



Review

Human viral pathogens in the wastewater-source water-drinking water continuum: Evidence, health risks, and lessons for future outbreaks in low-income settings

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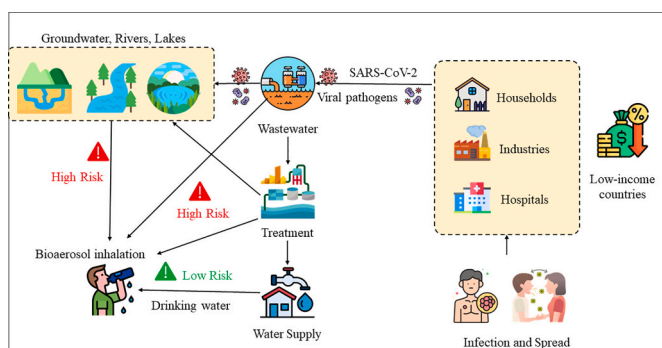
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HIGHLIGHTS

- Viral pathogens in the wastewater-source water-drinking water continuum are reviewed
- Controls of viral circulation in wastewater-water-drinking water system are discussed
- Risky behaviours, drivers, and high-risk environments exist in low-income settings
- Multiple exposure pathways and gender aspects of viral transmission are discussed
- Risk assessment approach, mitigation strategy, and future directions are presented

GRAPHICAL ABSTRACT



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ABSTRACT

Human viral pathogens, including SARS-CoV-2 continue to attract public and research attention due to their disruption of society, global health, and the economy. Several earlier reviews have investigated the occurrence and fate of SARS-CoV-2 in wastewater, and the potential to use such data in wastewater-based epidemiology. However, comprehensive reviews tracking SARS-CoV-2 and other viral pathogens in the wastewater-water-drinking water continuum and the associated risk assessment are still lacking. Therefore, to address this gap, the present paper makes the following contributions: (1) critically examines the early empirical results to highlight the occurrence and stability of SARS-CoV-2 in the wastewater-source water-drinking water continuum, (2) discusses the anthropogenic and hydro(geo)logical processes controlling the circulation of SARS-CoV-2 in the wastewater-source water-drinking water continuum, (3) discusses the risky behaviour, drivers and high-risk settings in the wastewater-source water-drinking water continuum, (4) uses the available empirical data on SARS-CoV-2 occurrence in the wastewater-source water-drinking water continuum to discuss human health risks from multiple exposure pathways, gendered aspects of SARS-CoV-2 transmission via shared on-site sanitation systems, and (5) develops and risk mitigation strategy based on the available empirical evidence and quantitative human risk assessment data. Finally, it presents a comprehensive research agenda on SARS-CoV-2/COVID-19 to guide the mitigation of future similar outbreaks in low-income settings.

1. Introduction and context

A large body of evidence predominantly drawn from developed countries shows that SARS-CoV-2 and its proxies occur and persist in raw wastewater from centralized municipal sewer systems, the dominant sanitation systems in high-income settings. This motivates the application of wastewater-based epidemiology for estimating COVID-19 prevalence in sewered catchments in such settings. However, >4 billion people, mostly in low-income settings in Asia, Africa, Latin America and the Caribbean region, still lack access to centralized municipal sewer systems and clean drinking water supply. Hence, they rely on shared community on-site sanitation and unsafe drinking water supply systems. The lack of advanced multi-barrier systems for wastewater and solid waste management leads to poor wastewater management systems resulting in the discharge of raw and partially treated wastewater into surface water and groundwater systems serving as drinking water supply sources in low-income settings. This increases the risk of community transmission of SARS-CoV-2 and other human pathogens via polluted aquatic environments.

Several reviews exist on SARS-CoV-2 in wastewater and the application of wastewater-based epidemiology to estimate COVID-19 prevalence (e.g., Ahmed et al., n.d.; Randazzo et al., 2020; Hart and Halden, 2020). However, the bulk of these earlier reviews focus on high-income or developed countries where centralized wastewater systems dominate (Hu et al., 2022). A few reviews and perspectives exist focusing on low-income countries (LICs), but these were based on inferential evidence (Adelodun et al., 2020; Gwenzi, 2022a,b; Street et al., 2020). This is because until just recently, no empirical data existed on SARS-CoV-2 in municipal wastewater, shared on-site sanitation systems, and water and drinking water supply systems in low-income settings.

An increasing number of recent studies, including those drawn from low-income settings, have detected SARS-CoV-2 in the following environmental media relevant to low-income settings. This includes (1) municipal wastewater from conventional wastewater treatment systems (Kumar et al., 2020; Pillay et al., 2021), (2) shared on-site sanitation systems such as septic tanks and pit latrines (Amoah et al., 2021; Del Brutto et al., 2021a,b; Liu et al., 2021; Zhang et al., 2020), and (3) raw source water (surface water and groundwaters) impacted by wastewaters (Guerrero-Latorre et al., 2020; Maidana-Kulesza et al., 2021; Mahlknecht et al., 2021; Rimoldi et al., 2020; Kolarević et al., 2021). Source water refers to bodies of surface water (e.g., lakes, streams, rivers, and reservoirs) as well as groundwater (e.g., springs, wells, and boreholes) that provide water to public and private drinking water supplies (CDC, 2022; Liu et al., 2024b). Yet until now, a comprehensive review of these recent early results and their implications on SARS-CoV-2 transmission and human health risks in low-income settings is still

lacking (Hu et al., 2024). Therefore, the availability of early results on SARS-CoV-2 in municipal wastewater, shared on-site sanitation systems and water and drinking water systems present an opportunity for a more nuanced analysis of the human exposure and health risks via multiple exposure routes (Lan et al., 2022).

The present review posits that wastewater from municipal and shared on-site sanitation systems, surface water and groundwater systems and drinking water supply systems in low-income settings are characterized by strong spatial and temporal hydrological connectivity. This hydrological connectivity, which facilitates faecal and SARS-CoV-2 contamination of surface water and groundwater systems, occurs via (1) accidental and illegal discharges and spillages of raw and partially treated municipal wastewaters, (2) infiltration and groundwater recharge by effluents and seepages from on-site sanitation systems, and (3) surface water-groundwater interactions. Thus, the wastewater-source water-drinking water systems constitute a SARS-CoV-2 continuum, facilitating the circulation and transmission of SARS-CoV-2 and other pathogens to humans.

In the present paper, we present the empirical and inferential evidence on the occurrence and fate of SARS-CoV-2 and other human viral pathogens in municipal wastewaters from typical wastewater treatment systems used in low-income settings, on-site sanitation systems, surface water and groundwater, and drinking water supply systems. Fig. 1 shows the low-income countries where viral pathogens were detected in wastewater, source water and drinking water systems. Then, potential human health risks and appropriate mitigation of SARS-CoV-2 in the wastewater-source water-drinking water continuum are discussed.

Future perspectives and research needs are presented focusing on (1) weak quantitative evidence linking SARS-CoV-2 in wastewater, source water and drinking water to specific human health outcomes in terms of infection, morbidity and mortality, (2) the need for further empirical evidence on SARS-CoV-2 occurrence and stability in wastewaters, water and drinking water systems in low-income settings such informal settlements, (3) source tracking of SARS-CoV-2 and its proxies in the wastewater-source water-drinking water continuum, (4) human health exposure and health risk assessment based on quantitative microbial risk assessment (QMRA) and disability-adjusted life years (DALYs) approach, and (5) opportunities and constraints offered by emerging analytical and monitoring tools. This includes prospects to develop and validate environmental surveillance of SARS-CoV-2 using municipal wastewaters, shared on-site sanitation systems, raw surface water and groundwater, and drinking water supply systems.

The present review uses the Source-Pathway-Receptor-Impact-Mitigation (SPRIM) framework to track the occurrence, and human exposure and health risks along the wastewater-source water-drinking water continuum in low-income settings. Compared to studies focusing

on one aspect (e.g., occurrence and persistence), the SPRIM framework allows a more comprehensive analysis of the exposure and health risks and their mitigation, focusing on the wastewater-source water-drinking water continuum.

Therefore, the objectives of this paper are to:

- (1) Critically examine the early empirical results to highlight the occurrence and stability of SARS-CoV-2 and viral pathogens in the wastewater-source water-drinking water continuum,
- (2) Discuss the anthropogenic and hydro(geo)logical processes controlling the circulation of SARS-CoV-2 and viral in the wastewater-source water-drinking water continuum.
- (3) Discuss the risky behaviours, drivers and high-risk settings in the wastewater-source water-drinking water continuum.
- (4) Present a risk assessment and mitigation strategy based on the available empirical evidence.
- (5) Present future research directions on SARS-CoV-2/COVID-19 and viral pathogens in low-income settings.

2. SARS-CoV-2 and other viral pathogens in wastewater-source water-drinking water continuum

The unhindered human-environmental interactions have continued to promote the pathogenic contamination of water systems. The prevalence of human pathogenic viruses (HPVs), including both enveloped and non-enveloped viruses, and their fate in the water environment, have become a serious health concern, especially with the scourge of the SARS-CoV-2 pandemic. Viruses are regarded as one of the most hazardous pathogens in wastewater, with low infectious doses sufficient to cause infections among the vulnerable population (Karimzadeh et al., 2021; Okoh et al., 2007). The microscopic size of viruses (22–140 nm) and their surface properties facilitate their easy transport in different environmental media while exhibiting high infectivity and disinfection resistance (Anand et al., 2021; Xagorarakis et al., 2014). The monitoring of these viruses, including their presence and fate in water environments, such as in wastewater, surface water, groundwater, and drinking water systems, is critical to assess the microbiological quality and safety of the water used for various functions (Adelodun et al., 2021c). Besides, the prevalence of HPVs and the associated indicators in water media can dictate the spread of viral diseases in a community using an approach called wastewater-based-epidemiology (Daughton, 2020; Kumar et al., 2020; Randazzo et al., 2020; Scott et al., 2021).

While wastewater, especially from urban settlements, is subjected to

different treatment processes before being reused for domestic and agricultural purposes or discharged into the environment, several studies have reported the prevalence of viruses before and after the subjected treatments (Adelodun et al., 2022; Tanhaei et al., 2021), indicating the recalcitrant nature of the viruses in different water media. The prevalence of SARS-CoV-2 and other viral pathogens and the associated health risks are more complex in low-income settings due to the inadequate availability of and accessibility to good water, sanitation, and hygiene (WASH) in the form of clean drinking water supply and centralized municipal sewer systems (Adelodun et al., 2020; Donde et al., 2021; Gwenzi, 2021; Street et al., 2020). Thus, this could exacerbate the risk of community transmission of SARS-CoV-2 and other human pathogens and subsequently spread the disease among the population. The fate of SARS-CoV-2 in wastewater-source water-drinking water continuum is, however, not yet fully developed as various factors affect the survival of HPVs, especially the enveloped viruses like SARS-CoV-2 in the water systems. Understanding the behaviour and survival of the HPVs as they transcend the boundaries of different water systems could aid in mitigating the transmission of the viruses and the associated health risks of human exposure. Fig. 2 shows the occurrence of viral pathogens in the wastewater-source water-drinking water continuum.

Note that the main transmission route of SARS-CoV-2 occurs via inhalation, not ingestion. Therefore, quantitative microbial risk assessment was limited to wastewater and surface water, while excluding drinking water. However, in Section 2.4 of the present paper, there are data and discussions about the potential human health hazards of viral polluted drinking water.

2.1. SARS-CoV-2 and other viral pathogens detection and fate in wastewater

HPVs, including the recently discovered SARS-CoV-2, have been identified in wastewater in different countries (Fig. 1). While the majority of the reported cases are from high-income and developed countries, studies with quantitative data on the occurrence and fate of SARS-CoV-2 are limited in LICs despite the vulnerability of the population to contracting the viral infections and waterborne related diseases (Adelodun et al., 2021b); thus, creating a significant knowledge gap in low-income settings. Nevertheless, emerging studies from selected LICs with data on the presence and fate of SARS-CoV-2 and other viral pathogens in wastewater can provide clues for understanding the behaviours of the viruses in such settings (Gwenzi, 2022). Before the emergence of SARS-

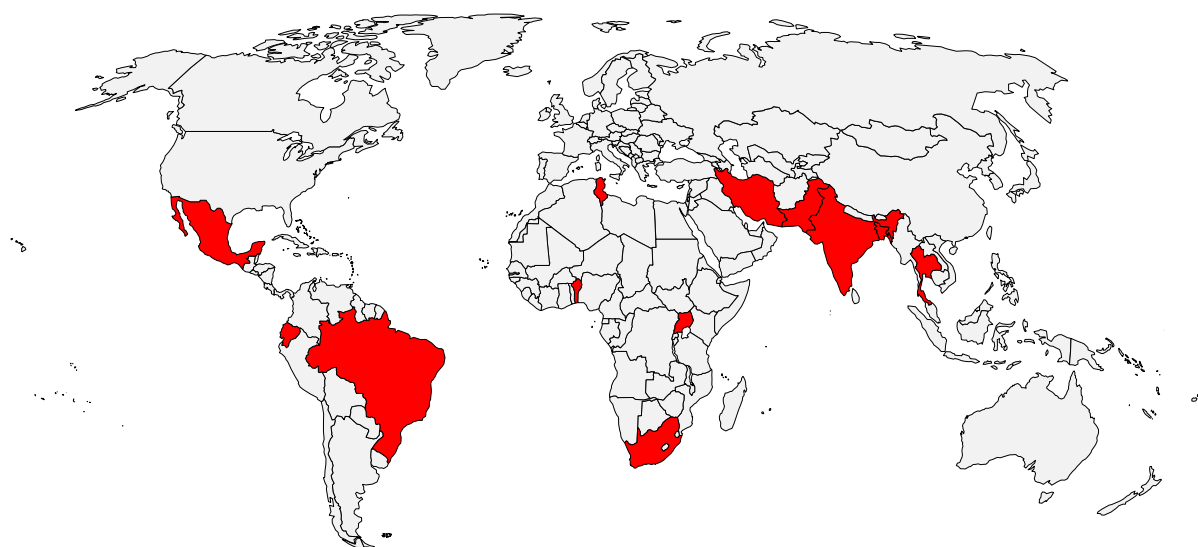


Fig. 1. Map of low-income countries reporting viral pathogens in the wastewater-source water-drinking water systems. Based on data in Tables 1–4.

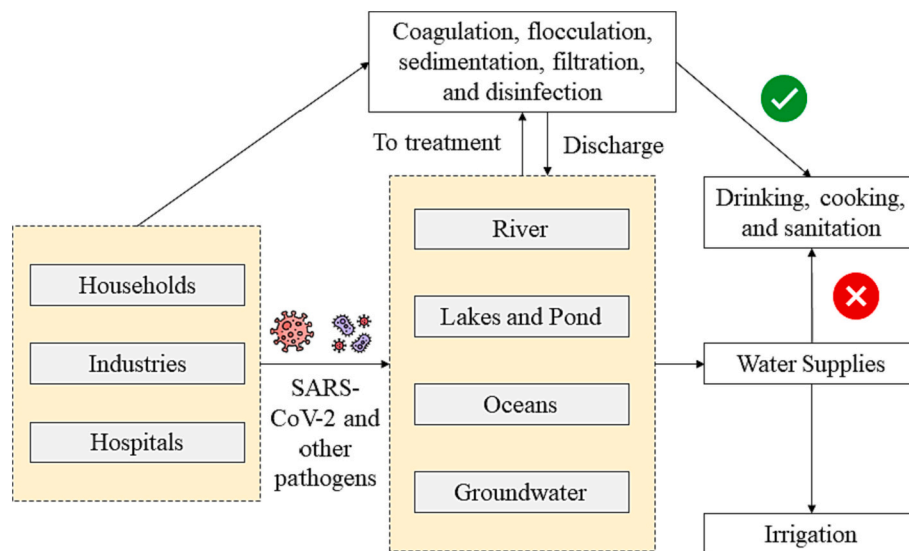


Fig. 2. Viral occurrence in the wastewater- source water-drinking water systems indicating potential points to control viral transmission via water treatment.

CoV-2, the most commonly detected pathogenic viruses in wastewater of low-income settings included human adenoviruses (HAdV), rotaviruses (RoV), enteroviruses (EV), noroviruses (NoV), and hepatitis A viruses (HAV), among many others (Kuodi et al., 2020; O'Brien et al., 2017; Okoh et al., 2010). These viruses are excreted through human faeces and subsequently concentrated in the wastewater system, where they are expected to be disinfected and removed. However, some studies have reported the detection of these viruses, not only in the influents but also, from the effluents of wastewater treatment plants (WWTPs), with many of the studies reporting detection rates above 40 % (Table 1).

The detection of SARS-CoV-2 RNA has recently been reported in wastewater in LICs. In a study conducted in India, the three genes (ORF1ab, N, and S) of SARS-CoV-2 RNA were detected in all the collected influent samples from a WWTP located in Ahmedabad, which is regarded as the largest in Asia with a capacity of 180 m³ per day (Kumar et al., 2020). However, the viral particles were not found in the effluents, which was attributed to the advanced treatment processes of up-flow anaerobic sludge blanket and aeration pond in the plant. Another study from Ahmedabad reported about 95 % (111/116) detection rate of SARS-CoV-2 RNA from the influents of wastewater sampled from pumping stations and treatment plants for thirteen weeks (September to November 2020) to confirm the temporal pattern of the virus detection and diseases incidence (Kumar et al., 2021). Similarly, In Iran, wastewater samples collected from sewage manholes had 100 % and 75 % detection rates of the N and ORF1ab genes of SARS-CoV-2 viral RNA, respectively (Rafiee et al., 2021). Arora et al. also reported the detection of SARS-CoV-2 RNA (S, E, ORF1ab, RdRp, and N genes) from untreated samples from WWTPs and hospital wastewater taken under the ambient temperature of 45 °C in Jaipur City, India (Arora et al., 2020).

Contrary to the negative detection of SARS-CoV-2 RNA in the outlet samples of the treatment plants, Tanhaei et al. (2021) investigated the detection of SARS-CoV-2 RNA in both raw and treated wastewater samples in Tehran, Iran. The treated wastewater samples had an 80 % detection rate of the viral RNA (ORF1ab and N genes). Also, Chakraborty et al. (2021) examined the detection of SARS-CoV-2 RNA in influent and sludge samples of treatment plants and pumping stations from Chennai City in India and hospital wastewater from the city's suburb. An elevated concentration of the viral particles was detected in the influent, sludge, and samples from the pumping station compared to the hospital wastewater samples. These results support the existing literature on the possible partitioning of enveloped virus in solid phase medium due to high levels of dissolved and suspended solids in sludge samples

(Adelodun et al., 2022). Meanwhile, Nasseri et al. (2021) also studied the detection of viral particles in raw and treated wastewater from three WWTPs that used different treatment disinfection methods from three cities (Tehran, Qom, and Anzali) in Iran, with all the influent samples showed positive detection rate (12/12). However, all the treated wastewater samples (14) subjected to ultraviolet disinfectant showed negative detection of the SARS-CoV-2 RNA, except for two samples collected from the treatment plant using chlorine as a disinfectant, which could be attributed to the inappropriate disinfectant dose or faulty operation and lack of maintenance of the treatment plant (Adelodun et al., 2022; Nasseri et al., 2021).

The quantification of SARS-CoV-2 RNA concentrations in wastewater samples has also been carried out in some LICs (Table 1). A viral load of up to 1.0×10^7 copies/L was detected in the wastewater samples collected from drains near the isolation centre for COVID-19 patients in Bangladesh (Ahmed et al., 2021). Similarly, in seven regions of Tunisia, the range of viral load detected from the sampled wastewater was 1.8×10^3 – 6.0×10^5 copies/L (Jmii et al., 2021). In a recent study conducted in Iran, a high viral particle load (4.0×10^1 – 4.5×10^4 copies/L) was reportedly present in the influent samples collected from seven WWTPs between September 2020 to April 2021 in Tehran (Amereh et al., 2022). Also, in Africa, a high viral load of up to 7.3×10^6 copies/L was detected in wastewater samples from centralized municipal sewer systems in South Africa (Pillay et al., 2021). Other LICs where the studies on the quantification of SARS-CoV-2 RNA concentration from wastewater have been conducted include India and Pakistan (Table 1).

The virus concentration and recovery methods, and targeted genes, play important roles in detecting the virus in wastewater (Adelodun et al., 2022). Differences in the detection and recovery of both enveloped and non-enveloped viruses have been reported, with the information on the SARS-CoV-2 as an enveloped virus still evolving (Tanhaei et al., 2021). The concentration and recovery methods used for the SARS-CoV-2 in wastewater include centrifugal ultrafiltration, polyethylene glycol (PEG) precipitation, aqueous two-phase PEG/dextran method, adsorption-extraction technique utilizing electronegative membrane, flocculation with beef extract solution, and aluminium hydroxide adsorption-precipitation technique; real-time reverse transcription polymerase chain reaction (RT-PCR) or droplet digital polymerase chain reaction (dd-PCR) is often used for the detection. Rafiee et al. (2021) observed different results by comparing three sampling methods such as Moore swabs, composite (16-h), and grab sampling for sewage manholes. The Moore swabs and composite sampling schemes had the same performance level for qualitative monitoring with

Table 1

Detection and treatment systems of SARS-CoV-2 and other human viral pathogens in wastewaters of low-income countries. NR: Not recorded.

Virus type	Media/sample	Location (settings)	Concentration (genome copies/L) and positive samples		Treatment system/process	Reference
			Influent	Effluent		
SARS-CoV-2 RNA	WWTP/ influent and effluent	Ahmedabad, India (Urban)	5.6×10^1 – 3.5×10^2 (100 % detection rate)	Negative	Up-flow Anaerobic Sludge Blanket and aeration pond	(Kumar et al., 2020)
SARS-CoV-2 RNA	Pumping station and WWTP/ influent	Ahmedabad, India (Rural and Urban)	4.5×10^2 – 1.1×10^4 (96 % detection rate) Pump station: 1.5×10^4 – 2.0×10^4 (100 % detection rate (5/5))	NR	Not indicated	(Kumar et al., 2021)
SARS-CoV-2 RNA	Treatment plant, pumping stations /influent and sludge	Chennai, India (Urban)	Treatment plant: 9.7×10^4 – 2.0×10^5 (100 % detection rate (4/4))	Negative	Not indicated	(Chakraborty et al., 2021)
SARS-CoV-2 RNA	WWTP/ influent	KwaZulu-Natal, South Africa	0 – 7.3×10^6	NR	Not indicated	(Pillay et al., 2021)
SARS-CoV-2 RNA	Wastewater/influent	Seven regions in Tunisia (Urban)	1.8×10^3 – 6.0×10^5 (26 % detection rate)	NR	Not indicated	(Jmii et al., 2021)
SARS-CoV-2 RNA	Pumping station and WWTP/ influent and effluent	Lahore, Pakistan (Town)	2.7×10^5 – 3.6×10^7 (22/28 samples tested positive)	6.0×10^3 5.4×10^5	Not indicated	(Yaqub et al., 2021)
SARS-CoV-2 RNA	WWTP/ influent and effluent	Bangkok, Thailand (Urban)	5.8×10^2 – 2.2×10^5	Negative or below detection level	Activated sludge processes	(Sangsanont et al., 2022)
SARS-CoV-2 RNA	WWTP/ influent	Isfahan, Iran (Urban)	2.0×10^4 – 4.0×10^4 (37.5 % (9/24) detection rate)	NR	Activated sludge processes	(Gholipour et al., 2021)
SARS-CoV-2 RNA	WWTP/ influent and effluent	Tehran, Iran (Urban)	1.1×10^6 (100 % (1/1) detection rate)	7.2×10^4 – 1.1×10^6 (80 % detection rate in 8 out of 10 samples)	Not indicated	(Tanhaei et al., 2021)
SARS-CoV-2 RNA	WWTP/ influent	Tehran, Iran (Urban)	4.0×10^1 – 4.5×10^4 (100 % detection rate of RNase P gene (91/91))	NR	Not indicated	(Amereh et al., 2022)
SARS-CoV-2 RNA	WWTP and sewer network/ wastewater	Rio de Janeiro, Brazil.	5 of the 12 samples (41.6 % detection rate)	NR	Not indicated	(Prado et al., 2020)
SARS-CoV-2 RNA	Surface water reservoir/ water	Monterrey, Mexico (Urban)	3.5×10^6 (38 % detection rate (3/8))	NR	Not indicated	(Chakraborty et al., 2021)
Human adenovirus	WWTP/ raw, treated, and sewage sludge	Egypt (Urban)	8.7×10^8 – 4.3×10^9 (84 % detection rate)	1.2×10^7 – 3.7×10^9 (50 % detection rate) 1.5×10^9 – 1.8×10^{10} (78 % detection rate) for sludge	Conventional treatment	(Elmahdy et al., 2019)
Rotavirus	WWTP/Effluent	Eastern Cape, South Africa (Urban)	NR	1.6×10^1 – 5.2×10^3 (41.7 % detection rate)	Bio-filter/PETRO (pond enhanced treatment and operation) with chlorine disinfection	(Osuolale and Okoh, 2017)
Rotavirus	WWTP/Effluent	Eastern Cape, South Africa (Urban)	NR	1.9×10^3 to 1.2×10^5 (41.7 % detection rate)	Activated sludge system with chlorine disinfection	(Osuolale and Okoh, 2017)
Rotavirus	WWTP/Effluent	Eastern Cape, South Africa (Urban)	NR	4.05×10^2 (9 % detection rate)	Bio-filter system with chlorine disinfection	(Osuolale and Okoh, 2017)
Human adenovirus	WWTP/Effluent	Eastern Cape, South Africa (Urban)	NR	1.05×10^1 to 1.10×10^4 (41.7 % detection rate)	Activated sludge system with chlorine disinfection	(Osuolale and Okoh, 2015)
Human adenovirus	WWTP/discharge point	Eastern Cape, South Africa (Urban)	NR	1.2×10^1 and 2.8×10^4 (54.5 % detection rate)	Activated sludge system with chlorine disinfection	(Osuolale and Okoh, 2015)
Human adenovirus	WWTP/Effluent	Eastern Cape, South Africa (Urban)	NR	7.92×10^1 – 2.37×10^5 (91.7 % detection rate)	Bio-filter/PETRO (pond enhanced treatment and operation) system with chlorine disinfection	(Osuolale and Okoh, 2015)
Human adenovirus	WWTP/Effluent	Eastern Cape, South Africa (Urban)	NR	5.32×10^1 – 2.20×10^5 (75 % detection rate)	Activated sludge system with chlorine disinfection	(Osuolale and Okoh, 2015)
Human adenovirus	WWTP/Effluent	Eastern Cape, South Africa (Urban)	NR	1.23×10^3 – 1.05×10^4 (66.7 % detection rate)	Both activated sludge and bio-filter systems with chlorine disinfection	(Osuolale and Okoh, 2015)
Human adenovirus	WWTP/Effluent	Eastern Cape of South Africa (Urban)	NR	1.08×10^1 – 5.16×10^4 (54.5 % detection rate)	Bio-filter system with chlorine disinfection	(Osuolale and Okoh, 2015)
Hepatitis A virus	WWTP/ raw and treated sewage sludge	Rio de Janeiro, Brazil (Urban)	1.2×10^5 – 8.9×10^5 (32 % detection rate)	1.7×10^5 – 3.8×10^5 (96 % detection rate)	Sedimentation and activated sludge	(Villar et al., 2007)
Hepatitis A virus	WWTP/ raw and treated effluents	Rio de Janeiro, Brazil (Urban)	3.7×10^6 (58 % detection rate)	Not detected	Sedimentation with an aerobic process using conventional activated sludge	(Prado et al., 2012)

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Table 1 (continued)

Virus type	Media/sample	Location (settings)	Concentration (genome copies/L) and positive samples		Treatment system/process	Reference
			Influent	Effluent		
Human adenovirus	WWTP/ influent and effluent	Southwest Kampala, Uganda (Urban)	3.33×10^6 – 1.8×10^7	1.67×10^6 – 1.98×10^7	Conventional activated sludge	(O'Brien et al., 2017)
Enterovirus	WWTP/ influent and effluent	Southwest Kampala, Uganda (Urban)	4.73×10^6 – 8.13×10^7	1.25×10^6 – 2.12×10^7	Conventional activated sludge	(O'Brien et al., 2017)
Rotavirus	WWTP/ influent and effluent	Southwest Kampala, Uganda (Urban)	4.22×10^2 – 3.77×10^3	5.79×10^1	Conventional activated sludge	(O'Brien et al., 2017)
Hepatitis A virus	WWTP/ influent and effluent	Southwest Kampala, Uganda (Urban)	2.01×10^3 – 8.39×10^3	1.93×10^3 – 8.70×10^3	Conventional activated sludge	(O'Brien et al., 2017)
Hepatitis A virus	WWTP/ Sewage sludge	Rio de Janeiro, Brazil (Urban)	1.2×10^5 – 8.9×10^5	1.7×10^5 – 3.8×10^5	Sedimentation and activated sludge	(Villar et al., 2007)
Human adenovirus	WWTP/ effluent	Stutterheim, Eastern Cape Province, South Africa (Urban)	NR	8.4×10^1 – 1.3×10^5	Conventional activated sludge and chlorination	(Adefisoye et al., 2016)
Human adenovirus	WWTP/ effluent	Keiskammahoek, Eastern Cape Province, South Africa (Urban)	NR	2.3×10^2 – 6.6×10^4	Conventional activated sludge and chlorination	(Adefisoye et al., 2016)
Hepatitis A virus	WWTP/ influent and effluent	Kairouan, Tunisia (Urban)	6.7×10^4 – 5.8×10^6	7.2×10^4 – 5.0×10^5	Secondary biological treatment with aeration oxidation ditch activated sludge (low charge)	(Ouardani et al., 2016)
Hepatitis A virus	WWTP/ influent and effluent	Tunisia (Urban)	3.52×10^5	2.56×10^5	Aerated pond system and activated sludge	(Béji-Hamza et al., 2014)
Hepatitis A virus	WWTP/ influent and effluent	Kasserine, West-central Tunisia (Rural)	6.67×10^6 – 2.4×10^8	7.7×10^5 – 1.17×10^7 (38.89 % detection rate)	Biological treatment with optional lagoon aerated process	(Ouardani et al., 2015)

a 100 % detection rate (34/34) of the SARS-CoV-2 RNA; it was more consistent and sensitive than the corresponding grab sample following the polyethylene glycol precipitation concentration method and targeting N and ORF1ab genes. Furthermore, Chakraborty et al. (2021) found that wastewater viral concentration by supernatant extraction is more effective than sediment, composite or syringe filtration. These variations in the methodologies could also account for the differences in the detection of SARS-CoV-2 in the wastewater samples. Furthermore, Amereh et al. (2022) opined that differences in results from different studies could be attributed to the severity and rate of faecal shedding in wastewater, viral particles recovery efficiency from sewage samples, and possible losses of the viral RNA in sewage pipes and during the experiment. The Moore swab sampling and centrifugation concentration method are suggested for disease surveillance in LICs considering their sensitivity, simplicity, and affordability (Rafiee et al., 2021).

The survival of SARS-CoV-2 and other HPVs outside the living host, especially in water environments like wastewater, depends on the temperature, pH, relative humidity, presence of organic matter, and exposure to light, among other environmental factors. A previous investigation on the inactivation of SARS-CoV-2 in urban and hospital wastewaters showed that the virus maintained its virulence for up to 14 days at low temperatures (4 °C) but was inactivated after only two days at a higher temperature of 20 °C (Wang et al., 2005). Gundy et al. (2009) demonstrated significant inactivation (99 %) of the human coronavirus 229E at 23 °C in urban primary and secondary WWTPs for 2.36 and 1.85 days, respectively. SARS-CoV-2 was found to maintain its viability for more than five days on contaminated surfaces at 22 to 25 °C and 40–50 % relative humidity (Chan et al., 2011). Similarly, the use of more residual chlorine (> 0.5 mg/L) or chlorine dioxide concentration of 2.19 mg/L completely inactivated SARS-CoV-2 in 30 min (Wang et al., 2005). It has been reported that ultraviolet light, temperatures above 23 °C, appropriate dose, and retention and contact time of disinfectant could inactivate SARS-CoV-2, while the abundance of organic materials could enhance the virus' survival by providing adsorbent surfaces (Adelodun et al., 2022; Collivignarelli et al., 2020; WHO, 2020b). This has been demonstrated by Chin et al., where the virus resistance declined from 7 days to 1 day with a temperature change from 22 °C to 70 °C (Chin et al., 2020). Randazzo et al. (2020) also used NaClO and UV as disinfectants during tertiary treatment in a WWTP, achieving complete inactivation of

SARS-CoV-2. However, a later study reported that the new SARS-CoV-2 (B.1.1.529) variant had higher environmental stability and virulence compared to other variants of the virus, indicating a concern for its extended survival outside living hosts (Hirose et al., 2022; NICD, 2021). This variant was named omicron (a variant of concern) by the WHO (2021), and first detected in South Africa.

Several studies have investigated the impact of various wastewater treatment unit processes on the fate of viruses, including SARS-CoV-2 (Masindi et al., 2021). However, the results appear to vary significantly among studies, potentially due to differences in the design and operational conditions of the unit processes. For instance, a comprehensive study conducted in South Africa detected SARS-CoV-2 genomes exclusively in the primary settling tanks, with none found in the source water (dams, rivers) and drinking water within the same catchment (Masindi et al., 2021). These findings suggest that most SARS-CoV-2 viral genomes were effectively eliminated through primary settlement with the sludge. One study conducted in two wastewater treatment plants in Mexico also showed secondary sludge had a higher SARS-CoV-2 RNA concentration than influent wastewater, indicating that viral RNA becomes enriched in the activated sludge (Carrillo-Reyes et al., 2021). Another study investigating the impact of different temperatures and solid contents on the viability of SARS-CoV-2 in wastewater and river water revealed that the virus's viability was longer in filtered than in unfiltered samples, indicating that the presence of solids promoted the persistence of the virus (Oliveira et al., 2021). Further studies investigating the effects of advanced wastewater treatment processes demonstrated their effectiveness in removing SARS-CoV-2 RNA (Randazzo et al., 2020). One study conducted on six wastewater treatment plants in the region of Murcia in Spain determined SARS-CoV-2 RNA titres in influent, secondary and tertiary treated effluent wastewater samples (Randazzo et al., 2020). The results showed that; (1) all untreated wastewater samples tested positive with average concentrations of $5.4 \pm 0.2 \log_{10}$ genomic copies/L, (2) only 2 out of 18 secondary water samples, equivalent to 11 % tested positive, while (3) all 12 tertiary water samples tested negative for SARS-CoV-2 RNA. These results indicate that the trends of SARS-CoV-2 RNA titres decreased with increasing levels of treatment. However, in China, SARS-CoV-2 RNA was identified in medical wastewater sampled from a septic tank even after disinfection with 800 g/m³ sodium hypochlorite (Zhang et al., 2020).

The presence of SARS-CoV-2 RNA after chlorination of raw medical wastewater could be attributed to the absence of free chlorine in the effluent. Comprehensive reviews on the fate of SARS-CoV-2 in aquatic systems, including wastewaters, are available elsewhere in the literature (Gwenzi, 2021; Saawarn and Hait, 2021; Foladori et al., 2022; Balboa et al., 2021).

2.2. SARS-CoV-2 and viral pathogens in on-site sanitation systems

On-site sanitation has become a common phenomenon in LICs. Informal settlements, including isolation centre for COVID-19 patients essentially depended on the shared on-site sanitation facilities, with sewage from these settings mostly not treated before discharging into the environment (Gwenzi, 2022). For instance, the percentages of households from Mali in sub-Saharan Africa, Philippines in Asia, and in Latin America that are not connected to a central sewerage system are 98 %, 98 %, and above 50 %, respectively (Strauss et al., 2006), while countries like India, Vietnam, Pakistan, Philippines, and Indonesia are only able to treat about 37 %, 10 %, 8 %, 4 %, and 1 %, respectively, of their wastewaters (Pandey et al., 2021). Another study shows that <10 % of the generated septage is reportedly treated in countries like Vietnam, Indonesia, and the Philippines (World Bank Group, 2013). Meanwhile, on-site treatment and disposal of faecal sludge and septage to satisfactory or acceptable standards have also become a serious health concern in many LICs. It was reported that the unsafe management of 80 % of faecal sludge generated in the cities of Dhaka and Khulna in Bangladesh led to environmental faecal contamination from exposure to partially treated and untreated faecal sludge (Amin et al., 2019).

Available data showed that the top ten countries that overtly rely on open defecation and other non-sewered sanitation systems are in sub-Saharan Africa (UNICEF and WHO, 2019). In Ghana, for instance, it was reported that open defecation is practised by more than one in every five households (Adzawla et al., 2020). Shared sanitation systems such as pit latrine are very common in many densely populated urban settlements of LICs, with 16 % of the population depending on shared sanitation (Rheinländer et al., 2015). For example, pit latrines account for 53 % of the toilet facilities in informal settles in South Africa

(Mutymbizi et al., 2020), while 67 % of the toilet facilities in Kampala, the capital city of Uganda, is shared pit latrine with lack of handwashing facilities (Ssemugabo et al., 2021), despite the critical role of handwashing with soap in mitigating the transmission of the SARS-CoV-2 and other viral pathogens (Donde et al., 2021). Also, countries like Bangladesh, Mongolia, and the Philippines have over 15 % of their population solely depending on all forms of shared sanitation (UNICEF and WHO, 2014). The situation is worrisome in sub-Saharan Africa, which has the highest population proportion (19 %) of multi-households using shared sanitation, among which the urban population stands at 33 %, with this figure increasing daily (Morella et al., 2008; Rheinländer et al., 2015; Street et al., 2020; Susmita et al., 2018). Elimination open defecation and providing adequate and equal access to sanitation and hygiene have been an ambitious aim of the UN sustainable development goal (SDG) 6 by 2030 (WHO, 2014). The detection of SARS-CoV-2 and other viral pathogens have been reported in on-site sanitation, which are often impacted by untreated wastewater discharge and faecal pollution (Table 2).

The SARS-CoV-2 virus and other HPVs, after being excreted in human faeces, are released into the on-site sanitation facilities (Amereh et al., 2022). The surfaces, wastewater, and the air in the on-site sanitation, especially which lack adequate sanitation and are often shared by multi-households, can easily be contaminated by viral pathogens (Amoah et al., 2021; Del Brutto et al., 2021a; Gholipour et al., 2021; van Doremalen et al., 2020). Amoah et al. (2021) reported the presence of SARS-CoV-2 RNA up to 1.3×10^2 gene copies/cm² on different surfaces of on-site sanitation facilities in South Africa. The faecal contamination of surfaces could promote a high risk of viral infections like COVID-19 (Amoah et al., 2021). Gholipour et al. (2021) reported a medium infection risk from exposure to SARS-CoV-2 RNA-contaminated wastewater and aerosols in a LIC (Iran) when compared to the baseline of infection risks proposed by EPA and WHO. Liu et al. (2021) also demonstrated the mechanism of possible transmission of SARS-CoV-2 from contaminated excreta in pit latrines to potential animal hosts in rural areas of China. Moreover, on-site sanitation, such as pit latrines has made it difficult to adequately treat or disinfect sewage from any pathogenic contamination to prevent further migration into surface

Table 2
Presence of SARS-CoV-2 in on-site sanitation systems of low-income countries.

Virus type	Media/sample	Location (settings)	Concentration (genome copies/L) and Positive samples (%)	Findings of faecal sludge contamination evidence	Reference
SARS-CoV-2	Contact surfaces/ swab samples	South Africa (Peri-urban)	2.8×10^4 – 1.3×10^5 (54–69 % detection rate)	The presence of faeces and urine on the shared toilet seats promotes the prevalence of SARS-CoV-2 RNA	(Amoah et al., 2021)
SARS-CoV-2	Isolation ward/ raw sewage	Bangladesh (Urban and rural)	1.0×10^3 – 1.0×10^7	The presence of SARS-CoV-2 is impacted by the faecal pollution and low sanitation	(Jakariya et al., 2021)
SARS-CoV-2	Latrine/swab sample	Atahualpa, Ecuador (Rural)	50 % detection rate (24/48)	The use of shared latrine promotes the prevalence of SARS-CoV-2 RNA due to faecal contamination of surfaces	(Del Brutto et al., 2021a)
SARS-CoV-2 RNA	Isolation centre drains/ wastewater	Noakhali, Bangladesh	8.6×10^6 – 1.0×10^7 (75 % detection rate (12/16))	The presence of SARS-CoV-2 is impacted by the faecal pollution and low sanitation	(Ahmed et al., 2021)
SARS-CoV-2 RNA	Hospital wastewater	Chennai, India (suburbs)	4.3×10^5 – 1.6×10^6 (85 % detection rate)	The presence of SARS-CoV-2 is impacted by the faecal pollution and low sanitation	(Chakraborty et al., 2021)
SARS-CoV-2 RNA	Presidio and workers accommodation/ raw sewage	Minas Gerais State region, Brazil (Rural)	Presidio: 1.3×10^7 Workers' accommodation: 4.3×10^7	The presence of SARS-CoV-2 is impacted by the faecal pollution and low sanitation	(Fongaro et al., 2021)
SARS-CoV-2 RNA	Sewage manhole/ wastewater	Tehran, Iran (Urban)	4.0×10^1 – 4.5×10^3 (detection rate of 100 % and 81 % for N and ORFlab genes, respectively)	The presence of SARS-CoV-2 is impacted by the faecal pollution and low sanitation	(Rafiee et al., 2021)
SARS-CoV-2 RNA	Sewage pumping station/ air sample	Isfahan, Iran (Urban)	5 – 1.9×10^2 (40 % (6/15) detection rate)	Virus-contaminated aerosol impacted by the wastewater	(Gholipour et al., 2021)
SARS-CoV-2 RNA	Drain near COVID-19 isolation centre/ wastewater	Guwahati, India	5.6×10^3	The presence of SARS-CoV-2 is impacted by the faecal pollution and low sanitation	(Kumar et al., 2022)

water and groundwater systems. Meanwhile, these water systems are often used, especially in rural areas of LICs, for domestic and agricultural activities without any advanced treatment processes (Adelodun et al., 2021b).

The use of pit latrines and open cesspools as form of sanitation systems in rural settings and LICs has been suggested to facilitate the spread of SARS-CoV-2 and other waterborne pathogens via exposure to the virus-contaminated excreta (Del Brutto et al., 2021b; Jakariya et al., 2021; Liu et al., 2021). The available data on the existing status of sanitation systems and hygiene pointed to potential associated risks of faecal-oral transmission of SARS-CoV-2 and other pathogenic viruses in LICs (Adelodun et al., 2020; Guerrero-Latorre et al., 2020; Pandey et al., 2021). Del Brutto et al. (2021b) demonstrated a high level of seroprevalence of SARS-CoV-2 (45 %) in rural settings of Ecuador due to the poor state of on-site sanitation. The prevalence of SARS-CoV-2 genetic material for on-site sanitation systems in rural areas was also found to be higher than the off-site sanitation with sewerage systems in Bangladesh (Jakariya et al., 2021), suggesting the negative impact the on-site sanitation could have on the transmission of the virus in LICs.

2.3. SARS-CoV-2 and other viral pathogens in raw surface water and groundwater systems

The occurrence of SARS-CoV-2 in drinking water sources such as surface water and groundwater systems is critical to understand potential transmission risks. A limited number of studies have detected SARS-CoV-2 RNA in raw water sources, especially those impacted by raw or poorly treated sewage/wastewater in low-income and high-income countries. A comprehensive discussion of the evidence, including concentrations of SARS-CoV-2 RNA detected, is presented elsewhere, hence is not repeated here (Gwenzi, 2022). Briefly, data from South America provide the most direct evidence of SARS-CoV-2 RNA in raw surface water and groundwater (Guerrero-Latorre et al., 2020; Maidana-Kulesza et al., 2021; Mahlknecht et al., 2021; Kolarević et al., 2021). For example, in Quito (Ecuador), SARS-CoV-2 RNA was detected in surface water sampled from various sites along a river receiving raw sewage (Guerrero-Latorre et al., 2020). Mahlknecht et al. (2021) detected SARS-CoV-2 RNA in various water sources in Monterrey Metropolitan Area in Mexico, including surface water in dams and rivers and groundwater. SARS-CoV-2 RNA was also detected in approximately half of the river water samples (75) receiving effluent from WWTPs (Maidana-Kulesza et al., 2021). In Europe, SARS-CoV-2 RNA was detected in surface water samples in the Danube River impacted by raw wastewater from Belgrade, Serbia (Kolarević et al., 2021). Elsewhere in Europe in metropolitan Milan, Italy, SARS-CoV-2 RNA was also detected in surface waters, and the source was claimed to be partially treated wastewater and/or combined sewer outflows (Adelodun et al., 2020; Rimoldi et al., 2020). These studies demonstrate strong connectivity between wastewater and drinking water systems through surface water and groundwater and wastewater flows, thus forming a continuum. Here, a summary of the evidence is presented.

The presence of SARS-CoV-2 and viral pathogens in surface water and groundwater systems is often due to the wastewater being discharged into surface water bodies and the environment without adequate treatment, especially when basic sanitation facilities are lacking in such settings. This has been demonstrated in a rural area of Brazil where SARS-CoV-2 was detected in the river water samples due to the direct release of human sewage in the river waters (Fongaro et al., 2021). Similarly, Kumar et al. (2022) observed high concentration of SARS-CoV-2 RNA in the river water samples collected from Ahmedabad in India, despite the wastewater being treated from the treatment plants before its discharge in the rivers. On-site sanitation is often responsible for the pathogenic contamination of water systems, including surface water and groundwater sources. For instance, about 64 % of the residences in a densely populated Tehran in Iran are connected to the central sewerage system, while the sewage from other residences flows

over the surfaces and underground, thereby contaminating the surface water and groundwater systems (Rafiee et al., 2021). The operational performance of sewerage and sanitation systems in many LICs is poor, with effluent generated not meeting the standard levels (Nakagiri et al., 2016; Pandey et al., 2021). It was reported that effluents from nearly 39 % of the sewage treatment plants in India do not meet the discharge standards into the surface waters as prescribed by the Environmental Protection Agency in India (IIHH, 2021). Besides, natural events like heavy rainfall and flooding could damage wastewater systems or overflow of the on-site sanitation systems like pit latrines, leading to overflow of untreated sewage (Dorji et al., 2019; Street et al., 2020; WHO, 2019). The evidence of highly contaminated effluents being discharged into the environment due to the overflow of septic tanks, especially when the soak pit system is lacking, was reported in Bhutan (Dorji et al., 2019). The discharged effluents in the environment were reported to likely contribute to the impacted water quality of the nearby Thimphu River (Giri and Singh, 2013). However, limited studies from LICs investigated the detection of infectious SARS-CoV-2 or its genetic materials in surface water and groundwater systems. However, many studies have reported the contamination of surface water and groundwater systems from other forms of HPVs, especially those impacted by faecal pollution and wastewater discharges, which could provide a clue on the fate of SARS-CoV-2 in the same water systems (Table 3).

The detection of high loads of SARS-CoV-2 RNA in the surface water from low-sanitation regions of Ecuador and Brazil points to the possibility of the prevalence of the virus in the water systems of LICs due to the high level of poor sanitation and hygiene in addition to the poor state of sewage treatment and disposal systems in such settings (Fongaro et al., 2021; Guerrero-Latorre et al., 2020). Mahlknecht et al. (2021) reported a high viral load of SARS-CoV-2 RNA in nearly 44 % (22 of the 50 samples) of the groundwater samples tested in Mexico, which was attributed to the possibility of untreated sewage entering the groundwater system via leaked sewerage system. Kolarević et al. (2021) detected up to 1.32×10^4 copies/L of the SARS-CoV-2 RNA in the Danube River in Serbia with only the samples impacted by the wastewater discharges indicating the virus's presence. Similarly, water samples from the Arenales River in Argentina were reported to contain RNA due to discharge from a WWTP, which significantly impacted the river by faecal pollution (Maidana-Kulesza et al., 2021). High concentrations of viral load genetic material close to the reported influent samples (Table 1) indicates the poor state of WWTPs discharging into the river. Some studies have reported other viral pathogenic contamination of surface water and groundwater from unregulated sewage or wastewater disposals in LICs (Bedada et al., 2019; Eze et al., 2017). The incessant water scarcity and unequal access to improved sanitation facilities have often led to the use of untreated water from streams in many LICs, which could impact the transmission of HPVs and contracting of waterborne diseases (Adelodun et al., 2021b; Pandey et al., 2021).

However, in the literature, data on SARS-CoV-2 RNA in drinking water systems in other low-income regions of Africa, Asia, and Oceania are scarce. In addition, some studies also suggest that even in high-income settings, households and communities using decentralized water and sanitation systems similar to those in low-income settings also exist. However, data on SARS-CoV-2 occurrence in such water and sanitation systems are scarce. Such low-income settings often rely on raw or partially treated drinking water, which increases the risk of human exposure to SARS-CoV-2 and other waterborne pathogens. This highlights the need for further work in such settings, particularly crowded settlements.

2.4. SARS-CoV-2 and other viral pathogens in drinking water supply systems

The accessibility to safe drinking water systems devoid of pathogenic contamination has remained one of the challenges facing the world, with LICs being more adversely affected (Adelodun et al., 2021b).

Table 3

Presence of SARS-CoV-2 in surface water and groundwater systems of low-income countries.

Virus type	Media/sample	Location (settings)	Findings: Concentration (genome copies/L) and/or Positive samples	Reference
SARS-CoV-2RNA	Surface water/ river and lake	Ahmedabad and Guwahati, India (Urban and rural)	Ahmedabad (with treatment plants): 3.5×10^2 (25.8 % (8/31) detection rate) Guwahati (without treatment facility): 5.2×10^2 (20 % (2/10) detection rate)	(Kumar et al., 2022)
SARS-CoV-2RNA	Surface water/river	Salta, Argentina (Urban)	3.2×10^4 – 1.1×10^6	(Maidana-Kulesza et al., 2021)
SARS-COV-2 RNA	Surface water/river	Quito, Ecuador (Urban)	2.9×10^5 – 3.2×10^6 (3/3 of the samples from 3 points were positive)	(Guerrero-Latorre et al., 2020)
SARS-CoV-2RNA	Surface/ downstream water	Minas Gerais State region, Brazil (Rural)	1.1×10^5 – 1.7×10^6 (2/2 of the samples were positive)	(Fongaro et al., 2021)
SARS-CoV-2RNA	Surface/ river water	Monterrey, Mexico (Urban)	2.5×10^3 – 7.0×10^3 (3/24 of the samples were positive)	(Mahlknecht et al., 2021)
SARS-CoV-2RNA	Groundwater/ water	Monterrey, Mexico (Urban)	2.9×10^3 – 3.8×10^4 (22/50 of the samples were positive)	(Mahlknecht et al., 2021)
SARS-CoV-2RNA	Surface water reservoir (dam)/ water	Monterrey, Mexico (Urban)	3.3×10^3 – 3.8×10^3 (2/16 of the samples were positive)	(Mahlknecht et al., 2021)
SARS-CoV-2RNA	Surface water/river water	Belgrade, Serbia (Urban)	5.97×10^3 – 1.32×10^4	(Kolarević et al., 2021)
Enteroviruses	Surface water/ river water	Kenya (Urban and rural)	100 % (10/10) detection rate from urban river samples. 25 % (3/12) detection rate from rural river samples. 28.5 % (60 rivers tested) of river samples.	(Kiulia et al., 2010)
Enteroviruses	Surface water and groundwater/ river, dam, and borehole	South Africa	26.7 % (101 dams tested) of dam and spring samples. 25.3 % (108 boreholes tested) of borehole samples (70/106) of Klip River samples (20/21) of Suikerbosrant River samples (5/24) of Rietspruit River samples	(Ehlers et al., 2005)
Norovirus	Surface water/ river water	Gauteng, South Africa (Urban)	(20/21) of Suikerbosrant River samples (5/24) of Rietspruit River samples	(Mans et al., 2013)
Hepatitis A	Surface water/irrigation water	KwaZulu-Natal, South Africa (Urban)	72.7 % (8/11) of irrigation water samples	(Rachida et al., 2016)
Hepatitis A	Surface water/ river and irrigation water	Limpopo, South Africa (Urban)	76 % (16/21) of river and irrigation water samples	(Saïd et al., 2014)
Hepatitis A	Surface water/ river	Eastern Cape, South Africa (Rural)	1.5×10^1 – 1.9×10^5 (43.1 % samples from Buffalo River)	(Chigor and Okoh, 2012)
Rotavirus	Surface water/ river	Eastern Cape, South Africa (Rural)	2.5×10^1 – 2.1×10^3 (13.9 % of samples from Buffalo River)	(Chigor and Okoh, 2012)
Enterovirus	Surface water/ river	Eastern Cape, South Africa (Rural)	1.3×10^1 – 8.6×10^1 (9.7 % of samples from Buffalo River)	(Chigor and Okoh, 2012)
Human adenovirus	Surface water/ river	South Africa	$<1.2 \times 10^{-5}$ – 4.16×10^{-2} (22.2 % of river water samples)	(Van Heerden et al., 2005)
Human adenovirus	Surface water/ swamp	Nakivubo, Uganda (Urban)	1.60×10^5 – 1.08×10^6 (All six samples were positive)	(O'Brien et al., 2017)
Enterovirus	Surface water/ swamp	Nakivubo, Uganda (Urban)	3.17×10^5 – 1.48×10^7 (All six samples were positive)	(O'Brien et al., 2017)
Rotavirus	Surface water/ swamp	Nakivubo, Uganda (Urban)	6.49×10^1 – 2.99×10^2 (33.3 % of the samples were positive)	(O'Brien et al., 2017)
Hepatitis A virus	Surface water/ swamp	Nakivubo, Uganda (Urban)	9.93×10^2 – 4.48×10^3 (66.7 % of the samples were positive)	(O'Brien et al., 2017)
Human adenovirus	WWTP/ discharge point	Stutterheim, Eastern Cape Province, South Africa (Urban)	8.4×10^1 – 1.0×10^5 (62.5 % (30/48) of the samples were positive) Upstream: 5.45×10^5	(Adefisoye et al., 2016)
Human adenovirus	WWTP/ upstream and downstream	Nakivubo, Uganda (Urban)	Downstream: 2.08×10^6 (100 % (6/6) of the samples were positive at both upstream and downstream) Upstream: 3.09×10^6	(O'Brien et al., 2017)
Enterovirus	WWTP/ upstream and downstream	Nakivubo, Uganda (Urban)	Downstream: 4.15×10^6 (100 % (6/6) of the samples were positive upstream, while 66.7 % (4/6) samples were positive downstream.) Upstream: 1.16×10^2	(O'Brien et al., 2017)
Rotavirus	WWTP/ upstream and downstream	Nakivubo, Uganda (Urban)	Downstream: 1.31×10^3 (16.7 (2/12) of the samples were positive upstream while 41.6 % (5/12) samples were positive downstream.) Upstream: 7.74×10^3	(O'Brien et al., 2017)
Hepatitis A virus	WWTP/ upstream and downstream	Nakivubo, Uganda (Urban)	Downstream: 6.12×10^3 (58.3 % (7/12) of the samples were positive upstream while 25 % (3/12) samples were positive downstream.)	(O'Brien et al., 2017)

Recently, Nigeria has witnessed a decline in access to piped water in many of its urban areas from 32 % in 1990 to 7 % in 2015 among its population (World Bank Group, 2017). While the quality or level of allowable contaminants in water supply systems varies with the intended purpose, the purest form with the least contaminants, including pathogenic levels, is required for drinking purposes. The drinking water system in LICs is usually sourced from groundwater (open and deep

wells), surface water (streams or rivers), and harvested rainwater. The seasonal factor plays an important role in the type of water sources used for drinking (Liddle et al., 2016). Although there are relatively available water resources in many of these LICs despite their huge populations, the inadequate water infrastructure required for distribution and storage has limited the accessibility to clean and contaminants-free water resources for drinking and other domestic purposes (Adelodun et al.,

2021b). These water sources are often contaminated by anthropogenic activities and other forms of natural contaminants due to the distance between the water source(s) and consumption point and the lack of adequate sanitation and hygiene in low-income settings (Mukherjee et al., 2015; Treacy, 2019).

Some studies have reported the presence viral pathogens in drinking water systems in LICs (Table 4). The main source of human viral pathogens in drinking water systems in these settings is faecal contamination from untreated sewage disposals. Since most low-income populations source the water directly from either groundwater or surface water without any form of treatment, these water sources are contaminated by anthropogenic activities and other natural contaminants. The incidences of waterborne diseases caused by various forms of HPVs are due to contaminated groundwater, indicating pathogens' potential to successfully transmit from disposed untreated wastewater to groundwater source (Craun et al., 2010).

Removing SARS-CoV-2, coronaviruses and other viral pathogens often requires advanced treatment techniques and expertise in operating and deploying the treatment processes. The majority of the countries in low-income settings cannot deploy such advanced treatment systems for solid waste, wastewater, and drinking water to effectively remove HPVs, including SARS-CoV-2 (Adelodun et al., 2021a; Gwenzi, 2022). The conventional treatment processes are the most recognised and available means of water treatment for drinking in the urban setting, while the water is directly sourced and used in rural settings without any major form of treatment targeting removing the viral pathogens (Gwenzi, 2022). Thus, there is a need for low-cost but effective methods that can be deployed in low-income settings to remove SARS-CoV-2, coronaviruses and other viral pathogens in drinking water systems. The use of low-cost household kits for drinking water purification, specifically for the removal of viral pathogens, are encouraged since the existing water treatment systems in many LICs are not properly maintained and often

overloaded leading to their inefficiency in the water treatment for human consumption.

The use of disinfectant has also been suggested as an effective tool to inactivate SARS-CoV-2 in the environment. However, the accessibility to disinfectant reagents could be very challenging in rural settings of LICs. Moreover, the determination of an appropriate dose of disinfectant that can inactivate SARS-CoV-2 and other viral pathogens without causing ecological and human hazards requires technical expertise, which is lacking in many low-income communities. Thus, there is a need to consider non-chemical alternatives that could effectively inactivate or remove the viral pathogens in water systems in LICs. The catalogue of non-chemical treatment processes that have been previously adopted to inactivate viruses and their relative performances is provided in (Adelodun et al., 2021b), which include coagulation-sedimentation, rapid sand filtration, ceramic water filter, micro and ultrafiltration, ultraviolet irradiation, and solar water disinfection. The use of hybrid systems combining two or more treatment processes and techniques has been found to be more effective, especially at the plant scale and could serve as an alternative to chemical and other advanced treatment processes in LICs due to their low-cost and easy-to-use features (Adelodun et al., 2021b). Furthermore, the effective storage of drinking water at the household plays an important role in protecting the drinking water supply from viral pathogenic contamination, which includes storage location, media or containers, and handling practices. Oftentimes, the drinking water is sourced from a far distance in rural communities of LICs, and there is a need to store it for an extended period. Brick et al. (2004) reported an increasing contamination of 67 % (25/37) of stored drinking water samples from 1 to 9 days. Thus, there is a need for an appropriate point-of-use device that could decontaminate the water in households before consumption (Adelodun et al., 2020).

Table 4
Presence of human pathogenic viruses in the drinking water systems of low-income countries.

Virus type	Sample	Location (settings)	Treatment process	Findings	Reference
Enteroviruses	Raw and treated drinking water	South Africa	Conventional treatment and disinfection	18.7 % (159/850 samples) of the treated drinking water samples tested positive for viable enteroviruses	(Ehlers et al., 2005)
Human adenoviruses	Artesian wells and springs	Tenente Portela, Brazil (Rural)	NR	High detection rate (67 %) of the virus with elevated environmental contamination due to the proximity of faecal sources and poor sanitation conditions.	(Spilki et al., 2013)
Human adenoviruses	Chlorinated and untreated drinking water	Florianopolis, Brazil (Rural)	Chlorination	Average concentrations of 5.73×10^6 and 1.33×10^7 (genome copies/L) of human adenovirus for chlorinated and untreated samples, with detection rates of 67 % and 33 %, respectively, due to the adverse impact of faecal pollution in the surrounding water sources.	(Rigotto et al., 2010)
Human adenoviruses	Treated drinking water	South Africa (Urban)	Coagulation with slaked lime, flocculation, sedimentation of the flocs, carbonation, filtration and chlorination.	5.32 % detection rate with concentration range $< 1.5 \times 10^{-6}$ – 5.25×10^{-3} of Human adenovirus in treated drinking water samples due to considerable sewage pollution of the source.	(Van Heerden et al., 2005)
Human adenoviruses and rotaviruses	Water wells, pumps, and surface water	Benin Republic (Rural)	NR	541 samples were positive from 287 sources of drinking water (247 water wells, 25 pumps, and 15 surface water) with 12.9 % and 2.1 % detection rates of adenoviruses and rotaviruses, respectively.	(Verheyen et al., 2009)
Human adenoviruses and rotaviruses	Tap water	Municipality of Taquara, Brazil (Rural)	NR	Detection of both Human adenovirus and rotavirus in tap water for drinking purposes due to deficient sanitation for the human excreta in the Brazilian dairy farms.	(De Oliveira et al., 2012)
Rotaviruses, noroviruses, enterovirus, and adenoviruses	River waters serving as drinking water source	Vhembe, South Africa	NR	9 of the 10 rivers tested positive for viruses, while only enterovirus and adenovirus were cultured from two rivers. The investigated river was impacted by anthropogenic activities, including domestic sewage discharge and animal faecal pollution.	(Potgieter et al., 2020)
Enteroviruses	Drinking water supplies	South Africa	Standard treatment process for safe drinking water	27 of the 172 treated drinking water samples from two treatment plants tested positive for viable enteroviruses.	(Vivier et al., 2004)

2.5. Controls on SARS-CoV-2 and viral circulation in wastewater-source water-drinking water continuum

Several anthropogenic and natural factors (e.g., hydrogeology) control the circulation of SARS-CoV-2 in the wastewater-source water-drinking water continuum. These factors control the degree of connectivity and water and microbial flows between the viral source (wastewater, sanitation systems) and the drinking water receptor (surface water, groundwater). Hydrological processes controlling the connectivity and circulation of viruses and other pathogens include (1) rainfall particularly extreme high-flow events such as heavy storms, cyclonic events and floods), (2) sewage discharges and spillages from poorly maintained decentralized and centralized wastewater systems, and runoff/erosion impacted by sewage, (3) infiltration and groundwater recharge from effluents from on-site sanitation systems.

Hydrogeological processes and factors controlling the circulation of SARS-CoV-2 and other wastewater-borne pathogens include (1) coarse-textured soils or geological systems, (2) fractured geological systems such as karst aquifers, and (3) shallow groundwater systems or aquifers such as wells and springs in wetlands or close to surface water bodies. In turn, these hydrogeological settings are characterized by; (1) high hydraulic saturated conductivity or transmissivity, (2) rapid or fast transit times between source and receptors, and (3) limited viral removal due to low residence times of fast transit times. For example, installing a soak pit system in the septic tank is expected to aid in removing pathogenic viruses and other pollutants as a part of land treatment measure of on-site sanitation for safe disposal of effluents in the septic tank. However, the soil conditions in some urban areas are not fit for the construction of soak pits due to the high compaction and low infiltration capacity required of a soak pit (Dorji et al., 2019). Leakage of septic tanks often occurs due to poor soil conditions and poor design and construction (Dorji et al., 2019). Septic tanks for on-site sanitation in developing or LICs are recommended to have a mean hydraulic retention time (HRT) of 1 to 3 days in addition to the soak pit system to absorb the overflowing effluents from the tank (Dorji et al., 2019; Iwugo, 1981). The role of hydraulic retention time in removing SARS-CoV-2 from wastewater has also been emphasized (Gwenzi, 2022).

Anthropogenic factors promoting the contamination of drinking water systems with SARS-CoV-2 and other wastewater-borne pathogens include (1) overcrowding leading to overloading and spilling of wastewater systems and on-site sanitation facilities, (2) weak and poorly enforced regulations promoting the illegal discharges of raw or partially treated wastewaters, (3) poor siting of on-site sanitation facilities relative to and drinking water sources, and (4) poor hygiene in shared sanitation and water supply systems. For example, the siting of on-site sanitation, especially soak pit, close to the residences and drinking water sources, has become a challenge in LICs. In urban areas, the increasing level of urbanization has reduced the space for the proper siting of soak pits in suitable locations away from drinking water sources (Dorji et al., 2019; Gwenzi, 2022; Nelson and Murray, 2008).

In rural areas, however, on-site sanitation, and sometimes open defecation, is performed close to streams and rivers, the main drinking water sources in rural settings. The ideal recommended distance for siting a soak pit is 3 m from a building structure, with a minimum diameter of 1.5 m, and a minimum distance of 3 m away from drinking water sources or 10 m from waterbodies for domestic purposes in saturated soil conditions (Dorji et al., 2019; Mondal et al., 2014). However, these design requirements are not often considered, undermining the safety of the drinking water sources and human health. When there is adequate space, the soil conditions are inappropriate (Dorji et al., 2019). Aside from open defecation close to water bodies like streams and rivers in rural settings, the indiscriminate disposal of septage close to riversides is rampant in urban areas of LICs due to the lack of dedicated landfill or sites for such. The downstream users of the river impacted by either faecal pollution or wastewater discharge are mostly farmers, and villagers who depend on these water sources for domestic

use and agricultural purposes could be susceptible to viral infections and waterborne diseases. For instance, it was reported that septage collected from Khuruthang town in Bhutan is disposed of at a site 30 m away from the Punatsangchu River, which many people downstream rely on for their domestic and agricultural water needs (Dorji et al., 2019). A mini-scale low-cost decentralized treatment system that can be adopted at the community level has been suggested (Dorji et al., 2019). This system has a community soak pit with individual septic tanks or community septic tanks with soak pit systems in which materials are locally sourced for the anaerobic treatment and anaerobic baffled reactor (Dorji et al., 2019).

Once in drinking water systems, viruses and other pathogens may enter the human body via (1) ingestion of contaminated water and/or (2) inhalation of viruses in bioaerosols. Potential high-risk settings for the transmission of SARS-CoV-2 have been discussed in an earlier paper (Gwenzi, 2022). These include prisons and correctional services facilities, which are often crowded, have poor sanitation facilities, and are well-known hotspots for the prevalence and transmission of respiratory infections such as tuberculosis. Educational institutions using shared on-site sanitation systems such as schools, universities or college campuses, often have large populations that may promote transmission. Healthcare facilities such as clinics and hospitals often use shared sanitation facilities and may promote transmission via fomite, bioaerosols or human-human contact. Lastly, quarantine and isolation centres housing symptomatic and non-symptomatic COVID-19 patients may promote transfer to other people due to overcrowding and shared sanitation facilities.

3. Risk assessment and mitigation strategy under low-income settings

Risk assessment and mitigation strategies for pathogenic viruses in low-income settings require a comprehensive approach to address the unique challenges faced by these communities (Qin et al., 2023; Liu et al., 2024a). These challenges can include limited access to testing and healthcare facilities, lack of suitable control and prevention measures, and limited data collection (Chang et al., 2021). Despite these challenges, conducting risk assessments is crucial in identifying and mitigating potential risks associated with the pathogenic viruses.

Risk assessment of microbial pathogens is the qualitative or quantitative estimation of adverse health risks following exposure to these agents which can be accomplished via epidemiological studies or quantitative microbial risk assessment (QMRA). The epidemiological approach is, however, more time-consuming and more expensive which practically may be unachievable in low-income settings. QMRA addresses the adverse health risks (infection, illness, death) for a specific exposure scenario to microbial pathogens such as viral particles through contaminated water. Since, exposure to even low levels of viral pathogens may pose some risk of infection, illness, or even mortality to susceptible populations, QMRA as a promising tool could predict risks associated with exposure to contaminated water (Bitton, 2011, 2014; Hass et al., 2014). On the other hand, QMRA could provide comprehensive information for controlling and management of adverse effects associated with exposure to contaminated water and therefore, WHO has emphasized the importance of applying QMRA in preventing waterborne diseases (WHO, 2017).

Several QMRA studies have been conducted to estimate the probable infection risk and disease burden attributed to both enteric and non-enteric viruses in various aquatic environments, including wastewater, drinking water, and recreational water (Gholipour et al., 2021, 2022b, 2023; McBride et al., 2013; Moazeni et al., 2017; Schijven et al., 2019; Vergara et al., 2016). Although comprehensive risk assessments can be difficult to carry out in low-income settings due to the limited availability and quality of data, this approach helps identify vulnerable populations and provides decision-makers with valuable information to make informed decisions on public health interventions, resource allocation, and mitigation strategies. In other words, comprehensive risk assessment and implementation of management strategies is needed to

prevent potential health problem associated with exposure to viral particles in wastewater and impacted surface water.

In this study, we comprehensively presented and discussed human health risks associated with the exposure to pathogenic viruses including enteric viruses and SARS-CoV-2 from wastewater/ surface water.

3.1. Health risks from enteric viruses

3.1.1. Hazard identification and exposure assessment

Several enteric viruses released in the faeces of infected individuals can potentially contaminate aquatic environments. Enteric viruses cause a broad spectrum of diseases ranging from gastroenteritis to aseptic meningitis and paralysis which gastroenteritis is probably the most frequent waterborne illness (Bitton, 2011; Pepper et al., 2015). The presence of enteric viruses in the wastewater-source water-drinking water continuum is of significant health importance due to their high excretion from infected individuals (even from asymptomatic individuals), inadequate removal in conventional water/wastewater treatment processes, prolonged survival in the environment, and low infectious doses (Gholipour et al., 2022a). From a public health perspective, the most important enteric viruses include rotaviruses, adenoviruses, noroviruses and enteroviruses (Bitton, 2011). Enteric viruses primarily spread through the faecal-oral route, either via direct contact with an infected person or through contaminated water. Transmission thorough contaminated water can occur directly (e.g., drinking water and swimming) or indirectly via contaminated food (e.g., aquaculture or agricultural use of polluted water) (Bitton, 2011; Pepper et al., 2015). As indicated in Table 4, enteric viruses were identified in various drinking water sources, treated water, and even in tap water, with the highest frequency of detection observed for human Adenovirus, emphasizing the potential risk of viral infections thorough water consumption in low-income countries. Enteric viruses, particularly human Adenovirus with double-stranded DNA, have demonstrated high environmental persistence and resistance to chlorination (Rames et al., 2016). Inadequate water treatment and improper wastewater and sewage disposal practices can contaminate water sources with enteric viruses. Exposure to viral contaminated surface water during recreational activities such as swimming or fishing, may also pose a risk for recreational users (Gholipour et al., 2023). Accidental ingestion of contaminated water and wastewater poses an occupational risk for farmers during field irrigation and wastewater workers, respectively, serving as another route of exposure to enteric viruses. Furthermore, the utilization of inadequately treated wastewater or contaminated water in agriculture, particularly for the irrigation of raw-consumed vegetables is a significant concern for foodborne exposure to enteric viruses. Additionally, the agricultural reuse of wastewater may introduce enteric viruses into irrigated soil, potentially leading to gastroenteritis through the accidental ingestion of contaminated soil by farmers or children playing in the field. Based on the exposure routes, the Eqs. (1) to (3) could be used for calculating exposure doses:

$$D_{\text{water ingestion}} = C_w \times V_w \quad (1)$$

$$D_{\text{soil accidental ingestion}} = C_w \times V_s \times 10^{-\text{SoilLog}} \quad (2)$$

$$D_{\text{crop consumption}} = C_w \times S \times e^{-kt} \times 10^{-R_{\text{wash}}} \times V_c \quad (3)$$

where C_w is the concentration of viral particles in contaminated water (drinking water, recreational water, wastewater, irrigation water). V_w stands for the volume of drinking water consumed daily or volume of recreational water ingested per event, as well as the volume of water ingested accidentally by WWTPs workers or farmers. V_s is the volume of soil accidentally ingested by farmers during their works or by children when playing in wastewater-irrigated field. V_c represents the volume of crops consumed by people. SoilLog signifies the reduction of virus concentration in the soil due to soil properties, climate condition and

predators' activity. S is the volume of irrigation water remained on crops (retention capacity of irrigation water). K is virus kinetic decay constant based on the environmental conditions, t is the interval time between the last wastewater irrigation event and harvesting, and R_{wash} is the reduction of viruses on crops surface due to washing with water. Based on the interval time between the harvesting and consumption as well as application of disinfectants more reduction of virus dose through food consumption can occur (Farhadkhani et al., 2018). However, it is important to note that detection and quantification of many pathogenic enteric viruses such as adenovirus, rotavirus and norovirus through cell culture-based is difficult. Therefore, these viruses generally detected by quantitative real-time PCR methods which reports the genomic copy (GC) number. Since all the viral particles detected by real-time PCR are not infectious, therefore, the conversion factor of genomic copies to TCID50 should be added to dose equations.

3.1.2. Influential factors on estimated risks and management strategies

Sensitivity analysis in QMRA studies has revealed that the virus concentration in aquatic environments is the most influential factor on estimated risks. However, the majority of viral particles detected in environmental samples using molecular methods may not pose health risks. In other words, to address the potential overestimation in microbial risk analysis, virus concentrations should be adjusted based on the infectious fraction value, which maybe variable based on the type of virus and media in which the viral particle is present as well as the climate condition. Additionally, in irrigated fields with wastewater/contaminated surface water, the viruses in soil and on crop surfaces would be reduced or inactivated by UV radiation and unfavorable conditions such as dry weather and high temperature. This is highlighting the importance of utilizing the virus decay rate and the interval time between irrigation and crop harvesting in QMRA. The use of personal protective equipment during occupational activities and crop washing/disinfection are additional factors that reduce the exposure dose. Additionally, it is important to note that the extent of crop contamination with viral particles through irrigation with wastewater/ contaminated surface water is related to the type of crop and the retention capacity of irrigation water by cultivated crop. Although there is limited data on the potential persistence of enteric viruses in the soil and on the crop surfaces, the consumption of wastewater- or contaminated water-irrigated crops eaten raw represents an additional pathway for exposure to enteric viruses (Farhadkhani et al., 2018).

The frequency of exposure to viruses is another important influential factor in the estimated risk. Furthermore, viruses exhibit varying minimum infectious doses, infection-to-disease rates, and disease severity, resulting in differences in dose-response models and ultimately calculated risks. Among the enteric viruses detected in the wastewater-source water-drinking water continuum, norovirus has the lowest infectious dose (<18 viral particles) (Hall, 2012), indicating a potentially higher risk compared to the other enteric viruses. However, the infectious dose can vary in different situations, and the actual risk depends on multiple factors, including the specific circumstances of exposure and the health status of exposed individuals.

Considering these influential factors is helpful to estimate more accurate and reduce uncertainties in QMRA of viral particles. There are acceptable health risk values available in guidelines for exposure to contaminated water. WHO and EPA proposed an acceptable infection risk of 10^{-3} and 10^{-4} per person per year (pppy) from exposure to waterborne pathogens, respectively (Gholipour et al., 2021; Mara et al., 2007). To meet this target, the implementation of mitigation strategies aimed at reducing exposure doses through various pathways, such as the promotion of water/wastewater treatment processes, utilization of personal protective equipment, extending the interval time between irrigation and crop harvest, and other measures, should be considered.

3.2. Health risk from SARS-CoV-2

3.2.1. Hazard identification and exposure assessment

During the COVID-19 pandemic, studies have reported survival of SARS-CoV-2 in gastrointestinal tract and shedding in faeces of infected individual, resulting in its high presence in WWTPs and surface waters contaminated with faecal matter (Tables 1–3). Although, genetic material of SARS-CoV-2 has been found in raw wastewater, there is no evidence about the incidence of COVID-19 because of direct exposure to treated or untreated wastewater or its spreading to people through the water in natural bodies of water (CDC, 2022). Since the berating of droplets and aerosols containing the SARS-CoV-2 is the main transmission route for COVID-19 (CDC, 2022), understanding the risk of COVID-19 from potential sources that may release SARS-CoV-2 aerosols,

where some individuals are exposed, can help authorities make informed decisions to keep exposed people safe. Evidence from an outbreak of SARS-CoV-2 in the Amoy Gardens apartment building in Hong Kong showed that aerosolized droplets of faecal-contaminated water were responsible for the spread of the viral infection in large numbers of people (McKinney et al., 2006). In WWTPs, some wastewater treatment processes such as pumping station and activated sludge release considerable aerosols/droplets which can carry infectious agents, including SARS-CoV-2, and therefore, might contribute to transmission of COVID-19 to the wastewater workers. Additionally, turbulent flow of surface water can spray droplets and produce aerosols. Therefore, inhalation of aerosols/droplets is emitted from different stages of WWTPs and from contaminated surface waters may pose health risks for exposed individuals via exposure to infectious agents such as

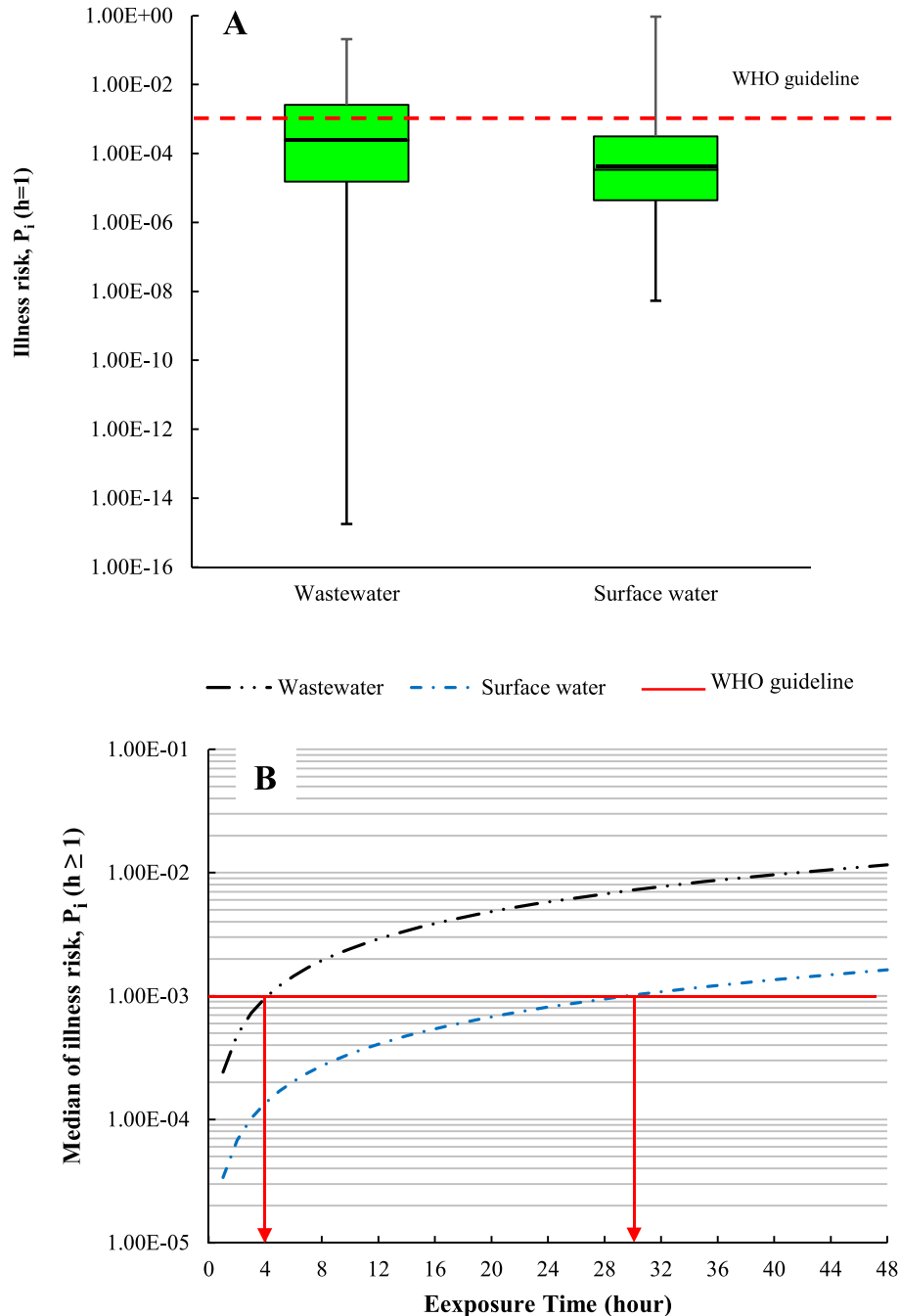


Fig. 3. Illness risk of SARS-CoV-2 (A) box plot of estimated illness risks from exposure to wastewater/surface water aerosols/droplets in comparison to reference level, (B) Relationship between illness risks and exposure time.

SARS-CoV-2. In this regard, we estimated the potential risk of COVID-19 from exposure to aerosols/droplets produced from SARS-CoV-2 contaminated wastewater/surface water. For this purpose, QMRA using Monte-Carlo simulation technique with 10,000 random sampling from each distribution input was performed on SARS-CoV-2 concentrations reported in wastewater and surface water (Tables 1 and 3), following the approach proposed by Gholipour et al. (2021). Briefly, the dose of SARS-CoV-2 inhaled by exposed individuals (d) for 1 h was determined using Eq. (4).

$$d = C_w PC_{wa} IR RR \quad (4)$$

C_w represents the concentration of SARS-CoV-2 in wastewater or surface water (TCID/L). PC_{wa} denotes the microbial water-to-air partitioning coefficient or aerosolization ratio (L/m³). IR is the average inhalation rate (m³/h). and RR represents the aerosol retention rate in the lungs. We assumed that WWTPs and surface water could generate inhalable-size aerosols (smaller than 10 µm) containing viral particles.

The probability of SARS-CoV-2 illness in exposed individuals for one hour P_i ($h = 1$) or longer exposure time P_i ($h \geq 1$) was estimated by Eqs. (5) and (6), respectively.

$$P_i(h = 1) = 1 - e^{-k \cdot d} \quad (5)$$

$$P_i(h \geq 1) = 1 - [1 - P_i(h = 1)]^n \quad (6)$$

Where, d is the exposure dose and k is the model parameter suggested by Watanabe et al. (2010) (Table S1) and n is the frequency of exposure (the number of hours on which an individual may be exposed to SARS-CoV-2 bioaerosols). QMRA input parameters and distributions introduced in the study are presented in Table S1.

3.2.2. Risk characterization

The results of this study showed a median illness risk of 2.4×10^{-4} (95 % CI: 4.34×10^{-8} – 3.9×10^{-2}) and 3.39×10^{-5} (95 % CI: 3.5×10^{-7} – 1.5×10^{-2}) thorough one-hour exposure to wastewater and surface water aerosols, respectively. As shown in the Fig. 3A, the estimated illness risk of SARS-CoV-2 thorough exposure to wastewater and surface water were lower than the WHO guideline value of 10^{-3} pppy. However, the results showed a higher risk thorough exposure to wastewater than surface water which is attributed to higher concentrations of SARS-CoV-2 reported in wastewater (Tables 1–3 & Table S1), since we applied similar assumptions for exposure to wastewater and surface water, except the concentrations of viral particles. However, as shown in Fig. 3B, an increase in exposure time led to an increase in the risk of illness, emphasizing the importance of exposure time in the context of COVID-19 risk. The results of Gholipour et al. (2021) also showed an annual respiratory illness risk of about 10^{-2} pppy for WWTPs workers.

Consistent with other viral QMRA studies, concentration of SARS-CoV-2 in wastewater/surface water is an important influential factor on the estimated risk. However, it is worth noting that detection of SARS-CoV-2 RNA in wastewater and surface water does not necessarily indicate the viability and infectivity of the viral particles. Despite employing a conversion factor for genomic copy to TCID₅₀ (Eq. S1 and Table S1), the estimated concentrations of SARS-CoV-2 in our risk analysis and other QMRA of SARS-CoV-2 is a significant uncertain parameters which could lead to under- or over-estimation of the risk. Moreover, the lack of optimized dose-response model for SARS-CoV-2 and variability of water-to-air partitioning coefficient due to the type of microorganism and the quality of water, are other critical limitations for conducting QMRA for this pathogen. In addition, viruses in bioaerosols may experience significant dilution through air currents or be inactivated by environmental factors. Virus survival in the atmosphere is highly affected by the type of virus and the weather conditions including temperature and relative humidity (Bitton, 2011; Pepper et al., 2015).

In this study, we assumed a similar rate of aerosolization for wastewater and surface water, which may introduce uncertainties in the

calculated human health risks. In WWTPs certain units such as pumping stations and aeration tanks may generate more aerosols/droplets containing viral particles compared to other units and surface water. Therefore, working close to wastewater pumping stations and aeration tanks may pose higher risks than exposure to other units at WWTPs and surface water. Overall, the accuracy and reliability of the risk assessment heavily depend on the availability and quality of data, which can be challenging especially in low-income settings. Therefore, to enhance the effectiveness of risk assessments in low-income settings, contextual factors specific to these settings should be considered.

3.2.3. Appropriate preventive and control methods of SARS-CoV-2 transmission

Despite the wide research on SARS-CoV-2, similar to influenza A virus, there is still debate about the modes of its transmission, specifically whether it is mainly transmitted via bioaerosols, or by droplets, or by direct or indirect contact (Pepper et al., 2015). However, due to the global health and socioeconomic effects of the COVID-19 pandemic, preventive measures must be taken wherever there is a potential risk for the transmission of viral particles. Although, the SARS-CoV-2 can be easily inactivated by the disinfection methods used in water/wastewater treatment (CDC, 2022), limited resources and infrastructure for water/wastewater treatment in some low-income countries could pose a barrier to control the circulation of SARS-CoV-2 in the wastewater-source water-drinking water continuum. The following measures are proposed to prevent and control the circulation and human health risks of SARS-CoV-2 in the wastewater-water-drinking water system.

(1) Occupational exposure

Wastewater workers or persons which may experience the exposure to aerosols/droplets of surface water should be encouraged to use appropriate PPE, especially N95 respirator, which is highly efficient for filtration of airborne particles such as bioaerosols. The exposed individuals should perform hand hygiene frequently; and they should avoid touching eyes, nose, and mouth with unwashed hands (WHO, 2020b). It is important to note that reduction of the exposure time decreases considerably the infection risk of SARS-CoV-2, therefore, rotating work shifts could effectively decrease the risk of COVID-19.

(2) On-site sanitation systems

Transmission via shared on-site sanitation systems can be minimized via (1) using PPE, (2) regular cleaning, (3) rotating shifts between men/boys and women/girls, (4) having on-site fixed handwashing facilities and sanitizers, and (4) improving sanitation and personal hygiene during outbreaks.

(3) Safeguarding drinking systems

Drinking water systems can be safeguarded via; (1) practicing proper sanitation to avoid sewage spillages and discharges into drinking water sources, (2) proper siting of sanitation facilities relative to drinking water sources considering the anthropogenic, hydrological and hydrogeological factors controlling the circulation of wastewater-borne pathogens. Several low-cost drinking water treatment systems also exist, and these are discussed in an earlier paper (Gwenzi, 2022). Other measures to mitigate transmission during outbreaks include (1) identifying and using low-risk drinking water sources (e.g., far away from human settlements), and (2) supply of clean drinking water during outbreaks. Implementing these mitigation measures should also address gendered aspects of COVID-19 discussed earlier.

4. Future perspectives and research directions

Several knowledge gaps exist with respect to viruses in the

wastewater-source water-drinking water continuum. In the case of SARS-CoV-2 in wastewater systems, some of these gaps are discussed in earlier studies focusing on low-income settings (Adelodun et al., 2020; Gwenzi, 2022). Most of the gaps are cross-cutting and relevant to other viral pathogens. In summary, future research on viral pathogens in the wastewater-source water-drinking water system continuum should address the gaps highlighted here.

- (1) Establishing strong quantitative evidence on human exposure and health risks.

Quantitative data linking viral pathogens including SARS-CoV-2 in wastewater, water and drinking water to specific human health outcomes regarding infection, morbidity and mortality are still lacking. Potential tools to achieve this include (1) quantitative microbial risk assessment (QMRA), and (2) disability-adjusted life years (DALYs) approach. Quantitative risk assessment should consider multiple sources of SARS-CoV-2 and multiple exposure routes or pathways. Quantitative risk assessment data are needed to serve as decision and policy-making tools.

- (2) Comprehensive database on viral pathogens in wastewater-source water-drinking water continuum.

The few available studies are limited to viral RNA, which does not indicate viable viruses. There is a need for further empirical evidence on the occurrence and stability of viable viral particle in wastewater, water and drinking water systems in low-income settings such as informal settlements.

- (3) Viral source tracking and apportionment in wastewater-source water-drinking water continuum.

The need for source tracking and apportionment of viral pathogens including SARS-CoV-2 and its proxies in the wastewater-source water-drinking water continuum. Source tracking and apportionment will identify the specific viral and SARS-CoV-2 sources and their relative contribution to the total viral load in drinking water systems and the human body. Such information is critical for decision-making, such as prioritizing resources to mitigate transmission from sources to receptors.

- (4) Development and validation of wastewater, source water and drinking water-based epidemiology.

The occurrence of SARS-CoV-2 and viral pathogens in the wastewater-source water-drinking water continuum could form the basis of wastewater-based epidemiology in low-income settings.

The potential for using viruses and SARS-CoV-2 in wastewater-source water-drinking water continuum as a tool for environmental surveillance has been discussed (Gwenzi, 2022). Specifically, an earlier paper has discussed in detail the wastewater-epidemiology, including principles, opportunities, potential applications and limitations (Gwenzi, 2022). However, there is a need to validate such a tool in low-income settings. To date, the bulk of studies have been limited to the use of wastewater, while excluding raw drinking water as a potential surveillance medium.

- (5) Currently under-utilized emerging and novel tools relevant to low-income settings.

Several currently under-utilized tools can offer insights into virus transmission dynamics via the wastewater-source water-drinking water continuum. These include genomics, big data analytics or artificial intelligence, sero-surveillance, GIS, and statistical techniques e.g., Bayesian inferences. During future outbreaks, drones or unmanned air vehicle systems can also be valuable technologies for delivering

emergency and healthcare supplies. An earlier review presented details of how these tools can be used for understanding SARS-CoV-2 (Gwenzi, 2022), and these applications can be extended to other viral pathogens.

- (6) Topical challenges in fighting SARS-CoV-2 and viral pathogens in low-income settings.

Several topical issues unique to low-income settings also exist. Detailed discussion of the risks and challenges associated with SARS-CoV-2 unique to in low-income settings relative to high-income settings are discussed in earlier papers by the first authors (Gwenzi, 2021; Gwenzi and Rzymiski, 2021; Gwenzi, 2022). These earlier papers cover a range of topical issues in low-income settings including weak research systems, healthcare and diagnostic facilities, vaccine inequity, gender inequality, and poor water, sanitation and hygiene facilities (Gwenzi, 2021; Gwenzi and Rzymiski, 2021; Gwenzi, 2022a, 2022b; Rzymiski et al., 2021). Therefore, tackling future outbreaks of viral infections including those caused by SARS-CoV-2 calls for addressing several other underlying topical issues.

5. Conclusions and outlook

The present review examined evidence to trace the occurrence and assess human exposure risks related to viral pathogens, including SARS-CoV-2, within the wastewater-source water-drinking water continuum. Using a combination of qualitative and quantitative analyses, the study revealed that viral pathogens, including SARS-CoV-2, have been identified in wastewater, on-site sanitation systems, and surface water and groundwater serving as potential sources for drinking water. Anthropogenic and hydro(geo)logical factors and processes were identified as crucial determinants governing the dissemination and circulation of viral pathogens within various aquatic compartments. Various risky behaviours and practices, such as wastewater reuse, were identified as contributors to human vulnerability in high-risk settings. The interactions of these risk drivers with anthropogenic and hydro(geo)logical factors demonstrate the multifaceted nature of the challenges posed by viral pathogens. A quantitative microbial risk assessment indicated that human exposure to viral pathogens through the inhalation of bio-aerosols was higher for wastewater than for surface water. However, the potential for novel exposure pathways, including fomite transmission and drinking water ingestion, added complexity to the assessment. While viral RNA of SARS-CoV-2 has been detected in surface water and groundwater serving as potential drinking water sources, limited evidence links this to viral disease outbreaks. Additionally, data on viable viral particles in drinking water systems, particularly for SARS-CoV-2, remain limited, preventing the quantification of human exposure risks through these systems. In addressing these uncertainties, a qualitative discussion explored multiple exposure pathways and gendered aspects of SARS-CoV-2 in low-income settings. The integration of both qualitative and quantitative analyses facilitated the development of a comprehensive risk assessment and mitigation strategy based on existing empirical evidence. This framework, designed to address and alleviate risks associated with viral pathogens, including SARS-CoV-2, across the wastewater-source water-drinking water continuum, stands as a foundational guide for mitigating future viral infections. Ultimately, future investigations into the complexities of viral pathogens were discussed to provide a research roadmap for the effective mitigation and prevention strategies in the face of future viral outbreaks.

CRedit authorship contribution statement

Willis Gwenzi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Bashir Adelodun:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Pankaj**

Kumar: Writing – review & editing, Writing – original draft, Investigation. **Fidelis Odedishemi Ajibade:** Writing – original draft, Investigation. **Luis F.O. Silva:** Writing – review & editing, Supervision, Investigation. **Kyung Sook Choi:** Writing – review & editing, Supervision, Investigation. **Ramganes Selvarajan:** Writing – original draft, Investigation. **Akebe Luther King Abia:** Writing – original draft, Investigation. **Sahar Gholipour:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Farzaneh Mohammadi:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Mahnaz Nikaeen:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2024.170214>.

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