Role of wastewater treatment in COVID-19 control

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ABSTRACT

The International Water Association (IWA) initiated a Task Force in April 2020 to serve as a leadership team within IWA whose role is to keep abreast and communicate the emerging science, technology, and applications for understanding the impact and the ability to respond to the COVID-19 pandemic and specifically designed for water professionals and industries. Expertise was nominated across the world with the purpose of collectively providing the water sector with knowledge products for the guidance on the control of COVID-19 and other viruses. This review paper developed by a working group of the IWA Task Force focuses on the control of COVID-19. The purpose of this review paper is to provide an understanding of existing knowledge with regards to COVID-19 and provide the necessary guidance of risk mitigation based on currently available knowledge of viruses in wastewater. This review paper considered various scenarios for both the developed world and the developing world and provided recommendations for managing risk. The review paper serves to pool the knowledge with regards to the pandemic and in relation to other viruses. The IWA Task Team envisage that this review paper provides the necessary guidance to the global response to the ongoing pandemic.

Key words | COVID-19, SARS-CoV-2, sludge, wastewater

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HIGHLIGHTS

- Review of existing research of the virus, SARS-CoV-2, that causes COVID-19 and other viruses in relation to wastewater process control and risk mitigation.
- Available techniques for wastewater process engineers to reduce health risks associated with COVID-19 within wastewater processes.
- Risk mitigation for developing countries that are serviced by small wastewater treatment works.

INTRODUCTION

Coronavirus Disease 2019 or COVID-19 is the infectious disease caused by the newly discovered coronavirus, *Severe Acute Respiratory Syndrome Coronavirus 2* (SARS-CoV-2). The new virus and disease were first reported in December 2019 in Wuhan, China (WHO 2020a). The disease outbreak was declared by the World Health Organization (WHO) as a Public Health Emergency of International Concern on 30 January 2020 and recognised as a pandemic on 11 March

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2020. While the evidence to date indicates that the virus spreads through respiratory droplets from infected people and direct contact with a surface that has the viable virus on it, existing knowledge to date suggest a possibility – although not definitive – for the faecal–oral transmission route (Sun *et al.* 2020; Xiao *et al.* 2020). Recent evidence has shown that the virus can be detected and persists in patients stool samples after pharyngeal swabs became negative (Chen *et al.* 2020a; Wang *et al.* 2020a), while infectious SARS-CoV-2 has been isolated from urine (Sun *et al.* 2020) and faeces of COVID-19 patients (Xiao *et al.* 2020). Further research is required to scientifically validate the faecal–oral pathway risk and the survival of the SARS-CoV-2 virus in sewage and other human faecal-origin wastes. Aerosol transmission potential also needs to be validated (Santarpia *et al.* 2020). With insufficient evidence with regards to faecal–oral pathways and aerosol transmission from wastewater systems, it is imperative that there be appropriate control measures put in place for wastewater treatment processes. This paper presents an overview of existing evidence-based research regarding the relationship between COVID-19 and wastewater, and presents an overview of appropriate control measures that could be used for disease transmission mitigation.

COVID-19 VIRUS IN HUMAN FAECAL WASTE

The virus that causes COVID-19 (SARS-CoV-2) has been detected in the faeces of a number of patients diagnosed with COVID-19. Recent reports revealed that 2–10% of COVID-19 patients had gastrointestinal symptoms, including diarrhoea (Chen *et al.* 2020b; Wang *et al.* 2020b) and one study showed that stool viral *ribonucleic acid* (RNA) was positive in 9 (15.3%) patients, and the median viral load was 4.7 (range: 3.4–7.6) log10 copies/mL (Cheung *et al.* 2020). Subsequently, SARS-CoV-2 RNA was detected in the faeces of 81.8% cases even with a negative result of throat swab test (Ling *et al.* 2020). SARS-CoV-2 RNA also could be detected in faeces of asymptomatic individuals (Tang *et al.* 2020), which may account for a significant proportion (17.9–30.8%) of infected individuals (Mizumoto *et al.* 2020; Nishiura *et al.* 2020). Shedding of SARS-CoV-2 RNA could be up to 7 weeks after the first symptom (Jiehao *et al.* 2020; Wu *et al.* 2020a). While human colonic fluid has been shown to inactivate the virus as shown from the analysis of faecal samples of COVID-19 patients (Zhang *et al.* 2020), in severe cases, it appears that this may not occur (Xiao *et al.* 2020).

Generally, the information about the percentage of patients shedding virus, the amount of virus discharged from a patient in stool, the length of shedding period, etc. are still very limited, and evidence whether the virus in stool is infectious is scant (Xiao *et al.* 2020). Although the risks caused by the virus in sewage and its removal in wastewater treatment processes have not been systematically assessed, the WHO has indicated that *there is no evidence to date that SARS-CoV-2 has been transmitted via sewerage systems, with or without wastewater treatment* (WHO 2020b).

COVID-19 VIRUS IN UNTREATED SEWAGE

Recent research has indicated that faecal shedding of SARS-CoV-2 is common and that the genetic material of viral SARS-CoV-2 can be detected in wastewater and sludges. The detection of viral SARS-CoV-2 RNA in wastewater and sludges does not mean that the virus is infectious. Infectious SARS-CoV-2 virus has yet to be recovered from wastewater. There have been quite a few preliminary reports of detection of SARS-CoV-2 viral RNA in wastewater using *quantitative reverse-transcription Polymerase Chain Reaction* (RT-qPCR), a method used in the Netherlands (Medema *et al.* 2020), USA (Nemudryi *et al.* 2020; Wu *et al.* 2020b), France (Wurtzer *et al.* 2020), Australia (Ahmed *et al.* 2020), Spain (Randazzo *et al.* 2020), Italy (La Rosa *et al.* 2020; Rimoldi *et al.* 2020), and Israel (Bar-Or *et al.* 2020). The maximum level of SARS-CoV-2 virus RNA untreated wastewater has been as high as 3.0×10^6 copies/L. Only one study in France detected SARS-CoV-2 virus RNA in treated wastewater as well, with concentrations of up to nearly 10^5 copies/L (Wurtzer *et al.* 2020). In addition to these reports, monitoring of SARS-CoV-2 virus in wastewater in different countries is ongoing following similar approaches and will further contribute to our understanding of the load and removal of the virus in wastewater treatment systems. Currently, little is known about the survival of the SARS-CoV-2 virus in sewage although previous studies showed that the most similar virus tested, SARS-CoV, could persist in wastewater for up to 2 days at 20 °C, and at least 14 days at 4 °C with around 2 Log_{10} inactivation (Rosa *et al.* 2020). Similarly, an earlier study evaluating the survivability of enveloped viruses – of which SARS-COV-2 belongs to – in municipal wastewater using two model enveloped viruses (MHV and $\phi 6$) in unpasteurised and pasteurised wastewater at 10 and 25 °C showed significantly slower inactivation at the lower temperature (Ye *et al.* 2016). Furthermore, in comparison to model non-enveloped viruses, a larger fraction of the model enveloped viruses partitioned to the wastewater solids than non-enveloped viruses indicating that enveloped viruses are removed to a greater extent than non-enveloped viruses during primary wastewater treatment (Ye *et al.* 2016).

COVID-19 VIRUS IN WASTEWATER SLUDGE

In treatment plants, sludge collected from primary, secondary, and tertiary wastewater treatment are combined and then treated with biological (i.e., aerobic digestion, anaerobic digestion, composting), chemical (i.e., lime), and thermal (i.e., heat drying, incineration) solids treatment processes. Effective sludge thermal treatment processes would likely kill viruses as well as other pathogens in sludge. Therefore, this paper does not place much focus on this process. SARS-CoV-2 may potentially be present in biologically and chemically treated sludge, and there are currently no published studies on the occurrence of SAR-CoV-2 in treated sludge (biosolids) as well as its fate after land application of biosolids.

As mentioned previously, RNA of SARS-CoV-2 has been found in the guts and faeces of some COVID-19 patients (Wu *et al.* 2020a) and in raw sewage (Medema *et al.* 2020). In the USA, SARS-CoV-2 RNA has been reported in primary sludge, detectable in 100% of the samples the concentrations ranged from 1.7×10^7 virus RNA copies/L to 4.6×10^8 copies/L, which is several orders of magnitude higher than in untreated wastewater (Peccia *et al.* 2020). It has also been shown that the SARS-CoV-2 RNA concentrations were highly correlated with the COVID-19 epidemiological curve and local hospital admissions indicating the potential of the technique as a disease outbreak surveillance tool (Peccia *et al.* 2020). In Spain, SARS-CoV-2 RNA was higher in some sludge sampling spots, specifically in primary sludge and thickened sludge, compared with the influent samples while none was detected in the final effluent (Balboa *et al.* 2020). In Turkey, SARS-CoV-2 RNA was detected not only in primary sludge but also in waste activated sludge collected from two treatment plants in Istanbul (Kocamemi *et al.* 2020).

It is important to note that the detection of viral RNA does not mean that infectious virus particles are present, and the stability and infectivity of SARS-CoV-2 in faeces and raw sewage still need to be investigated. Knowledge from previous studies, particularly from those on coronaviruses and other enveloped viruses, may provide insight into the fate and persistence of SARS-CoV-2 through wastewater and sludge treatment processes.

Coronaviruses are known to survive for a few days in the environment outside of a host cell (Kampf *et al.* 2020) and in wastewater between 2 and 4 days (Gundy *et al.* 2009). Temperature, organic matter, and antagonistic bacteria were reported to play a major role in the inactivation of coronaviruses (Gundy *et al.* 2009). Viruses are sensitive to temperature increases due to increased denaturation of their proteins, and the activity of extracellular polymers secreted by wastewater bacteria (John & Rose 2005). Gundy *et al.* (2009) reported that the survival time of coronavirus in filtered tap water increased from 10 days at 23 °C to over 100 days at 4 °C. Coronavirus inactivation was very quick in wastewater, likely due to the presence of detergents and solvents that caused damage to their envelope. Thus, sludge itself would not be a good environment for coronavirus survival. SARS-CoV was also reported to have low stability in the environment and to be very sensitive to high temperatures and oxidants (Wang *et al.* 2005; Pinon & Vialette 2018).

Adsorption of coronavirus on suspended solids and organic matter protected them from inactivation, and also assisted with their removal from the liquid phase through sedimentation (Gundy *et al.* 2009). The hydrophobicity of the viral envelope increases partitioning to solids resulting in their accumulation in sludge. Enveloped viruses were reported to associate more strongly with wastewater solids compared with non-enveloped viruses, which would mean their higher removal, particularly in primary sedimentation tanks (Ye *et al.* 2016). The above findings indicate that coronaviruses would be present in sludge but would not likely be able to survive sludge treatment processes which typically involve high temperatures (i.e., mesophilic and thermophilic aerobic and anaerobic digestion, composting), pH changes (i.e., anaerobic digestion, lime treatment), and diverse microbial populations and predatory microorganisms (i.e., biological treatment processes). Wang *et al.* (2005) reported that it was easier to inactivate SARS-CoV than *Escherichia coli* with chlorine, and when the total inactivation of SARS-CoV was achieved, *E. coli* was still not inactivated. *E. coli* is one of the easier microorganisms to inactivate in sludge compared with enteric viruses, protozoa, and other bacteria, and sludge stabilisation processes are typically designed to achieve the desired reduction in *E. coli*. Based on the findings of Wang *et al.* (2005), it can be concluded that current sludge treatment processes would likely be effective against coronaviruses.

Viruses with lipid envelopes, such as coronaviruses, lose their infectivity in water environments more quickly than non-enveloped viruses. However, significant variations in inactivation rates may exist between related strains. For example, the T_{90} value (time to reach 90% inactivation) for SARS-CoV-1 was reported to be 9 days and less than 1 day for MHV (Wigginton *et al.* 2015). Similarly, it has been predicted SARS-CoV-2 to be among the sturdiest in the coronavirus family based on the rigidity of its outer shell and to be more resilient in the environment in comparison to SARS-CoV-1, MERS-CoV, and other coronaviruses (Goh *et al.* 2020). Therefore, it is important to have the actual inactivation data from sludge treatment processes for SARS-CoV-2 and other coronavirus strains to better understand the occurrence, fate, persistence, and infectivity of these emerging viruses.

Recent studies that used viral metagenome analysis provided new insights to viral pathogen diversity in sewage sludge. In biosolids treated with mesophilic anaerobic digestion, 43 different human viruses were identified, and surprisingly emerging viruses, including *Coronavirus HKU1*, were found to have a high abundance in comparison to *Enteroviruses* with relatively minor abundance (Bibby & Peccia 2013). These results suggest that coronaviruses might be present in biosolids, and their concentrations and infectivity need to be investigated. Previous studies almost exclusively focused on non-enveloped enteric viruses, and there is an urgent need for studies on SARS-CoV-2 and other enveloped viruses.

WASTEWATER TREATMENT PROCESSES FOR COVID-19 CONTROL

Conventional municipal wastewater treatment has preliminary, primary, and secondary treatment processes, while some municipal wastewater treatment plants also employ tertiary treatment. Basically, except for preliminary treatment with screening and grit chamber, all sewage treatment processes could remove or destroy viruses including the SARS-CoV-2 to some extent, although none is likely to remove all of the viruses present in sewage.

Primary treatment

Viruses can be taken as fine particles with colloidal characteristics and could be absorbed by suspended particles. Therefore, some percentage removal of viruses is usually accompanied by the removal of suspended solids. In primary treatment, mechanical screening and the grit chamber only remove coarse solid particles; thus, the removal of virus associated with coarse particles usually is less than 0.3 Log_{10} (Table 1). Primary sedimentation settles 50–75% of total suspended solids, removing a portion of the viruses in sewage, especially for those associated with the suspended solids. By sedimentation, virus is only transported to the separated sludge but not fully inactivated yet. The sludge and virus in it should be further treated to reduce the risk. Generally, primary treatment only removes a small percentage of viruses. Combining coagulation–flocculation and sediment – *Chemically Enhanced Primary Treatment* (CEPT) – a treatment process which involves the adding of chemicals to primary sedimentation tanks to facilitate improved settling properties – could be more effective regarding virus removal from the liquid stream.

Secondary treatment

Among different secondary treatment processes, activated sludge is one of the best biological methods for removing viruses from sewage, with well-controlled biodegradation conditions for virus decay in the aeration tank combined with secondary sedimentation. Conventional activated

Table 1 | Log_{10} removal/inactivation of viruses by different treatment processes

Process	Virus/Indicator	Removal/ Inactivation (Log_{10})	References
Primary treatment			
Grit chamber	MS-2 phage	0.0–0.3	Prakashi & Chaudhuri (1982)
Fine screen	Enterovirus, rotavirus, and norovirus	0.1–0.2	Zhou *et al.* (2015)
Secondary treatment			
Activated sludge	Human adenovirus (AdV and AdV species F), enterovirus, and norovirus	0.7–2.9	Hewitt *et al.* (2011)
	Noroviruses genotype 1 and genotype 2, enteroviruses, and adenoviruses in sewerage systems		Katayama *et al.* (2008)
Trickling filter	MS-2 phage	0.0–0.8	Prakashi & Chaudhuri (1982)
MBR	Noroviruses genotype 1 and genotype 2, enteroviruses, and adenoviruses in sewerage systems	3.4–6.8	Katayama *et al.* (2008)
	Enterovirus, norovirus genogroup II (NoV GGII), human adenovirus (HAdV)		Simmons *et al.* (2011)
Tertiary/advanced treatment			
Chemical coagulation-alum, iron salts	Enterovirus, rotavirus, and norovirus	1.0–2.9	Zhou *et al.* (2015)
Microfiltration	Poliovirus, Coliphage f_2	0.2–5.1	Madaeni *et al.* (1995) and Zheng & Liu (2006)
Ultrafiltration	MS-2 and PRD-1 phage	>3.0	Jacangelo *et al.* (2005) and Lovins *et al.* (2002)
Nanofiltration	MS-2 and PRD-1 phage	>5.4	Lovins *et al.* (2002)
Reverse osmosis	MS-2	>6.5	Adham *et al.* (1998)
Disinfection			
Chlorination	F-specific and somatic coliphage, enterovirus, adenovirus, norovirus, rotavirus, and Hepatitis A	0.8–2.8	Francy *et al.* (2012)
	F + -specific RNA (FRNA) bacteriophage (MS-2)		Tree Adams & Lees (2003)
Ozonation	F-specific and somatic coliphage, enterovirus, adenovirus, norovirus, rotavirus, and Hepatitis A	0.2– >6.0	Francy *et al.* (2012)
UV radiation	Poliovirus, adenovirus, reovirus, MS-2, rotavirus, calicivirus, and Hepatitis A	1.43–6.0	Owens *et al.* (2000) and National Research Council (NRC) (2012)

Removal/inactivation is dependent on the virus. Adapted from Zhang *et al.* (2016).

sludge process could remove 11 different enteric viruses by 0.65–2.85 Log_{10} (Kitajima *et al.* 2014), and while another study conducted at a full-scale *Wastewater Treatment Plant* (WWTP) in Canada showed that activated sludge could remove 1.0–2.6 Log_{10} of seven viruses (Qiu *et al.* 2015). The removal percentage could be even higher for Membrane Bioreactors (MBR), up to 6.8 Log10 reduction, due to further removal by membrane filtration (see Table 1).

Tertiary treatment and disinfection

For the tertiary treatment, coagulation using aluminium or iron coagulant could remove fine suspended particle and colloidal particles, resulting in less than 1–3 Log_{10} virus removal. The removal efficiency of virus using membrane filtration could be a very large range, depending on membrane pore size, i.e., 0.2–5 Log_{10} for *Microfiltration* (MF), >3 Log_{10}

for *Ultrafiltration* (UF), >5 Log_{10} for nanofiltration, and >6 Log_{10} for *Reverse Osmosis* (RO).

Two general classes of polymeric membranes are commonly used for advanced water treatment plants. These are low-pressure membranes (MF and UF) and high-pressure membranes (nanofiltration and reverse osmosis). Rejection of viruses can be achieved by each of these types of membranes and involves a number of mechanisms, including size exclusion and electrostatic repulsion from the membrane surface. Size exclusion is a function of the physical porosity of the membrane material, while electrostatic repulsion is a function of the surface charge on both the membrane surface and the virus particle, both of which are dependent upon ambient water pH.

Under challenge testing conditions, low-pressure membranes can achieve 4–6 Log_{10} reduction for viruses with MF providing removal at the lower end of this range and UF at the higher end (WHO 2017). Many of the challenge tests undertaken to derive these Log_{10} reduction values were undertaken using MS-2 bacteriophage since these are non-pathogenic to humans and can be easily cultivated in a laboratory.

MS-2 virions are approximately 30 nm in diameter (Strauss & Sinsheimer 1963), which is as small or smaller than many important waterborne viruses, such as Hepatitis A virus (30 nm), Rotavirus (80 nm), and Adenovirus (90 nm). Comprising an external lipid envelope, SARS-CoV-2 is larger again at around 120 nm. This is slightly larger than the typically quoted porosity of MF membranes (~100 nm) and an order of magnitude larger than the typically quoted porosity of UF membranes (~10 m).

MS-2 virions have an isoelectric point of 3.9 (Dowd *et al.* 1998), indicating that at pH > 3.9, the virion poses a net-negative charge and would experience electrostatic repulsion from a net-negatively charged membrane. A published isoelectric point for SARS-CoV-2 has not yet been identified, but a similar value (or even up to 6) would indicate a similar degree of electrostatic repulsion as a rejection mechanism for MS-2.

Under challenge testing conditions, RO membrane filtration can achieve 6 Log_{10} reduction for viruses (Pype *et al.* 2016) and this figure is accepted in WHO Guidelines for Potable Reuse (WHO 2017). However, fully validated credit for RO removal for viruses is commonly limited to 1.5–2 Log_{10} reduction since this is typically the limit of sensitivity for currently available online monitoring methods (WHO 2017).

As the last step of wastewater treatment, disinfection by chlorination, *Ultraviolet* (UV) or ozone could sufficiently inactivate viruses and provide a solid barrier to prevent them from entering the environment with the effluent, and ozone and UV seem to be more effective than chlorine. Very limited information about SARS-CoV-2 removal is available by different disinfection processes although generally what we do know is that the virus that causes COVID-19 is enveloped and is expected to be more sensitive to disinfection than non-enveloped viruses such as coxsackievirus, Hepatitis A and adenovirus which had been studied before. The details of disinfection will be covered in the following section.

Standard water disinfection technologies, such as free chlorine, chlorine dioxide, ozone, and UV have been reported to be effective for viral inactivation. These disinfection technologies played an important role in fighting against previous global epidemics, including the SARS epidemic in 2003, the influenza A virus subtype H1N1 (Swine flu) epidemic in 2009, the *Middle East Respiratory Syndrome* (MERS) epidemic in 2012, and the Coronavirus pandemic since December 2019, although water, wastewater, and sludge are not the main routes of transmission. As the SARS-CoV-2 is an enveloped virus, it is regarded to be sensitive to typical disinfection technologies.

Chlorine disinfection is widely used for virus inactivation, with applied doses described in terms of the product of chlorine concentrations and *Contact Time* (CT). When free chlorine is used as a disinfectant, the efficiency of inactivation is also influenced by the temperature and pH of the water. At pH 7.5, CT required for 3 Log_{10} reduction of *Giardia* cysts can range from 50 to 300 mg min/L, depending on temperature, whereas for 4 Log_{10} reduction of viruses, CT <12 mg min/L is typically required (United States Environmental Protection Agency 2003). Thus, when chlorine doses are selected for effective control of *Giardia* cysts, even greater control of waterborne viruses can generally also be assumed. Furthermore, virus CT requirements have typically been derived from experiments with non-enveloped viruses, such as Hepatitis A virus, which is known to persist in water under a variety of conditions (Sobsey *et al.* 1988). Inactivation of Hepatitis A virus is used since it is known to require higher CT values than those for inactivation of polio and rotaviruses under similar conditions of pH and temperature. Experiments with enveloped viruses (as SARS-CoV-2 is) have revealed that the envelope provides no additional protection from free chlorine disinfection, as free chlorine readily penetrates the lipid envelope to react with proteins in the nucleocapsid and polymerase complex which is internal to the nucleocapsid (Ye *et al.* 2018). As the *weakest link* in the overall virus structure to withstand the impact of free chlorine, it is these rapidly oxidised proteins that determine the overall inactivation rate of the virus during chlorination. There is no apparent reason to assume that CT values based on data from Hepatitis A virus inactivation will not be equally effective for reliable inactivation of SARS-CoV-2.

One valuable disinfection study with SARS-CoV virus-containing wastewater revealed that free chlorine was found to inactivate SARS coronavirus better than chlorine dioxide (Wang *et al.* 2005). Free residue chlorine over 0.5 mg/L for chlorine or 2.2 mg/L for chlorine dioxide in wastewater ensures complete inactivation of SARS coronavirus while it does not inactivate completely *E. coli* and f_2 *phage* at that dosage. Thus, the *E. coli* and f_2 phage could be potentially used as the indicators for SARS-Cov-2 inactivation in WWTPs.

The Ministry of Ecology and Environment of China issued guidelines for hospital and domestic wastewater disinfection on 1 February 2020 after the start of the epidemic. It was suggested to use liquid chlorine, chlorine dioxide, or bleach for disinfection with the dosage of 50 mg/L (as available chlorine). The CT for disinfection should be no less than 1.5 h, the residual chlorine should be over 6.5 mg/L (as free chlorine), and the faecal coliform should be less than 100 CFU/L in the finished water. For the facilities not able to satisfy the CT, a higher residual dosage of free chlorine is required. For example, over 10 g/L residual free chlorine is required in the case of 1 h contact. Considering the quick reaction of free chlorine and ammonia in hospital and domestic wastewater to form chloramines with lower inactivation ability, higher dosage of free chlorine was applied to achieve the breakpoint and maintain the sufficient free chlorine residual. Ozone disinfection cannot be interfered by ammonia which is quite useful for virus inactivation in wastewater. The guideline requires the utilities to reduce the suspended solids to less than 20 mg/L, to add ozone over 50 mg/L and to keep the CT over 0.5 h. The 4 Log_{10} removal of total coliform and the residual faecal coliform less than 100 CFU/L are used as the indicators for good performance also.

This guideline echoed the previous reports on virus inactivation experiments and the US EPA (1999) Disinfection profiling and benchmarking guidance manual for drinking water which is included in Table 2.

Ozone disinfection requirements are also described by standard CT values for *Giardia* ($CT_{3\text{-log, Giardia}}$) and viruses ($CT_{4\text{-log, Virus}}$) (US EPA 2003). At temperatures up to 25 °C, ozone CT 0.5–3.0 mg min/L is typically required for 3 Log_{10} reduction Giardia, whereas doses in a similar range (0.3–1.8 mg min/L) are applied to target 4 Log_{10} reduction for viruses. These were based on experiments for the inactivation of poliovirus 1 (Roy *et al.* 1982), noting that they were also conservative for the inactivation of rotavirus (Vaughn *et al.* 1987). While few data are available to compare the ozone susceptibility of coronaviruses with poliovirus 1, it is assumed that it will be at least similar. Thus, ozonation CT values selected to target virus or (especially) *Giardia* disinfection should be expected to be similarly effective for SARS-CoV-2.

UV radiation in the short-wavelength UV (*UVC*) range (200–280 nm) is known to be effective for inactivating

Table 2 | The CT or dosage for different disinfectants to inactivate enteric viruses

Disinfectant removal	Free chlorine (min mg/L)	Monochloramine (min mg/L)	Chlorine dioxide (min mg/L)	Ozone (min mg/L)	UV (mJ/cm^2)
2 Log_{10}, 99%	5.8/3.0	1243/643	8.4/4.2	0.90/0.50	100
3 Log_{10}, 99%	8.7/4.0	2063/1067	25.6/12.8	1.40/0.80	143
4 Log_{10}, 99%	11.6/6.0	2883/1491	50.1/25.1	1.80/1.00	186

Note: The former four columns present the enteric viruses inactivation efficiency by main chemical disinfectants on 1 or 10 °C (separated by /). The last column presents the UV inactivation efficiency on adenovirus which is the most resistant to UV.

The successful practices in WWTPs in China and other countries have proven that this virus cannot spread in wastewater once the disinfection process is conducted properly.

many types of microorganisms, including viruses, bacteria, and protozoa. Thus, it is increasingly used in water reuse applications for this purpose. There are two main types of lamps used to produce the UVC radiation for water treatment plants, some of which produce a narrow band of UV wavelengths, and some produce a broader range of wavelengths. But in all cases, UV radiation at 254 nm is produced, and this wavelength is known to be highly effective for microbial inactivation. Thus, UV of 254 nm wavelength (UV_{254}) is the focus of practically all UV-related water treatment, process control, regulation, and scientific studies.

When UV radiation is used to cause direct chemical disruptions to microorganisms (or to chemical contaminants), this is referred to as *direct UV photolysis*. Often, more indirect pathways are also important, whereby the UV causes reactions with other chemicals present in the water, the products of which then go on to inactivate the microorganisms. This process is referred to as *indirect UV photolysis*. UV inactivation of microorganisms is primarily achieved by the UV radiation causing chemical disruptions by direct UV photolysis of the microorganisms' genetic material (DNA or RNA), known as nucleic acids.

Key components of DNA and RNA nucleotides are *nucleobases*. Some nucleobases strongly absorb UV_{254} radiation, leading to photochemical reactions, including the formation of chemical bonds between two consecutive nucleobases (a process known as *dimerisation*). The most studied are the formation of thymine–thymine dimer products, but thymine–cytosine, cytosine–cytosine, and uracil–uracil dimer products have also been reported (Douki 2013). These dimerisation reactions disrupt essential genetic processes, such as transcription and replication, and ultimately lead to inactivation of the microorganism. Other photochemical reactions can also contribute to inactivation, such as hydration, protein–nucleic acid linkages, covalent cross-links between complementary strands, and nucleic acid backbone breakages (Görner 1994).

Experiments comparing UV-induced dimerisation of virus genetic material have revealed that external components of virus particles, including lipid enveloped and protein nucleocapsids, provide no protection since UV_{254} is able to penetrate these components and reach the genetic material within (Qiao *et al.* 2018). Thus, variability in UV_{254} susceptibility among viruses is assumed to be primarily a function of genome size, sequence, and structure. The genetic material of viruses can be composed of single-stranded RNA, double-stranded RNA, single-stranded DNA, or double-stranded DNA.

During UV_{254} photolysis experiments, single-stranded DNA was observed to undergo the most rapid photolysis reactions, followed by single-stranded RNA and double-stranded DNA. The slowest photolysis reactions were observed for double-stranded RNA, indicating a higher level of resistance for these types of viruses to UV_{254} photolysis.

SARS-CoV-2 is a single-stranded RNA virus, and thus, it is possible to make a rough estimation of the likely susceptibility of SARS-CoV-2 to UV_{254} photolysis, compared with other known waterborne viruses, which are regularly targeted for inactivation by UV_{254} photolysis. Doing that, we could assume that SARS-CoV-2 has:

- at least the same susceptibility to UV photolysis as other single-stranded RNA viruses (e.g., Hepatovirus A, Polioviruses, Noroviruses, Coxsackieviruses, and MS-2 bacteriophage), and likely higher susceptibility to resistance since the coronaviruses have very large genomes compared with other single-stranded RNA viruses;
- roughly the same susceptibility to UV photolysis as double-stranded DNA viruses (e.g., Adenoviruses); and
- greater susceptibility to UV photolysis than double-stranded RNA viruses (e.g., Rotaviruses).

These suppositions will need to be validated. However, until such direct validation is available, we can assume that they are based on the best available information. A logical conclusion is that current UV disinfection practices, targeting waterborne viruses such as those listed above, can be assumed to be (at least) similarly effective for the inactivation of SARS-CoV-2.

WATER REUSE FROM TREATED EFFLUENTS

Following conventional wastewater treatment, treated effluents may be reused for various applications. Conventional approaches to water reuse include reuse for municipal irrigation, agricultural irrigation, household reuse (toilet flushing, garden watering, etc.), industrial reuse, and reuse as a component of drinking water supplies, known as potable reuse. Potable reuse may occur by the planned and purposeful augmentation of a groundwater or surface water system, or may simply be a consequence of *de facto* potable reuse, whereby treated effluents are discharged to waterways which are subsequently used as a source of raw water for a drinking water supply, regardless of whether such a connection is formally acknowledged. A small but an increasing number of cities also practise *direct potable reuse*, whereby highly purified water is returned directly to a drinking water supply system without first being used to augment the groundwater or surface water body.

Depending on the nature of particular water reuse practices, various types and degrees of human exposure may be anticipated. While some practices would normally involve relatively low levels of exposure, others such as potable reuse imply high levels of water exposure by oral ingestion, dermal contact, and inhalation of aerosols. This anticipated degree of exposure is a key factor in determining risks associated with waterborne contaminants, including viruses. As a general principle, reuse practices involving higher levels of human exposure will require greater levels of water treatment to ensure greater effectiveness and reliability of pathogen removal, including viruses. In such cases, advanced water treatment processes may be applied, including additional chemical disinfection (e.g., chlorine or ozonation), UV disinfection, membrane filtration, and advanced oxidation processes (AOPs).

A range of AOPs has been developed for water treatment, including processes based on ozone and a range of heterogeneous catalysts. However, by far the most commonly applied to potable reuse projects are high-dose UV processes (Khan *et al.* 2017). Compared with a typical drinking water UV disinfection dose (40–180 mJ/cm^2), the applied UV fluence in a UV-AOP (usually $>$500 mJ/cm^2) is many times greater. The *United States Environmental Protection Agency* (US EPA) has developed UV fluence requirements for potable water systems to receive credit for inactivation of viruses (US EPA 2006). These range from 39 mJ/cm^2 for 0.5 Log_{10} virus inactivation to 186 mJ/cm^2 for 4.0 Log_{10} virus inactivation (US EPA 2006).

These UV inactivation credits were developed in the context of a US drinking water regulation (The Long-Term 2 Enhanced Surface Water Treatment Rule). Consequently, they have mostly been applied to drinking water applications and do not account for the much higher UV fluences used for AOPs in potable reuse projects. It is generally recognised that the much higher energy applied for UV AOPs is more than sufficient to achieve effective disinfection to the limits at which regulatory agencies commonly credit disinfection performance. For example, Californian potable reuse regulations provide a maximum credit of 6 Log_{10} reduction for viruses by any advanced water treatment process. The WHO Guidelines for Potable Reuse concur that UV-AOP can achieve 6 Log_{10} reduction under challenge testing conditions, and also indicate that UV AOPs can be validated to this level of performance (WHO 2017).

In order to fully assess risks associated with SARS-CoV-2 in water reuse projects, including potable reuse projects, some form of *Quantitative Microbial Risk Assessment* (QRMA) will be necessary (Kitajima *et al.* 2020). Such an assessment will not be possible until estimates are available for some key parameters, including excretion rates or wastewater concentrations of viable infectious virions. Once such data are available, it will be possible to provide treatment-based Log_{10} reduction values by conservatively applying existing virus-related Log_{10} reduction values for processes such as additional chemical disinfection (e.g., chlorine or ozonation), UV disinfection, membrane filtration, and AOPs.

However, risks will remain unquantifiable until estimates for dose–response relationships for infection are available. Whether existing dose–response relationships for other coronaviruses are applicable (Watanabe *et al.* 2010) that needs to be determined. The WHO drinking water guidelines and potable reuse guideless have set tolerable levels of risk for microbial pathogens in terms of *Disability-Adjusted Life Years* (DALYs) (WHO 2011, 2017). To do this, same for SARS-CoV-2 will require the establishment of a numerical value for the number of DALYs-per-case of infection with SARS-CoV-2, taking into account anticipated rates of death and other illnesses for various age groups in the community.

SMALL WASTEWATER TREATMENT PLANTS

This section provides guidance for COVID-19 disease transmission regarding small WWTPs. The definition of what constitutes a small city (as compared with a large city) can vary, but it is important to recognise that there are wastewater collection systems and treatment technologies available for treating small flows that are not feasible for large flows. The demand for decentralised small systems is being considered as an alternative or complement to large, centralised collection and treatment systems. This is much easier to adopt in developments outskirts of the city or suitable for small community development and has been applied in both developed and developing world contexts.

Wastewater treatment in small populations is not straightforward. The high variability of wastewater characteristics together with the fact that these small towns often present a lack of financial, technical, and human resources, has led to the conclusion that the implementation of the treatment solutions commonly used in larger populations has not produced the desired results (Aragón *et al.* 2011). The design capacity of several WWTPs in small communities is significantly less than 10,000 person equivalents. As the population in the area increases, the operation capacity of the plant is increased. One of the challenges with small systems is that they are not designed for large fluctuations in flow, either they over flow or end up with small flow. Small systems can, therefore, be easily overloaded beyond their limits or hydraulically and/or organically underloaded. The technical alternatives range from mechanical and simple biological systems such as ponds, sand filters, and reed beds to complex high rate suspended and fixed biomass reactors.

Most small WWTPs apply not more than secondary treatment process to the wastewater. This usually involves relatively low technology or basic treatment processes. Where the plant is discharging to a sensitive area, tertiary treatment may be applied. Treatment processes in many small WWTPs do not usually possess automated instrumentation or telemetric system. One of the challenges in understanding the risk associated with COVID-19 from small WWTPs is the general lack of scientific information regarding virus removal from these options. As small WWTPs come in a variety of technical options and dependent on local operating conditions, there is no single COVID-19 control measure that is applied for all systems. Rather, the appropriate action would be to ensure proper operation and maintenance. This would involve regulation and control of the treatment process, i.e., clean the pre-treatment screen, remove debris, monitor equipment, and attend to operational challenges immediately. The inclusion of tertiary treatment processes as part of the treatment train would provide an additional control measure as evidence presented earlier has shown. The major challenge for developing countries is the effective operation and maintenance of systems. While there is a large body of evidence available that illustrates this challenge with large WWTPs (Eales 2008; Hawkins *et al.* 2013; United Nations (UN)-Water 2015), it is assumed that similar challenges may be experienced for small WWTPs. Best practices for protecting the health of workers at sanitation treatment facilities should be followed. Workers should wear appropriate *Personal Protective Equipment* (PPE), which includes protective outerwear, gloves, boots, goggles or a face shield, and a mask; they should perform hand hygiene frequently; and they should avoid touching eyes, nose, and mouth with unwashed hands.

A DEVELOPING COUNTRY PERSPECTIVE

In developing countries, a mixture of sanitation systems may be implemented in a single city. Technologies range from sewerage-based systems to non-sewered sanitation systems, such as pour-flush latrines, conventional dry latrines, and septic tanks. The coverage of each sanitation system is largely dependent on the household, community, town, or city preferences. Regarding COVID-19, a large percentage of human faecal waste in developing countries is not adequately treated. For WWTPs, a critical shortage of skilled staff to operate and maintain the treatment works is a common theme as well as the inability of the treatment works to deal with increasing pollution loads, unstable water and energy supply, and the lack of investment in the current infrastructure. The challenge would be to place more emphasis of process control and include additional treatment steps, such as chlorination, to manage COVID-19 risk.

Non-sewered sanitation systems can also pose a challenge. In India, for example, large parts of that country do not have underground drainage systems that connect directly to a treatment plant. More than 60% of urban households are dependent on non-sewered sanitation systems such as septic tanks. These systems eventually require safe emptying, transportation, and treatment of the faecal sludge collected. Similar patterns exist throughout the developing world. It is estimated that close to 3 billion people use non-sewered sanitation systems globally (Strande *et al.* 2014) with the systems found to be the predominate technology in developing cities of varying population size (Chowdhry & Koné 2012). Challenges occur throughout the sanitation value chain with respect to the safe collection, emptying, treatment, and disposal of accumulated faecal sludges. Little is known so far on the infectious nature in faecal sludges although recent evidence suggests that this may be possible (Xiao *et al.* 2020). In a study conducted in China, SARS-CoV-2 viral RNA was observed in septic tank effluents from Wuchang Fangcang Hospital after disinfection with 800 g/m^3 sodium hypochlorite, the recommended disinfection guideline by the WHO and Chinese Center for Disease Control and Prevention (Zhang *et al.* 2020). Viral RNA was not detected in limited influent samples (3-day sampling). The researchers have noted that the study was limited with sample size and sample transport due to outbreak restrictions at the time of the study. The researchers indicated that the need for further exploration of the optimal dosage of sodium hypochlorite required for complete removal of SARS-CoV-2 viral RNA and understanding viral escape from disinfection procedures in faecal sludge (Zhang *et al.* 2020).

Strengthening of cleaning and disinfection protocols and occupational health and safety are recommended for the sanitation value chain. The WHO recommends that utility gloves or heavy-duty, reusable plastic aprons are cleaned with soap and water, and then decontaminated with 0.5% sodium hypochlorite solution each time they are used. Single-use gloves made of nitrile or latex, and gowns should be discarded as infectious waste after each use and not reused; hand hygiene should be performed after PPE is removed. In addition, wearing masks is suggested due to the potential formation of bioaerosols from contaminated wastewater. If greywater includes disinfectants used in prior cleaning, it may not need to be chlorinated or treated again. However, it is important that such water is disposed of in drains connected to a septic system, a sewer or in a soak-away pit. If greywater is disposed of in a soak-away pit, the pit should be fenced off within the health facility grounds to prevent tampering and to avoid possible exposure in the case of overflow.

CONCLUSIONS

This review paper considered various scenarios for both the developed world and the developing world and provided recommendations for managing risk related to COVID-19 and other viruses. While research into the virus that causes COVID-19 and its implications for wastewater process control is, at the time of this publication, in its infancy, there is a wide body of knowledge related to virus control through the wastewater process chain that could prove applicable for the control of COVID-19. This review paper summarised this knowledge to provide guidance to the water sector on the various process control options available and their efficiencies in virus control.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Adham, S., Trussell, R., Gagliardo, P. & Trussell, R. 1998 Rejection of MS-2 virus by RO membranes. *Journal of the American Water Works Association* **9** (90), 130–135. https://doi.org/10.1002/j.1551-8833.1998.tb08505.x.

Ahmed, W., Angel, N., Edson, J., Bibby, K., Bivins, A., O'Brien, J. W., Choi, P. M., Kitajima, M., Simpson, S. L., Li, J., Tscharke, B., Verhagen, R., Smith, W. J. M., Zaugg, J., Dierens, L., Hugenholtz, P., Thomas, K. V. & Mueller, J. F. 2020 First confirmed detection of SARS-CoV-2 in untreated wastewater in Australia: a proof of concept for the wastewater surveillance of COVID-19 in the community. *The Science of the Total Environment* **728**, 1–8. https://doi.org/10.1016/j.scitotenv.2020.138764.

Kocamemi, B., Kurt, H., Sait, A., Sarac, F., Saatci, A. M. & Pakdemirli, B. 2020 SARS_CoV-2 detection in Istanbul wastewater treatment plant sludges. *medRxiv*, 1–11. doi: https://doi.org/10.1101/2020.05.12.20099358.

Aragón, C., Salas, J., Ortega, E. & Ferrer, Y. 2011 Lacks and needs of R&D on wastewater treatment in small populations. *Water Practice & Technology* **6** (2), 1–9. https://doi.org/10.2166/wpt.2011.030.

Balboa, S., Mauricio-Iglesias, M., Rodriguez, S., Martínez-Lamas, L., Vasallo, F., Regueiro, B. & Lema, J. 2020 The fate of SARS-COV-2 in WWTPS points out the sludge line as a suitable spot for monitoring. *medRxiv*, 1–24. https://doi.org/10.1101/2020.05.25.20112706.

Bar-Or, I., Yaniv, K., Shagan, M., Ozer, E., Erster, O., Mendelson, E., Mannasse, B., Shirazi, R., Kramarsky-Winter, E., Nir, O., Abu-Ali, H., Ronen, Z., Rinott, E., Lewis, Y. E., Friedler, E., Bitkover, E., Paitan, Y., Berchenko, Y. & Kushmaro, A. 2020 Regressing SARS-CoV-2 sewage measurements onto COVID-19 burden in the population: a proof-of-concept for quantitative environmental surveillance. *medRxiv*, 1–11. https://doi.org/10.1101/2020.04.26.20073569.

Bibby, K. & Peccia, J. 2013 Identification of viral pathogen diversity in sewage sludge by metagenome analysis. *Environmental Science & Technology* **47** (4), 1945–1951. https://doi.org/10.1021/es305181x.

Chen, C., Gao, G., Xu, Y., Pu, L., Wang, Q., Wang, L., Wang, W., Song, Y., Chen, M., Wang, L., Yu, F., Yang, S., Tang, Y., Zhao, L., Wang, H., Wang, Y., Zeng, H. & Zhang, F. 2020a SARS-CoV-2-positive sputum and feces after conversion of pharyngeal samples in patients with COVID-19. *Annals of Internal Medicine* **172** (12), 832–834. https://doi.org/10.7326/M20-0991.

Chen, N., Zhou, M., Dong, X., Qu, J., Gong, F., Han, Y., Qui, Y., Wang, J., Liu, Y., Wei, Y., Xia, J., Yu, T., Zhang, X. & Zhang, L. 2020b Epidemiological and clinical characteristics of 99 cases of 2019 novel coronavirus pneumonia in Wuhan, China: a descriptive study. *The Lancet* **395** (10223), 507–513. https://doi.org/10.1016/S0140-6736(20)30211-7.

Cheung, K. S., Hung, I. F. N., Chan, P. P. Y., Lung, K. C., Tso, E., Liu, R., Ng, Y. Y., Chu, M. Y., Chung, T. W. H., Tam, A. R., Yip, C. C. Y., Leung, K. H., Fung, A. Y., Zhang, R. R., Lin, Y., Cheng, H. M., Zhang, A. J. X., To, K. K. W., Chan, K. H., Yuen, K. Y. & Leung, W. K. 2020 Gastrointestinal manifestations of SARS-CoV-2 infection and virus load in fecal samples from a Hong Kong cohort: systematic review and meta-analysis. *Gastroenterology* **159** (1), 81–95. https://doi.org/10.1053/j.gastro.2020.03.065.

Chowdhry, S. & Koné, D. 2012 *Business Analysis of Fecal Sludge Management: Emptying and Transportation Services in Africa and Asia.* Draft Report, Bill & Melinda Gates Foundation, Seattle, USA. Available from: https://www.susana.org/en/knowledge-hub/resources-and-publications/library/details/1662 (accessed 10 October 2020).

Douki, T. 2013 The variety of UV-induced pyrimidine dimeric photoproducts in DNA as shown by chromatographic quantification methods. *Photochemical & Photobiological Sciences* **12** (8), 1286–1302. https://doi.org/10.1039/C3PP25451H.

Dowd, S., Pillai, S., Wang, S. & Corapcioglu, M. 1998 Delineating the specific influence of virus isoelectric point and size on virus adsorption and transport through sandy soils. *Applied Environmental Microbiology* **64** (2), 405–410. doi:10.1128/AEM.64.2.405-410.1998.

Eales, K. 2008 *Rethinking sanitation improvement for poor households in urban South Africa.* IRC Symposium Sanitation for the Urban Poor: Partnerships and Governance, 19–21 November 2008, Delft, Netherlands. Available from: https://www.ircwash.org/resources/rethinking-sanitation-improvement-poor-households-urban-south-africa-paper-presented-irc (accessed 10 October 2020).

Francy, D. S., Stelzer, E. A., Bushon, R. N., Brady, A. M., Williston, A. G., Riddell, K. R., Borchardt, M. A., Spencer, S. K. & Gellner, T. M. 2012 Comparative effectiveness of membrane bioreactors, conventional secondary treatment, and chlorine and UV disinfection to remove microorganisms from municipal wastewaters. *Water Research* **46** (13), 4164–4178. doi:10.1016/j.watres.2012.04.044.

Goh, G.-M., Dunker, A., Foster, J. & Uversky, V. 2020 Rigidity of the outer shell predicted by a protein intrinsic disorder model sheds light on the COVID-19 (Wuhan-2019-nCoV). *Infectivity. Biomolecules* **10** (2), 331–333. http://dx.doi.org/10.3390/biom10020331.

Görner, H. 1994 New trends in photobiology: photochemistry of DNA and related biomolecules: Quantum yields and consequences of photoionization. *Journal of Photochemistry and Photobiology B: Biology* **26** (2), 117–139. https://doi.org/10.1016/1011-1344(94)07068-7.

Gundy, P., Gerba, C. & Pepper, I. 2009 Survival of coronaviruses in water and wastewater. *Food and Environmental Virology* **1** (1), 10–14. doi:10.1007/s12560-008-9001-6.

Hawkins, P., Blackett, I. & Heymans, C. 2013 *Poor-Inclusive Urban Sanitation: An Overview: Targeting the Urban Poor and Improving Services in Small Towns.* The World Bank Water and Sanitation Program Report, International Bank for Reconstruction and Development, Washington, USA. Available from: https://www.wsp.org/sites/wsp/files/publications/WSP-Poor-Inclusive-Urban-Sanitation-Overview.pdf (accessed 10 October 2020).

Hewitt, J., Leonard, M., Greening, G. & Lewis, G. 2011 Influence of wastewater treatment process and the population size on human virus profiles in wastewater. *Water Research* **45** (18), 6267–6276. https://doi.org/10.1016/j.watres.2011.09.029.

Jacangelo, J., Madec, A., Schwab, K., Huffman, D. & Mysore, C. 2005 Advances in the use of low_pressure, hollow fiber membranes for the disinfection of water. *Water Supply* **5** (5), 109–115. https://doi.org/10.2166/ws.2005.0045.

Jiehao, C., Jin, X., Daojiong, L., Zhi, Y., Lei, X., Zhenghai, Q., Yuehua, Z., Hua, Z., Ran, J., Pengcheng, L., Xiangshi, W., Yanling, G., Aimei, X., He, T., Hailing, C., Chuning, W., Jingjing, L., Jianshe, W. & Mei, Z. 2020 A case series of children with 2019 novel coronavirus infection: clinical and epidemiological features. *Clinical Infectious Diseases* **71** (6), 1547–1551. doi:10.1093/cid/ciaa198.

John, D. & Rose, J. B. 2005 Review of factors affecting microbial survival on groundwater. *Environmental Science & Technology* **39** (19), 7345–7356. doi:10.1021/es047995w.

Kampf, G., Todt, D., Pfaender, S. & Steinmann, E. 2020 Persistence of coronaviruses on inanimate surfaces and their inactivation with biocidal agents. *Journal of Hospital Infection* **104** (3), 246–251. https://doi.org/10.1016/j.jhin.2020.01.022.

Katayama, H., Haramoto, E., Oguma, K., Yamashita, H., Tajima, A., Nakajima, H. & Ohgaki, S. 2008 One-year monthly quantitative survey of noroviruses, enteroviruses, and adenoviruses in wastewater collected from six plants in Japan. *Water Research* **42** (6–7), 1441–1448. https://doi.org/10.1016/j.watres.2007.10.029.

Khan, S., Walker, T., Stanford, B. & Drewes, J. 2017 Advanced treatment for potable water reuse. Chapter 14. In: *Advanced Oxidation Processes for Water Treatment: Fundamentals and Applications* (M. I. Stefan, ed.). IWA Publishing, London, pp. 581–606.

Kitajima, M., Ahmed, W., Bibby, K., Carducci, A., Gerba, C. P., Hamilton, K. A., Haramoto, E. & Rose, J. B. 2020 SARS-CoV-2 in wastewater: state of the knowledge and research needs. *Science of the Total Environment* **739** (15), 1–19. https://doi.org/10.1016/j.scitotenv.2020.139076.

Kitajima, M., Iker, B., Pepper, I. & Gerba, C. 2014 Relative abundance and treatment reduction of viruses during wastewater treatment processes – identification of potential viral indicators. *Science of the Total Environment* **488–489C** (1), 290–296. doi:10.1016/j.scitotenv.2014.04.087.

La Rosa, G., Iaconelli, M., Mancini, P., Ferraro, G. B., Veneri, C., Bonadonna, L. & Lucentini, L. 2020 First detection of SARS-COV-2 in untreated wastewater in Italy. *Science of the Total Environment* **736**, 139652, 1–17. https://doi.org/10.1016/j.scitotenv.2020.139652.

Ling, Y., Xu, S. B., Lin, Y. X., Tian, D., Zhu, Z. Q., Dai, F. H., Wu, F., Song, Z. G., Huang, W., Chen, J., Hu, B. J., Wang, S., Mao, E. Q., Zhu, L., Zhang, W. H. & Lu, H. Z. 2020 Persistence and clearance of viral RNA in 2019 novel coronavirus disease rehabilitation patients. *Chinese Medical Journal* **133** (9), 1039–1043. doi:10.1097/CM9.0000000000000774.

Lovins III, W., Taylor, J. & Hong, S. 2002 Microorganism rejection by membrane systems. *Environmental Engineering Science* **19** (6), 453–465. https://doi.org/10.1089/109287502320963436.

Madaeni, S., Fane, A. & Grohmann, G. 1995 Virus removal from water and wastewater using membranes. *Journal of Membrane Science* **102**, 65–75. https://doi.org/10.1016/0376-7388(94)00252-T.

Medema, G., Heijnen, L., Elsinga, G., Italiaander, R. & Brouwer, A. 2020 Presence of SARS_Coronavirus-2 RNA in sewage and correlation with reported COVID-19 prevalence in the early stage of the epidemic in The Netherlands. *Environmental Science & Technology Letters* **7** (7), 511–516. https://doi.org/10.1021/acs.estlett.0c00357.

Mizumoto, K., Kagaya, K., Zarebski, A. & Chowell, G. 2020 Estimating the asymptomatic proportion of coronavirus disease 2019 (COVID-19) cases on board the Diamond Princess cruise ship, Yokohama, Japan. *Euro surveillance: bulletin Europeen sur les maladies transmissibles = European Communicable Disease Bulletin* **25** (10), 1–5. doi:10.2807/1560-7917.ES.2020.25.10.2000180.

National Research Council (NRC) 2012 *Water Reuse: Potential for Expanding the Nation's Water Supply Through Reuse of Municipal Wastewater.* The National Academies Press, Washington DC. https://doi.org/10.17226/13303.

Nemudryi, A., Nemudraia, A., Surya, K., Wiegand, T., Buyukyoruk, M., Wilkinson, R. & Wiedenheft, B. 2020 Temporal detection and phylogenetic assessment of SARS-CoV-2 in municipal wastewater. *Cell Reports Medicine* **1** (6), 1–6. https://doi.org/10.1016/j.xcrm.2020.100098.

Nishiura, H., Kobayashi, T., Suzuki, A., Jung, S.-M., Hayashi, K., Kinoshita, R., Yang, Y., Yuan, B., Akhmetzhanov, A. R. & Linton, N. M. 2020 Estimation of the asymptomatic ratio of novel coronavirus infections (COVID-19). *International Journal of Infectious Diseases* **94**, 154–155. https://doi.org/10.1016/j.ijid.2020.03.020.

Owens, J., Miltner, R., Rice, E., Johnson, C., Dahling, D., Schaefer, F. & Shukairy, H. 2000 Pilot_scale ozone inactivation of cryptosporidium and other microorganisms in natural water. *Ozone Science & Engineering* **22** (5), 501–517. https://doi.org/10.1080/01919510009408793.

Peccia, J., Zulli, A., Brackney, D. E., Grubaugh, N. D., Kaplan, E. H., Casanovas-Massana, A., Ko, A. I., Malik, A. A., Wang, D., Wang, M., Warren, J. L., Weinberger, D. M. & Omer, S. B. 2020 SARS_CoV_2 RNA concentrations in primary municipal sewage sludge as a leading indicator of COVID_19 outbreak dynamics. *medRxiv*, 1–12. doi:10.1101/2020.05.19.20105999.

Pinon, A. & Vialette, M. 2018 Survival of viruses in water. *Intervirology* **61** (5), 214–222. https://doi.org/10.1159/000484899.

Prakashi, T. & Chaudhuri, M. 1982 Virus removal during coagulation and filtration of primary wastewater. *Journal of General and Applied Microbiology* **28** (3), 245–253. https://doi.org/10.2323/jgam.28.245.

Pype, M.-L., Lawrence, M., Keller, J. & Gernjak, W. 2016 Reverse osmosis integrity monitoring in water reuse: the challenge to verify virus removal – a review. *Water Research* **98**, 384–395. https://doi.org/10.1016/j.watres.2016.04.040.

Qiao, Z., Ye, Y., Chang, P. H., Thirunarayanan, D. & Wigginton, K. R. 2018 Nucleic acid photolysis by UV254 and the impact of virus encapsidation. *Environmental Science & Technology* **52** (18), 10408–10415. https://doi.org/10.1021/acs.est.8b02308.

Qiu, Y., Lee, B. E., Neumann, N., Ashbolt, N., Craik, S., Maal-Bared, R. & Pang, X. L. 2015 Assessment of human virus removal during municipal wastewater treatment in Edmonton, Canada. *Journal of Applied Microbiolology* **119** (6), 1729–1739. https://doi.org/10.1111/jam.12971.

Randazzo, W., Cuevas-Ferrando, E., Sanjuan, R., Domingo-Calap, P. & Sanchez, G. 2020 Metropolitan wastewater analysis for

COVID-19 epidemiological surveillance. *International Journal of Hygiene and Environmental Health* **230**, 1–4. https://doi.org/10.1016/j.ijheh.2020.113621.

Rimoldi, S. G., Stefani, F., Gigantiello, A., Polesello, S., Comandatore, F., Mileto, D., Maresca, M., Longobardi, C., Mancon, A., Romeri, F., Pagani, C., Cappelli, F., Roscioli, C., Moja, L., Gismondo, M. R. & Salerno, F. 2020 Presence and infectivity of SARS-CoV-2 virus in wastewaters and rivers. *Science of the Total Environment* **744**, 1–8. https://doi.org/10.1016/j.scitotenv.2020.140911.

Rosa, G., Bonadonna, L., Lucentini, L., Kenmoe, S. & Suffredini, E. 2020 Coronavirus in water environments: occurrence, persistence and concentration methods – a scoping review. *Water Research* **179**, 1–11. https://doi.org/10.1016/j.watres.2020.115899.

Roy, D., Englebrecht, R. S. & Chian, E. S. K. 1982 Comparative inactivation of six enteroviruses by ozone. *Journal of the American Water Works Association* **74** (12), 660–664. https://doi.org/10.1002/j.1551-8833.1982.tb05034.x.

Santarpia, J., Rivera, D., Herrera, V. L., Morwitzer, M. J., Creager, H. M., Santarpia, G. W., Crown, K. K., Brett-Major, D. M., Schnaubelt, E. R., Broadhurst, M. J., Lawler, J. V., Reid, S. P. & Lowe, J. J. 2020 Aerosol and Surface Transmission Potential of SARS-CoV-2. *Scientific Reports* **10**, 1–8. https://doi.org/10.1038/s41598-020-69286-3.

Simmons, F. J., Kuo, D. H.-W. & Xagoraraki I. 2011 Removal of human enteric viruses by a full-scale membrane bioreactor during municipal wastewater processing. *Water Research* **45** (9), 2739–2750. https://doi.org/10.1016/j.watres.2011.02.001.

Sobsey, M. D., Fuji, T. & Shields, P. A. 1988 Inactivation of Hepatitis A virus and model viruses in water by free chlorine and monochloramine. *Water Science & Technology* **20** (11/12), 385–391. https://doi.org/10.2166/wst.1988.0310.

Strande, L., Ronteltap, M. & Brdanovic, D. 2014 *Faecal Sludge Management: Systems Approach for Implementation and Operation*. IWA Publishing, London. https://doi.org/10.2166/9781780404738.

Strauss, J. H. & Sinsheimer, R. L. 1963 Purification and properties of bacteriophage MS2 and of its ribonucleic acid. *Journal of Molecular Biology* **7** (1), 43–54. https://doi.org/10.1016/S0022-2836(63)80017-0.

Sun, J., Zhu, A., Li, H., Zheng, K., Zhuang, Z., Chen, Z., Shi, Y., Zhang, Z., Chen, S. B., Liu, X., Dai, J., Li, X., Huang, S., Huang, X., Luo, L., Wen, L., Zhuo, J., Li, Y., Wang, Y., Zhang, L., Zhang, Y., Li, F., Feng, L., Chen, X., Zhong, N., Yang, Z., Huang, J., Zhao, J. & Li, Y. M. 2020 Isolation of infectious SARS-CoV-2 from urine of a COVID-19 patient. *Emerging Microbes & Infections* **9** (1), 991–993. doi:10.1080/22221751.2020.1760144.

Tang, A., Tong, Z. D., Wang, H. L., Dai, Y. X., Li, K. F., Liu, J. N., Wu, W. J., Yuan, C., Yu, M. L., Li, P. & Yan, J. B. 2020 Detection of novel coronavirus by RT-PCR in stool specimen from asymptomatic child, China. *Emerging Infectious Diseases* **26** (6), 1337–1339. https://doi.org/10.3201/eid2606.200301.

Tree, J. A., Adams, M. R. & Lees, D. N. 2003 Chlorination of indicator bacteria and viruses in primary sewage effluent. *Applied and Environmental Microbiology* **69** (4), 2038–2043. doi:10.1128/AEM.69.4.2038-2043.2003.

United Nations (U.N.) Water. 2015 *Wastewater Management: A UN-Water Analytical Brief*. pp. 1–54. Available from: http://www.unwater.org/fileadmin/user_upload/unwater_new/docs/UN-Water_Analytical_Brief_Wastewater_Management.pdf (accessed 10 October 2020).

United States Environmental Protection Agency (US EPA) 2003 *LT1ESWTR Disinfection Profiling and Benchmarking – Technical Guidance Manual*. EPA 816-R-03-004, Office of Water (4606M). Available from: https://nepis.epa.gov/Exe/ZyPDF.cgi/20002649.PDF?Dockey=20002649.PDF (accessed 10 October 2020).

US EPA 1999 *Disinfection Profiling and Benchmarking Guidance Manual*, EPA 815-R-99-013, 1–192.

US EPA 2006 *Ultraviolet Disinfection Guidance Manual For The Final Long Term 2 Enhanced Surface Water Treatment Rule*. EPA 815-R-06-007, US EPA Office of Water (4601), Washington DC. Available from: https://nepis.epa.gov/Exe/ZyPDF.cgi/600006T3.PDF?Dockey=600006T3.PDF (accessed 10 October 2020).

Vaughn, J. M., Chen, Y. S., Lindburg, K. & Morales, D. 1987 Inactivation of human and simian rotaviruses by ozone. *Applied Environmental Microbiology* **53** (9), 2218–2221. doi:10.1128/AEM.53.9.2218-2221.1987.

Wang, X., Zhou, Y., Jiang, N., Zhou, Q. & Ma, W. 2020a Case report: Persistence of intestinal SARS_CoV_2 infection in patients with COVID-19 leads to re-admission after pneumonia resolved. *International Journal of Infectious Diseases* **95**, 433–435. https://doi.org/10.1016/j.ijid.2020.04.063.

Wang, D., Hu, B., Hu, C., Zhu, F., Liu, X., Zhang, J., Wang, B., Xiang, H., Cheng, Z., Xiong, Y., Zhao, Y., Li, Y., Wang, X. & Peng, Z. 2020b Clinical characteristics of 138 hospitalized patients with 2019 novel coronavirus-infected pneumonia in Wuhan, China. *Journal of the American Medical Association* **323** (11), 1061–1069. doi:10.1001/jama.2020.1585.

Wang, X. W., Li, J. S., Jin, M., Zhen, B., Kong, Q. X., Song, N., Xiao, W. J., Yin, J., Wei, W., Wang, G. J., Si, B. Y., Guo, B. Z., Liu, C., Ou, G. R., Wang, M. N., Fang, T. Y., Chao, F. H. & Li, J. W. 2005 Study on the resistance of severe acute respiratory syndrome-associated coronavirus. *Journal of Virological Methods* **126** (1), 171–177. doi:10.1016/j.jviromet.2005.02.005.

Watanabe, T., Bartrand, T. A., Weir, M. H., Omura, T. & Haas, C. N. 2010 Development of a dose_response model for SARS coronavirus. *Risk Analysis* **30** (7), 1129–1138. https://doi.org/10.1111/j.1539-6924.2010.01427.

WHO (World Health Organization) 2011 *Guidelines for Drinking-Water Quality*. 4th edn. WHO, Geneva. Available from: https://apps.who.int/iris/handle/10665/44584 (accessed 10 October 2020).

WHO 2017 *Potable Reuse: Guidance for Producing Safe Drinking Water*. WHO, Geneva. Available from: https://apps.who.int/iris/bitstream/handle/10665/258715/9789241512770-eng.pdf?sequence=1 (accessed 10 October 2020).

WHO 2020a *Q&A on Coronaviruses (COVID-19)*. Available from: www.who.int:https://www.who.int/emergencies/diseases/novel-coronavirus-2019/question-and-answers-hub/q-a-detail/q-a-coronaviruses (accessed 10 October 2020).

WHO 2020b *Water, Sanitation, Hygiene, and Waste Management for the COVID-19 Virus: Interim Guidance*. Available from: www.who.int:https://www.who.int/publications-detail/water-sanitation-hygiene-and-waste-management-for-covid-19 (accessed 10 October 2020).

Wigginton, K., Ye, Y. & Ellenberg, R. 2015 Emerging investigators series: the source and fate of pandemic viruses in the urban water cycle. *Environmental Science: Water Research and Technology* **1** (6), 735–746. https://doi.org/10.1039/C5EW00125K.

Wu, Y., Guo, C., Tang, L., Hong, Z., Zhou, J., Dong, X., Yin, H., Xiao, Q., Tang, Y., Qu, X., Kuang, L., Fang, X., Mishra, N., Lu, J., Shan, H., Jiang, G. & Huang, X. 2020a Prolonged presence of SARSCoV-2 viral RNA in faecal samples. *The Lancet Gastroenterology & Hepatology* **5** (5), 434–435. https://doi.org/10.1016/S2468-1253(20)30083-2.

Wu, F., Zhang, J., Xiao, A., Gu, X., Lee, W. L., Armas, F., Kauffman, K., Hanage, W., Matus, M., Ghaeli, N., Endo, N., Duvallet, C., Poyet, M., Moniz, K., Washburne, A. D., Erickso, T. B., Chai, P. R., Thompson, J. & Alm, E. J. 2020b SARS-CoV-2 titers in wastewater are higher than expected from clinically confirmed cases. *Applied and Environmental Science* **5** (4), 1–9. https://doi.org/10.1128/mSystems.00614-20.

Wurtzer, S., Marechal, V., Mouchel, J. M., Maday, Y., Teyssou, R., Richard, E., Almayrac, J. L. & Moulin, L. 2020 Evaluation of lockdown impact on SARS-CoV-2 dynamics through viral genome quantification in Paris wastewaters. *Eurosurveillance* **25** (5), 2000776. https://doi.org/10.2807/1560-7917.ES.2020.25.50.2000776.

Xiao, F., Sun, J., Yonghao, X., Li, F., Huang, X., Li, H., Zhao, J., Huang, J. & Zhao, J. 2020 Infectious SARS-CoV-2 in feces of patient with severe COVID-19. *Emerging Infectious Diseases*, **26** (8), 1920–1922. https://doi.org/10.3201/eid2608.200681.

Ye, Y., Ellenberg, R. M., Graham, K. E. & Wigginton, K. R. 2016 Survivability, partitioning, and recovery of enveloped viruses in untreated municipal wastewater. *Environmental Science & Technology* **50** (10), 5077–5085. https://doi.org/10.1021/acs.est.6b00876.

Ye, Y., Chang, P., Hartert, J. & Wigginton, K. 2018 Reactivity of enveloped virus genome, proteins, and lipids with free chlorine and UV_{254}. *Environmental Science & Technology* **52** (14), 7698–7708. https://doi.org/10.1021/acs.est.8b00824.

Zhang, C.-M., Xu, L.-M., Xu, P.-C. & Wang, X. C. 2016 Elimination of viruses from domestic wastewater: requirements and technologies. *World Journal of Microbiology & Biotechnology* **32** (4), 69–77.

Zhang, D., Ling, H., Huang, X., Li, J., Li, W., Yi, C., Zhang, T., Jiang, Y., He, Y., Deng, S., Zhang, X., Wang, X., Liu, Y., Li, G. & Qu, J. 2020 Potential spreading risks and disinfection challenges of medical wastewater by the presence of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) viral RNA in septic tanks of Fangcang Hospital. *Science of the Total Environment* **741**, 140445. https://doi.org/10.1016/j.scitotenv.2020.140445.

Zheng, X. & Liu, J. 2006 Mechanism investigation of virus removal in a membrane bioreactor. *Water Supply* **6** (6), 51–59. https://doi.org/10.2166/ws.2006.957.

Zhou, J., Wang, X., Ji, Z., Xu, L. & Yu, Z. 2015 Source identification of bacterial and viral pathogens and their survival/fading in the process of wastewater treatment, reclamation, and environmental reuse. *World Journal of Microbiology and Biotechnology* **31** (1), 109–120. https://doi.org/10.1007/s11274-014-1770-5.

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