REVIEW ARTICLE

A Review on the Potential of Common Disinfection Processes for the Removal of Virus from Wastewater

Sevda Jalali Milani¹ · Gholamreza Nabi Bidhendi¹

Received: 24 August 2021 / Revised: 4 December 2021 / Accepted: 25 December 2021 / Published online: 6 January 2022
© University of Tehran 2022

Abstract

Due to the prevalence of the COVID-19 outbreak, as well as findings of SARS-CoV-2 RNA in wastewater and the possibility of viral transmission through wastewater, disinfection is required. As a consequence, based on prior investigations, this work initially employed the viral concentration detection technique, followed by the RT-qPCR assay, as the foundation for identifying the SARS-CoV-2 virus in wastewater. After that, the ability and efficacy of chlorine, ozone, and UV disinfection to inactivate the SARS-CoV-2 virus from wastewater were examined. Chlorine disinfection is the most extensively used disinfection technology due to its multiple advantages. With a chlorine dioxide disinfectant dose of 40 mg/L, the SARS-CoV virus is inactivated after 30 min of contact time. On the other hand, ozone is a powerful oxidizer and an effective microbicide that is employed as a disinfectant due to its positive characteristics. After 30 min of exposure to 1000 ppmv ozone, corona pseudoviruses are reduced by 99%. Another common method of disinfection is using ultraviolet radiation, which is usually 253.7 nm suitable for ultraviolet disinfection. At a dose of 1048 mJ/cm², UVC radiation completely inactivates the SARS-CoV-2 virus. Finally, to evaluate disinfection performance and optimize disinfection strategies to prevent the spread of SARS-CoV-2, this study attempted to investigate the ability to remove and compare the effectiveness of each disinfectant to inactivate the SARS-CoV-2 virus from wastewater, summarize studies, and provide future solutions due to the limited availability of integrated resources in this field and the spread of the SARS-CoV-2 virus worldwide.

Keywords COVID-19 · SARS-CoV-2 · Coronavirus · Wastewater treatment · Ozonation · Chlorination · UV radiation · Ultraviolet radiation · Outbreak

Article Highlights

- **Disinfection can be a solution to prevent virus transmission through wastewater.**
- **Chlorination is the most widely used disinfection method.**
- **The detection of SARS-CoV-2 RNA does not prove its viability or transmissibility.**

Introduction

Three major outbreaks of human coronavirus have occurred in the last 17 years, the first of which was the severe acute respiratory syndrome coronavirus (SARS-CoV), which was reported in China in 2002 and 2003 and affected 26 countries, and the second, the Middle East Respiratory Syndrome Coronavirus (MERS-CoV) outbreak, which began in 2012 in the Middle East and has spread to 27 countries with over 2,400 cases by the end of 2019 (Amoah et al. 2020). The third outbreak is linked to a new type of coronavirus, the first case of which was reported to the World Health Organization (WHO) in December 2019 in Wuhan, Hubei Province, China (Tran et al. 2021).

The outbreak of COVID-19 was declared a public health emergency of international concern by the WHO on January 30, 2020 (Mandal et al. 2020), and the new virus was given the name SARS-CoV-2 by the International Committee on Taxonomy of Viruses (ICTV) due to its genetic similarity

✉ Sevda Jalali Milani
sevdajalali75@gmail.com

¹ School of Environment, College of Engineering, University of Tehran, Tehran, Iran

to SARS (SARS-CoV). The acute respiratory pandemic was named Corona Virus 2019, abbreviated as COVID-19, by the World Health Organization on February 11, 2020, and declared by the World Health Organization on March 11, 2020 (Saawarn and Hait 2021).

Six coronaviruses, including HCoV-229E, HCoV-OC43, HCoV-NL-63, HCoV-HUK-1, SARS-CoV, and MERS-CoV, were known to cause infection in humans before SARS-CoV-2. SARS-CoV-2, a single-stranded, positive-sense RNA virus that belongs to the Beta coronavirus (Beta-CoV) group, is the seventh known virus from this family to cause human disease. There are over 30 viruses in this virus family (Amoah et al. 2020; Saawarn and Hait 2021). They are responsible for a wide range of diseases, including the common flu and upper respiratory tract infections. Fever, cough, dyspnea, myalgia, headache, sore throat, diarrhea, and rhinorrhea are the clinical symptoms of this disease, which can lead to pneumonia, acute respiratory distress syndrome (ARDS), and multi-organ dysfunction in severe cases (Caraturro et al. 2020; Saawarn and Hait 2021).

The SARS-CoV-2 virus is primarily transmitted through small respiratory droplets that carry the disease and are spread in space by humans (known as human-to-human or respiratory transmission) (Tran et al. 2021) or through direct contact with an infected person. On the other hand, the wastewater plumbing system is described as a transmission route for SARS-CoV-2 (Mandal et al. 2020). SARS-CoV-2 nucleic acid has recently been identified and reported in sludges from wastewater treatment plants, medical wastewater, municipal wastewater, secondary treated wastewater, commercial pleasure craft wastewater, and commercial passenger aircraft (Tran et al. 2021). The presence of SARS-CoV-2 RNA, which has been excreted by the human body through saliva, sputum, and feces, contaminates sewage. The prevalence of SARS-CoV-2 RNA in feces is higher than in urine because, after the virus is excreted from the feces, it is diluted in toilet water, mixed with wastewater, and then enters the wastewater treatment plant, along with greywater from showers and washing machines, making the stool the main agent of viral genomic units prevailing in wastewater (Sangkhom 2021).

In addition, in 2003, the WHO released a report on a widespread SARS outbreak in a Hong Kong residential block, in which a 50-story building had 342 SARS-approved cases and 42 deaths, and defects in the wastewater plumbing system were identified as a disease transmission agent indoors (Gormley et al. 2020). As a result of this study, it has been proven that the SARS-CoV-2 virus can be transmitted through the wastewater plumbing system and wastewater treatment plants, as it is likely to remain in the system for a long time and become a secondary source of diffusion (Zhang et al. 2020). However, environmental factors can influence the SARS-viability CoV-2's and infectivity. For

example, indoor heating, ventilation, and air conditioning (HVAC) systems have the potential to spread SARS-CoV-2 and aid transmission. The distance and velocity of the spread will, of course, vary depending on the type of HVAC system being considered. On the other hand, in outdoor environments where sewers are exposed and open, contaminated aerosolized particles can be the main source of SARS-CoV-2 transmission, so specific actions such as sewer cover-ups, disinfection treatments, and aerosolized air control systems can be very effective (Senatore et al. 2021).

In addition, due to SARS-rapid CoV-2's spread and high infection and death rates, many cities and countries have implemented transportation and travel bans to reduce and control the virus's spread. As a result, many sources of pollution, particularly industrial and commercial activities, were shut down, resulting in improved air quality and lower levels of key pollutants, as well as improved water quality. The quality of the wastewater has deteriorated as a result of the presence of the SARS-CoV-2 virus in the wastewater, and proper wastewater treatment is required to prevent the spread of the SARS-CoV-2 virus infection. Furthermore, increased use of disinfectants and hand sanitizers, as well as any medications, has been shown to increase the organic load of wastewater, which, if not properly treated, can become a means of transporting and spreading SARS-CoV-2 infection (Elsaid et al. 2021).

As a result, information on the persistence of coronaviruses in wastewater is critical, and considering the potential risks of virus exposure and transmission is important due to the community's overall health. As a result, quantitative reverse transcription-polymerase chain reaction (RT-qPCR) can be used to identify and quantify SARS-CoV-2 RNA in wastewater samples. Before wastewater is discharged into surface water bodies, wastewater treatment plants must eliminate pathogens. One of the most effective methods is disinfecting wastewater, which can reduce or inactivate SARS-CoV-2 RNA before discharge (Sangkhom 2021).

Chlorine, chlorine dioxide, ozone, and ultraviolet (UV) radiation are the most common disinfection processes (Paleologos et al. 2021). All these treatments, however, have their own set of benefits and drawbacks (Table 2), with chlorine-based disinfectants being the most widely used method worldwide (Zhang et al. 2020). While all disinfection methods can inactivate pathogens in some way, not all disinfection methods are equally effective at inactivating viruses. Furthermore, the effectiveness is dependent on the species and water characteristics (Paleologos et al. 2021). On the other hand, given the scarcity of integrated resources in this field and the global spread of the SARS-CoV-2 virus, more research is needed to prevent or slow the virus's spread. As a result, to assess disinfection performance and optimize disinfection strategies to prevent the spread of SARS-CoV-2, it is necessary to compare and evaluate the ability of each

disinfectant to eliminate the virus in wastewater treatment plants.

Occurrence of Virus in Wastewater

Viruses are microscopic pathogens with sizes ranging from 18 to 1500 nm that are abundant in water and wastewater. Virus detection in wastewater and drinking water necessitates sensitive detection methods that are resistant to false-positive results, as well as the possibility of complete automation. Furthermore, the method used must be quick and inexpensive (Lahrich et al. 2021). However, because SARS-CoV-2 can survive in wastewater for several days under favorable conditions, the surveillance technique of wastewater-based epidemiology (WBE) based on quantitative data linked to the virus concentration method, followed by the RT-qPCR assay, is required for the detection of the SARS-CoV-2 virus in wastewater (Sangkhom 2021). Two viral concentration methods, one based on polyethylene glycol (PEG) precipitation and the other on PAC (Polyaluminium Chloride) flocculation, are more effective than others. The detection limit for PAC flocculation was lower (4.3×10^2 GC/mL) than for PEG precipitation (4.3×10^3 GC/mL) (Barril et al. 2021). Although several studies have been conducted in this field, the degree of accuracy of virus detection is highly dependent on the sample volume, nucleic acid extraction yield, and purity (Ali et al. 2021). As a result, detecting viral RNA levels in wastewater samples using the RT-qPCR technique to detect SARS-CoV-2 proves to be a warning tool for preventing the spread of COVID-19 at the community level. The prevalence of SARS-CoV-2 RNA in different wastewater samples and their viral concentrations are summarized in Table 1.

Virus detection is usually broken down into three stages: (1) concentration, (2) nucleotide extraction and

amplification, and (3) detection and quantification. The reverse transcriptase-polymerase chain reaction (RT-PCR) is used to identify viruses based on their RNA. Since the SARS-CoV-2 virus is an RNA-based virus, most studies have chosen to identify it using this method. The nucleocapsid staining method has also been used in some studies (Saba et al. 2021).

Coronavirus enters sewage via a variety of routes, including handwashing, sputum, and vomiting (Giacobbo et al. 2021). Furthermore, coronavirus has been found in the urine and feces of people infected with SARS-CoV and SARS-CoV-2 (Amoah et al. 2020). As a result, viruses can enter water systems through a variety of channels, including sewage discharged from hospitals and quarantine centers, as well as homes and other residential buildings (Giacobbo et al. 2021).

SARS-CoV-2 was isolated and identified in wastewater for the first time by researchers in the Netherlands. 58% of positive untreated wastewater samples were reported in this study (Medema et al. 2020). In a separate study conducted in Rome, Italy, 50% of the samples tested positive. In addition, 20% of the samples of Yamanashi, Japan's secondary treated wastewater with a viral load of 2.4×10^3 copies/L were found to be positive. Furthermore, all the samples collected in Paris, France were positive. In addition, the collection of untreated samples twice a week (100%) yielded positive results. Similarly, 100% of untreated wastewater samples with viral concentrations of $> 3.2 \times 10^6$ copies/L and 75% of treated wastewater samples with a concentration of $\sim 10^5$ copies/L were found to be positive in another study (Ali et al. 2021; Saawarn and Hait 2021). According to the findings of a similar study conducted in the United Arab Emirates, the viral load of the wastewater treatment plants studied ranged between 7.5×10^2 and 3.4×10^4 copies/L (Saawarn and Hait 2021).

Table 1 Detection of the SARS-CoV-2 virus in different wastewater samples

Virus	Type of sample	Range of concentration (copies/L)	References
SARS-CoV-2	Untreated wastewater	1.9×10^1 – 1.2×10^2	Ahmed et al. (2020)
SARS-CoV-2	Fecal samples	-	Wu et al. (2020)
SARS-CoV-2	Raw wastewater Sample	5×10^4 GU/L	Wurtzer et al. (2020)
SARS-CoV-2	Untreated wastewater	9.33×10^4	Kocamemi et al. (2020)
SARS-CoV-2	Municipal wastewater	3.1×10^3 – 7.5×10^3	Sherchan et al. (2020)
SARS-CoV-2	Municipal wastewater	42.7 GC/mL	Green et al. (2020)
SARS-CoV-2	Untreated wastewater	1×10^5 – 3.4×10^5	Randazzo et al. (2020)
SARS-CoV-2	Treated wastewater samples of different WWTPs	10^1 – 10^3	Tanhaei et al. (2021)
SARS-CoV-2	Primary and secondary wastewater treatment outlet and sludge	–	Balboa et al. (2021)
SARS-CoV-2	Primary sludge samples	1.7×10^6 – 4.6×10^8	Peccia et al. (2020)

Furthermore, extensive viral load variability has been studied in clinical specimens of individuals infected with SARS-CoV-2, with viral loads ranging from 10^5 to 10^8 copies/L in urine samples, 10^6 – 10^{11} copies/L in feces samples, and 10^4 – 10^{14} copies/L in saliva and sputum, implying that an infected person could contaminate wastewater with billions of SARS-CoV-2 genomic copies. On the other hand, studies found SARS-CoV-2 RNA in wastewater samples before COVID-19 cases were reported at the site; for example, SARS-CoV-2 RNA was discovered in sewage samples collected at a wastewater treatment plant in South East England 3 days before the first case was reported. Similarly, in another study, 6 days before the first case was reported in the Netherlands, SARS-CoV-2 RNA was detected in Amersfoort wastewater (Giacobbo et al. 2021).

Overall, the findings show that SARS-CoV-2 is detected in approximately 52.5% of wastewater effluent globally (Ali et al. 2021), and that increasing virus load in the population increases virus load in sewage systems (Mohan et al. 2021). Expect a reduction in viral load when feces and other human excreta reach the sewer system due to dilution, the influence of environmental conditions (temperature, pH, solids content), the presence of antagonistic germs and chemicals (detergents, disinfectants) in the sewage (Giacobbo et al. 2021).

In a study to assess microbial risk for wastewater workers, the presence of SARS-CoV-2 in sewage may be a cause for additional concern in areas where combined sewage systems are used because, during rainy periods, urban flooding is a threat and may cause sewage overflow, posing a high risk of spreading SARS-CoV-2 (Saba et al. 2021). On the other hand, wastewater disposal in nature without proper treatment is a potential SARS-CoV-2 transmission route to humans as well as aquatic mammals. Given the current state of the COVID-19 pandemic, a more thorough examination of SARS-CoV-2 infection from contaminated sewage and water is required (Giacobbo et al. 2021).

Survival of Viruses in Wastewater

The emergence of SARS and the issue of its transmission through wastewater highlight the need for more information, particularly on the survival of the SARS-CoV-2 virus in water and wastewater. While there is limited information on the survival of SARS-CoV-2 in water or wastewater, the survival periods of SARS-CoV-1 and MERS-CoV coronaviruses, which have been reviewed previously, can be used as a comparison reference (Tran et al. 2021).

Temperature, pH, suspended solids and organic matter concentrations, light exposure, disinfectant dose, and aerobic organisms all have an impact on coronavirus survival in wastewater (Achak et al. 2021; Tran et al. 2021).

Temperature is the most important factor affecting coronavirus survival; for example, the survival of SARS-CoV-1 in hospital wastewater, domestic sewage, and dechlorinated tap water was investigated in a study. According to the findings, SARS-CoV-1 only survived for 2 days at 20 °C in dechlorinated tap water, hospital wastewater, and domestic sewage, but it could survive for 14 days at 4 °C in various water samples (hospital wastewater, domestic sewage, and dechlorinated tap water) (Tran et al. 2021). In another study, the survival of two surrogate coronaviruses, TGEV (transmissible gastroenteritis virus, a porcine coronavirus) and MHV (murine hepatitis virus), in reagent-grade water and settled human sewage was investigated. The results showed that at 25 °C, the time required for a 99% reduction in reagent-grade water was 22 days for TGEV and 17 days for MHV. In pasteurized settled sewage, the times for 99% reduction were 9 days for TGEV and 7 days for MHV. After 4 weeks at 4 °C, both viruses had a < 1 log₁₀ decrease in infectivity (Casanova et al. 2009). As a result, it can be concluded that coronaviruses in the aqueous medium are more sensitive to temperature. Another study examined the survival of two types of coronaviruses, human CoV 229E (HCoV) and feline infectious peritonitis virus (FIPV) in wastewater treatment plant primary effluent (filtered and unfiltered) and secondary effluent (unfiltered). At 23 °C, 99 and 99.9% reductions in HCoV virus were obtained in filtered and unfiltered primary effluent after 1.57, 2.35, 2.36, and 3.54 days, respectively, and 99 and 99.9% reductions in virus titer were obtained in unfiltered secondary effluent after 1.85 and 2.77 days, respectively. Given that HCoV and FIPV survival was higher in the primary unfiltered effluent than in the filtered effluent, this suggests that the organic matter and suspended solids in the effluent may protect the virus (Mandal et al. 2020). These findings are consistent with reports (Zhang et al. 2020) evaluating the presence of SARS-CoV-2 RNA in hospital septic tanks after disinfection with sodium hypochlorite and identifying high levels of SARS-CoV-2 RNA, which corresponds to the organic matter in the patient's stool, as a protective agent against the SARS-CoV-2 virus during the medical wastewater disinfection process. In another study examining the effects of different doses of chlorine dioxide (5, 10, 20, and 40 mg/L), there were reports of increased inactivation of SARS-CoV-1 in wastewater by increasing the disinfectant dose, indicating the importance and effectiveness of the disinfectant dose used in inactivating viruses (Achak et al. 2021).

On the other hand, because the viruses of concern in aquatic media are mostly non-enveloped enteric viruses, they are more resistant to environmental conditions, water treatments, and disinfectants than enveloped viruses like coronavirus, according to WHO guidelines. As a result, studies show that SARS-CoV is less resistant to bacteria when exposed to chlorine. In addition, a study of the

survival and partitioning of two enveloped viruses, MHV and Pseudomonas phage $\phi 6$, and two non-enveloped viruses, bacteriophages MS2 and T3, in untreated municipal wastewater found that enveloped viruses inactivate faster than non-enveloped viruses (La Rosa et al. 2020). However, one study estimated the half-life of SARS-CoV-2 in wastewater to be between 4.8 and 7.2 h, while another found that the COVID-19 virus could live for hours to days in untreated wastewater (Ihsanullah et al. 2021). On the other hand, since after several hours in wastewater, the SARS-CoV-2 virus has difficulties surviving and remaining viable, the detection of SARS-CoV-2 virus RNA in wastewater does not prove its viability or transmissibility (Foladori et al. 2020).

Although studies on SARS-CoV-2 survival in wastewater are necessary and important, the virus's stability in wastewater has yet to be fully investigated. On the other hand, the method and approach described in the preceding text can be used as a solution for future studies on SARS-CoV-2 survival in wastewater.

Disinfection Methods Against the Virus in Wastewater

With the global spread of the SARS-CoV-2 virus and the high risk, it poses to society, it is critical to reduce and control this virus. Because of the risk of virus transmission through wastewater, disinfecting COVID-19-infected wastewater is just as important as disinfecting healthcare facilities, medical instrumentation public transport, and other public-use amenities in preventing COVID-19 spread (Singh et al. 2021). On the other hand, assuming that the treatment plants collecting hospital wastewater are receiving sewage containing a high concentration of SARS-CoV-2 and considering the conflicting results regarding the effective inactivation of SARS-CoV-2 in wastewater, as well as the fact that conventional wastewater treatment plants are not currently specifically designed to remove the SARS-CoV-2 virus (Mohan et al. 2021), as a result, it can be concluded that SARS-CoV-2 is not effectively inactivated, and that disinfection of secondary treated wastewater before disposal or reuse is required to reduce viral contamination (Saawarn and Hait 2021). Disinfection with ultraviolet light, ozone, and chlorine is currently used to disinfect wastewater (chlorine, sodium hypochlorite, or chlorine dioxide).

Disinfection with Chlorine

Because of its ease of use, broad sterilization, cost-effectiveness, and high efficiency, chlorine disinfection has a long history of inactivating pathogens. However, one of the main concerns in this area is the formation of harmful and carcinogenic disinfection by-products (Joo and Choi 2021).

Chlorine mostly reacts with intracellular components and inactivates viral capsids by damaging them and destroying virus nucleic acids (Kong et al. 2021). Chlorine elements, chloramines, sodium hypochlorite, chlorine dioxide, calcium hypochlorite, and chloroisocyanurates are the main sources of chlorine (Teymoorian et al. 2021). Chlorine reacts with water to produce chloride ions and hypochlorous acid, which can be ionized further to produce hypochlorite (Kong et al. 2021). Hypochlorous acid has chlorine disinfectant properties, and hypochlorite is a powerful oxidizer that effectively oxidizes organic contaminants (Kuzniewski 2021). The most efficient way to inactivate viruses is to use chlorine as a hypochlorite ion or hypochlorous acid (Teymoorian et al. 2021). However, hypochlorous acid is usually considered the main disinfectant (Kong et al. 2021).

Chlorine disinfection, in combination with other treatment methods, is also used to inactivate viruses in wastewater (Kuzniewski 2021). After primary and secondary wastewater treatment, 30–50 mg/L and 15–25 mg/L of chlorine are usually added to the effluent. Nevertheless, viruses are more resistant to bacteria than chlorine disinfectants, which could be due to viruses' lack of a metabolic enzyme system (Singh et al. 2021).

SARS-CoV and HCoV-229E have been inactivated in wastewater using disinfection techniques to understand the response of SARS-CoV-2 to treatment. According to the findings, SARS-CoV-1 was completely inactivated in 30 min with a residual chlorine concentration greater than 0.5 mg/L or with a chlorine dioxide concentration of 2.19 mg/L. In another study, SARS-CoV-2 was completely inactivated after 5 min using 1:99 diluted household bleach. On the other hand, organics in the secondary treated effluent are expected to act as a physical barrier against SARS-CoV-2 disinfection. As a result, chlorine-based disinfectants were used, lowering the total residual chlorine for viral disinfection (Saawarn and Hait 2021).

On the other hand, chlorine dioxide disinfectant is used to inactivate viruses as a substitute for chlorine, but it is less effective than chlorine at inactivating SARS-CoV-1 (Singh et al. 2021), but this does not mean that chlorine dioxide is a weak disinfectant. Chlorine dioxide, which is formed when sodium chloride reacts with chlorine, damages various structural components of enveloped and non-enveloped viruses, rendering them inactive (Kuzniewski 2021). For example, after 30 min of contact time with a dose of 40 mg/L chlorine dioxide disinfectant, the SARS-CoV virus is inactivated (Singh et al. 2021).

To inactivate the SARS-CoV-2 virus in wastewater, chlorine can be used as sodium hypochlorite (bleach) in addition to chlorine dioxide. The most common chlorine-based disinfectants are aqueous solutions of 5.25–6.15% sodium hypochlorite. For inactivating the SARS-CoV virus, hypochlorite is a more effective disinfectant than chlorine

dioxide (Singh et al. 2021). With a contact time of less than 1 min, a study found that using a 0.05% hypochlorite solution can completely inactivate SARS-CoV (Thakur et al. 2021). Zhang et al. (2020) investigated the presence of SARS-CoV-2 RNA in hospital septic tanks and discovered that using 800 g/m³ sodium hypochlorite at a contact time of 1.5 h does not completely disinfect the SARS-CoV-2 virus in medical wastewater, but using a dose of 6700 g/m³ sodium hypochlorite does. On the other hand, the use of extremely high doses of sodium hypochlorite resulted in the formation of significant levels of DBPs in the effluent, which were roughly 15 times higher than other hospital effluents. Given the high ecological risks that DBPs pose to environmental systems and human health, alternative strategies to improve disinfection performance and reduce DBPs should be considered. Separation of wastewater and suspended solids from primary disinfection tanks, for example, is one possible solution for preventing the long-term release of SARS-CoV-2 from fecal particles into the aqueous phase. However, the recommended dose of sodium hypochlorite of 800 g/m³ is sufficient to ensure viral negativity and lower DBP production in the effluent, and suspended solids can be treated separately as medical waste (Zhang et al. 2020). In another study, the presence of coronavirus RNA in wastewater after secondary and tertiary treatment was investigated. They discovered that after the standard activated sludge process, about 11% of the samples were positive for corona RNA, but after the third treatment with sodium hypochlorite disinfection, 100% of the samples were negative, which could be combined in several cases by ultraviolet radiation (Teymoorian et al. 2021). In a study that looked at the inactivation of the SARS-CoV-2 virus, physical and chemical disinfection technologies were compared under different conditions. According to this study (Joo and Choi 2021), small hospitals should disinfect with ozone, ultraviolet radiation, or sodium hypochlorite, while large hospitals should disinfect with liquid chlorine or chlorine dioxide.

Effect of Physico-chemical Characteristics on Chlorine Disinfection

Since physical–chemical characteristics such as pH, turbidity, and temperature influence disinfection efficiency, it is necessary to investigate the impact of each of these variables. pH is a determining factor in the inactivation of viruses in wastewater, with low pH inactivation rates being higher than high pH inactivation rates (Singh et al. 2021). However, because hypochlorous acid is a weak acid, the pH of the wastewater can have a significant impact on the ionization balance of the acid (Kong et al. 2021). In addition, pH affects the disinfection efficiency of chlorine by determining the rate of dissociation of hypochlorous acid into hypochlorite ions (Singh et al. 2021). Organic and inorganic matter are

particles that increase turbidity and reduce disinfection efficiency by masking microorganisms from disinfectant contact or by consuming disinfectants. Turbidity, on the other hand, is influenced by effective composition. When humic acid is used to create turbidity, the disinfection efficiency of chlorine is significantly reduced when the turbidity reaches 1 NTU, but when chalk is used to create turbidity, the disinfection efficiency remains unchanged even at 5 NTU turbidity (Kong et al. 2021). On the other hand, the efficiency of all chemical reactions is affected by temperature. Despite the lack of research, it is clear that at higher temperatures, lower disinfectant doses are required for the same level of inactivation. In the winter, it is also necessary to increase the contact time or chlorine dose (Kong et al. 2021).

Disinfection with Ozone

Ozone is a powerful oxidizer and an effective microbicide against protozoans, bacteria, and viruses (Teymoorian et al. 2021). It works by reacting with the cytoplasmic membrane and breaking lipid bonds at various bond sites to inactivate microorganisms (Singh et al. 2021). Ozone can also effectively inactivate viruses through oxidative damage caused by free radicals. Since viruses can only multiply inside their host cells, they convert the proteins of the host cells into their own. By diffusing through the virus's protein coat into the nucleic acid core and damaging viral RNA, ozone inactivates it. When ozone interacts with a virus, it converts the protein to protein hydroxides and protein hydroperoxides, inactivating the virus by causing oxidative stress, which the virus has no defense against (Thakur et al. 2021). Ozone is used as a disinfectant for effluents instead of chlorine because of its beneficial properties, such as strong oxidation, the production of fewer disinfection by-products, and the elimination of color and odor in wastewater used for irrigation and surface discharge (Kong et al. 2021; Saawarn and Hait 2021). Ozone disinfection is effective against non-enveloped and enveloped viruses in water, aerosols, and surfaces that are morphologically similar to SARS-CoV-2 (Teymoorian et al. 2021). Enveloped viruses are extremely sensitive to chemical treatments such as disinfection because they require a lipid envelope to attach to the host cell, which can be damaged by chemical agents (Ibrahim et al. 2021). Since viruses are more resistant to ozone than bacteria, using ozone as a wastewater treatment technology still has some drawbacks (Kuzniewski 2021).

Given that ozonation has positive results against SARS-CoV-1 disinfection, it is thought that ozone can also be effective as a substance for the elimination of SARS-CoV-2 in theory and using molecular modeling (Singh et al. 2021) (Kuzniewski 2021). According to the findings of (Zucker et al. 2021), corona pseudoviruses could be used as a viral model to assess ozone disinfection. After

30 min of exposure to 1000 ppmv ozone, the virus was reduced by 99%. Therefore, it can be concluded that ozone gas can be used as an effective disinfectant for SARS-CoV-2 instead of liquid disinfectants. In addition, during treatment, ozone disinfection eliminates the color and odor of wastewater. On the other hand, micro-ozone bubbles (less than 50- μ m in diameter with high solubility and reactivity) provide better and more efficient wastewater disinfection. Ozone microbubbles can penetrate wastewater and create local hotspots where intense heat is generated by compressing the gas in the microbubbles, resulting in pyrolytic decomposition and the formation of shockwaves and OH radicals in the water. As a result of this phenomenon, microbial contaminants in wastewater are inactivated, resulting in better and more efficient wastewater disinfection (Jacob et al. 2021).

Effect of Physico-chemical Characteristics on Ozone Disinfection

As previously stated, each of these cases will be investigated in turn, given the importance of investigating the effect of physicochemical properties on disinfection efficiency. The solubility of ozone in water is reduced at high temperatures, which speeds up the decomposition of ozone and the disinfection process. When temperatures are between 5 and 30 °C, increasing the temperature improves ozone disinfection efficiency while lowering the CT value (Kong et al. 2021). At a higher pH, ozone decomposes more quickly and produces radicals. Both ozone molecules and hydroxyl radicals can attack microbes, but a direct ozone attack is more effective. As a result, ozone decomposition prevents it from being activated (Kong et al. 2021). On the other hand, the presence of organic matter has a significant impact on ozone disinfection. Since ozone is quickly consumed due to the presence of organic matter at the beginning of the disinfection process, large amounts of ozone are required, so the amount of CT required for sewage disinfection is much higher than for drinking water disinfection (Kong et al. 2021). The initial level of ozone has a special effect on disinfection. The lower the CT value required to achieve the same inactivation rate, the higher the initial ozone level. Turbidity has a different effect on ozone efficiency depending on the properties of the substance that causes turbidity. Bromide and iodide ions, for example, reduce efficiency by forming bromate and iodine with ozone, but side reactions can be effectively reduced by lowering the pH (Kong et al. 2021). However, in the case of wastewater treatment, the main issue is the use of ozone to raise the acidity level in the treated water, which necessitates additional research (Thakur et al. 2021).

Ultraviolet (UV) Disinfection

UV radiation is one method for deactivating viruses in wastewater. Kuzniewski (2021) says ultraviolet radiation stops the spread of viruses in the environment by destroying their ability to replicate. The formation of pyrimidine dimers (thymine and cytosine in DNA, uracil, and cytosine in RNA) after the absorption of ultraviolet energy is the main mechanism of UV disinfection, and it affects some biochemical processes such as DNA amplification, RNA transcription, and protein translation (Kong et al. 2021). UV radiation, in many cases, reacts with H_2O_2 to produce hydroxyl radicals, also known as strong oxidants, which have a high disinfectant efficiency due to their superior ability to transform organic molecules. Since they react quickly, disinfection requires only a brief contact time (Ibrahim et al. 2021). Another study found that hydroxyl radicals were effective in reducing the concentration of coronaviruses in wastewater, including SARS-CoV-2 (Kuzniewski 2021).

Based on their wavelengths, ultraviolet waves are classified as ultraviolet A (315–400 nm), ultraviolet B (280–315 nm), ultraviolet C (200–280 nm), and vacuum ultraviolet (100–200 nm). UVB and UVC have excellent bactericidal effects and can be used to disinfect wastewater, but they may cause some health risks. Wavelengths between 200 and 300 nm damage the genetic material of microorganisms, including bacteria and viruses, and inhibit protein synthesis. For ultraviolet disinfection, a wavelength of 253.7 nm is generally thought to be optimal (Singh et al. 2021). UV disinfection also has several advantages, including the absence of disinfectant by-products, a short retention time, the effective range of resistant viruses, and a lower cost than chlorine disinfection (Nasseri et al. 2021).

It is difficult to calculate the average UV dose for a UV reactor used in engineering, and the hydraulic retention time and UV light intensity vary depending on reactor position. As a result, one solution to this problem is to use fluid dynamics simulations. However, caution must be exercised, particularly in the field of wastewater, which contains high levels of dissolved organic carbon (DOC) and suspended solids (SS) (Kong et al. 2021). On the other hand, UV disinfection is dependent on contact time, irradiation intensity, and suspended particles/color/turbidity of water/wastewater (Mohan et al. 2021). Combining UV and UVC treatments with other disinfection techniques is more effective than using UV alone. A study that combined ozonation and ultraviolet techniques, for example, increased UV penetration into the water by 20 to 30%, resulting in a reduction in UV doses (Teymoorian et al. 2021). Another study found that when hydrogen peroxide was combined with ultraviolet (UV) radiation to inactivate adenovirus, less UV radiation (120 m J/cm²) was required, whereas UV radiation alone required more UV radiation (200 m J/cm²). The use of

hydrogen peroxide, on the other hand, produced hydroxyl radicals, which, in addition to causing DNA damage in adenovirus, is also likely to cause damage to the attachment proteins (Kuzniewski 2021). In a separate study, the effects of UV radiation and H_2O_2 on MS2 were investigated. MS2 was not inactivated when only filtered UV radiation was used, but when 25 mg/L H_2O_2 was added in the presence of UV filtered for 15 min, MS2 was reduced by 2.5 logs. Inactivation of MS2 necessitates a high level of oxidation power, which can be obtained by adding H_2O_2 (Mamane et al. 2007).

Recently, UVC radiation has been studied as a non-contact technology that could be useful in preventing the spread of the SARS-CoV-2 virus. The virus is inactivated by UVC photon absorption by nucleic acid bases or capsid proteins when using ultraviolet radiation. The findings showed that for low virus concentrations, a very small dose of UVC is enough to completely inactivate the virus. Furthermore, with high doses, complete inactivation of high viral concentrations is possible (Ibrahim et al. 2021). Similarly, a study on SARS-CoV-2 found that a dose of 292 mJ/cm² UVA radiation only reduced the virus by 1-log, whereas a dose of 1048 mJ/cm² UVC radiation completely inactivated the virus. Coronaviruses, on the other hand, are more resistant to UV radiation than other viruses (Kong et al. 2021). Another study discovered that using a UVC dose of 0.2 J/cm² reduced SARS-CoV infection. Other factors that affect virus inactivation include the type of wastewater treatment system, temperature, season, suspended solids, organic matter, and sunlight exposure (Saba et al. 2021). The benefits

and drawbacks of each disinfectant method listed in Table 2 are discussed in the following sections.

Discussion

The goal of this study was to investigate the potential of common disinfection processes for the removal of viruses from wastewater, particularly the SARS-CoV-2 virus. The prevalence of SARS-CoV-2 RNA in feces is higher than in urine, which is diluted in toilet water, mixed with sewage, and then entered the treatment plant with gray water from showers and washing machines after the virus is excreted in feces. Thus, making the stool the main agent of viral genomic units prevailing in wastewater converts it into a SARS-CoV-2 transmission pathway (Sangkham 2021). For example, in outdoor environments where sewers are exposed and open, contaminated aerosolized particles can be the main source of SARS-CoV-2 transmission, so specific actions such as sewer cover-ups, disinfection treatments, and aerosolized air control systems can be very effective (Senatore et al. 2021). On the other hand, the increasing use of disinfectants and hand sanitizers, as well as any medications, has shown that the organic load in wastewater has increased, which, if not properly treated, can become a means of transporting and spreading SARS-CoV-2 infection (Elsaid et al. 2021).

Virus detection is generally based on three main steps: (1) concentration, (2) nucleotide extraction and amplification, and (3) detection and quantification. The reverse

Table 2 Advantages and disadvantages of disinfection methods

Disinfectant	Advantages	Disadvantages
Chlorine	Easy deployment (Joo and Choi 2021)	Harmful and carcinogenic disinfection byproduct formation (Joo and Choi 2021)
	Broad sterilization (Joo and Choi 2021)	Temperature-dependent (Kong et al. 2021)
	Cost-effectiveness (Joo and Choi 2021)	Dependent on turbidity (Kong et al. 2021)
	High efficiency (Joo and Choi 2021)	pH dependent (Kong et al. 2021)
Ozone	Strong oxidation ability (Thakur et al. 2021)	Expensive (Kuzniewski 2021)
	Produce less unwanted by-products (Kong et al. 2021)	Increased water acidity (Kuzniewski 2021)
	Ability to eliminate the color and odor of wastewater (Kong et al. 2021)	Has a short half-life (Kuzniewski 2021)
	An effective microbicide against protozoans, bacteria, and viruses (Teymoorian et al. 2021)	Toxic (Kuzniewski 2021)
		Usually need to be treated with chlorine after disinfection with ozone (Kuzniewski 2021)
Ultraviolet radiation	Formation of no disinfection by-products (Nasseri et al. 2021)	Efficiency dependent on suspended particles (García-Espinoza et al. 2021)
	Short retention time (Nasseri et al. 2021)	Survive some of the antibiotic-resistant bacteria after ultraviolet disinfection (García-Espinoza et al. 2021)
	Effective on a wide range of resilient viruses (Nasseri et al. 2021)	
	Economical (Singh et al. 2021)	
	Produce hydroxyl radicals (Ibrahim et al. 2021)	

transcriptase-polymerase chain reaction (RT-PCR) is used to identify viruses based on their RNA. Since the SARS-CoV-2 virus is an RNA-based virus, and considering that SARS-CoV-2 can survive in wastewater for several days under favorable conditions, the surveillance technique of wastewater-based epidemiology (WBE) based on quantitative data linked to the virus concentration method, followed by the RT-qPCR assay, is necessary to detect SARS-CoV-2 virus in wastewater (Saba et al. 2021; Sangkham 2021). The two most widely used methods in the field of viral concentration-based diagnosis are the use of polyethylene glycol (PEG) precipitation and PAC (Polyaluminium Chloride) flocculation (Barril et al. 2021). On the other hand, since after several hours in wastewater, the SARS-CoV-2 virus has difficulties surviving and remaining viable, so detection of SARS-CoV-2 virus RNA in wastewater does not prove its viability or transmissibility (Foladori et al. 2020).

According to the study, disinfection of COVID-19-infected wastewater is critical for limiting virus spread, but physical and chemical properties such as pH, turbidity, and temperature can affect disinfection efficiency. The potential for eliminating common disinfection processes such as chlorine, ozone, and ultraviolet radiation disinfection was investigated for this purpose in the current study. The study's first finding was that chlorine disinfection has become more popular due to the numerous benefits it provides, but one of the main concerns in this area is the formation of harmful and carcinogenic halogenated by-products (Joo and Choi 2021). On the other hand, the most effective way to inactivate viruses was to use chlorine as a hypochlorite ion or hypochlorous acid (Teymorian et al. 2021). However, hypochlorous acid was usually considered the main disinfectant (Kong et al. 2021). Chlorine disinfection, in combination with other treatment methods, is also used to inactivate viruses in wastewater (Kuzniewski 2021). After primary and secondary wastewater treatment, 30–50 mg/L and 15–25 mg/L of chlorine are usually added to the effluent. The most common chlorine-based disinfectants are aqueous solutions of 5.25–6.15% sodium hypochlorite (Singh et al. 2021). In addition, SARS-CoV-2 was completely inactivated with a dose of 6700 g/m³ sodium hypochlorite. However, the use of very high doses of sodium hypochlorite resulted in significant levels of DBPs in the effluent, suggesting that alternative strategies for improving disinfection performance and reducing DBPs should be considered. The recommended dose of sodium hypochlorite of 800 g/m³ will, however, be sufficient to ensure viral neutrality and lower DBP production in the effluent (Zhang et al. 2020).

On the other hand, ozone is a powerful oxidizer and an effective microbicide that has excellent performance against non-enveloped and enveloped viruses, including similar viruses in the morphology of SARS-CoV-2 (Teymorian et al. 2021). Ozone inactivates viruses with oxidative

damage and has been used as a disinfectant due to its good properties (Thakur et al. 2021), such as less production of unwanted by-products and the removal of color and odor in wastewater (Kong et al. 2021; Saawarn and Hait 2021). In theory, using molecular modeling, it is believed that it can also be effective as a substance for the elimination of SARS-CoV-2 ozone (Kuzniewski 2021; Singh et al. 2021). For example, corona pseudoviruses were reduced by 99% after 30 minutes of exposure to 1000 ppmv of ozone. On the other hand, micro-ozone bubbles provide better and more efficient wastewater disinfection by the formation of shockwaves and OH radicals in the water, resulting in better and more efficient wastewater disinfection (Jacob et al. 2021).

Another common disinfection method is ultraviolet radiation, which has several advantages, including the absence of disinfectant by-products, a short retention time, an effective range of resistant viruses, and a lower cost than chlorine disinfection (Nasseri et al. 2021). UV disinfection is typically performed at a wavelength of 253.7 nm (Singh et al. 2021). Previous research has discovered that using 1048 mJ/cm² UVC radiation to completely inactivate the SARS-CoV-2 virus or 0.2 J/cm² UVC radiation to reduce SARS-CoV infection (Kong et al. 2021; Saba et al. 2021). Combining UV and UVC disinfection processes with other disinfection techniques is more effective than using only UV to inactivate viruses, resulting in lower UV dose usage (Teymorian et al. 2021).

However, due to the limitations of studies conducted in this field, as well as the increasing spread of the SARS-CoV-2 virus worldwide, which was declared a public health emergency of international concern by the WHO on January 30, 2020 (Mandal et al. 2020), more research is needed to prevent or reduce the virus's spread. As a result, the ability to remove and the effectiveness of each disinfectant to eliminate the virus from wastewater were investigated in this study to evaluate disinfection performance and optimize disinfection strategies to prevent the spread of SARS-CoV-2.

Conclusion

To stop SARS-CoV-2 from spreading around the world, wastewater disinfection was used in this study as a solution to stop SARS-CoV-2 spreading. On the other hand, due to the scarcity of resources in the field, we attempted to investigate and summarize the potential of common disinfection processes for removing the virus from wastewater in this study. The findings revealed that chlorination is the most widely used method in the world and that different doses of common disinfectants (chlorine-ozone and ultraviolet rays) were effective in deactivating and reducing coronavirus infection. Given the study's current limitations, more research into the different types of disinfectants and their

effectiveness, particularly disinfection with ozone and ultraviolet rays, is recommended in the future to prevent the spread of the SARS-CoV-2 virus around the world. It is hoped that the current study will help in this path.

Declarations

Conflict of Interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

References

- Achak M, Alaoui Bakri S, Chhiti Y, Mhamdi Alaoui FE, Barka N, Boumya W (2021) SARS-CoV-2 in hospital wastewater during outbreak of COVID-19: a review on detection, survival and disinfection technologies. *Sci Total Environ.* <https://doi.org/10.1016/j.scitotenv.2020.143192>
- Ahmed W, Angel N, Edson J, Bibby K, Bivins A, O'Brien JW, Choi PM, Kitajima M, Simpson SL, Li J, Tschärke B, Verhagen R, Smith WJM, Zaugg J, Dierens L, Hugenholtz P, Thomas KV, Mueller JF (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. *Sci Total Environ.* <https://doi.org/10.1016/j.scitotenv.2020.138764>
- Ali W, Zhang H, Wang Z, Chang C, Javed A, Ali K, Du W, Niazi NK, Mao K, Yang Z (2021) Occurrence of various viruses and recent evidence of SARS-CoV-2 in wastewater systems. *J Hazard Mater.* <https://doi.org/10.1016/j.jhazmat.2021.125439>
- Amoah ID, Kumari S, Bux F (2020) Coronaviruses in wastewater processes: source, fate and potential risks. *Environ Int.* <https://doi.org/10.1016/j.envint.2020.105962>
- Balboa S, Mauricio-Iglesias M, Rodriguez S, Martínez-Lamas L, Vasallo FJ, Regueiro B, Lema JM (2021) The fate of SARS-CoV-2 in WWTPS points out the sludge line as a suitable spot for detection of COVID-19. *Sci Total Environ.* <https://doi.org/10.1016/j.scitotenv.2021.145268>
- Barril PA, Pianciola LA, Mazzeo M, Ousset MJ, Jaureguiberry MV, Alessandrello M, Sánchez G, Oteiza JM (2021) Evaluation of viral concentration methods for SARS-CoV-2 recovery from wastewaters. *Sci Total Environ.* <https://doi.org/10.1016/j.scitotenv.2020.144105>
- Carraturo F, Del Giudice C, Morelli M, Cerullo V, Libralato G, Galdiero E, Guida M (2020) Persistence of SARS-CoV-2 in the environment and COVID-19 transmission risk from environmental matrices and surfaces. *Environ Pollut.* <https://doi.org/10.1016/j.envpol.2020.115010>
- Casanova L, Rutala WA, Weber DJ, Sobsey MD (2009) Survival of surrogate coronaviruses in water. *Water Res* 43(7):1893–1898. <https://doi.org/10.1016/j.watres.2009.02.002>
- Elsaid K, Olabi V, Sayed ET, Wilberforce T, Abdelkareem MA (2021) Effects of COVID-19 on the environment: an overview on air, water, wastewater, and solid waste. *J Environ Manag.* <https://doi.org/10.1016/j.jenvman.2021.112694>
- Foladori P, Cutrupi F, Segata N, Manara S, Pinto F, Malpei F, Bruni L, La Rosa G (2020) SARS-CoV-2 from faeces to wastewater treatment: What do we know? A review. *Sci Total Environ.* <https://doi.org/10.1016/j.scitotenv.2020.140444>
- García-Espinoza JD, Robles I, Durán-Moreno A, Godínez LA (2021) Photo-assisted electrochemical advanced oxidation processes for the disinfection of aqueous solutions: a review. *Chemosphere.* <https://doi.org/10.1016/j.chemosphere.2021.129957>
- Giacobbo A, Rodrigues MAS, Zoppas Ferreira J, Bernardes AM, de Pinho MN (2021) A critical review on SARS-CoV-2 infectivity in water and wastewater. What do we know? *Sci Total Environ.* <https://doi.org/10.1016/j.scitotenv.2021.145721>
- Gormley M, Aspray TJ, Kelly DA (2020) COVID-19: mitigating transmission via wastewater plumbing systems. *Lancet Glob Health* 8(5):e643. [https://doi.org/10.1016/S2214-109X\(20\)30112-1](https://doi.org/10.1016/S2214-109X(20)30112-1)
- Green H, Wilder M, Collins M, Fenty A, Gentile K, Kmush BL, Zeng T, Middleton FA, Larsen DA (2020) Quantification of SARS-CoV-2 and cross-assembly phage (crAssphage) from wastewater to monitor coronavirus transmission within communities. *MedRxiv.* <https://doi.org/10.1101/2020.05.21.20109181>
- Ibrahim Y, Ouda M, Kadadou D, Banat F, Naddeo V, Alsafar H, Yousef AF, Barceló D, Hasan SW (2021) Detection and removal of waterborne enteric viruses from wastewater: a comprehensive review. *J Environ Chem Eng.* <https://doi.org/10.1016/j.jece.2021.105613>
- Ihsanullah I, Bilal M, Naushad M (2021) Coronavirus 2 (SARS-CoV-2) in water environments: current status, challenges and research opportunities. *J Water Process Eng.* <https://doi.org/10.1016/j.jwpe.2020.101735>
- Jacob S, Mohapatra S, Siddharth R, Nag S, Santhosh Venkat SK, Rajeswari G (2021) Impediments of coronavirus in healthcare wastewater treatment and ways to ameliorate them. *Environ Health Manag Novel Coronavirus Dis (COVID-19).* <https://doi.org/10.1016/b978-0-323-85780-2.00006-8>
- Joo SH, Choi H (2021) Field grand challenge with emerging superbugs and the novel coronavirus (SARS-CoV-2) on plastics and in water. *J Environ Chem Eng.* <https://doi.org/10.1016/j.jece.2020.104721>
- Kocamemi BA, Kurt H, Sait A, Sarac F, Saatci AM, Pakdemirli B (2020) SARS-CoV-2 detection in Istanbul wastewater treatment plant sludges. *MedRxiv.* <https://doi.org/10.1101/2020.05.12.20099358>
- Kong J, Lu Y, Ren Y, Chen Z, Chen M (2021) The virus removal in UV irradiation, ozonation and chlorination. *Water Cycle* 2:23–31. <https://doi.org/10.1016/j.watcyc.2021.05.001>
- Kuzniewski S (2021) Prevalence, environmental fate, treatment strategies, and future challenges for wastewater contaminated with SARS-CoV-2. *Remediation.* <https://doi.org/10.1002/rem.21691>
- La Rosa G, Bonadonna L, Lucentini L, Kenmoe S, Suffredini E (2020) Coronavirus in water environments: Occurrence, persistence and concentration methods—a scoping review. *Water Res.* <https://doi.org/10.1016/j.watres.2020.115899>
- Lahrich S, Laghrib F, Farahi A, Bakasse M, Saqrane S, El Mhammedi MA (2021) Review on the contamination of wastewater by COVID-19 virus: impact and treatment. *Sci Total Environ.* <https://doi.org/10.1016/j.scitotenv.2020.142325>
- Mamane H, Shemer H, Linden KG (2007) Inactivation of *E. coli*, *B. subtilis* spores, and MS2, T4, and T7 phage using UV/H₂O₂ advanced oxidation. *J Hazard Mater* 146(3):479–486. <https://doi.org/10.1016/j.jhazmat.2007.04.050>
- Mandal P, Gupta AK, Dubey BK (2020) A review on presence, survival, disinfection/removal methods of coronavirus in wastewater and progress of wastewater-based epidemiology. *J Environ Chem Eng.* <https://doi.org/10.1016/j.jece.2020.104317>
- 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. *Environ Sci Technol Lett* 7(7):511–516. <https://doi.org/10.1021/acs.estlett.0c00357>
- Mohan SV, Hemalatha M, Kopperi H, Ranjith I, Kumar AK (2021) SARS-CoV-2 in environmental perspective: occurrence, persistence, surveillance, inactivation and challenges. *Chem Eng J.* <https://doi.org/10.1016/j.cej.2020.126893>
- Nasseri S, Yavarian J, Baghani AN, Azad TM, Nejati A, Nabizadeh R, Hadi M, Jandaghi NZS, Vakili B, Vaghefi SKA, Baghban M, Yousefi S, Nazmara S, Alimohammadi M (2021) The presence

- of SARS-CoV-2 in raw and treated wastewater in 3 cities of Iran: Tehran, Qom and Anzali during coronavirus disease 2019 (COVID-19) outbreak. *J Environ Health Sci Eng* 19(1):573–584. <https://doi.org/10.1007/s40201-021-00629-6>
- Paleologos EK, O'Kelly BC, Tang CS, Cornell K, Rodríguez-Chueca J, Abuel-Naga H, Koda E, Farid A, Vaverková MD, Kostarelos K, Goli VSNS, Guerra-Rodríguez S, Leong EC, Jayanthi P, Shashank BS, Sharma S, Shreedhar S, Mohammad A, Jha B, Singh DN (2021) Post Covid-19 water and waste water management to protect public health and geoenvironment. *Environ Geotech* 8(3):193–207. <https://doi.org/10.1680/jenge.20.00067>
- Peccia J, Zulli A, Brackney DE, Grubaugh ND, Kaplan EH, Casanovas-Massana A, Ko AI, Malik AA, Wang D, Wang M, Warren JL, Weinberger DM, Arnold W, Omer SB (2020) Measurement of SARS-CoV-2 RNA in wastewater tracks community infection dynamics. *Nat Biotechnol* 38(10):1164–1167. <https://doi.org/10.1038/s41587-020-0684-z>
- Randazzo W, Truchado P, Cuevas-Ferrando E, Simón P, Allende A, Sánchez G (2020) SARS-CoV-2 RNA in wastewater anticipated COVID-19 occurrence in a low prevalence area. *Water Res.* <https://doi.org/10.1016/j.watres.2020.115942>
- Saawarn B, Hait S (2021) Occurrence, fate and removal of SARS-CoV-2 in wastewater: current knowledge and future perspectives. *J Environ Chem Engin.* <https://doi.org/10.1016/j.jece.2020.104870>
- Saba B, Hasan SW, Kjellerup BV, Christy AD (2021) Capacity of existing wastewater treatment plants to treat SARS-CoV-2. A Review. *Bioresour Technol Rep.* <https://doi.org/10.1016/j.biteb.2021.100737>
- Sangkham S (2021) A review on detection of SARS-CoV-2 RNA in wastewater in light of the current knowledge of treatment process for removal of viral fragments. *J Environ Manag.* <https://doi.org/10.1016/j.jenvman.2021.113563>
- Senatore V, Zarra T, Buonerba A, Choo K-H, Hasan SW, Korshin G, Li C-W, Ksibi M, Belgiorio V, Naddeo V (2021) Indoor versus outdoor transmission of SARS-COV-2: environmental factors in virus spread and underestimated sources of risk. *Euro-Mediterr J Environ Integr.* <https://doi.org/10.1007/s41207-021-00243-w>
- Sherchan SP, Shahin S, Ward LM, Tandukar S, Aw TG, Schmitz B, Ahmed W, Kitajima M (2020) First detection of SARS-CoV-2 RNA in wastewater in North America: a study in Louisiana, USA. *Sci Total Environ.* <https://doi.org/10.1016/j.scitotenv.2020.140621>
- Singh S, Kumar V, Kapoor D, Dhanjal DS, Bhatia D, Jan S, Singh N, Romero R, Ramamurthy PC, Singh J (2021) Detection and disinfection of COVID-19 virus in wastewater. *Environ Chem Lett* 19(3):1917–1933. <https://doi.org/10.1007/s10311-021-01202-1>
- Tanhaei M, Mohebbi SR, Hosseini SM, Rafieepoor M, Kazemian S, Ghaemi A, Shamloei S, Mirjalali H, Asadzadeh Aghdaei H, Zali MR (2021) The first detection of SARS-CoV-2 RNA in the wastewater of Tehran, Iran. *Environ Sci Pollut Res.* <https://doi.org/10.1007/s11356-021-13393-9>
- Teymorian T, Teymourian T, Kowsari E, Ramakrishna S (2021) Direct and indirect effects of SARS-CoV-2 on wastewater treatment. *J Water Process Engi.* <https://doi.org/10.1016/j.jwpe.2021.102193>
- Thakur AK, Sathyamurthy R, Velraj R, Lynch I, Saidur R, Pandey AK, Sharshir SW, Kabeel AE, Hwang JY, GaneshKumar P (2021) Secondary transmission of SARS-CoV-2 through wastewater: concerns and tactics for treatment to effectively control the pandemic. *J Environ Manage.* <https://doi.org/10.1016/j.jenvman.2021.112668>
- Tran HN, Le GT, Nguyen DT, Juang RS, Rinklebe J, Bhatnagar A, Lima EC, Iqbal HMN, Sarmah AK, Chao HP (2021) SARS-CoV-2 coronavirus in water and wastewater: a critical review about presence and concern. *Environ Res.* <https://doi.org/10.1016/j.envres.2020.110265>
- 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 (2020) Prolonged presence of SARS-CoV-2 viral RNA in faecal samples. *Lancet Gastroenterol Hepatol* 5(5):434–435. [https://doi.org/10.1016/S2468-1253\(20\)30083-2](https://doi.org/10.1016/S2468-1253(20)30083-2)
- Wurtzer S, Marechal V, Mouchel JM, Maday Y, Teyssou R, Richard E, Almayrac JL, Moulin L (2020) Evaluation of lockdown effect on SARS-CoV-2 dynamics through viral genome quantification in waste water, Greater Paris, France, 5 March to 23 April 2020. *Eurosurveillance.* <https://doi.org/10.2807/1560-7917.ES.2020.25.50.2000776>
- 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. *Sci Total Environ.* <https://doi.org/10.1016/j.scitotenv.2020.140445>
- Zucker I, Lester Y, Alter J, Werbner M, Yecheles Y, Gal-Tanamy M, Dessau M (2021) Pseudoviruses for the assessment of coronavirus disinfection by ozone. *Environ Chem Lett* 19(2):1779–1785. <https://doi.org/10.1007/s10311-020-01160-0>