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Review

The Urban Water Cycle as a Planning Tool to Monitor SARS-CoV-2: A Review of the Literature

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Abstract: COVID-19 is a terrible virus that has impacted human health and the economy on a global scale. The detection and control of the pandemic have become necessities that require appropriate monitoring strategies. One of these strategies involves measuring and quantifying the virus in water at different stages of the Urban Water Cycle (UWC). This article presents a comprehensive literature review of the analyses and quantifications of SARS-CoV-2 in multiple UWC components from 2020 to June 2021. More than 140 studies worldwide with a focus on industrialized nations were identified, mainly in the USA, Australia, and Asia and the European Union. Wastewater treatment plants were the focus of most of these studies, followed by city sewerage systems and hospital effluents. The fewest studies examined the presence of this virus in bodies of water. Most of the studies were conducted for epidemiological purposes. However, a few focused on viral load and its removal using various treatment strategies or modelling and developing strategies to control the disease. Others compared methodologies for determining if SARS-CoV-2 was present or included risk assessments. This is the first study to emphasize the importance of the various individual components of the UWC and their potential impacts on viral transmission from the source to the public.

Keywords: COVID-19; urban water cycle; monitoring; epidemiology

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1. Introduction

Coronavirus disease 2019 (COVID-19) is responsible for a disastrous pandemic that, as of June on 2021, has resulted more than 3 million deaths and more than 180 million infected people worldwide. SARS-CoV-2 that causes COVID-19 is characterized by its efficient transmission via liquid droplets (saliva and nose), aerosols and surfaces that have been touched by symptomatic or asymptomatic patients [1–3]. The virus can enter the body through the eyes, nose or throat. A rapid growth in infections has been observed throughout the world, with epicenters in Asia, Europe and North America. The pandemic is generating abrupt and radical changes in global dynamics in terms of economic, social, environmental and human health issues. The ongoing rise in infections, deaths and inadequate human immune system responses highlights the importance of a careful evaluation of SARS-CoV-2. In particular, evaluations should focus on the short- and long-term impacts on public health, different viral transmission routes, and potential strategies for the prevention and control of the virus [4–9].

According to the literature, the main transmission routes for other viruses are either through direct contact or through microscopic droplets or aerosols generated from sneezes and the saliva of infected individuals [10]. Many reports have indicated the survival of a variety of viruses during water treatment processes, including corona and enteroviruses. The SARS outbreak in Hong Kong in 2003, where the infection of over 300 people was linked to a faulty sewage system, proved that wastewater could be a significant source of viral transmission. Also, different coronavirus survival times have been reported at various stages of wastewater treatment processes, hence, recent publications and reports have raised concerns about the possibility of SARS-CoV-2 spread via wastewater [11] and that this could generate new transmission routes, such as faecal transmission, when ingested orally after the discharge of wastewater into drinking water [11,12]. SARS-CoV-2 and its transmission via water and wastewater requires more attention and research.

The objective of this article is to present a global review of the studies published between 2020 and 2021, in which measurements of SARS-CoV-2 levels were carried out on the different components of the urban water cycle. The aim is to establish and analyze the usefulness of these information as an epidemiological and public health monitoring tool for the control of the COVID-19 pandemics. The article is divided into three parts. First, the presence of viral nucleic acid found in the feces of patients infected with COVID-19 is discussed in order to show the main sources of SARS-CoV-2 RNA in wastewater. Second, the concept and components of the urban water cycle are presented as well as the sources of SARS-CoV-2 in wastewater. Finally, an analysis of the applications of SARS-CoV-2 measurement data in studies worldwide is performed.

2. COVID-19 and Its Presence in Human Faeces

2.1. Diarrhea and Its Association with COVID-19

Depending on the types of analyses carried out in different patients, the COVID-19 symptoms that are associated with the gastrointestinal system are nausea, vomiting, abdominal pain, diarrhea and loss of appetite, all of which can also occur simultaneously [13,14]. According to the meta-analysis of international data conducted by D'Amico et al. [15], found that the range of patients with diarrhea was between 2 and 50% and, when calculating an overall rate, the approximate value was 10% of patients with COVID-19.

However, when patients from China were excluded, that proportion was 18.3%. In another study of hospitalized patients (39 studies, 8,521 patients), the pooled prevalence for diarrhea was slightly higher at 10.4%. Overall, 5–20% of confirmed COVID-19 patients experience diarrhea as one of their initial symptoms, suggesting that faeces are the main vector for the virus to enter into wastewater treatment plants (WWTPs). Moreover, faeces from the asymptomatic infected population may be another source of/virus in wastewater.

The dynamics between pathogenesis and diarrhea are not fully understood [15–17]. However, several authors have suggested that SARS-COV-2 infects human cells through angiotensin-converting enzyme II (ACE2) [15,18–23]. Further research is needed to understand the consequences of SARS-CoV-2 in faeces and its potential impact on urban water.

2.2. COVID-19 in Faecal Samples

A wide variety of studies have shown viral nucleic acids in faecal samples and anal smears from patients with COVID-19. Some studies also recorded faecal measurements from patients after recovery from COVID-19 and discovered the presence of viruses in their faecal matter [24–27]. Table 1 shows some reports on the occurrence of the virus in patient faecal samples.

Table 1. Reported evidence of SARS-CoV-2 measurements in faecal samples.

Authors	Country	Number of Patients	Comments
[26]	China	73	The viral RNA test results remained positive in faecal matter forlonger than in pharyngeal swab samples.
[28]	China	305	Based on a comparison between two series of patients, there was a higher positivity rate for the group with severe symptoms vs. those with mild symptoms (94.6% vs. 82.5%)
[29]	Singapore	18	Using PCR, the virus was detected in the faecal matter of four out of eight patients.
[20]	China	84	Faecal samples from a higher proportion of patients with diarrhea (69%) were positive for virus RNA than from patients without diarrhea (17%).
[30]	China	42	The presence of SARS-CoV-2 RNA in the faeces of COVID-19 patients was not associated with gastrointestinal symptoms or disease severity. Faecal samples from 67% of patients remained positive for viral RNA after pharyngeal swabs were negative.
[31]	USA	1	Analysis of faecal matter obtained on day 7 of the disease yielded positive results.
[22]	China	10	Rectal smears from eight children consistently tested positive even after their nasopharyngeal tests were negative, increasing the possibility of faecal-oral transmission.

3. Urban Water Cycle as Tool for SARS-CoV-2 Epidemiology

3.1. Urban Water Cycle

According to Peña-Guzmán et al. [32], the Urban Water Cycle (UWC) is the spatio-temporal interaction between water and hydrological processes, as well as the supply, treatment, distribution, consumption, collection, and reuse that is carried out in urban or partially urban areas. Based on the interconnections and multiple processes that exist within this cycle, many authors [11,33–38], have examined how SARS-CoV-2 can be monitoring into urban waters, mainly wastewater and affluents.

As shown in Figure 1, traces of virus can enter the urban water cycle mainly through the use of water by people infected with COVID-19. The traces in wastewater are associated with the discharge of fluids or faeces from the infected population. Depending on the city 's sanitation infrastructure, wastewaters are discharged directly into the receiving water bodies (e.g., surface waters) or sent to WWTPs. These WWTPs may or may not remove the virus, depending on the treatment technology that is applied.

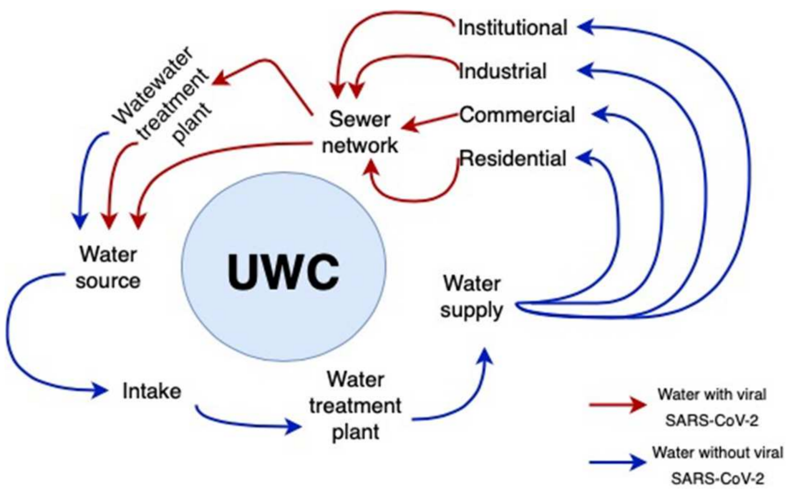

Figure 1. Movement of water flow within the urban water cycle in times of COVID-19.

3.2. Wastewater and SARS-CoV-2

The introduction of SARS-CoV-2 into wastewater through human waste sources is a global health concern during the current pandemic. Further, our limited understanding of potential virus transmission through wastewater and the viability, persistence and inactivation of the virus using current treatment processes lead us to question the current water quality and wastewater management strategies [39]. This suggests the need for precautions and the strict control of faeces of infected patients with the coronavirus (mainly in hospitals). At the same time, there has been increased management, measurement and monitoring of wastewater quality related to viral presence [40,41]. This is because in wastewater could result in high concentrations of viral RNA in the receiving water bodies if the wastewater is not adequately treated [42]. Hence, to help contribute to the monitoring of the virus across the globe, academic and governmental communities (mainly in developed countries) have initiated strategies that seek to report and quantify the presence of the virus in wastewater and surface water sources. Multiple approaches have been implemented, such as risk assessments of contact with contaminated water, quantification of genetic chains, determination of SARS-CoV-2 genetic chain, detection methodologies, evaluation of treatment efficiencies and epidemiological assessment and surveillance. These approaches are being used to obtain additional information on the virus, to better understand its presence and control its transmission through wastewater [43–48]. According to [49], viral RNA can be detected in wastewater, even when only one person in a population of 10,000 is infected with SARS-CoV-2. This emphasizes the high levels of potential for viral transmission through wastewater and the importance of the high sensitivity of current measurement methods. A total of 142 studies were found in scientific articles in 38 different countries (Table 2). This table shows the country where the study was conducted, the component of the UWC where the measurements of SARS-CoV-2 are carried out, and the specific objective of the study. The search for studies was carried out between January 2020 and June 2021 in scientific article databases.

Table 2. Analysis of SARS-CoV-2 in components of the UWC.

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[50]	Argentina			X	X		Wastewater from a pumping system and a water surface	Identify the presence of SARS-CoV-2 in surface waters and use the results as an epidemiological tool.
[51]	Argentina	X					Wastewater of one WWTP	Compare various methods to determine RNA SARS-CoV-2.
[43]	Australia	X		X			Wastewater of two WWTPs and non-treated wastewater	Evaluate the presence of SARS-CoV-2 in wastewater and apply results as an epidemiological tool.
[52]	Australia	X					Wastewater of one WWTP	Comparison of decay of SARS-CoV-2 of three types of wastewaters (treated and non-treated).
[53]	Australia	X					Wastewater of one WWTP	Improve methods to detect SARS-CoV-2.

Table 2. *Cont.*

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[54]	Australia	X					Wastewater of three WWTPs	Evaluation as an epidemiological tool
[55]	Australia			X			Wastewater of three sewer networks	Evaluation of new method for SARS-CoV-2 measurement in wastewaters
[56]	Bangladesh			X			Wastewater from a sewer	Evaluation of the genetic load in sewers waters
[57]	Belgium		X				Wastewater from four hospitals	Evaluation of a measurement kit for SARS-CoV-2 in hospital wastewaters
[58]	Belgium	X					Wastewater of eight WWTP	Comparison of bioanalytics methods for RNA SARS-CoV-2 analysis.
[59]	Brazil			X			Wastewater at the sewer	Use as an epidemiological tool to evaluate the virus presence in wastewaters.
[60]	Brazil	X	X	X			Wastewater of two WWTPs, eight sewer locations and wastewater of two hospitals	Use as an epidemiological tool to evaluate the virus presence in wastewaters.
[61]	Brazil	X					Wastewater of two WWTPs	Risk evaluation for WWTP workers using QMRA.
[62]	Brazil	X					Wastewater of two WWTPs	Risk evaluation for WWTP workers using QMRA.
[63]	Brazil	X		X			Wastewater of two WWTPs, 17 sewer specific locations	Use as an epidemiological tool to evaluate the virus presence in wastewaters.
[64]	Brazil	X		X	X		Wastewater of one WWTP, 17 sewer networks and a river	Evaluation of presences of SARS-CoV-2 in different types of waters.
[65]	Canada						Wastewater of one WWTP (treatment processes)	Comparison of methods to identify proteins of SARS-CoV-2 in wastewaters.

Table 2. *Cont.*

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[66]	Canada	X					Solids at the sieving system and primary treatment at a WWTP	Detection of SARs-V-2 RNA en solids resulting from primary clarification of wastewaters
[67]	Canada	X					Wastewater of five WWTPs	Detection of Genomic variants of SARS-CoV-2 in wastewaters based on PCR
[68]	Canada	X					Wastewater of one WWTP	Evaluation of inter-laboratory result variability for SARS-CoV-2 analysis.
[69]	Canada			X	X		Wastewater of sewer network and lake	Use as an epidemiological tool to evaluate the virus presence.
[70]	Canada		X				Wastewater of three hospitals	Evaluation of a relationship between SARS-CoV-2 dynamics COVID-19 related hospitalizations.
[71]	Canada		X				Wastewater from two hospitals	Evaluation of the prevalence of SARS-CoV-2 contact surfaces and wastewaters of two hospitals.
[72]	Canada	X		X			Wastewater of one WWTP and a sewer network	Evaluation and use of a new extraction method for ARS-CoV-2 analysis.
[73]	Chile			X			Wastewater at three sewer points	Evaluation of microbiome profiles using nanopores and their relationships with SARS-CoV-2.
[74]	Chile			X			Wastewater at two sewer points	Use as an epidemiological tool to evaluate the virus presence.
[75]	China	X	X		X		Wastewater of two WWTPs, rivers, lakes and 24 hospitals	Use as an epidemiological tool to evaluate the virus presence.
[76]	China		X				Wastewater from one hospital following the treatment	Evaluation of the viral load of RNA SARS-CoV-2 of a hospital septic tank and and its treatment by disinfection.

Table 2. *Cont.*

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[77]	China	X	X				Wastewater of four WWTP and six hospitals	Use as an epidemiological tool to evaluate the virus presence.
[78]	Czech Republic	X					Wastewater of 33 WWTPs	Use as an epidemiological tool to evaluate the virus presence.
[57]	Denmark	X	X				Wastewater of 11 WWTPs and two hospitals	Evaluation of a kit for SARS-CoV-2 analysis in hospital wastewaters and WWTPs.
[79]	England	X					Wastewater of one WWTP	Use as an epidemiological tool to evaluate the virus presence.
[80]	England	X					Wastewater of one WWTP	Use as an epidemiological tool to evaluate the virus presence.
[81]	England	X					Wastewater of six WWTP	Use as an epidemiological tool to evaluate the virus presence. And evaluation of RNA removal in treatment processes.
[82]	Ecuador				X		River waters	Evaluation of SARS-CoV-2 presence in surface waters.
[83]	Finland	X					Wastewater of two WWTPs	Evaluation of characteristics and stability of SARS-CoV-2 RNA at different laboratory temperatures.
[84]	France	X					Wastewater of one WWTP	Use as an epidemiological tool to evaluate the virus presence based on PCR (RT-qPCR).
[85]	France	X					Wastewater of one WWTP	Quantification of RNA SARS-CoV-2 in wastewaters.
[57]	France	X					Wastewater of one WWTP	Efficiency evaluation of a kit for measuring SARS-CoV-2 concentrations in wastewaters of WWTPs.
[86]	France			X			Wastewater from two sewer networks	Correlations between RNA SARS-CoV-2 registered positive cases.

Table 2. *Cont.*

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[87]	France	X					Wastewater of 10 WWTPs	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[88]	Germany	X					Wastewater of nine WWTPs	Comparison of SARS-CoV-2 measurement methods.
[89]	Germany	X					Wastewater of two WWTPw	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[90]	Germany	X					Wastewater of one WWTP	Evaluation of methods for the detection of SARS-CoV-2 for wastewaters.
[91]	Germany	X		X			Wastewater of two WWTPs and a sewer network	Detection of new variants of SARS-CoV-2.
[92]	Greece	X					Wastewater of 1 WWTP and analysis by sewer system modelling	Development of a mathematical model at different spatial levels, using physicochemical parameters to rationalize the quantitative measurements of RNA SARS-CoV-2.
[93]	Greece	X					Wastewater of one WWTP	Use different alternative methodology to detect SARS-CoV-2.
[94]	Hong Kong	X	X	X			Wastewater of one WWTP, a sewer network and a hospital sewer	Use as an epidemiological tool to evaluate the virus presence.
[95]	Hungary	X					Wastewater of three WWTPs	Use as an epidemiological tool to evaluate the virus presence.
[96]	India	X					Wastewater of six WWTPs	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[34]	India	X					Wastewater of one WWTP	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.

Table 2. *Cont.*

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[45]	India	X					Wastewater of one WWTP (virus decay was estimated)	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[97]	India	X	X				Wastewater of six WWTPs, two hospital effluents	Correlations between SARS-CoV-2 levels in wastewaters and positive COVID-19 cases
[98]	India				X		Water of five lakes from urban, peri-urban and rural zones	Evaluation of SARS-CoV-2 presence in lakes associated with different land uses.
[99]	India	X		X			Wastewater of one WWTP and eight wastewater pumping stations	Use as an epidemiological tool to evaluate the virus presence.
[100]	India	X		X	X		Wastewater of six WWTPs, wastewater pumping stations and water surfaces	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[101]	India	X					Wastewater of two WWTPs	Comparison of SARS-CoV-2 removal by two wastewater treatments.
[102]	India	X					Wastewater of two WWTPs	Evaluation of treatment efficiency removal of SARS-CoV-2
[103]	India			X			Wastewater of a sewer network	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[104]	Iran	X					Wastewater of two WWTPs	Evaluation of the presence of SARS-CoV-2 in wastewater and air samples and exposure risk assessment for WWTP workers using QMRA.

Table 2. *Cont.*

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[105]	Iran			X			Wastewater of a sewer network	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[106]	Israel	X	X	X			Wastewater of 16 WWTPs, one hospital effluent, seven locations at the sewer system	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[107]	Israel	X					Wastewater of two WWTPs	Evaluation of RNA SARS-CoV-2 behaviors in an activated sludge treatment.
[108]	Italy	X			X		Wastewater of three WWTP and three receiving bodies	Quantification of RNA SARS-CoV-2 in wastewaters and source waters for epidemiological applications.
[109]	Italy	X					Wastewater before treatment of three WWTP	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[110]	Italy	X					Wastewater of five WWTPs	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[111]	Italy	X					Wastewater of two WWTPs	Evaluation of various methods for detection of SARS-CoV-2 in wastewaters.
[112]	Italy	X		X			Wastewater of two WWTPs and four pumping locations of a sewer system	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[113]	Italy	X					Wastewater of eight WWTPs	Alternative methods for measurement of SARS-CoV-2.
[114]	Japan	X			X		Wastewater of one WWTP and a river	Quantification of RNA SARS-CoV-2 in rivers receiving wastewater discharges.

Table 2. *Cont.*

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[48]	Japan	X					Wastewater of three WWTPs	Alternative methods for measurement of SARS-CoV-2.
[115]	Japan	X					Wastewater of four WWTPs	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[116]	Mexico	X					Wastewater of two WWTPs	Correlations between RNA SARS-CoV-2 and registered positive cases.
[117]	Netherlands	X					Sewer system wastewater in six cities	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[118]	Netherlands			X			Wastewater of eight WWTPs	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[119]	Netherlands			X			Sewer system wastewater	Emplean una metodología alternativa para la detección de SARS-CoV-2 con fines epidemiológicos.
[120]	Netherlands			X			Sewer system wastewater of an airport	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[121]	Pakistan	X					Wastewater of one WWTP	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[122]	Qatar	X					Wastewater of five WWTP	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[123]	Russia			X			Ten inspection boxes for wastewater	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[124]	Saudi Arabia		X				Wastewater of one hospital	Correlations between SARS-CoV-2 genes hospitalizations. Included gene detection in septic tank and activated sludge treatment effluents.

Table 2. *Cont.*

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[125]	Saudi Arabia		X				Hospital wastewater effluent (at the septic tank and biological treatment)	Verification of the efficiency of the results as a tool for an epidemiological model. Also, the capacity of a water treatment system is evaluated.
[126]	Serbia				X		Three points in river waters	Evaluation of RNA SARS-CoV-2 levels in a river before and after a discharge of treated water from a WWTP
[127]	Singapore			X			Local sewer network	Use of wastewaters to evaluate COVID-19 in a residential building.
[128]	Slovenia		X				Non-treated wastewater of a hospital	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[129]	South Africa	X					Wastewater of four WWTPs	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[130]	South Africa	X					Wastewater of four WWTPs	Quantification of RNA SARS-CoV-2 in 4 WWTP influents.
[131]	Spain	X					Wastewater of three WWTPs	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications and evaluation of tertiary treatment impacts on SARS-CoV-2 removal.
[132]	Spain	X					Wastewater of six WWTP	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[133]	Spain	X					Wastewater of one WWTP	Quantification and behavior of RNA SARS-CoV-2 in water and sludge of a WWTP.
[134]	Spain	X					Wastewater of two WWTPs	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.

Table 2. *Cont.*

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[135]	Spain			X			Wastewater of a sewer network	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[136]	Spain	X					Wastewater of one WWTP	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[137]	Spain	X					Wastewater of two WWTPs	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[138]	Spain	X					Wastewater of 32 WWTP	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications. Evaluation of a technique to analyze SARS-CoV-2.
[139]	Spain	X					Wastewater of 32 WWTP	Evaluation of the relationship between positive cases of COVID-19 and SARS-CoV-2 levels in wastewaters.
[111]	Sweden	X					Wastewater of three WWTP	Evaluation of different methods for measuring SARS-CoV-2 in wastewaters.
[140]	Sweden	X		X			Wastewater of one WWTP and five locations at the sewer system	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[141]	Switzerland	X					Wastewater of three WWTPs	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[142]	Switzerland	X					Wastewater of one WWTP	Method evaluation for the detection of SARS-CoV-2 in wastewaters
[143]	Turkey	X		X			Wastewater of seven WWTPs and manholes	Evaluation of SARS-CoV-2 presence in sludges from wastewater treatment.

Table 2. *Cont.*

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[144]	UAE	X		X			Wastewater of eleven WWTPs, manholes and sewer pumping systems	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[145]	UAE	X		X			Wastewater of three WWTPs, sewer system and nine pumping systems	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[146]	USA	X					Wastewater of one WWTP	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[147]	USA	X					Wastewater of one WWTP	Use as a tool for determination of SARS-CoV-2 genome.
[148]	USA	X					Wastewater of one WWTP	Use as a tool for determination of SARS-CoV-2 genome.
[149]	USA	X					Solids from sedimentation primary treatment of a WWTP	Evaluation of the presence of SARS-CoV-2 in sludge in a WWTP.
[150]	USA			X			Samples from four sewer interceptors	Determination of different genotypes of SARS-CoV-2.
[151]	USA	X					Wastewater of one WWTP	Description of an analytical technique to detect and quantify genetic material of SARS-CoV-2
[152]	USA	X					Wastewater of nine WWTP	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[153]	USA	X					Wastewater of two WWTP	Used of concentration methods to evaluate SARS-CoV-2 RNA.
[154]	USA	X					Wastewater of one WWTP	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.

Table 2. *Cont.*

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[155]	USA	X	X				Wastewater of one WWTP and a hospital	Comparison and validation of molecular techniques for monitoring of SARS-CoV-2 in wastewaters.
[156]	USA	X					Wastewater of one WWTP	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[157]	USA			X			Wastewater of three interceptor sewer networks	Use of SARS-CoV-2 to anticipate pandemic infection peaks.
[158]	USA			X			Wastewater from a local sewer network	Evaluation of an alternative method to detect SARS-CoV-2.
[159]	USA	X		X			Wastewater of six WWTPs	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[160]	USA	X					Wastewater of two WWTPs	Comparison of methods conducted in 32 laboratories to identify SARS-CoV-2.
[40]	USA	X					Wastewater of two WWTPs and solids from sedimentation primary treatment	Evaluation of SARS-CoV-2 in WWTP.
[161]	USA			X			Wastewater from a university sewer	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[162]	USA	X					Wastewater of one WWTP	Evaluation of different methods for SARS-CoV-2 analysis in wastewaters and sludge.
[163]	USA	X		X			Wastewater of 10 WWTPs and eight locations of the sewer system	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.

Table 2. *Cont.*

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[164]	USA	X					Wastewater of two WWTPs	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[165]	USA			X			Wastewater from a local sewer network	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[166]	USA	X					Wastewater of 12 WWTPs	Determination of optimal monitoring frequency for epidemiological purposes.
[167]	USA			X			Wastewater from a university sewer network	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[168]	USA	X			X	X	Wastewater of two WWTPs, one river, one lake, three water treatment plants *	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[169]	USA	X		X			Wastewater of five WWTPs and one point in a local sewer system	Quantification of RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[170]	USA	X					Settled solids from seven WWTPs	Comparison of recorded CO-VID-19 rates with SARS-CoV-2 measurements and generation of a mass balance model between solids and SARS-CoV-2 RNA.
[142]	USA	X					Settled solids from one WWTP	Valuation of detection methods for SARS-CoV-2 in wastewaters.
[171]	USA	X					Wastewater of two WWTPs	Variability of RNA SARS-CoV-2 WWTP during different periods of the pandemic.
[172]	USA			X			Wastewater from a local sewer network	Correlation between COVID-19 in saliva RNA SARS-CoV-2 levels in wastewaters

Table 2. *Cont.*

Author	Country	WWTP	Hospital Effluent	Sewer Network	Surface Water	Drinking Water	Component of the UWC	Study Objective
[173]	USA			X			Wastewater from a local sewer network	Use as an epidemiological tool to evaluate the virus presence.
[174]	USA			X			Local sewer network	Quantification of de RNA SARS-CoV-2 in wastewaters for epidemiological applications.
[175]	USA	X					Settles solids from one WWTP	Evaluation of RNA SARS-CoV-2 in solids.
[176]	USA	X		X			Wastewater of a WWTP and wastewater catchment in 40 states	Use as an epidemiological tool to evaluate the virus presence.
[177]	USA	X					Wastewater of 39 WWTP	Use as an epidemiological tool to evaluate the virus presence.
[178]	USA	X					Wastewater of 39 WWTP	Use as an epidemiological tool to evaluate the virus presence.
[179]	USA	X					Wastewater of 39 WWTP	Use as an epidemiological tool to evaluate the virus presence.
[180]	USA	X					Wastewater of six WWTPs	Comparison of different methods for SARS-CoV-2 quantification.
[181]	USA	X					Wastewater of 14 WWTPs	Use as an epidemiological tool to evaluate the virus presence.
[182]	USA	X					Wastewater of nine WWTPs	Use as an epidemiological tool to evaluate the virus presence.

* Concentrations are not detected in drinking water and in surface source waters. For this reason, analysis of these UWC components is not included.

4. Analysis for Each UWC Component

4.1. Wastewater Treatment Plants (WWTPs)

As indicated in Table 2, most studies have reported the presence of the virus in WWTPs, either in wastewater entering the plant, in effluents or at different stages of the treatment processes. These studies account for 84% of the reported cases. Additionally, more than 50% of the WWTP component measurements were carried out in more than two WWTPs that were located in different cities in the same country. One of the main objectives for this type of monitoring is to use WWTPs as an epidemiological surveillance system. According to [183], WWTPs capture the viral loads of 104 to 106 individuals in a single sample, which facilitates spatial analyses and accelerates epidemiological investigations. Hence, the obtained biological measurements (quantity and occurrence) of SARS-CoV-2 from WWTPs could reflect the community's health and act as an indirect population-level diagnostic tool. Indeed, the study of WTPs by [152] allowed them to identify growth trends in viral loads according to study area and analysis time, which allows government entities to exercise specific epidemiological control measures. On the other hand, Kumar et al. [34], evaluated the temporal variation of COVID-19 occurrence in India. This information could be used for controlling the growth of the virus in wastewater. Results from Ahmed et al. [43], Trottier et al. [85], Randazzo et al. [131], Medema et al. [117], Hasan et al. [144] and Wurtzer et al. [84], among others, led to the conclusion that these analyses could generate early warnings about the presence of the virus that include individuals with mild and no symptoms.

In addition, the wastewater component of the UWC makes it possible to understand the behavior of SARS-CoV-2 and the capacity of the WWTPs to eliminate this virus. Wastewater effluent discharges generally flow into receiving water bodies that are then used as drinking water supply sources for cities located downstream within the watershed. In some cases, these waters are reused for other purposes [184], creating a public health problem [185,186]. The removal of SARS-CoV-2 from wastewaters was evaluated by Westhaus et al. [88]. They observed that while three conventional activated sludge treatment plants did not efficiently remove SARS-CoV-2, ozonation treatment improved the removal performance. Besides, Balboa et al. [187], Randazzo et al. [131] and Rimoldi et al. [108] found that the removal efficiency was 89% after the secondary treatment and 100% after the tertiary treatment. This suggests that each WWTP's efficiency at removing the virus mainly depends on the type of treatment process it applies. Thus, evaluating each treatment process of WWTP would allow a better understanding of viral elimination in wastewater.

Studies on sludge and the wastewater that results from WWTPs (screening, primary and secondary sedimentation) make it possible to evaluate the risks associated with the handling of these media and the consequent health impacts due to the virus's ability to survive from hours to days in wastewater [66,149,188]. For example, Zaneti et al. [61,62] used quantitative analyses with various scenarios to determine the likelihood of health risks for WWTP workers and concluded that there is a need to create protection protocols and develop training and preparation measures for municipal WWTP personnel. Balboa et al. [187] observed that the secondary treatment sludge did not contain SARS-CoV chains. However, they found high viral loads in the primary treatment sludge. The enveloped virus's high affinity could explain this for biosolids which leads to viral retention in sludge. Hence, the higher solid content in the primary sludge retains more viral particles compared to the secondary sludge. Research on sludge allows for confirming or refuting studies to be carried out on wastewater from WWTPs (as the influent). Finally, the poor or lack of wastewater treatment facilities in underdeveloped or developing countries poses a greater risk to public health.

Researchers studied the production of microbial aerosols and their health impacts on plant operators during WWTP processes [38,189,190]. Recent publications have proved that COVID-19 is highly stable in aerosols (viruses live for several hours) and on surfaces (viruses live for several days) [1]. Hence, the microbial aerosol exposure of workers during WWTP processes needs to be addressed to create safe work environments. Balboa et al. (2020) and other studies did not find virus chains in the secondary effluents (<11%), reducing the risk of aerosol production during the aeration process. However, the preliminary results indicate a need to expand these types of studies, both in treatment systems and in different components of the UWC [46,190]. A survey developed by Dada and Gyawali [191] where online data on WWTP characteristics in New Zealand were collected (without measurements, therefore not included in Table 2) provides further evidence on aerosolized viral exposure. The researchers in this study characterized exposure to SARS-CoV-2 via inhalation and determined it to be low. However, Gholipor et al. [104], observed a high risk in WWTP workers due to the exposure to bioaerosols. The measurement of RNA chains at every possible step in WWTPs should be considered in order to control the dissemination of viruses in the WWTP environment.

4.2. Sewer Systems

Sewage that leaks into surface water might enable virus transmission through airborne spray and enter drinking water systems. Therefore, sewage networks represent the second most crucial component of the UWC and are featured in the greatest number of studies on SARS-Cov-2 (24%). The most effective use of the results obtained from sewage network samples is a potential epidemiological monitoring tool. This approach is called wastewater epidemiology (WBE), which allows for the development of early warning monitoring systems [183,192]. Gonzales et al. [152], Curtis at al. [156], Kuryntseva et al. [123], Fangaro et al. [59], Betancourt et al. [161] and Colosi et al. [155], among others, have proposed epidemiological models and analyses of growth rates according to the study area and temporalities. These proposed models and methodologies have made it possible to understand the continuity, behaviour and growth of the virus in a given population [56,193,194]. Additionally, this kind of study provides reliable information on the behaviour of the virus in asymptomatic patients and allows researchers to determine the number of undiagnosed infections in a population [192]. These studies can also help evaluate the impacts of the sanitation measures that are recommended by public health authorities [163]. It is important to mention that WBE studies in developing countries have shown great potential for epidemiological surveillance and control tools. For example, Iglesias et al. [50] determined, with high reliability, the changes in the prevalence of COVID-19 in a marginal community in Argentina, even with low coverage of sewage systems. This study illustrated that in developing countries where COVID-19 tests are limited, this web/larger-scale approach is a useful decision-making tool for public health authorities.

Other authors have proposed monitoring programs to understand and identify the behaviour of the virus in sewage systems. For example, a study by Petala et al. [92] proposed a mathematical model that looked for possible effects of SARS-CoV-2 RNA based on commonly measured parameters, such as dissolved oxygen and total suspended solids, to explain the behaviour of the virus in the pipes of a sewage system. It is important to expand the studies by including parameters such as temperature and pH, among others, which may impact the survival time of the virus in wastewater [195]. Previous studies of other SARS-like viruses showed that at 4 °C, the virus has a longer survival time compared to at 20 °C [196]. In the case of the SARS-CoV-2 viral genome, survival was detected at higher ambient temperatures (above 40 °C) in wastewater. Further research is needed to understand the effect of environmental parameters on the persistence of the new SARS-CoV-2.

Furthermore, authors such as Scott et al. [173], Crowe et al. [172] and Gibas et al. [167] conducted measurements on educational sectors (university and colleges) and Wong et al. [127] evaluated the trend of RAN SARS-CoV-2 in wastewater from a residential building to evaluate the temporal epidemiological behavior and identify and prioritize control strategies. This opens the door for the sectorized application and prioritization of different sectors, since it allows to evaluate the feasibility of the epidemiological strategies elaborated by local authorities or the sanitary measures adopted by the populations.

4.3. Surface Waters/Groundwater

Similar to WWTPs and sewage systems, SARS-CoV-2 monitoring in surface waters also indicates that the virus is transmitted from WWTPs to natural water sources. Often, untreated wastewater is discharged into the surface water (river, lakes), affecting groundwater sources. This is especially relevant in low-income countries and regions, including rural and peri-urban communities where untreated surface and groundwater sources are often directly used for drinking water. Surface water monitoring in low-income/developing countries requires more attention to control the potential risk of community spread of COVID-19. To date, surface waters have mainly been measured for viral loads, focusing on the possible use of these measurements as an epidemiological tool. According to Guerrero-Latorre et al. [82], the viral loads that were measured suggest that the number of people infected in the city of Quito are likely higher than that reported in the official data. This indicates the need to expand epidemiological data. Additionally, the lack of wastewater treatment in the city led to higher source water viral loads compared to other studies in which WWTPs were utilized. Rimoldi et al. [108] observed the same situation in Italian surface watersheds, where they found high viral loads in three rivers due to wastewater that was not treated or inefficiently treated or from combined sewage overflows in those rivers. The same types of evaluations were performed by Haramoto et al. [114] in rivers in Japan and by Zhao et al. [75] in rivers and lakes in China and found no positive values for viral load were observed in these water bodies, which can likely be explained by the presence of WWTPs in these study areas.

4.4. Wastewater from Hospitals

Wastewater from hospitals presents serious environmental and public health risks due to the presence of high concentrations of medical waste. In addition, the presence of SARS-CoV-2 in hospital wastewater poses additional risks of COVID-19 transmission [75,106]. Studies have explored the efficiency of the different technologies to treat this wastewater. Zhang et al. [76] found that viral RNA was removed after a preliminary disinfection treatment with sodium hypochlorite. However, after disinfection, SARS-CoV-2 RNA was found in the septic tank effluent, likely due to the release of viruses embedded in faecal particles. The high organic content and solid compounds in faeces decrease the efficiency of the treatment, which therefore requires an increase in hypochlorite doses in the septic tank to achieve complete viral elimination. Similarly, Arora et al. [97] showed the efficiency of sodium hypochlorite as a virus treatment solution in hospitals. These results demonstrate the need for optimized disinfection treatment systems that are effective at disinfecting wastewater from hospitals. Appropriate disinfection treatments and/or alternatives should be considered in prevention protocols to control COVID-19 transmission. Additionally, in developing countries where there are no WWTPs, it is necessary to implement treatment measures that reduce viral loads in sewage systems or water sources that receive sewage discharge.

Also, authors such as Hong et al. [125], Xu et al. [94] and Arora et al. [97] reported the use hospital effluents as pilot studies for the quantification of viral loads; based on the number of patients who have been admitted with CO-VID-19, models that reduce the variability and uncertainty of the relationships between the loads and the number of infected are elaborated. These models can then be applied to larger spatial scales.

4.5. Benefits and Outcomes of Monitoring the Different UWC Components

Based the literature review carried out, Table 3 presents benefits and outcomes associated with the monitoring of each UWC component.

4.6. Spatial Analysis

The country with the highest number of reported studies that examine SARS-CoV-2 in the UWC is the USA with a total of 39 (28%), followed by India with 10 (7.1%), Spain with nine (6.4%), Canada with eight (5.7%) Italy and Brazil with six (4.2% individual and 8.4% by two countries), Australia, France and Germany with five (3.5% individually, and 10.5% by three countries), the Netherlands with four (2.8%). Countries such as China, Japan and England with three studies each and other countries with one or two studies represent a total of 24.8%. It is important to emphasize that some studies involved multi-country measurements showing the potential of collaboration networks that facilitate the monitoring of the pandemic worldwide. Figure 2 presents the global distribution of the reported studies on SARS-CoV-2 measured in the UWC.

Table 3. Benefits and Outcomes of Monitoring the Different UWC Compo.

Component of UWC	Benefits	Outcomes
Wastewater treatment plant	High research opportunities, due to the variability of existing treatments and the combinations that can be generated. Allows monitoring of solids generated in primary and secondary treatments, where highly reliable results are obtained. Relevant for epidemiological control studies, since the wastewater contributing areas are known facilitating SARS-CoV-2 evaluations in conditions where it is not possible to monitor various locations of the sewer network. Allow to observe the dynamics of viral loads (growth and decay), which is useful for epidemiological analysis purposes.	In combined sewer networks the dilution rate can be very high, which could generate variability in the measurements.
Hospital efluent	High research opportunities, due to the variability of existing hospital water treatments. Optimal control location for quantification and establishing relationships between viral loads and number of infected by COVID-19.	Does not allow a wide spatial scale to be considered for epidemiological surveillance strategies. Does not allow to identify areas with asymptomatic infected persons
Sewer network	Opportunity to evaluate specific areas, such as educational centers, residential, commercial and industrial areas, among others, which allows the development of very specific epidemiological surveillance strategies. Allows to evaluate the behavior and the spatio-temporal dynamics in large wastewater drainage areas. High opportunity to expand research to improve knowledge about the behavior of the pandemic, and on the environmental alterations of SARS-CoV-2 at different spatial and temporal scales.	In combined sewer systems, the dilution rate can be very high, which generates variability in the measurements.
Surface Water	Allows identifying the dynamics of viral loads, which could be used as an epidemiological tool. Many watersheds are bordering between cities, provinces (states) and countries, which increases the opportunities to conduct epidemiological evaluations at large scales.	In waterbodies receiving large number of wastewater discharges, it is very difficult to identify the contributing areas of the viral loads, since it's hard to disaggregate the measured concentrations of SARS -CoV-2-

According to Figure 2, high concentrations of studies were conducted mainly in North America, Europe, Oceania, and Asia. In Latin America, studies have been carried out in Brazil, Chile, Argentina, Ecuador and Mexico. In Africa only one study was reported in South Africa. This distribution of studies indicates that most epidemiological monitoring in wastewater or natural waters have been conducted in highly industrialized countries.

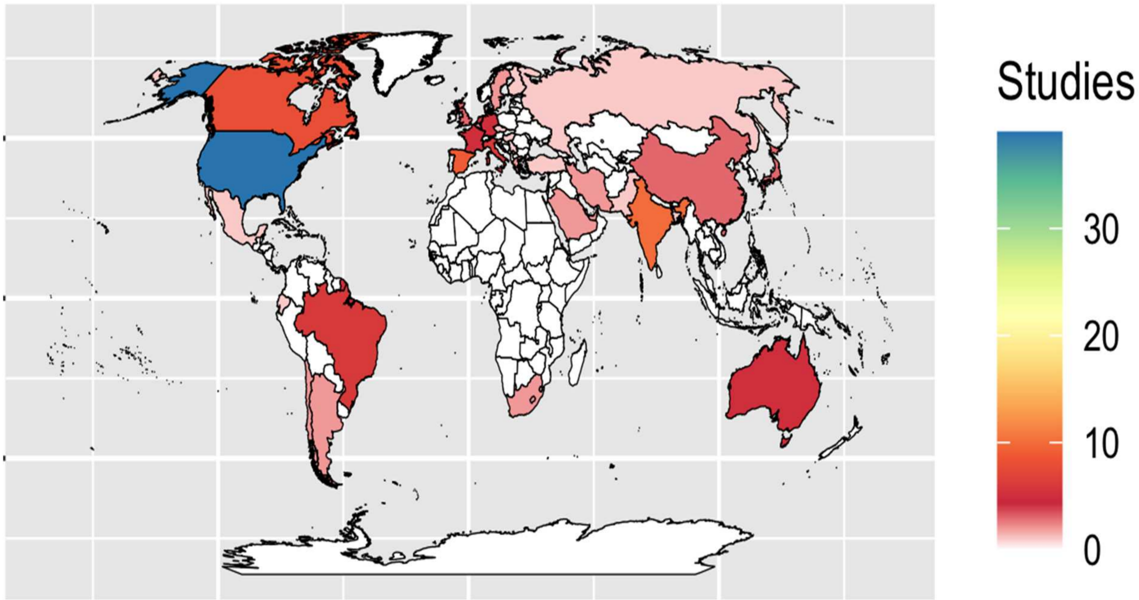

Figure 2. Global map of SARS-CoV-2 measured in UWCs by countries.

It is important to mention that the absence of investigations and measurements in wastewater, mainly in Africa, Central America and parts of Latin America, is due to relatively low sanitation coverage and limited capacity to diagnose infection [120]. It is also worth noting that according to the United Nations in 2017, 80% of the wastewater worldwide (>95% in some developing countries) is discharged into receiving water bodies without prior treatment or with little preliminary treatment, which poses a significant challenge for these countries in terms of water pollution and monitoring of public health [197,198].

The low coverage of sanitation and wastewater treatment, the shortage of certified laboratories and the low financial investments in public health in developing countries [199] indicate that monitoring SARS-CoV-2 for epidemiological purposes is a huge challenge. It is thus urgent to provide these countries with the required infrastructure and human resources as well as with the scientific capacities to implement monitoring of SARS-CoV-2 for epidemiological surveillance purposes.

5. Conclusions

The SARS-CoV-2 virus has generated huge numbers of infected people and unfortunately, has resulted in more than 1.65 million deaths worldwide. Most measurements and quantification efforts focus mainly on individuals who are currently infected. However, new studies based on wastewater epidemiology are increasingly being reported. An urban water cycle is a useful tool that allows for the expansion of integral management of urban water resources. Additionally, wastewater epidemiology can be used to identify interconnections between water sources and discharged pollutants during the various processes and at individual components of the system. These characteristics make this monitoring approach for COVID-19 in UWCs a vital tool for epidemiological monitoring and control studies and is quickly gaining popularity worldwide. This approach comes with a high benefit-to-cost ratio and can provide temporal and spatial estimates of the number of infected individuals in a given population [34,117,200].

Patients infected with COVID-19 can discharge SARS-CoV-2 in their faeces, which allows us to use wastewater and surface waters to monitor viral loads. The impact of SARS-CoV-2 in wastewater and surface water on the environment and on public health compels thorough research to assess and manage the associated risks [201]. It is also necessary to expand our understanding of the behaviour of the virus in wastewater. We need to be able to estimate the impact that characteristics and conditions of the environment and water (e.g., pH, temperature, light exposure, the concentration of solids, dissolved oxygen and organic matter) have on the survival of the virus [33,202]. These studies help to determine the conditions that favor environmental transmission. They are also incredibly important since large amounts of untreated wastewater are discharged into surface waters, which are then used in agriculture, fishing and recreational activities [185,203].

The diverse techniques used for the detection and quantification of SARS-CoV-2 levels have shown high efficiency when used as epidemiological monitoring tools. However, it is important to mention that differences in measurements can be observed in their quantification, due to the characteristics of each test. Public health authorities must take into account these differences and their possible impact for epidemiological decision-making [204,205]. Therefore, it is essential to continue the improvement of methods and procedures for the detection of SARS-CoV-2 in the different components of the UWC. In addition, it is essential to develop new methodologies that extend the knowledge and facilitate the massification of the application of epidemiological studies [188]. Developing conventional and robust techniques allows for the extrapolation and large-scale application of epidemiological studies using wastewater, facilitating their wide application and reducing technical and conceptual errors, as well as economic costs.

The objective of the measurements is to quantify the concentrations of SARS-CoV-2 in UWC waters as a public health tool. New research opportunities must be generated as a result of such monitoring. It is essential to identify the behavior of SARS-CoV-2 in the different types of wastewaters (residential, commercial, industrial, institutional, etc.), and evaluate the relationships with the physico-chemical characteristics of these waters, since factors such as pH and temperature may influence the results. Also, it is necessary to compare the concentrations of SARS-CoV-2 at the different steps of WWTPs treatment processes.

It is essential to identify adequate treatment systems that can be used to reduce virus loads in community and hospital wastewater. Apart from secondary treatment (>90% removal), studies show the need for tertiary systems or disinfection treatments to remove viruses efficiently. Lesiemple et al. [193] and Bhatt et al. [206] are useful resources as they reviewed different treatment processes and provide recommendations for wastewater treatment. It is paramount that we study the presence of SARS-CoV-2 in surface water, groundwater and drinking water, mainly in sectors where water treatment is unreliable (including rural areas with inadequate sanitation and developing countries). These studies should be mainly carried out in heavily urbanized watersheds where untreated wastewaters are discharged into surface waters (which also affects groundwater) and drinking water treatment for human consumption is not available [207].

It is necessary to create collaborative networks between highly industrialized countries and developing countries for the application of surveillance strategies of SARS-CoV-2 in UWC waters for epidemiological purposes. The previous experiences and knowledge acquired by the scientific community of the countries that have already used high benefit-cost protocols for SARS-CoV-2 surveillance in waters must be transferred as soon as possible to the authorities of developing countries.

The monitoring of SARS-CoV-2 in the various components of the UWC has been growing rapidly. Countries such as the United States, Holland, Italy, Brazil, Spain, Australia and India have already benefitted from the implementation of surveillance protocols during this pandemic. Indeed, authors such as Kopperi et al. [208] have already proposed a standard methodological approach for the study and epidemiological surveillance of SARS-CoV-2 in wastewater, that could be applied worldwide.

At this time of global and local re-opening, where new strains are increasingly being identified, the use of epidemiological control with wastewater becomes a powerful tool for decision-making and public health planning. Additionally, since mass vaccination processes are progressing in many countries, epidemiological monitoring in wastewater will allow the identification of areas where vaccination must be intensified.

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