A Global Overview of SARS-CoV-2 in Wastewater: Detection, Treatment, and Prevention

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ABSTRACT: A novel coronavirus (SARS-CoV-2) causing coronavirus disease 2019 (COVID-19) has attracted global attention due to its highly infectious and pathogenic properties. Most of current studies focus on aerosols released from infected individuals, but the presence of SARS-CoV-2 in wastewater also should be examined. In this review, we used bibliometrics to statistically evaluate the importance of water-related issues in the context of COVID-19. The results show that the levels and transmission possibilities of SARS-CoV-2 in wastewater are the main concerns, followed by potential secondary pollution by the intensive use of disinfectants, sludge disposal, and the personal safety of workers. The presence of SARS-CoV-2 in wastewater requires more attention during the COVID-19 pandemic. Thus, the most effective techniques, i.e., wastewater-based epidemiology and quantitative microbial risk assessment, for virus surveillance in wastewater are systematically analyzed. We further explicitly review and analyze the successful operation of a sewage treatment plant in Huoshenshan Hospital in China as an example and reference for other sewage treatment systems to properly ensure discharge safety and tackle the COVID-19 pandemic. This review offers deeper insight into the prevention and control of SARS-CoV-2 and similar viruses in the post-COVID-19 era from a wastewater perspective.

1. INTRODUCTION

The outbreak of coronavirus infectious disease 2019 (COVID-19) is caused by a novel coronavirus (SARS-CoV-2), resulting in symptoms of coughing, sneezing, etc. As a single-stranded RNA virus, SARS-CoV-2 has caused an increasing number of infections because of its high transmissibility. The influenced countries have taken emergency measures to minimize the spread of SARS-CoV-2, which has become a hot topic around the world. Researches are focusing on the monitoring of SARS-CoV-2 in water, wastewater, sludge, and air and on surfaces to assess the risk of contracting the virus from contaminated environments. People have paid a great deal of attention to the spread of SARS-CoV-2 in aerosols, and the possibility of SARS-CoV-2 being spread in wastewater cannot be ignored. Bhatt et al. summarized the presence of SARS-CoV-2 in wastewater, showing substantial evidence of the existence of SARS-CoV-2 RNA and other pathogenic bacteria in wastewater. SARS-CoV-2 RNA may be released from COVID-19 patients into wastewater and subsequently enter the sewage pipe networks in hospitals or communities, although no confirmed cases from wastewater and fecal–oral transmission have yet been reported. During the COVID-19 pandemic, sewage treatment plants face more serious threats from emerging contaminants, including a variety of disinfectants, antibiotics, drugs, and viruses, raising new challenges for wastewater treatment management. The serious threats posed by the fecal–oral route are the main concern for wastewater during the outbreak of COVID-19, and more problems arise from water contaminated by the coronavirus. Theoretically, potential routes of transmission of the virus to humans include directly touching contaminated surface water or groundwater, bathing or swimming in contaminated water, and eating contaminated seafoods or crops in contaminated soils. We used bibliometrics in this study to assess the recent research highlights of this topic and gain a more comprehensive understanding of the presence and spillover of SARS-CoV-2 in water environments. Commonly

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used surveillance methods like wastewater-based epidemiology (WBE) and quantitative microbial risk assessment (QMRA) are systematically reviewed and analyzed to provide insights into their proper application during the COVID-19 pandemic. Subsequently, the combination of WBE and QMRA is proposed for water safety management in the COVID-19 and post-COVID-19 era. Lastly, the successful operation of sewage treatment facilities and the presence of SARS-CoV-2 in different treatment sectors in Huoshenshan Hospital in China are explicitly discussed to offer a reference for other sewage treatment systems facing the challenges of treating SARS-CoV-2-containing wastewater during the COVID-19 pandemic.

2. METHODS AND DATA ANALYSIS

As a widely accepted method for quantifying and analyzing big data by keyword retrieval, bibliometrics offers a good opportunity to carry out a comprehensive study of scientific topics or subjects. Here, we use bibliometrics to visualize the hot points related to coronavirus and discuss the future research trends. The keywords “coronavirus” and “water” were chosen for a search of all literature in the Web of Science on December 31, 2020, and the publication date was set from 2020 without language restrictions. In total, 296 articles were retrieved, and 254 papers were finally selected for further analysis after repetitive and irrelevant articles had been screened out. The “Analytical Search Results tool” was used to analyze these articles, identifying countries and regions that paid a great deal of attention to water-related concerns caused by the coronavirus. WBE and QMRA, as important methods for epidemic surveillance and prevention, were widely applied in the fight against COVID-19. They were then both used as the keywords for a search with the same retrieval method to provide insights into their principles and recent applications. All of these papers were thoroughly read and scientifically analyzed in detail.

3. BIBLIOMETRICS ANALYSIS

The number of articles with the keywords of “coronavirus” and “water” in the Web of Science from 2011 to 2020 is illustrated in Figure 1a. It remained at a low level (3–10 articles per year) from 2011 to 2019, and a dramatic increase was found in 2020 when 254 articles were retrieved. Obviously, the COVID-19 pandemic has attracted significant attention to the risks and safety management of water environments. Figure 1b shows the country-based distribution of the 254 retrieved articles. The United States and China together contributed to ~50% of the relevant publications, indicating that the researchers from these two countries participated most in the investigation of the impacts of coronaviruses on water environments. In addition, the most productive journals (e.g., Science of the Total Environment and International Journal of Environmental Research and Public Health) are closely linked to the “environmental” area, hinting that more attention is being paid to the potential impacts of the coronavirus on the environment and human health (Figure 1c).

As tools for monitoring pathogens, WBE (Figure 2a) and QMRA (Figure 2b) have been widely applied for wastewater surveillance and become popular. Considering the requirements of sewage management and monitoring, WBE and QMRA can rapidly detect viruses in the sewage and establish a specific diffusion model to support the epidemiological study of infectious diseases. As shown in Figure 2, WBE-related publications have significantly grown in 2020, whereas the number articles addressing QMRA has remained relatively stable. This indicates that researchers have recognized the important roles of WBE in SARS-CoV-2 surveillance in wastewater. Although the role of QMRA cannot be denied in the analysis and quantification of harmful microorganisms, including viruses, viral load is normally small and challenges the assessment. Therefore, current QMRA usually optimizes the parameters and assess the risks on the basis of mathematical models (Table 2). In addition, application of
More seriously, the regions with limited water and the possibility of viral transmission increase during the pandemic, accompanied by high population densities, both water shortage and utilization. For the cities with superior water resources, often pathogenic contamination and poses a challenge for water resources. The process of fetching water resources (such as the process of queuing or the contact of water containers) or washing with disinfected water increases the risk of water cross-infection.

4. WATER-RELATED CONCERNS AND STRATEGIES FOR CONTROLLING CORONAVIRUSES

4.1. Impacts of SARS-CoV-2 on the Utilization of Water Resources. Water resources are critical for human life and regional socioeconomic health. However, the outbreak of the COVID-19 pandemic increases the risk of water pathogenic contamination and poses a challenge for water utilization. For the cities with superior water resources, often accompanied by high population densities, both water shortage and the possibility of viral transmission increase during the pandemic. More seriously, the regions with limited water resources may be troubled by more severe problems, including water pollution, poor sanitation, a lack of clean water, etc. The process of fetching water resources (such as the process of queuing or the contact of water containers) or washing with water resources that cannot meet the World Health Organization’s sanitation standards will bring a greater risk of cross-infection. In addition, countries and regions with water scarcity are more likely to use wastewater for irrigation, which might increase the likelihood of accumulation of the virus in crops or soils. These potential risks in water environments necessitate a systematic review of the current technologies for monitoring and controlling viruses in water and wastewater.

4.2. Persistence and Transmission of SARS-CoV-2 in Water Environments. SARS-CoV-2 causes diarrhea and hampers the gastrointestinal function of humans. A large number of viruses in excreta may be discharged into the municipal sewage network and remain active in the sewage for a prolonged period of time, posing a risk of exposure to operators. During the COVID-19 pandemic, SARS-CoV-2 genetic materials were widely detected in fecal wastewater. More precisely, septic tanks for wastewater (especially hospital wastewater) contain large amounts of fecal debris and suspended solids, which poses significant risks by releasing viruses from these organic solids. Considering the fact that 1.8 billion people worldwide still use cleaned fecal-contaminated water as drinking water, it is very important to take this transmission route into account.

Furthermore, it has been found that most fecally transmitted viruses are highly persistent in the aquatic environment. SARS-CoV-2 is an enveloped virus and more likely to be inactivated than non-enveloped viruses. Enveloped viruses have similar persistent rates compared to those of non-enveloped ones in dark water environments as determined by viral decay constants. Additionally, the persistence of SARS-CoV-2 RNA is significantly longer than that of other closely related coronaviruses. For example, SARS-CoV-2 RNA is present in wastewater for 7 days, longer than human coronavirus (HCoV) 229E (~2 days). The long persistence of SARS-CoV-2 in water leads to the non-neglectable significance of its potential transmission in water environments. Researchers have found that the time that SARS-CoV-2 persists is different in wastewater (>7 days) and groundwater (>10 weeks), indicating that SARS-CoV-2 is subject to environmental factors. Additionally, enveloped SARS-CoV-2 possibly has stronger mobility in the underground aquifer systems and viral adsorption on soil is crucially affected by pH, ion strength, and soil properties, posing challenges in virus detection and control. Consequently, the persistence, transmission, and risks of SARS-CoV-2 in wastewater are affected by many factors, including viral load, viral activity, viral survival time, water type, and organic or microbial matter in water. Correspondingly, pertinent evaluation and detection methods should be adopted according to these real-world scenario, to ensure the accuracy and effectiveness of water surveillance.

4.3. Inactivation of SARS-CoV-2 in Water Environments. SARS-CoV-2 can remain stable in feces and wastewater for a long time at low temperatures. To prevent the infectivity of SARS-CoV-2, virus inactivation is imperative. The main methods of inactivating SARS-CoV-2 in a wastewater environment include the following. (1) SARS-CoV-2 is more vulnerable to ultraviolet (UV) (254 nm) exposure than is non-enveloped virus, and the exposure time for effective inactivation is just several seconds. (2) The thermal effect for the inactivation of SARS-CoV-2 is confirmed effectively at 70 °C in 5.7 min. (3) Chemical disinfection quenched viral infectivity within a short exposure time as the most effective and economical solution. Thus, a large number of disinfectants (chlorine disinfectants, hypochlorous acid, ozone, etc.) have been applied to inactivate SARS-CoV-2 in wastewater. At present, chlorine disinfectants are most widely used, as free chlorine could effectively inactivate SARS-CoV-2.
CoV-2 by destroying the proteins on its envelope. Despite the rapid response around the world, SARS-CoV-2 continues to show a pandemic trend due to the shortage of disinfectants. Extensive efforts have been devoted to developing new disinfectants or disinfection alternatives for the effective control of SARS-CoV-2.\textsuperscript{11,61,62} Unfortunately, the overuse of disinfectants may cause the entrance of the disinfectants into the city sewer network or surrounding water bodies through rainwater or wastewater, which may lead to an accumulation of disinfectants in surface waters during the outbreaks. This would present an emerging problem with a serious concern about the disinfection byproducts (DBPs). Methods for the accurate and swift determination of DBPs should be explored to reduce their risks to human health.\textsuperscript{63}

### 4.4. Surveillance and Assessment of SARS-CoV-2

Infectious diseases caused by SARS-CoV-2 and other pathogens have become one of the main threats to public health. Efficient monitoring of viral transmission is critical for the control and prevention of infectious diseases.\textsuperscript{65,66} Although SARS-CoV-2 is considered as a respiratory virus, it also leads to intestinal infections and can be detected in feces and wastewater.\textsuperscript{35,66} As a result, there is growing concern about the transmission of SARS-CoV-2 in water environments. In particular, the greatest risk arises in wastewater discharged from communities where COVID-19 patients, asymptomatic patients, and medical staff are concentrated.\textsuperscript{67,68} It is reported that the presence of coronaviruses in wastewater can be used to qualitatively and quantitatively evaluate the viral load in communities.\textsuperscript{24} To meet the needs of virus surveillance in wastewater, cost-effective and real-time monitoring protocols should be proposed. WBE, which can provide comprehensive assessments of the viral load in water environments, has been rapidly developed.\textsuperscript{64} In addition, as an optimized protocol for SARS-CoV-2 assessment, the quantitative microbial risk assessment is also limited for exploring a modeling-based approach. As a consequence, standardized information about QMRA is summarized in a table to obtain an implementation scheme of risk assessments from previous studies.

#### 4.4.1. Application of WBE during the COVID-19 Outbreak

Waterborne viruses are the main cause of many diseases. They can be ingested through contaminated drinking water or food, inhaled through droplets or aerosols, or contagiously injected through contact mucosa or wounds, finally leading to infection. As the wastewater environment is reported to shield SARS-CoV-2 over 7 days due to the rich organic matter,\textsuperscript{69} the presence of SARS-CoV-2 RNA in wastewater or soil might pose remarkable risks to the surroundings. WBE is a method for analyzing the concentrations of target substances in the sewage of a specific area and then assessing its consumption within the region.\textsuperscript{69} It was first applied in the monitoring of illicit drugs since being introduced in 2001.\textsuperscript{70–72} Recently, researchers proposed WBE as a strong surveillance tool for monitoring waterborne viruses (such as osteomyelitis virus) and have achieved excellent performance.\textsuperscript{73}

In tackling COVID-19 pneumonia, it is crucial to detect SARS-CoV-2 and other viruses in water, especially wastewater environments, for effective prevention and control. In particular, the existence of asymptomatic patients carrying SARS-CoV-2 necessitates wider detection. By analyzing SARS-CoV-2 RNA in wastewater, WBE can qualitatively and quantitatively evaluate the health status of residents within a certain area.\textsuperscript{74,75} The introduction of WBE can identify viruses that exist in feces and sewage even when local residents show mild or no symptoms,\textsuperscript{76} which might serve as an early warning system during the COVID-19 pandemic. Meanwhile, WBE can work as an tool for long-term surveillance of not only emerging but also re-emerging viruses in a community.\textsuperscript{23} As shown in Table 1, the spatial and temporal accuracy of sampling should be improved for WBE, which can help in confirming the expected critical pathways.\textsuperscript{77} In addition, the collection and concentration methods are important in WBE to provide the exact data for viral load evaluation.

Recently, a WBE-based building sewage monitoring system was reported and successfully identified nine potential COVID-19 patients carrying SARS-CoV-2 in Hong Kong.\textsuperscript{78} During the entire wastewater monitoring process, they paid more attention to the sampling location, time, and frequency. First, the sampling point should be carefully chosen to locate the specific building clearly. Second, the sampling time is a key factor in WBE because appropriate sampling after discharge of feces can ensure a sufficient viral titer. Thus, the sampling time was 8:00 to 11:00 in the morning, and four samples were collected at hourly intervals. Subsequently, the 12 samples were mixed to be employed as a representative sample. Lastly, virus concentration and extraction are crucial to improve the accuracy of the results. In addition, the support and cooperation from government departments are significant to the success of WBE. As mentioned above, the application of WBE in Hong Kong successfully helped in the identification of COVID-19 patients and prevention of the spread of SARS-CoV-2. This sewage monitoring system for buildings developed by the University of Hong Kong offered an excellent example to fight against COVID-19 with the aid of WBE and imply virus control in water environments. Accordingly, WBE is recommended as an initial warning tool, which can contribute to the diagnosis of COVID-19 patients and the measures for quick response strategies.\textsuperscript{46,83–85}

#### 4.4.2. Effective Risk Assessment of QMRA

Microbial risk assessment is another method for risk analysis to protect public health. QMRA is a process for identifying and quantifying the adverse effects of exposure to certain microorganisms on human health by using the established scientific data and appropriate experimental methods, eventually providing a description of the risk characteristic.\textsuperscript{86} It mainly includes risk assessment, risk management, and risk information. On the basis of scientific evaluation, QMRA carries out hazard identification, hazard characterization, exposure assessment, and risk characterization.\textsuperscript{97} QMRA is a valuable tool for supporting water safety plans and could be used to assess human health risks associated with exposure to pathogens in different environmental matrices.\textsuperscript{88,89} Therefore, QMRA is suitable for addressing the following questions raised by the COVID-19 pandemic: (1) to identify the risks of SARS-CoV-2 transmission in different wastewaters by determining the diffusion mode and volatilization rate, (2) to determine the safe distance and areas regarding the outbreak of COVID-19, and (3) to evaluate the disinfection technology for inactivating SARS-CoV-2. Recently, QMRA in empirical mode has been proposed for virus assessment of virus, aiming at sewage from different sources,\textsuperscript{25,90,91} because QMRA can develop a scalable model for interpreting case reporting data and predicting the risk of spread of viruses. From 762 articles in the Web of Science on QMRA application for coronavirus (Table 2), we summarize the details of assessment steps and risk assessment procedures. It is worth noting that the parameters should be modified during this dynamic process and the relationships...
Table 1. Key Processes for Applying WBE for SARS-CoV-2 Surveillance

| key processes of WBE methods | influencing factors | highlights | refs |
|-----------------------------|---------------------|-----------|------|
| sampling and collection     | sampling location and time | Representative samples and storage conditions are critical. | 77, 78 |
| concentration and extraction| pH, viral aggregation, temperature, water type, and sample volume | Selection of the concentration strategy depends on the initial sample volume. | 79 |
| detection                   | target genes, specificity, quality control, and internal standard | Ultrafast and on-site detection tools are urgently required and under development. | 80–82 |

Water samples are taken from the supernatant and stored at 4 °C. Measurements of the diurnal changes in flow and viral detection rates are taken. Aqueous polymer separation by PEG, multistage ultracentrifugation, or centrifugal ultrafiltration are critical. pH, viral aggregation, temperature, water type, and sample volume are key factors influencing the results. The selection of the concentration strategy depends on the initial sample volume. Target genes, specificity, quality control, and internal standard are critical.

Table 2. Application of QMRA for Assessing Coronavirus

| microorganism | source of risk | assessment steps | highlights | ref |
|---------------|----------------|------------------|------------|-----|
| SARS-CoV-2    | wastewater     | wastewater sampling, information about transformation and environmental factors, exposure assessment (dose–response model), risk characterization | By evaluating the risks of infection of workers at different viral concentrations and epidemic stages, QMRA can provide effective early warning and hypothetical strategies for virus prevention and control. | 89 |
|               | wastewater     | data collection, hazard analysis, exposure assessment (dose–response model), risk characterization | exponential dose–response model applied for different outbreak scenarios | 92 |
|               | wastewater     | information identification, COVID-19 epidemiology, SARS-CoV-2 detection, survival and inactivation, exposure assessment (dose–response and relevant respiratory viruses), risk characterization | New QMRA parameters from previous studies can be used for risk assessments of SARS-CoV-2 in wastewater. | 93 |
|               | river          | research area and data sources, exposure assessment (risk index), risk characterization | improved QMRA index model identifying the risk distribution and COVID-19 transmission possibility in watershed cities | 17 |
| MERS-CoV      | hospital       | data collection, exposure dose, dose–response equation, risk of infection, risk after intervention | QMRA can evaluate the transmission risk of exposure scenarios by analyzing virus-containing aerosols released by droplets from individual patients. | 94 |
| human pathogens | wastewater     | concentration, detection, survival times in wastewater, risk characterization | QMRA can establish the early warning system for the release of pathogens in the sewage system. | 26 |
|               | environment    | source, bacterial hazards, transmission, measurements, mathematical modeling [dose–response models, Markov chain models, single-zone or multizone mass balance models, and computational fluid dynamics (CFD) models], epidemiology analysis | QMRA, coupled with microbiology and mathematical models and epidemiological methods, can elucidate possible interaction mechanisms. | 95 |
|               | irrigation water | sampling, concentration, detection, and statistical methods (paired Student’s t test) | QMRA exposure assessment can produce accurate exposure data to control and reduce foodborne infections. | 96 |
between virus and environmental factors crucially affect the results. An effective implementation scheme of QMRA in water environments is necessary for its successful application during the COVID-19 pandemic.

As predicted by many experts, the COVID-19 will last irregularly or seasonally for a long period, and SARS-CoV-2 is very likely to coexist with human beings. Therefore, establishing the immunological barrier to SARS-CoV-2 is essential. At present, all countries around the world are actively developing vaccines against COVID-19 for herd immunity, the threshold of which can be achieved only with a high vaccination rate of 60−70% of the population. Some experts have alleged that herd immunity to COVID-19 is probably impossible. Accordingly, before herd immunity can be achieved, SARS-CoV-2 surveillance in water environments is significant in preventing the wide outbreak of the COVID-19 pandemic. WBE can be employed to monitor the spasmodic infection cases in real time. With the expected immunization effect, the application of WBE in the future will be different from the patterns we used now, e.g., lower sampling frequency with the improvement in monitoring sensitivity. In addition to the successful WBE case qualitatively discovering potential patients as described above in Hong Kong, future WBE should provide a quantitative assessment of risks in different regions instead of only the numbers of patients and predict the trends of the COVID-19 outbreak. Furthermore, QMRA can establish the relationships between influential factors and the degree of infection based on a small number of spasmodic cases, providing an effective warning. The interactive risk assessment model obtained by QMRA will be used to trace the source of infection cases with a posteriori probability.

4.5. Design and Operation Management of a Wastewater Treatment Station during the COVID-19 Outbreak. 4.5.1. Main Concerns in the Operation of Sewage Treatment Plants. SARS-CoV-2 RNA has been widely identified in fecal particles and is protected by the surrounding organic matter after being discharged into wastewater. Without sufficient disinfectants, these viruses may again be released into the aqueous water. As a result, the test result can still be positive regardless of whether water has been disinfected. In addition, the overdose of disinfectants can cause the secondary contamination problem in which a large number of DBPs (e.g., chloroform, chlorite, etc.) accumulate in wastewater and pose ecological risks. For example, the residual chlorine can affect the persistence of ecological morphology and damage the respiratory systems or organs. Chlorine-containing disinfectants may even react with organic substances in water to produce BPPs, which pose more serious risks to human health and the ecological environment. Therefore, the use of chlorine-containing disinfectants should be reasonably regulated and substitute disinfectants require further development.

During the COVID-19 outbreak, sewage treatment plants face the problem of sludge disposal. Suspended particles from SARS-CoV-2-containing sludge might be produced and aerosolized into the air during the sludge treatment process. In addition, after being directly transported to a land use area, sludge can release SARS-CoV-2 into surrounding soils, which might maintain infectivity for at least 10 weeks and even cause groundwater pollution. Currently, cement kiln incineration is the most common way to treat sludge from urban sewage treatment plants. During the COVID-19 pandemic, there has been a large gap in sludge disposal due to the suspension of some cement production enterprises. Certainly, sewage treatment plants, as the most important basic facilities in cities, are greatly significant for protecting the water environment and public health. Therefore, the operation of the sewage treatment facilities needs to be standardized, and
this review comprehensively discusses the details in Huoshenshan Hospital.

4.5.2. Successful Control of Contaminated Wastewater in China. At the beginning of the COVID-19 pandemic, China took timely and effective measures to prevent and control the initial spread in Wuhan.\textsuperscript{12,109–111} Two specialized emergency hospitals for COVID-19 patients were established in China (Leishenshan Hospital and Huoshenshan Hospital) and received more than 5000 COVID-19 patients. Strict treatment measures were employed to prevent SARS-CoV-2 spillover or spread into the surrounding environment, including wastewater treatment processes. As the two hospitals have the same design capacity of the sewage treatment plant, the design and operation of the facilities for wastewater treatment in Huoshenshan Hospital are representative and described in detail to provide an example and reference for other operational problems of medical wastewater, which is also of great significance for the protection of public health.\textsuperscript{112}

The building area of Huoshenshan Hospital is 33900 m\textsuperscript{2}, and a total of 1000 beds are designed for COVID-19 patients. The drainage pipe network collecting rainwater, sewage from a contaminated area (patient wards), and sewage from a clean area (staff living areas) separately is properly designed and illustrated in panels a and c of Figure 3. To meet landfill standards, Huoshenshan Hospital uses the high-density polyethylene (HPDE) and the basement adopts impervious “composite geomembrane”. Therefore, there is minimal impact or risk of medical activities on groundwater. The treatment process adopted by the Huoshenshan Hospital sewage treatment station is shown in Figure 3b.

The main task of this water treatment station in Huoshenshan Hospital is to disinfect SARS-CoV-2 viruses and ensure the safety of discharged water. Wastewater is first treated in a presterilized contact pool, which has a designed scale of 40 m\textsuperscript{3}/h with two groups, an average hydraulic retention time (HRT) of 3 h, and a maximum HRT of $\leq 5$ h for each group. As wastewater contains a large amount of feces debris responsible for virus release, the water treatment station separates suspended solids from the wastewater in the predisinfection tank to avoid the long-term presence of feces particles and virus release.\textsuperscript{67} Chlorine dioxide and sodium hypochlorite are used as the disinfectants for wastewater, and the designed dosage is 40 mg/L (in terms of residual chlorine). Wastewater is then transferred into five reinforced fiberglass septic tanks with an effective volume of 100 m\textsuperscript{3} to preprecipitate suspended solids. Simultaneously, partial disinfection is employed in the septic tanks to reduce the stress of regulating the reservoir. Effluent from the septic tank is raised to the regulating reservoir by lifting pumps. Subsequently, the wastewater is treated in the moving bed biofilm reactor (MBBR), which is designed in parallel with an HRT of 5.6 h. Sludge from MBBR is separated in the coagulation and sedimentation tanks, stored in the auxiliary sludge concentration tank, and then treated in the sludge thickener. A sodium hypochlorite solution is added to the sludge thickener by the metering pump for the sludge deactivation. After gravity concentration in a concentration tank, the supernatant is discharged back into the regulating reservoir. The concentrated sludge is transferred into the spiral dewatering machine by the sludge screw pump. When the dewatering machine is started, cationic polyacrylamide (CPAM) is added for conditioning and sludge dehydration. The filtrate from the dewatering machine is pumped into the regulating reservoir again.

The designed flow rate of secondary disinfection is 40 m\textsuperscript{3}/h for two groups, with an average residence time of 3 h, a maximum residence time of $\leq 5$ h, and a unit chlorine dosage of 25 mg/L (in terms of available chlorine). Meanwhile, the design of disinfection equipment possesses a certain surplus capacity, which can be adjusted flexibly according to the actual operational situation of the treatment station to fully guarantee the disinfection effects.

The waste gas from the sewage treatment station and patient wards (negative pressure) in Huoshenshan Hospital may contain SARS-CoV-2.\textsuperscript{113} Additionally, hydrogen sulfide, ammonia methanethiol, burning soot sulfur, and other toxic waste gases will be generated during the sewage treatment process and the incineration of medical waste. Accordingly, the waste gas requires a careful treatment for avoiding potential risks to the medical staffs and secondary air pollution in the surrounding area. The waste gas from the sewage treatment sector is discharged after the combination of activated carbon adsorption and UV photolysis oxidation. The waste gas from medical waste incineration is first cooled and then treated by desulfurization and deacidification. Afterward, the waste gas is collected using a polyether (PE) microporous dust collector and finally adsorbed by activated carbon. Via the control of the air volume in and out of the wards, pressure gradients are formed between different areas to ensure appropriate air flow from the clean area to the contaminated area. Finally, the authors concluded that this comprehensive treatment approach provided a successful control of contaminated wastewater and waste gas in Huoshenshan Hospital during the COVID-19 pandemic.\textsuperscript{112}
indoor air pressure is kept 15 Pa lower than outdoors. The exhaust duct is equipped with an antivirus device to sterilize the discharged air to meet the requirements of environmental protection and COVID-19 prevention. The design and operation of the Huoshenshan Hospital exhaust gas treatment system can provide a reference for the exhaust gas treatment of emergency respiratory hospitals for infectious diseases.

During the operation of Huoshenshan Hospital, the residual chlorine in effluent and other wastewater quality parameters were monitored in real time to ensure the treatment efficiency and safety of the sewage treatment system. As shown in Figure 4a, the daily treated wastewater did not exceed the maximum designed treatment capacity (1920 m³/day). However, the wastewater flux was significantly affected by the rainfall when it exceeded 20 mm a day (February 26 and March 29). As illustrated in Figure 4b, the levels of residual chlorines in the effluent met the standard. The dilution effect of rainwater led to a decrease in the level of organic matter in influent and caused the carbon level to be insufficient. Thus, the COD removal efficiency in MBBR was decreased.

The presence of SARS-CoV-2 in the sewage treatment system (wastewater, soil, and aerosol) of Huoshenshan Hospital is illustrated in Figure 5. Among 10 wastewater, three aerosol, and two soil samples collected from all reactors (Figure 3b), three wastewater samples, one aerosol sample, and one soil sample were positive for SARS-CoV-2. SARS-CoV-2 levels in the first regulating reservoir, MBBR, and sedimentation tank were 633, 505, and 2208 copies/L, respectively. No SARS-CoV-2 was detected in effluents after disinfection, indicating that complete disinfection is greatly important for removing SARS-CoV-2 in wastewater and securing discharge safety. For aerosol samples, SARS-CoV-2 RNA was detected only in the septic tank (603 copies/m³), suggesting that aerosol SARS-CoV-2 mainly came from the aerosolized droplets from the feces debris of the COVID-19 patients. The soil samples collected from 2 m distance to the first regulating reservoir contained a significant level of SARS-CoV-2 RNA (550 copies/g). Notably, SARS-CoV-2 was not detected in surrounding aerosols and soils of Wuchang Cabin Hospital because of the temporary enclosed system, which effectively prevented the spread of SARS-CoV-2. It is suggested that the appropriate sealing of the wastewater treatment system may prevent the transmission of SARS-CoV-2.

Hand hygiene and ocular protection are critical for preventing COVID-19 cases among staff in sewage treatment plants. It is most important to have sufficient COVID-19 personal protective equipment during the operation and maintenance period. For staffs, daily double temperature measurement and regular disinfection should be strictly carried out to ensure their safety. Centralized medical observation for working staff should be arranged after work to ensure no safety accidents.

5. CONCLUSION

Although there has been no confirmed case of COVID-19 from SARS-CoV-2 transmission in wastewater to date, a significant number of studies have demonstrated that water safety is a major hidden danger in the prevention and control of the COVID-19 pandemic. Previous studies have focused on the detection of SARS-CoV-2 in wastewater, and the widely accepted methods are WBE and QMRA. From the comprehensive analysis in this review, WBE is the most reliable surveillance method tackling the COVID-19 for its rapid response and thus should be further developed and widely applied. Supplementarily, QMRA provides a strategy for assessing human health risks associated with exposure to pathogens in different environmental matrices. The successful operation of Huoshenshan Hospital helps the successful prevention and control of COVID-19 in China and also provides references for the operation and management of sewage treatment systems around the world for the post-COVID-19 era.

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Notes

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