Mini Review

Received: 2 March 2023 Revised: 9 April 2023 Accepted article published: 12 April 2023 Published online in Wiley Online Library: 25 April 2023

(wileyonlinelibrary.com) DOI 10.1002/jctb.7401

Wastewater treatment risks and challenges for public health and the environment during the Covid-19 pandemic: a review

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Abstract

During the coronavirus disease 2019 (COVID-19) pandemic, caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), viral transport, fate, disinfection and environmental release in wastewater treatment plants have been issues of high importance for overall management. Although a huge number of scientific publications related to coronaviruses have been published, the number of studies on different aspects of wastewater treatment strategies to deal with SARS-CoV-2 abatement is still relatively limited and results are often confusing. To define real wastewater risks for public health and the environment, we have performed a systematic review and identified 96 papers from the PubMed database. We focused on SARS-CoV-2 wastewater treatments and how the type and level of treatments affect the virological quality of the effluents, the role of disinfectants, the treatment of medical wastewater, the role of new technologies, as well as the wastewater treatment in low- and middle-income countries. It was concluded that, in general, well-designed and well-functioning wastewater treatment plants (WWTPs) and on-site reliable sanitation systems may significantly limit the risk of SARS-CoV-2. The development of cost-effective decentralized water and wastewater treatment facilities for low- and middle-income countries for the abatement of coronaviruses should be enhanced. Lessons learned during the COVID-19 pandemic with regard to wastewater treatment are expected to support an improved detection, response and containment of future viral disease outbreaks.

Keywords: COVID-19 pandemic; severe acute respiratory syndrome; wastewater treatment; disinfection

INTRODUCTION

COVID-19, caused by severe acute respiratory syndrome coronavirus 2, has severely impacted public health worldwide. Coronaviruses (CoVs) are enveloped, single-stranded, positive-sense RNA viruses, ranging from 60 to 220 nm in size. They are introduced into wastewater through several sources, such as hand washing, sputum and vomit, urine, but mainly via the feces of infected individuals.[1,2] Enveloped viruses like CoVs have been found to have shorter survival periods than the non-enveloped ones, since the envelope is less robust against environmental conditions and disinfecting agents.[3,4] However, several reports indicate that they may be able to survive longer than presumed, thus leading to potential health risks via waterborne and aerosolized wastewater pathways.

A limited number of studies have been performed on CoVs and their surrogates in wastewater, mainly because of the assumption that they are not waterborne, and prior to the pandemic there was a common belief that CoVs could not survive for extended periods in water.[5] The COVID-19 pandemic has raised, among others, awareness on the efficiency of wastewater treatment strategies to deal with this new biothreat. It is well known that conventional wastewater treatment has only a partial effect on viral load. Moreover, high influent viral loads during pandemics can lead to insufficient reduction of viruses before discharge; thus safe disposal or reuse will depend on the efficiency of final disinfection. Mechanisms of removal of viruses from wastewater treatment plants (WWTPs) include adsorption of viruses on larger aggregated particles that are separated by sedimentation, retention by membrane and biofilm layers, predation and enzymatic breakdown in membrane bioreactors, as well as inactivation by different disinfection processes (e.g., ultraviolet (UV) irradiation, chlorination, ozonation).[6-10]

In view of the ongoing COVID-19 pandemic and in order to focus on wastewater treatment strategies, we have systematically reviewed the published data, since the fate of SARS-CoV-2 in WWTPs has emerged as a matter of utmost significance. Interestingly, despite a significant increase of the number of publications

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related to CoVs because of the current pandemic, the number of published studies on wastewater treatment strategies to deal with SARS-CoV-2 is still relatively limited.

In the context of the present review, we have summarized studies related to SARS-CoV-2 wastewater treatment and evaluated how the type and level of treatments affect the virological quality of the effluents, which disinfectants have been tested, how medical wastewater is treated and what the role of new technologies in sewage treatment during the pandemic is, as well as the wastewater treatment situation in low- and middle-income countries (Fig. 1).

METHODOLOGY

The PubMed database was used to carry out a systematic literature search. The keywords used were: 'COVID-19 AND sewage AND treatment', 'COVID-19 AND wastewater AND treatment', 'coronavirus AND wastewater AND treatment', 'coronavirus AND wastewater AND treatment AND technology', 'COVID-19 AND sewage AND treatment AND technology', 'COVID-19 AND wastewater AND treatment AND technology', searching in the fields 'Article title, Abstract, Keywords'. In the systematic review, no publication time limit was included. Books, book chapters, book series, letters to the editor, presentations, and conference proceedings were excluded. Articles in languages other than English were also excluded.

Research articles and review papers on SARS-CoV-2 wastewater treatment have been included. Wastewater-based epidemiology, methodological studies on SARS-CoV-2 detection, as well as studies on the new challenges faced by WWTPs due to the change in contaminant loads during the pandemic were not included, since the aim of the present review was to demonstrate the efficiency of wastewater treatment technologies for the abatement of SARS-CoV-2. The results of bibliographic searches up until 1 December 2022 were used.

Identified records through the bibliographic database (1829) were checked to eliminate duplicates, and 603 single documents were found. Papers were also checked to eliminate out-of-scope documents. A first-step screening resulted in the exclusion of 124 records based on abstract. Full-text papers checked for eligibility were 479. Based on eligibility and exclusion criteria 383 of these records were finally excluded, resulting in 96 papers included in the present review. A systematic review flow diagram is shown in Fig. 2.

To construct a network visualization map of co-occurrence keywords of the finally selected bibliographic references included in this review (Fig. 3), VOS Viewer software tool was used, which visualizes bibliometric networks. Colors represent different clusters, the size of the circle is related to the frequency of the keyword use, and the distance between terms indicates the frequency of two terms occurring together in either the abstract title or keyword listing of publications. Since the color of an item is determined by the cluster to which the item belongs, four clusters have been revealed, depicted with red, green, blue and yellow.

GENERAL ISSUES ON SARS-CoV-2 WASTEWATER

The COVID-19 pandemic has been a rapidly evolving situation affecting different aspects of everyday life.[11,12] It has underlined the need to assess the impact on water compartments for the protection of public health and the environment, from its first start and during its evolvement, with special focus on the new challenges faced by WWTPs.[13-16] The change in the load of contaminants of the influents of WWTPs, including viruses, has triggered research around the globe, with different studies on wastewater treatment and disinfection techniques, targeting the improvement of treatment processes in terms of efficiency, as well as economic cost.[14,17-19] To reduce viral spread, different single technologies have been evaluated, while hybrid technologies have been proposed based on multi-stage processes for synergistic treatment of virus-contaminated water and wastewater.[20,21] Joo and Choi underlined the limitations of conventional treatment technologies (ineffectiveness, restrictions of long-term performance, production of toxic by-products) to treat superbugs or SARS-CoV-2.[22] A broad variability in absolute removal of viruses from wastewater by conventional treatment processes threatens both human health and the environment.[3,4] Coronaviruses are known to be stable both in body secretions and sewage at reduced temperatures.[7] Low resistance of SARS-CoV-2 to high temperature has been shown by *in vitro* tests, whereas even notable changes of pH did not result in viral abatement.[23] Human coronaviruses or their surrogates have been shown to survive for several days at 4 °C, under lab scale conditions. Their perseverance is strongly affected by temperature and organic or microbial pollution, while it is generally lower than non-enveloped viruses.[5]

The analysis of 1060 research papers performed by Chen *et al.* revealed that membrane and disinfection methods resulted in 0.5–7 and 0.09–8 log-reduction values, respectively, due to different interactions between membranes or disinfectants and viruses, affecting viral capsid integrity and their genetic material.[24] Ji *et al.* stated that some standard wastewater treating

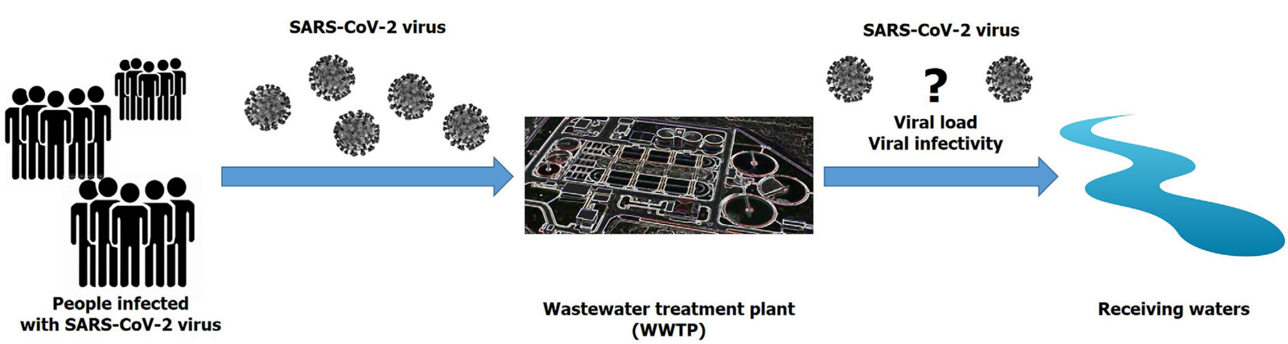

Figure 1. Infected people of a community linked to a WWTP shed SARS-CoV-2 in wastewater which is treated and disinfected to remove the virus and protect the environment and public health.

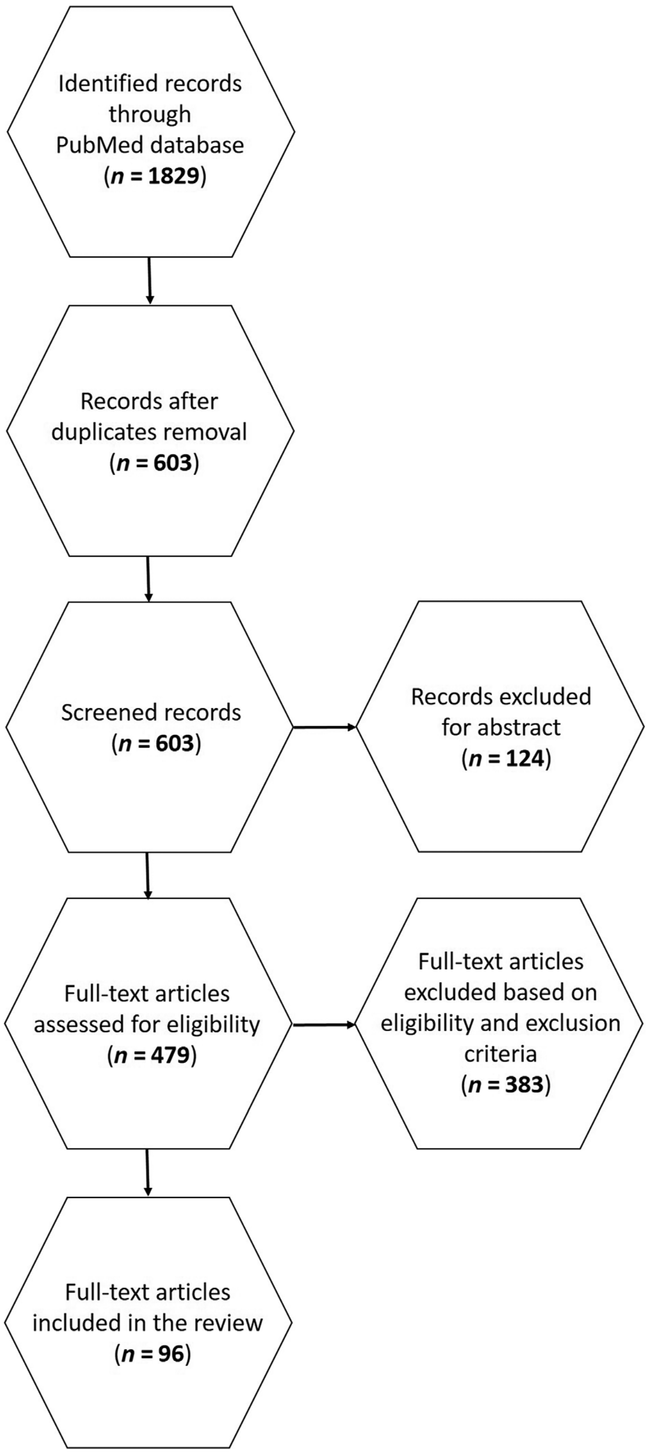

Figure 2. Systematic review flow diagram detailing PubMed database searches, the number of records after duplicate removal, exclusion for abstract and based on eligibility and exclusion criteria, and full text articles finally included in the review.

systems were effective for the abatement of SARS-CoV-2. Depending on the filtration and disinfection strategies applied, it has been proved that these processes may reduce the total waterborne virus load over 4 log units. However, the high number of sewage treatment technologies, along with the limited data available on virus transmission and survival in air, water, wastewater and sludge, underline the need for further studies before establishing reliable controlling strategies. These studies also need to be supported by specific and sensitive analytical tools.[25] Similarly, Rocío Girón-Navarro *et al*. underlined the pivotal role of conventional wastewater treatment systems to remove SARS-CoV-2 for the efficacious management of the pandemic.[26] Similarly, conventional wastewater treatment may significantly reduce the detected signal of SARS-CoV-2 RNA genetic material in wastewater.[2] Godini *et al*. stated that water and wastewater treatment methods may reduce the virological load of water sources, with disinfection having a central role for viral abatement.[27] Viability of SARS-CoV-2 decreases in wastewater due to temperature, pH, solids and micropollutants, but an effective abatement can only be obtained using disinfection (free chlorine, UVC light).[8] Disinfectants used to control viral spread, including UV light, ozone, chlorine dioxide, hypochlorites and hydrogen peroxide.[12] Additionally, Cimolai *et al*. discussed the susceptibility of CoVs to temperature and pH extremes, halogens, aldehydes, various solvents and alcohols.[7] Viral susceptibility against different disinfection methods varies.[28] Anand *et al*. stressed the need to optimize disinfection processes for SARS-CoV-2 abatement, in terms of dosage and potential adverse impacts, as well as of monitoring the virological quality of sewage sludge and landfill leachates.[29] Similarly, underlined the need for revised disinfection guidelines and suggested the application of viral remediation methods (i.e., membrane bioreactors and advanced oxidation processes).[30] Similarly, Núñez-Delgado evaluated current treatments for wastewater and sewage sludge, and suggested the development of novel techniques (based on sorption, nanotechnology, etc.), for viral dissemination control.[31] Viruses are charged colloidal particles, which can be adsorbed on surfaces; this is a pH-dependent process that eventually dictates their fate in water matrices, sewage sludge, soil, as well as their removal by treatment methods.[10] Since CoVs are very sensitive to increased temperature, thermophilic digestion is effective for the treatment of sludge.[8] Bhatt *et al*. reviewed different methods (physical, chemical and biological) for viral abatement in wastewater, as well as the microalgae-mediated virus removal and inactivation.[4] Two common processes in wastewater treatment facilities, i.e., filtration and UV disinfection, have been recommended by the World Health Organization (WHO) for the abatement of SARS-CoV-2. However, it has been shown that the interference from other aqueous chemical and physical factors may complicate SARS-CoV-2 treatment; therefore, the development of effective new strategies compatible with current treatment approaches is imperative.[21] CoVs tend to attach to solids, which indicates that they can be successfully removed using membranes. The suggested commercial membranes for the removal of CoVs, and specifically of SARS-CoV-2, should be in the field of ultrafiltration (UF; nominal pore size <0.1 μm), since CoVs and SARS-CoV-2 virions have a diameter range of 80–220 nm and 60–140 nm, respectively.[8] The adoption of membrane bioreactors (MBR) with UF to separate SARS-CoV-2 virions is an effective strategy, resulting also in a reduction of the quantity of used disinfectants.[8]

Based on the likely emergence of more resistant and infectious mutations of SARS-CoV-2, Giacobbo *et al*. stated that contamination due to contact with sewage or polluted water cannot be neglected.[32] On the other hand, Dada and Gyawali showed that the risk of occupational exposure to SARS-CoV-2 via inhalation at the WWTP environment is negligible, especially when the

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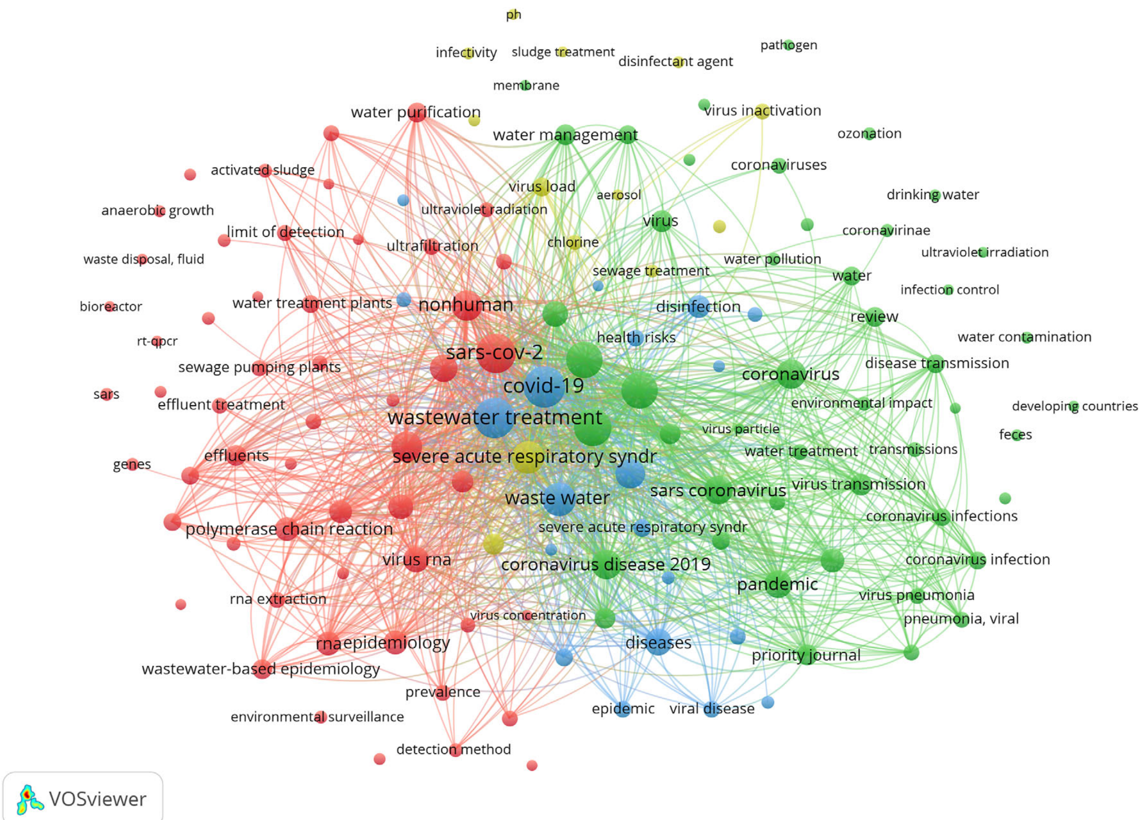

Figure 3. Network visualization map of co-occurrence keywords of the finally selected bibliographic references included in this review, with colors representing different clusters.

percentage of active infections in the population served by the plant is low (<0.3%).[33]

LEVEL OF TREATMENT

In general, the level of wastewater treatment affects the virological quality of the effluent. WWTP effluents have been reported to be mostly free from SARS-CoV-2 RNA, and conventional treatment processes were generally considered effective.[34] Although the concentration of SARS-CoV-2 RNA in the influent was high, it decreased substantially during the principal treatment steps and was below detection in the final effluent, demonstrating the efficiency of treatment processes in protecting receiving waters and public health.[35,36] Similarly, all effluent samples tested negative for SARS-CoV-2 RNA in the study of Carrillo-Reyes *et al*., indicating an effective treatment process.[37] The viral load of WWTP influents was removed, mainly in the biological reactors and at the disinfection step, as reported by Novoa *et al*.[38] Moreover, advanced purification processes resulted in negative effluent samples for SARS-CoV-2 RNA.[35] A significant reduction of biochemical oxygen demand (BOD), >95% removal of caffeine and absence of viral copies demonstrated the efficiency of WWTPs in Chennai city, India.[39] Standard wastewater treatment processes were effective for the removal of SARS-CoV-2 RNA, and upflow anaerobic sludge blanket (UASB) treatment substantially reduced its load.[34] Detection, occurrence and fate of SARS-CoV-2 during primary, secondary and tertiary wastewater treatment have been reviewed.[40,41] According to Foladori *et al*., WWTP influents may contain a viral load ranging between 20 and 3×10^6 genomic units (GU) L^{-1}, while secondary biological treatment may reduce the load to values below 2.5×10^5 GU L^{-1}. Final disinfection results in negative effluents for SARS-CoV-2 (below detection limit).[8] According to Varbanov *et al*., all thermal or pH-based treatments that can remove or significantly reduce infectious somatic coliphages (>4 $\log_{10}$) can be appraised as effective towards infective SARS-CoV-2.[42]

The risk of SARS-CoV-2 dissemination by treated effluents, which are disposed of or reused in the urban water cycle has to be assessed based on viral infectivity data.[43] A lack of infectious SARS-CoV-2 viral particles in secondary-treated wastewater, filling a gap of knowledge on the public health risks of SARS-CoV-2 across the water cycle.[44] According to Shi *et al*., the viability of infectious CoVs found in bulk wastewater overestimated the infectivity risk of coronavirus during wastewater flow in sewers or subsequent treatment.[45]

The abatement of SARS-CoV-2 in WWTPs is directly linked to the operational parameters and is usually boosted by tertiary treatment and the use of higher doses of disinfectants.[43] A study performed in Argentina showed that 30% of the analyzed samples ($n = 30$) tested positive for SARS-CoV-2 RNA. A total of 77% of the positive samples corresponded to untreated urban wastewater, compared to 23% for pre-chlorination step samples. Interestingly, no positive sample was recorded at the post-chlorination step.[46] Another study including 10 WWTPs in Chile (based on activated sludge, aerated lagoons, bio-discs, constructed wetlands, vermifilters and mixed systems) showed that SARS-CoV-2 was detected in influents at values between <5 and 462 GC mL^{-1}. Virus removal efficiencies ranged between 0% and 100%, with activated sludge with bio-discs achieving up to 98% SARS-CoV-2 removal; it was also reported that temperature, pH and solids were the most important factors for the removal of viruses.[47] An Italian study confirmed the efficiency of current wastewater treatments to remove the virus at appropriate retention times combined with hostile environmental conditions (temperature, high pH values, solar irradiation, indigenous microbial populations) and showed that final disinfection steps achieved complete viral abatement.[48] In the study of Randazzo *et al*., all tertiary samples ($n = 12$) tested negative, while two (out of 18) secondary samples were positive for SARS-CoV-2.[49] In a study of six WWTPs in Virginia, Florida and Georgia in the USA, eight (out of 42) untreated wastewater samples collected from primary influents were found positive, while none of the secondary and tertiary samples was positive.[50] Similarly, none of the effluents from 11 WWTPs operating a battery of technologies (preliminary, primary, secondary (ASP/clarification), and tertiary (sand filtration, disinfection, chlorination)) for irrigation reuse purposes was tested positive in the United Arab Emirates.[51] Additionally, tertiary treatment and UV disinfection resulted in negative effluents ($n = 8$) for SARS-CoV-2 RNA in the study of Tomasino *et al*.[52]

Conversely, Arora *et al*. reported positive samples even after tertiary disinfection based on UV and chlorine disinfection, during the time window of maximum active cases in the city, which resulted in increased genome concentrations in influent samples. The removal efficiency of six treatments was as follows: sequencing batch reactor + chlorine disinfection (81.2%) > moving-bed biofilm reactor with UV disinfection (68.8%) > sequencing batch reactor (57.1%) > activated sludge process (50%) > moving-bed biofilm reactor with UV + chlorine disinfection (36.4%).[53] Similarly, Kumar *et al*. showed that treated effluents (conventional activated sludge and root zone treatments, $n = 44$) occasionally tested negative for SARS-CoV-2 RNA, with the removal efficiency exhibiting temporal variability due to variations in active cases in the served population and the accumulation of the genetic material over time. The authors also pointed out that the efficiency of adsorption and coagulation processes was higher than disinfection and underlined the need for the application of treatments considering solid–liquid partitioning.[54] The first study on the detection of SARS-CoV-2 RNA in wastewater in Japan showed that secondary-treated wastewater samples tested positive for SARS-CoV-2 RNA when the cases peaked in the community.[55] In Padua, Italy, both untreated and treated wastewater samples tested positive for SARS-CoV-2 RNA (4 out of 9 untreated wastewater samples and 2 out of 2 tertiary treated samples).[56] All 28 influent wastewater and primary effluent samples tested positive for SARS-CoV-2 RNA, secondary effluent showed 4 out of 9 positive samples, and all tertiary and final effluent samples were below the detection limit for the viral markers, in the study of Gharoon *et al*. The authors showed significant virus reduction in secondary treatment (1.4–2 $\log_{10}$ removal), while primary treatment achieved removal values up to 0.5 $\log_{10}$.[57] A study involving three WWTPs in the Paris metropolitan area in France demonstrated significant reduction of SARS-CoV-2 RNA loads along the treatment lines (2.5–3.4 log reduction), with very low loads detected in effluents (non-detected in over half of the samples).[58] In another study of 16 WWTPs, 50.5% ($n = 101$) of influent samples were found to be positive for SARS-CoV-2 RNA, while a significant reduction of viral load along the treatment lines occurred, with 23.3% of secondary effluents being positive and all samples after MBR and chlorination negative.[59] In a study to assess the removal efficiency of different secondary processes in Japan, the reduction of SARS-CoV-2 was 2.7 ± 0.86 $\log_{10}$ in conventional activated sludge, 1.6 ± 0.50 $\log_{10}$ in anaerobic–anoxic–oxic, and 3.6 ± 0.62 $\log_{10}$ in MBR. The lowest recorded value was 2.8 $\log_{10}$ in MBR, 1.2 $\log_{10}$ in activated sludge and 1 $\log_{10}$ in the anaerobic–anoxic–oxic process, showing that MBR was the best process for reducing SARS-CoV-2.[60] SARS-CoV-2 RNA was detected in wastewater composite samples from the inlet of WWTPs of three cities in Iran. Although different disinfection methods were used (chlorine *vs*. UV), no effluent samples tested positive. Similarly, no positives were found in the WWTP of Tehran, where UV disinfection was applied. Two out of four effluent samples disinfected with chlorine were found positive for SARS-CoV-2 RNA, indicating operation deficiencies. Overall, the authors stated that meeting operation and maintenance standards of WWTPs can markedly support the production of safe wastewater and public health protection.[61]

The study of Belhadi *et al*. on seamless assessment and prioritization of infectious wastewater treatment technologies, which was based on a four-dimensional criteria system (i.e., environmental safety, technology, economics and socio-politics), showed that combined chlorination and UV were the most sustainable technologies.[62] In China, water reclamation processes with modified conditions due to the pandemic (advanced treatments using ozone, UV light and higher chlorine doses), resulted in high removal levels for both pathogens and trace organic compounds, along with rational concentrations of disinfection by-products.[63]

Thakur *et al*. stressed the efficiency of the ultrafiltration method for wastewater treatment, which may usually achieve more than 4 log of virus removal. They also pointed out the high removal rates that can be achieved by biological treatment using microalgae.[64] A Brazilian study to assess SARS-CoV-2 abatement and partitioning through the complete cycle of a wastewater treatment system, consisting of an upflow anaerobic sludge blanket reactor followed by high-rate algal pond post-treatment, showed >1 $\log_{10}$ reduction. Interestingly, most of the remaining SARS-CoV-2 RNA (about 60%) left the system in the sludge, thus implying viral affinity for solids. These findings depict the need for higher levels of treatment (e.g., tertiary treatment) to yield an effluent of better virological quality and potentially reusable.[65]

Saba *et al*. reported that existing wastewater treatments may remove 1–6 $\log_{10}$ viable SARS-CoV-2 but also underlined the need to effectively treat sludge and biosolids since they may protect viruses from treatment and, thus, impede their inactivation.[66] Due to hydrophobic properties, CoVs may be found in the separated sludge in primary and secondary settlings.[8] Accordingly, a higher viral load was found in secondary sludge than in influent wastewater, indicating the viral concentration in activated sludge.[37] In the study of Yanaç,[67] influent and primary sludge samples were found positive for SARS-CoV-2 RNA, while secondary and final effluents were negative, demonstrating the efficiency of primary and secondary treatments to reduce the viral load.[67] In a study to assess the SARS-CoV-2 gene copy numbers in biosolids throughout the wastewater treatment process, primary clarifier sludge was found to contain a significantly higher viral load than other sludge types (return activated sludge and anaerobically digested sludge), in the range 10^5–10^6 GC L^{-1}. These findings show that SARS-CoV-2 tends to partition into primary clarifier sludge, and most is removed by sedimentation.[68] Non-treated sludge (from primary and secondary treatments) was found to be more positive for SARS-CoV-2 RNA than the corresponding water samples, which shows the viral affinity for solids. Moreover, treated sludge was found positive after thickening and anaerobic digestion, while thermal hydrolysis resulted in negative samples.[59] Thermophilic anaerobic digestion has been found to be an effective treatment for the sanitation of SARS-CoV-2 sludge, in accordance with existing data concerning other coronaviruses.[69] Thermophilic digestion (55 °C) is able to effectively remove CoVs and SARS-CoV-2 in the sludge (1.2×10^4 to 4.6×10^8 GU L^{-1}), unlike mesophilic digestion (33–37 °C).[8]

Roman *et al*. reported that even conventional WWTPs may be effective if they are designed and operate properly despite the different loading conditions they may receive during the pandemic.[70] In addition to standard physicochemical and biological treatment processes that are typically employed to remove pathogens, advanced oxidation processes may also be efficacious for viral removal. However, the industrial application of such technologies is challenging.[71]

DISINFECTANTS

The SARS-CoV-2 pandemic gave rise to studies on the assessment of various disinfectants targeting different environmental matrices. Disinfection approaches by chemical disinfectants, heat and radiation for the abatement of SARS-CoV-2 have been assessed.[72-74]

Numerous studies have shown the effectiveness of ozone at low residual concentrations and contact time, towards rapid inactivation of different viruses in water and wastewater, with reductions of 4 $\log_{10}$, and thus it is expected that ozone should also be highly effective for the abatement of SARS-CoV-2 in different water matrices.[8] A 99% reduction in corona pseudoviruses has been recorded after exposure to 1000 ppmv ozone for 30 min.[72]

Virucidal efficiency has been verified for chlorine, sodium hypochlorite, benzalkonium chloride and peracetic acid.[64] Totaro *et al*. verified the virucidal efficiency of chlorine dioxide in various environmental matrices; concentrations of 20 mg L^{-1} could eliminate SARS-CoV-2 from sewage.[75] However, sodium hypochlorite was shown to be more effective than chlorine dioxide for SARS-CoV-2 disinfection in sewage.[76] A complete (100%) inactivation of SARS-CoV was achieved in wastewater by chlorine (concentration 10 mg L^{-1}, contact time 10 min, residual chlorine 0.4 mg L^{-1}) and chlorine dioxide (concentration 40 mg L^{-1}, contact time 5 min, residual chlorine 17.59 mg L^{-1}).[74]

Many different disinfectants (i.e., ethanol, 1-propanol, 2-propanol, povidone iodine, glutardialdehyde, formaldehyde) have been shown to be effective towards CoV inactivation by >4 $\log_{10}$, while many others (e.g., hypochlorites, hydrogen peroxide, chlorine dioxide, quaternary ammonium salts, monopersulfates, peracetic acids) are listed by USEPA for the disinfection of SARS-CoV-2.[73]

Milani *et al*. studied the efficiency of disinfection and demonstrated viral inactivation by chlorine dioxide (40 mg L^{-1}, 30 min), ozone (1000 ppmv, 30 min) and UVC (1048 mJ cm^{-2}).[72] Compared to other viruses, coronaviruses are more resistant to UV radiation. Although a dose of 292 mJ cm^{-2} UVA radiation resulted in a limited abatement of SARS-CoV-2 by only 1 $\log_{10}$, a dose of 1048 mJ cm^{-2} UVC radiation totally removed the virus.[72]

Greaves *et al*. studied SARS-CoV-2 disinfection in municipal wastewater primary influent by sodium hypochlorite and found that more than 5 mg L^{-1} was effective for 3 $\log_{10}$ $TCID_{50}$ reduction.[77] Coronaviruses are known to survive longer in low-temperature wastewater.[74] Although different physical, chemical and biological treatment methods have been evaluated, with promising results, further research is needed taking into account numerous parameters (disinfectant concentration, environmental effects, variations of viral load during outbreak peaks, cost, etc).[64]

MEDICAL WASTEWATER

A special management plan is required for hospital wastewater during an outbreak of infectious disease. Such a plan should consider many different issues, including a leak-proof sealed collection system, the application of biological and chemical treatment technology, and the adoption of a medical wastewater quality monitoring accountability system.[78]

Škulcová *et al*. assessed effervescent ferrate tablets based on citric acid or sodium dihydrogen phosphate for the treatment of hospital wastewater. The authors found that this treatment could result in total RNA and DNA destruction with efficiencies of 70–100% and 51–94%, respectively, thus demonstrating the ability to remove SARS-CoV-2 RNA from wastewater and confirming their disinfection potential, with no resistant microorganisms being observed after treatment.[79] Majumder *et al*. reviewed the abatement of SARS-CoV-2 RNA in hospital wastewater by existing treatment facilities. Tertiary treatments (adsorption, ozone, UV, etc.) were required for the abatement of many persistent pollutants, including viruses. In particular, more intensive chlorination or UV treatment was demanded for viral inactivation.[80] Wang *et al*. studied the management, technological and operational issues of hospital wastes and wastewater disinfection in China during the COVID-19 pandemic. Different disinfectants have been used for hospital wastewater treatment (liquid chlorine, chlorine dioxide, sodium hypochlorite, ozone, UV).[81]

Pourakbar *et al*. assessed viral reduction efficiency of two processes – that is, sequencing batch reactor and conventional activated sludge – in a study where all untreated hospital wastewater samples were positive for SARS-CoV-2 RNA. They recorded high levels of viral accumulation in biosolids compared to the liquid phase, and demonstrated the efficiency of the treatment to produce effluents of an acceptable virological quality given the proper function of the WWTPs.[82] Electron beam technology was assessed as an advanced treatment process for hospital wastewater during the pandemic, and its disinfection ability was demonstrated since it was capable of removing pathogenic bacteria and viruses.[83] Recently, secondary treatment effluent was collected from a WWTP in Iran, and the ability of a mixed matrixed membrane (MMM) (polycarbonate (PC)–hydrous manganese oxide and PC–silver nanoparticles) for the abatement of SARS-CoV-2 was evaluated. Results showed that MMMs had the strongest absorption performance during the studied period.[84]

Iwamoto *et al*. studied the ability of a large-scale septic tank employing anaerobic, anoxic and oxic processes in a sequential batch reactor for the abatement of SARS-CoV-2 in wastewater derived from a quarantine facility. The authors showed that most SARS-CoV-2 particles were associated with the suspended solids. Mean $\log_{10}$ reduction values of SARS-CoV-2 were 2.47 (range: 2.25–2.68), demonstrating the efficiency of the treatment system in removing viruses at a comparable or even better level than fecal indicators.[85]

For the treatment of wastewater derived from medical units, quarantine centers, testing facilities and isolation wards, decentralized wastewater treatment units should be used where central treatment facilities do not exist. The adoption of disinfection barriers (single or multiple) has been suggested, using different emerging virucidal agents (chlorine dioxide, benzalconium chloride, performic acid, peracetic acid, sodium dichloroisocyanurate, chloramines), taking into consideration performance, dosage and environmental issues.[9]

NEW TECHNOLOGIES

During the COVID-19 pandemic, emerging wastewater treatment processes have been proposed as promising solutions to address the water quality crisis. Gururani *et al*. suggested the use of cold plasma as a wastewater treatment technique, since its efficiency in removing coronaviruses, and SARS-CoV-2 in particular, has been documented. The authors stressed the need to consider different issues (e.g., investment and operating costs, applicability, sustainability).[86] Advanced membrane technology (membrane distillation, nanocomposite membrane, membrane bioreactor, photocatalytic membrane reactor) has been discussed by Nasir et al. to address water quality problems of microbiological nature.[87] Similarly, Venugopal et al. suggested the application of nanofiber filters as a wastewater pretreatment step.[88] Demarco et al. suggested the use of low-cost biofilters for the abatement of SARS-CoV-2 in water matrices. Significant adsorption was documented resulting in 98.4% removal by the aquatic macrophyte *Hymenachne grumosa* '*in natura*', and 99.6% by *Hymenachne grumosa* with carbon activation (activated carbon produced with *H. grumosa* and zinc chloride impregnation and carbonization), which was comparable to commercial activated carbon (99.7%).[89]

The efficiency of semiconductor photocatalysts towards SARS-CoV-2 disinfection has been reviewed by Kumar *et al*., who also presented commercially available methods for the photo-inactivation of viruses.[90] The applicability of photodynamic inactivation for controlling SARS-CoV-2 in wastewater has been documented by Gomes *et al*., who suggested it as a potential tertiary disinfection method.[91]

Finally, the reliability of using small-scale solar stills during the pandemic has been questioned, since SARS-CoV-2 is known to survive for many days in different water matrices at 4–37°C, while solar stills can be operated at a broad range of temperatures (20–50°C) and even at temperatures less than 20°C.[92]

WASTEWATER TREATMENT IN LOW- AND MIDDLE-INCOME COUNTRIES

Underprivileged societies face more severe risks during the COVID-19 pandemic due to poor sanitation related to nonexistent or deficient wastewater treatment infrastructures, overpopulation, and wastewater and outbreak management strategies.[93-95] The prevalence of SARS-CoV-2 in wastewater, sewage sludge and landfill leachate poses a risk to water resources and threatens public health in marginalized countries.[29] Direct discharge and reuse of raw sewage are common practices in low-income countries.[96] Different actions including cost-effective decentralized wastewater treatment, wastewater community screening of SARS-CoV-2, better sanitation, point-of-use devices for wastewater decontamination and targeted policy interventions have been proposed for low-income countries.[25,97]

In areas with abundant solar energy, solar-assisted disinfection (SODIS) methods are proposed since they are cost effective.[64] However, SODIS systems that usually function at temperatures <45°C and in the UVA and visible part of the solar spectrum are not expected to be efficient, since SARS-CoV-2 is known to be removed at higher temperature (>56°C) and UVC wavelength (100–280 nm).[98]

Moreover, biological wastewater treatment using micro-algae is suggested, since its efficiency for viral removal has been documented.[64] Upflow anaerobic sludge blanket (UASB) reactors are commonly used in many low- and middle-income countries for wastewater treatment, with high-rate algal ponds sustainably applied as post-treatment technology of the UASB effluent. The study of Espinosa *et al*. demonstrated the efficiency of such systems to reduce viral and bacterial indicators from domestic sewage.[99] Additionally, the application of low-cost, point-of-use treatment systems such as ozonation, chlorination and UV irradiation have been proposed for the effective management of SARS-CoV-2 wastewater in Africa.[100]

CLOSING REMARKS

Different factors (viral structure, pH, temperature, wastewater composition) may affect the survival of CoVs in wastewater. SARS-CoV-2 has been found to be particularly sensitive to long retention times, high temperatures and extreme pH values. It is well known that viral survival is substantially very low at wastewater temperatures >20°C, with organic and microbial pollution enhancing their removal. Conventional wastewater treatments can potentially inactivate or remove these viruses. However, additional information on (i) removal efficiencies through the wastewater treatment train, (ii) disinfection requirements according to virus load, specifically during outbreak waves, and (iii) transmission via WWTPs is required for safe wastewater reuse. It should be noted that reports on the prevalence of SARS-CoV-2 in wastewater are mainly based on nucleic acid (RNA) detection, a finding that does not indicate whether these viral particles are intact and infectious, even in the treated wastewater. In general terms, treatment approaches that maximize retention and removal of solids (e.g., membrane bioreactors) have been proven particularly effective in removing wastewater viral loads. Ultrafiltration may be effective in removing SARS-CoV-2 with a diameter of ∼100 nm. However, filtration approaches are focused only on the separation of viral particles, and the pathogens may still remain infective. In addition, this approach is associated with some drawbacks (i.e., energy-intensive and high operational costs, requirements for appropriate disposal of produced virus-contaminated sludge, etc.).

Disinfection of treated wastewater has been identified as the most important step in ensuring reliable SARS-CoV-2 inactivation. Treated wastewater may still be SARS-CoV-2 positive in the case of inefficiency/absence of disinfection. Different disinfectants have been tested with virucidal properties. Chlorine dioxide was found to be less effective for the inactivation of SARS-CoVs than free chlorine. The type of disinfectant, dosage during various viral loads, costs, continuous monitoring of the treated effluents and environmental effects must be considered. Enveloped viruses like CoVs are more sensitive to UV than non-enveloped viruses. However, UVC-induced disinfection is limited by a lack of residual disinfection capacity and drawbacks such as high energy and infrastructure costs.

Although viral RNA was detected in WWTPs influents, it was generally not found in tertiary effluents, indicating that tertiary wastewater treatment processes, such as chlorination and UV irradiation, typically present in the majority of WWTPs, could suffice to remove SARS-CoV-2. Moreover, it should be underlined that published data are generally not directly comparable because of differences in terms of coronavirus strain, use of different indicators, type and volume of water samples, quantity of seeded virus and detection method.

It can be concluded that well-designed and well-functioning WWTPs and on-site reliable sanitation systems (with *in situ* disposal or a network for emptying and discharge to a sewage sludge treatment plant) may significantly limit the risk of different pathogens including SARS-CoV-2. Conversely, sewage water contamination from combined sewer overflows during heavy rainfall may be a threat to humans and the environment due to the dissemination of pathogens and other pollutants. Contamination risks are higher in overpopulated regions, as well as unprivileged regions with total absence or deficient wastewater management systems. The development of cost-effective decentralized water and wastewater treatment facilities for low- and middle-income countries for the abatement of CoVs should be enhanced. Lessons learned during the COVID-19 pandemic regarding wastewater treatment are expected to support an improved detection, response and containment of future viral disease outbreaks.

In a nutshell, risks associated with the presence of coronaviruses in waters and wastewaters are rather limited and can be easily controlled through conventional and hybrid processes that can be synergistically and sustainably integrated into modern WWTPs. Such risks and the associated treatment challenges can be considered comparable to other public health-related issues that have recently emerged, such as antibiotic resistance bacteria and chemical micro-contaminants.

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