Q_{10} = \left( \frac{P_2}{P_1} \right)^{\frac{1}{T_2 - T_1}}$$

(4)

Where, $T_1$ is the temperature and $P_1$ is the CT value required to achieve a certain inactivation rate, while $T_2$ is the changed temperature and $P_2$ is the changed CT value required to achieve the same inactivation rate. The average Q10 of Poliovirus 1 calculated from multiple data is 2.12 at pH 7.2 [37]. The predicted Q10 of murine norovirus are 1.56 and 1.68 according to different models at pH 7 [38]. The Q10 is 1.74 for Escherichia coli [39] and 2.26 for Bacillus subtilis spores [40]. It was found that the CT value required to achieve a 2-log inactivation of Giardia lamblia cysts at 5 °C and pH 7 was 0.53 mg·min·L−1, which was decreased to 0.17 mg·min·L−1 at 25 °C and pH 7 [41]. The calculated Q10 of G. lamblia cysts is 1.77. For Cryptosporidium parvum oocysts, a CT value of 10.1 mg·min·L−1 was required to reach a 4-log inactivation at 20 °C but 60.7 mg·min·L−1 at 5 °C and the Q10 is 3.31 [42]. The CT values for 2-log inactivation of Naegleria gruberi and Giardia muris at 15 °C, pH 7 are 2.04 and 0.375 mg·min·L−1. However, the CT value is doubled (Q10=2.07) and fivefold (Q10=5.17) respectively at 5 °C [43]. The spores of Aspergillus niger, Trichoderma harzianum and Penicillium polonicum have smaller Q10s of 1.13, 1.33 and 1.50 respectively [29]. The sensitivity to temperature changes varies among different microbes. According to various comparative studies, the CT value at pH 7 and under 30 °C approximately doubles for every 10 °C decrease ($Q_{10}\approx2$) to achieve the same log removal of viruses and other microorganisms (Fig. 4).

3.2. The effect of pH on ozone disinfection

The higher the pH, the more easily the ozone decomposes and the more radicals are produced. Both ozone molecules and hydroxyl radicals can attack microbes, however the direct attack of ozone is more effective observed in the study [44]. The decomposition of ozone thus hinders the inactivation. Previous study has proved that the half-life of ozone in water of pH 10 is 1/10 of that in water of pH 9 and 1/100 of that in water of pH 8 [45]. The test on MS2 phage showed that a CT value of 0.125 mg·min·L−1 was able to achieve 100% inactivation at pH 6.5, but the same CT value could only achieve more than 2-log removal at pH 7.5, and 10 mg·min·L−1 was needed to reach a 4.2-log inactivation at pH 8.5 [36]. For hepatitis A virus, the CT value required to reach 4-log inactivation at pH 6 and 7 was 0.4 mg·min·L−1, while 0.87 mg·min·L−1 was required at pH 8. Lim et al. [38] found that the CT value of 2-log inactivation of murine norovirus was 0.17 mg·min·L−1 at pH 5.6 and 0.72 mg·min·L−1 at pH 7. Other researchers found that pH had little effect on rotavirus, since the CT value to achieve a 2-log inactivation was less than 0.05 mg·min·L−1 [46]. It can be deduced that neutral pH (6.5–7.5) has a limited effect on CT value.

3.3. The effects of organic matter on ozone disinfection

The organic matter in water has a strong effect on ozone disinfection [47]. It creates a large amount of ozone demand, resulting in a rapid consumption of ozone at the beginning of disinfection, so the CT value for sewage disinfection is much higher than that for drinking water. A study on MS2 phage showed that the CT value required to reach a 4-log inactivation was 0.32 mg·min·L−1 in pure water, but more than 5 mg·min·L−1 in filtered river and reservoir effluent [36]. The same rule was observed for E. coli that 0.09 mg·min·L−1 and 2 mg·min·L−1 were needed to achieve 5-log inactivation in drinking water and secondary effluent respectively [48]. Another study [49] found the similar pattern that a CT value of 0.04 mg·min·L−1 achieved a 4-log inactivation of E. coli in the laboratory water and 0.98 mg·min·L−1 in the secondary effluent. The properties of different wastewater may vary greatly, and basically the CT value required to inactivate the microorganism in secondary effluent is over 20 times larger than that in pure water. In recent years, some studies used the abatement in OD254 as a surrogate to monitor the disinfection process [50]. Ozone can break the C=C bonds and aromatic rings, which contribute to the absorbance at 254 nm. Gamage et al. [48] explored the relationship between O32:TOC ratios and inactivation levels in secondary effluents and found O3:TOC ratios greater than 0.25 can achieve at least a 5-log inactivation for MS2 phages. However, this ratio parameter cannot predict the inactivation of Bacillus spores accurately.

3.4. The resistance of different microorganisms to ozone

In order to make a comparison under similar conditions, the CT values of inactivation in literatures were obtained and converted by the following rules: (1) studies using pure water or laboratory buffer water within pH 6.5–7.5 were selected for comparison to exclude the interference of COD and pH; (2) the CT values were unified to 20 °C and 4-log inactivation condition according to the approximation that the CT value is halved for every 10 °C increase and the log inactivation rate under 4–5 is linear with CT. Data on enveloped viruses are relatively scarce. The unified result shows that most viruses are hypersensitive or high-sensitive to ozone, and all viruses can be inactivated by 4-log within the CT of 2 mg·min·L−1 (Fig. 2). Therefore, ozone can be used to control virus risk in drinking water and further improve the water taste and odor. Bacteria and their spores are relatively more resistant to ozone, and can be 4-log removed within CT values of 10 mg·min·L−1. Aspergillus spores are the most resistant to ozone.
3.5. Other factors that affect ozone inactivation

The initial level of ozone has a certain effect on disinfection. The higher the initial level of ozone is, the lower the CT value is needed to achieve the same inactivation rate [36, 51]. The influence of turbidity depends on the properties of the substance that causes the turbidity. When kaolin was added to make a 20 NTU turbidity, the inactivation rate of MS2 only decreased by 0.02% [36]. Apart from kaolin, turbidity can also be caused by organic materials such as humic acid [52]. In that case, the ozone disinfection efficiency is compromised because the turbidity-inducing substance brings more ozone demand as DOC [53]. Bromide and iodide ions also lower the efficiency by consuming ozone to form bromate and iodate, but lowering pH can effectively reduce these side reactions [26]. Different strains of viruses may have different resistance to ozone. CT values of 4-log inactivation for coxsackievirus B3 and B5 environmental strains is 2-fold and 1.8-fold greater than the laboratory strains respectively possibly due to the difference of the capsid structure and composition [54].

4. The removal of viruses by chlorination

Chlorine disinfection has a long history of application. Chlorine dissolves with water to form chloride ion and hypochlorous acid. Hypochlorous acid is generally considered as the main disinfectant. There is also a sensitive sequence to chlorination in viral genome. Li et al. [58] found the 1–671 nt sequence in the 5’-non-coding region of HAV is most vulnerable to chlorine. This sequence region contains a stem-loop structure which is associated with virus replication. Chlorine is less reactive than ozone, which makes their inactivation processes different in the case of bacteria. Chlorine reacts more with intracellular components and the cells show better structural integrity and less plasma leakage after chlorination because the diffusion of chlorine into cells are less compromised by reaction with cell walls [59]. Factors affect ozone disinfection have similar impacts on chlorination to some extent.

4.1. The effects of pH on chlorine disinfection

Since hypochlorous acid is a weak acid, the pH value of wastewater can significantly affect the ionization balance of hypochlorous acid, thus affecting the disinfection efficiency of chlorine. Most studies investigated the effects of pH within the range of 6–10 [60–64]. The percentage of hypochlorous acid at pH 6 and 15°C is 97.5%, so pH lower than 6 should make a limited difference compared with pH 6. Sobsey et al. [65] showed that chlorine had the highest disinfection efficiency at pH 6 for coxsackievirus B3 and MS2 phage, and the CT values for 4-log inactivation were 6.6 mg-min/L and 0.6 mg-min/L, respectively. The chlorination efficiency peaked at pH 7 for HAV (1.8 mg-min/L) and ΦX174 (0.2 mg-min/L) respectively.
mg·min/L). Among the four viruses, only HAV had a smaller CT value at pH 8 than at pH 6. To make comparisons, the CT values for 2-log inactivation rates at different pH are divided by the CT values at pH 6 ([51, 64–66], Fig. 3). The relative CT value of MS2 phage at pH 8 is 13.78 and is not shown in the figure. Generally, the chlorination is more efficient at pH 6–7.

pH can also affect the adsorption of virus by suspended particles in wastewater. The isoelectric points (pI) of both the virus and adsorbent interact in the process. pI values of some viruses (reovirus 3, vaccinia, echovirus 1, MS2, T2, T4 and Qβ phages) are in the range of around 4–5, while pI values of poliovirus 1 (Mahoney) and Fr phage are 8.2 and 9.0 respectively [67]. Typical solid surfaces in water like quartz and humic matter have pI lower than 3.5, while pI of allophane (6.5) and tenorite (9.5) are higher [68]. Therefore, the properties of both viruses and solid surfaces affect adsorption pattern at certain pH.

4.2. The effects of turbidity on chlorine disinfection

The turbidity affects chlorine disinfection in a similar pattern as ozonation. The particles that increase the turbidity can be organic and inorganic matters. These particles reduce disinfection efficiency by consuming disinfectant, or by masking microorganisms from the contact with disinfectant. In natural water and wastewater, viruses are often adsorbed or trapped in particles [67]. However, a low turbidity (5 NTU) generated by kaolin provides little or no protection to MS2 phages and B. subtilis spores [69]. In the range of 0.2–5 NTU, an increase in turbidity did not affect or only slightly reduce the chlorine disinfection efficiency of coxsackievirus B5. However, at a high turbidity (20 NTU), the CT value required for 4-log inactivation was at least doubled than that of 5 NTU [70]. The composition contributing to turbidity also plays a role. When humic acid was added to create turbidity, the disinfection efficiency of chlorine decreased significantly when turbidity reached 1 NTU. But when chalk was added instead, the turbidity did not affect the disinfection efficiency even at 5 NTU [52].

4.3. The effects of temperature on chlorine disinfection

Temperature affects the disinfection efficiency of all chemical reactions involved. Although there are very limited studies, the results are predictable as the higher temperature the lower dose needed for the same inactivation level. The Q10 for inactivation of MS2 phages at pH 8.5 is 1.75 [69], and for human adenovirus 2, coxsackievirus B5, echovirus and murine norovirus at pH 7, the calculated Q10 are 1.46, 2.91.81 and 1.53 respectively [71]. Spores of Bacillus spp. Have Q105 in the range of 1.79–2.00 at pH 7 [72], and Campylobacter jejuni has a Q10 value of 1.97 at pH 6.5 [73]. Aspergillus terreus, Cladosporium tenuissimum and Phoma glomerata have Q10 of 1.82, 2.74 and 2.26 at pH 7 respectively [74]. Some pathogens may have a much higher Q10 (10.08 for Yersinia enterocolitica 304 [73]), but most viruses and other microbes have a Q10 value of around 2 at pH 7 (Fig. 4). It is necessary to increase the contact time or chlorine dose in the seasons with lower temperature.

4.4. The tolerance of viruses to chlorine

pH, temperature, disinfectant dose and water conditions all affected the virus inactivation. In order to make a reliable comparison of the chlorine tolerance of microorganisms, studies carried under the condition of pH 7–7.2 and a chlorine dose of 0.2–3 mg/L are selected. All the studies used buffered water or partially treated water with 1.9 mg/L TOC and 0.17 NTU [71]. The majority of chlorination experiments selected are performed under around 5 °C [64,66,70–72,75–78]. All viruses included are hypersensitive or high-sensitive to chlorination and can be inactivated within a CT value of 10 mg·min/L. Norovirus and rotavirus can be easily inactivated with a CT value less than 0.04 mg·min/L [64, 71]. Most bacteria are sensitive or high-sensitive to chlorination and a CT value of 40 mg·min/L can achieve a 4-log inactivation. However, the bacterial spores are low-sensitive to chlorination and CT values under 100 mg·min/L are unable to get a satisfactory removal. A CT value of 472.8 mg·min/L is required to achieve a 4-log inactivation of Bacillus subtilis spores at 22 °C and pH 7 [79]. The CT value would be 1536 mg·min/L and is not shown in Fig. 5. Fungi spores are all low-sensitive to chlorination. Some free-living protozoa trophozoites can be 4-log inactivated with CT values around 100 mg·min/L, but their cysts are much more resistant to chlorination [80]. The Cryptosporidium parvum oocysts are most resistance to chlorination and a CT value of 3600 mg·min/L is needed to achieve a 4-log inactivation at 20 °C [81], which could be 10, 182 mg·min/L at 5 °C and is not shown in Fig. 5.

5. Conclusions

This review introduces three commonly used disinfection processes and discusses the resistance of different viruses to these processes. The doses for 4-log removal of most common pathogenic microorganisms are compared. UV irradiation is not a highly efficient disinfection method for viruses, but is more effective to inactivate bacteria. Ozonation and chlorination have a satisfactory performance in virus inactivation, and are recommended for SARS-CoV-2 inactivation since most coronaviruses are UV insensitive. The inactivation effect can be influenced by temperature, pH, organic matter, turbidity and so on. With a 10 °C decrease in temperature, the CT value required to achieve a certain removal rate approximately doubles for ozonation and chlorination. Generally low pH favors inactivation while high pH hinders it and neutral pH (6.5–7.5) has limited influence for ozonation and chlorination. In applications of disinfection technologies on drinking water and wastewater treatment, it is recommended to combine different disinfection processes and take considerations of influential parameters to achieve inactivation.

Fig. 3. Relative CT values needed at different pH for chlorination.
economically and effectively.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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