



Monitoring the presence and persistence of SARS-CoV-2 in water-food-environmental compartments: State of the knowledge and research needs

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ABSTRACT

The recent spread of severe acute respiratory syndrome coronavirus (SAR-CoV-2) and the accompanied coronavirus disease 2019 (COVID-19) has continued ceaselessly despite the implementations of popular measures, which include social distancing and outdoor face masking as recommended by the World Health Organization. Due to the unstable nature of the virus, leading to the emergence of new variants that are claimed to be more and rapidly transmissible, there is a need for further consideration of the alternative potential pathways of the virus transmissions to provide the needed and effective control measures. This review aims to address this important issue by examining the transmission pathways of SARS-CoV-2 via indirect contacts such as fomites and aerosols, extending to water, food, and other environmental compartments. This is essentially required to shed more light regarding the speculation of the virus spread through these media as the available information regarding this is fragmented in the literature. The existing state of the information on the presence and persistence of SARS-CoV-2 in water-food-environmental compartments is essential for cause-and-effect relationships of human interactions and environmental samples to safeguard the possible transmission and associated risks through these media.

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Furthermore, the integration of effective remedial measures previously used to tackle the viral outbreaks and pandemics, and the development of new sustainable measures targeting at monitoring and curbing the spread of SARS-CoV-2 were emphasized. This study concluded that alternative transmission pathways via human interactions with environmental samples should not be ignored due to the evolving of more infectious and transmissible SARS-CoV-2 variants.

1. Introduction

The current global pandemic hit many nations in different ways unimaginable, spanning from economic sustainability to survival and healthcare challenges. Currently, the coronavirus disease 2019 (COVID-19) has spread to almost 223 countries with over 160 million confirmed cases and more than 3.3 million deaths as of May 13, 2021, with community transmissions responsible for the significant percentage (WHO, 2021). Despite the measures many countries had engaged in, including the use of alcohol-based sanitizers, washing of hands frequently, use of facemasks, social distancing, and keeping up with good personal hygiene as recommended by the World Health Organization (WHO, 2020a); the virus continuously spreading unabated with an increasing number of confirmed daily cases (Singh et al., 2020; WHO, 2021). The reoccurring cases in some quarters after the adequate compliances of the recommended measures have become a misery (Rettner, 2020), which suggests the existence of indirect pathways of the virus transmission.

The current COVID-19 pandemic and the various implemented measures had offered the planet earth positive and negative impacts, which majorly relay back to the environmental compartments such as soil, water, and air while extending to the food and food materials (Anand et al., 2021; Sarkar et al., 2021; Adelodun et al., 2021a,b; Núñez-Delgado, 2020; Rizou et al., 2020). For instance, the country-wide lockdown in different nations of the world has impacted greatly on the emission level and waste generations. Europe, specifically Spain, Italy, and France, recorded about 106 megatons of CO₂ emission reductions between January and June 2020 as compared to the same period of the previous year before the pandemic (Andreoni, 2021). Similarly, Elsaid et al. (2021) reported noticeably improved water resource quality due to a reduction in heavy metal and organic load discharges. However, the recycling programs due to the possibility of virus spread on surfaces have been halted in many countries, thereby causing an increase in domestic waste generation, both organic and inorganic, as a result of a high surge in online food services and increase in medical wastes (Zambrano-Monserrate et al., 2020; Gupta et al., 2015; Yadav et al., 2018a). The wastewater quality has also been significantly deteriorated, not only from the SARS-CoV-2 contamination itself but from various forms of disinfectants and pharmaceutical products used in managing the virus and the infected people (D. Zhang et al., 2020; Elsaid et al., 2021).

The SARS-CoV-2, due to its novelty and distinctive features of mutation, recombination, and replication, has continued to become a mystery for the research community (Rehman et al., 2020). As the world is winding up the year 2020 that has been ravaged with the novel virus, the new variant of the virus called “the first variant of concern from 2020, December (SARS-CoV-2 VOC, 202012/01)” which is claimed to be more and rapidly transmissible was pronounced in the United Kingdom and has been further discovered in other countries like South Africa, India, the United State (USA), Japan, Spain, Sweden, France, and others (CDC, 2020; Ueno and Ives, 2020). On this note, it has become a necessity requiring intense research into the presence, survival, transmission, and inactivation of the SARS-CoV-2 in different environmental media (Núñez-Delgado, 2020; Anand et al., 2021b). Since SARS-CoV-2 has the potential to remain stable in different environmental compartments and under different environmental conditions (Ren et al., 2020; Chin et al., 2020; Anand et al., 2021b), this signifies alternative potential pathways through which the virus can spread. To avoid the introduction of the virus to the immediate environment, it is pertinent to treat

contaminated medical wastes such as facemasks, hand gloves, and other items used in tackling the COVID-19 pandemic separately by proper waste management process (Adelodun et al., 2021a,b; Zambrano-Monserrate et al., 2020; Malav et al., 2020).

The fact that SARS-CoV-2 can survive outside the living hosts for a short period (Kampf et al., 2020; Núñez-Delgado, 2020), which could be sufficient enough to enter other living hosts for further proliferation, possible mutation, and character changes (Gwenzi, 2021). This study hypothesizes the possible cause-and-effect relationships i.e., interplays among the environmental matrices and food. Briefly, the wastewater and sewage contamination of SARS-CoV-2 may result in spillover soil and water contamination if such wastewater is used for irrigation and sewage as a soil amendment which in turn may lead to contamination of food materials during food production and consumption. Therefore, the potential transmission through water-food-environment interactions is essential for consideration.

This study aims to review the state of knowledge on the presence, survival, and transmission of SARS-CoV-2 in water, food, and other environmental compartments concerning human interactions. Hence, suggesting the research needs on the resourceful strategies for restricting the current and future pandemics, while safeguarding the human health risks.

2. Methodology

To address the stated aims of this study, the following three-stage procedures were followed. Firstly, the literature search of peer-reviewed articles published up to May 13, 2021, only in the English language and in the Scopus database (scopus.com), the largest abstract and citation database of peer-viewed literature, was conducted. The keywords, which are relevant to the topic and aims of this study, used for the search were SARS-CoV-2, Severe Acute Respiratory Syndrome, coronavirus, COVID-19, water, wastewater, sewage, food, food material, inanimate surfaces, environmental compartments, and persistence, and health risks. These keywords were combined with the Boolean operators of ‘OR’ and ‘AND’. The titles and abstracts of articles with information on the presence and persistence of the SARS-CoV-2 in water, food, and environmental media were evaluated. Also, considering the similarities in the transmission of SARS-CoV-2 with other human coronaviruses, the articles on SARS-CoV, MER-CoV, and their surrogates targeted at the water, food, and environmental matrices were also considered. Secondly, the retrieved articles were manually screened for relevance and appropriateness to the subject matter of this study, while the relevant articles from the references of the retrieved articles were also checked and added. Since COVID-19 is relatively new, no year restriction was placed on the literature search. A total of 548 articles were retrieved; however, after the screening, only 114 were selected while the remaining 435 were excluded as they did not contain the required information that meets the aim of this study, with the majority are review articles. Lastly, the retrieved articles were, thereafter, carefully reviewed, synthesized, and included in this study.

3. Life cycle and persistence of SARS-CoV-2 in water-food-environment interactions

3.1. Life cycle of SARS-CoV-2

SARS-CoV-2 belongs to the family *Coronaviridae*, which is grouped

into enveloped viruses with a single-stranded and positive-sense RNA genome (Gorbalenya et al., 2020). Osman et al. (2020) posited that seven known coronaviruses are zoonotic (majorly transmitting from animal to human), including alphacoronavirus (such as HCoV-NL63 and HCoV-229E) and betacoronavirus (such as HCoV-OC43, HCoV-HKU1, SARS-CoV, Middle East Respiratory Syndrome Coronavirus (MERS-CoV) and SARS-CoV-2), which have led to outbreaks of different scales (Cui et al., 2019). While both SARS-CoV-2 and SARS-CoV are closely related due to their subgenus Sarbecovirus origin, the MERS-CoV belongs to different species within the genus betacoronavirus (Kitajima et al., 2020; Gorbalenya et al., 2020). About 79–82% genetic similarity was found between SARS-CoV-2 and SARS-CoV while approximately 50% similarity was only shown with MERS-CoV (Arslan et al., 2020; Lai et al., 2020). SARS-CoV has been reported as the most proximal virus to SARS-CoV-2 (Andersen et al., 2020). However, the SARS-CoV-2 tends to have a relatively high environmental stability and transmissibility level than other viruses in the same betacoronavirus category due to its higher basic reproductive number (R_0), which refers to the average new infections caused by the infected or contagious person in an uninfected population (Liu et al., 2020; van Doremalen et al., 2020). The estimated average value of R_0 for SARS-CoV-2 ranges from 1.40 to 6.49 compared to an average value of 2.2–3.7 for the SARS-CoV and 1.4–2.5 of WHO presumed value range (Liu et al., 2020; Riley et al., 2003).

Generally, coronaviruses were reported to originate from the bat as the natural host and transmitted directly to humans from intermediate hosts like dromedary camels, cats, pangolins, civets, and many more (Cui et al., 2019; Tiwari et al., 2020). For instance, civet cats have been stated to responsible for the transmission of SARS-CoV to humans, while MERS-CoV is being transmitted to humans from camel (Cui et al., 2019), and the likelihood of bats being the natural host of SARS-CoV-2 (Rehman et al., 2020). However, the specific intermediate hosts for the SARS-CoV-2 remain unclear, with some studies linking pangolins as a possible intermediate transmission host to humans (Cyranoski, 2020). The viruses can cause various forms of system infections in animals, while human beings are mainly infected through the respiratory tract (Tiwari et al., 2020). However, the virus does result in different syndromes such as neurologic, enteric, hepatic, and respiratory (Adelodun et al., 2021a,b; Lai et al., 2020), thereby making the rate of human-to-human transmission high via droplets from coughing, sneezing, and exhalation from an infected individual or perhaps from fomites (Rehman et al., 2020). It is important to know the origin and transmission routes of the novel SARS-CoV-2 to help in curbing the wide-spread; the former has been established in different studies while the latter is still evolving.

The International Committee on Taxonomy of Viruses (ICTV) was subsequently identified the novel coronavirus as SARS-CoV-2 and the disease caused as COVID-19 (Gorbalenya et al., 2020). Also, it was noted that the SARS-CoV of 2003 has a mortality rate of 9% across 26 countries, while SARS-CoV-2 of 2019 has a mortality rate of 2.9% across 109 countries (Zhu et al., 2020; Gorbalenya et al., 2020). This indicates that SARS-CoV-2 has a greater transmission rate and ability than SARS-CoV and the reason is likely traced to be genetic recombination event at S protein in the receptor-binding domain (RBD) region of SARS-CoV-2 (Rehman et al., 2020). Nevertheless, the similarity index of 75–80% nucleotide was confirmed for both SARS-CoV-2 and SARS-CoV (Zhu et al., 2020). The need to identify the possibility of SARS-CoV-2 transmission within water, food, and environment routes has become a subject of interest to researchers.

The life cycle of the virus in human beings begins by infecting the cells of the respiratory systems while binding to the receptors and making an entry in the cell to duplicate its genome materials and use the cellular machinery to synthesize the proteins required to sprouts out new virions from the surface of the cell (Chhikara et al., 2020; Osman et al., 2020). It was further reported by Chhikara et al. (2020) that after the SARS-CoV-2 infection, the infected patients have similar characteristics with the infected culture cells. However, as a result of the delicate

specific nature of the SARS-CoV-2, the damage in its lipid envelope could likely make the viral particles non-infectious, irrespective of the presence of its genetic fragments (Nghiem et al., 2020). Meanwhile, the complete mechanism for the novel SARS-CoV-2 is not yet fully known but the available data of other coronaviruses may be enough to unravel some of the mystery, especially regarding the different pathways of transmission.

3.2. Presence and persistence of SARS-CoV-2 in water-food-environmental compartments

The presence and persistence of infectious SARS-CoV-2 and/or its RNA have continued to receive significant interest in the science community. A growing number of studies have confirmed the presence of SARS-CoV-2 in the water environment due to unhindered human activities of infected people on the use of water resources. The presence of infectious SARS-CoV-2 and its RNA in the stool, urine, sputum, and other clinical samples of infected patients have been reported by many authors despite the respiratory samples tested negative after some days (Holshue et al., 2020; Wu et al., 2020; Xiao et al., 2020b, 2020a; Yeo et al., 2020; Amirian, 2020; Tong et al., 2020; Du et al., 2020; Kim et al., 2020; Wölfel et al., 2020; Young et al., 2020; Zhang et al., 2020; Zheng et al., 2020; To et al., 2020; Jeong et al., 2020; Wang et al., 2020; Zhang et al., 2020; Wölfel et al., 2020, 2020; Sun et al., 2020), which may ultimately end up in wastewater. Some authors have also reported the presence of SARS-CoV-2 strains in the wastewater generated from the isolation centers and nearby hospitals where COVID-19 patients are being managed (J. Wang et al., 2020; Ge et al., 2020; Feng et al., 2021; Chakraborty et al., 2021; Ahmed et al., 2021; Hong et al., 2021), while others studies reported the presence of SARS-CoV-2 RNA in water and wastewater collected from wastewater treatment plants (Ahmed et al., 2020a; La Rosa et al., 2020; Hasan et al., 2020; Haramoto et al., 2020; Mlejnkova et al., 2020; Peccia et al., 2020; Randazzo et al., 2020; J. Wang et al., 2020; W. Wang et al., 2020; Rimoldi et al., 2020; Medema et al., 2020; Hokajärvi et al., 2021; Chavarria-Miró et al., 2021; Kitamura et al., 2021; Saguti et al., 2021), which are of course do not necessarily indicate the infectivity of the virus (Buonerba et al., 2021). However, few studies have reported the detection and isolation of infectious SARS-CoV-2 from different environmental samples such as wastewaters (Bivins et al., 2020; Lee et al., 2020; Sala-Comorera et al., 2021). Gholipour et al. (2021) also confirmed the presence of SARS-CoV-2 in the wastewater aerosols generated from wastewater treatment plant pumping stations, with quantitative microbial risk analysis indicating a high risk of infections to wastewater workers (Zaneti et al., 2021). A recent study by Chen et al. (2020) has indicated that SARS-CoV-2 could become more infectious with the possibility of an appearance of more infectious strains. Furthermore, Giacobbo et al. (2021) reported that infectious SARS-CoV-2 can be present in water and sewage for up to 4.3 and 6 days, respectively, depending on the sample conditions.

The disparity in the results where many of these studies could not identify the infectious virus could be due to the differences in protocols used in isolation of the virus from the samples in those various studies (Kitajima et al., 2020). Similarly, Bivins et al. (2020) opined that the inability to culture SARS-CoV-2 despite detecting the genetic material of the virus could be attributed to the concentration method adopted in those studies. More importantly, the concern of the possibility of the false-negative result was raised by Buonerba et al. (2021) in their recent review study on the methods of detection of SARS-CoV-2. In their report, Barceló (2020) suggested that the use of biomolecules containing proteins of SARS-Cov-2 for the detection of the virus, which has been successfully used in the clinical samples, rather than the RNA could reduce the numbers of false-positive results. The high level of biosafety require (laboratories with biosafety-level 3) to culture and propagate the viable SAR-CoV-2 due to the high risks of infection have also limited the studies in this area (de Oliveira et al., 2021). Nevertheless, the emerging

methodologies and technologies that are being deployed for the detection and isolation of the infectious SARS-CoV-2 in different environmental samples indicating the presence and persistence of infectious SARS-CoV-2 in such samples (de Oliveira et al., 2021; Buonerba et al., 2021; Sala-Comorera et al., 2021; Leifels et al., 2021). Table 1 presents the available methods for the detection, persistence, and isolation of SARS-CoV-2 from the environmental samples.

Meanwhile, the use of environmental surveillance like wastewater-based-epidemiology (WBE) has been continuously suggested (Daughton, 2020; Adelodun et al., 2020; Kitajima et al., 2020), with some selected implementations currently reported (La Rosa et al., 2020; Sherchan et al., 2020; Randazzo et al., 2020; Medema et al., 2020; Ahmed et al., 2020; Zhao et al., 2020; Saththasivam et al., 2021) as a better approach for the environmental surveillance of SARS-CoV-2 in the water environment. The use of the WBE procedure is to gain insights into the degree of infection spread in a defined population and to obtain the needed epidemiological data that can be used for the assessment of any potential public health risks (Adelodun et al., 2020; Kitajima et al., 2020; Ahmed et al., 2020; Lodder and de Roda Husman, 2020). One of the significant advantages of the WBE tool is the ability to monitor the virus epidemiology in the water environment, which the laboratory and clinical surveillance systems might fail to detect due to the asymptomatic and paucisymptomatic infecting nature of SARS-CoV-2 (Jiang et al., 2020; Mizumoto et al., 2020).

The use of the WBE approach aids early detection of SARS-CoV-2 RNA in wastewater before the revealing of cases from clinically diagnosed patients (La Rosa et al., 2021), which signifies its ability to serve as an early warning for possible re-emergence of the COVID-19 pandemic in a community by complementing the clinical surveillance (Polo et al., 2020; Medema et al., 2020; Westhaus et al., 2021). The analysis and interpretation of the data generated from wastewater surveillance to assess the prevalence of COVID-19 incidences could be a challenging task (Graham et al., 2021). Modeling and forecasting have been recognized as part of the key steps in building a robust WBE system for COVID-19. The correlation between SARS-CoV-2 concentration in wastewater and COVID-19 confirmed cases was established in two communities of the state of Utah in the USA (Weidhaas et al., 2021), indicating the potential for future forecasting of the pandemic based on the occurrence of SARS-CoV-2 in sewage. Using the SARS-CoV-2 viral loads (genome copies) in wastewater samples from a wastewater treatment plant with 2.3 million residents (San Diego County) and correlated

with clinical reported cases including temporal information in an autoregressive integrated moving average model enabled prediction of up to 3 weeks in advance (Karthikeyan et al., 2021). Similarly, Cao and Francis (2021) investigated the integration of SARS-CoV-2 concentration in wastewater into WBE using a vector auto-regression statistical model to forecast the COVID-19 infection cases in the Borough of Indiana community. The authors concluded that only long-term concentration of the SARS-CoV-2 in the sewage could produce reliable forecasting results of COVID-19 cases in such a community (Cao and Francis, 2021). Nevertheless, the WBE protocols need to be refined and standardized to be able to address some of the differences in the RNA detectability with existing molecular markers while ensuring validation of such protocols for both concentration and quantification of the virus and associated biomarkers (Rimoldi et al., 2020; Polo et al., 2020). This could be addressed through the adjustment of the virus concentration estimation in sewage via the incorporation of the kinetics of unobserved concentrations due to temporal variation in virus concentration (Miura et al., 2021).

In a recent study, the infectious SARS-CoV-2 was also identified from the air samples collected from the COVID-19 patient's isolated rooms (Ong et al., 2020; Razzini et al., 2020). Similarly, Schuit et al. (2020) demonstrated the infectivity and persistence of SARS-CoV-2 in an aerosol under suitable environmental conditions. Ren et al. (2020) reported that SARS-CoV-2 can sustain its virulence for up to 30 min in an enclosed environment like unventilated buses. Similarly, the presence and persistence of SARS-CoV-2 have been demonstrated on different inanimate materials in the environment with an extended period of up to 72 h for its viability (Ren et al., 2020; van Doremalen et al., 2020; Ong et al., 2020). Kampf et al. (2020) reported varying viability of coronaviruses on the surfaces from 2 h to 9 days. Moreover, Shutler et al. (2021) posited that SARS-CoV-2 could maintain its stability for up to 25 days in the water environment with varying levels of infection risks in different countries. The challenges of lack of standardized protocol specifically for the monitoring, detection, and quantification of SARS-CoV-2 in water and wastewater, and other environmental compartments have limited the current knowledge on the occurrence, fate, persistence, and removal of the virus in various environmental media (Kitajima et al., 2020; Naddeo and Liu, 2020). This has led to relatively low or negatives results of its occurrence in environmental samples among the reported studies (Miyani et al., 2020). Table 2 shows an overview of the presence and persistence of SARS-CoV-2 in the

Table 1
Detection and isolation of infectious SARS-CoV-2 from environmental samples

Sample type	Virus detection and/or isolation methods	Genetic genes analyzed	Limit of detection (viable virus)	References
Feces	rRT-PCR	ORF1ab gene.	<40 Ct.	W. Wang et al. (2020)
Urine	RT-PCR and Vero E6 cells.	ORF1ab gene and N-gene.	NA	Sun et al. (2020)
Feces	qRT-PCR and Vero E6 cells with the indirect immunofluorescent assay.	N-gene and ORF1ab gene.	NA	Xiao et al. (2020a)
Urine and feces	qPCR and Vero E6 cells with Immunofluorescence antibody assays.	S-gene	0.3 log ₁₀ copies/mL per reaction	Jeong et al. (2020)
Feces	Vero E6 cells	NA	Unclear	Y. Zhang et al. (2020)
River water and seawater	RT-qPCR and TCID ₅₀ assays, and Vero E6 cells	N-gene	4.5 gc/μl	Sala-Comorera et al. (2021)
Tap water and untreated primary influent	RT-qPCR and Vero E6 cells	E-gene	Below 5.6 TCID ₅₀ /mL	Bivins et al. (2020)
Tap water	plaque assay with Vero cells	N-gene	10 ³ PFU/mL	Lee et al. (2020)
Air sample (hospital room)	rRT-PCR and Vero E6 cells	N-gene	6 to 74 TCID ₅₀ units/L of air	Lednický et al. (2020)
Air sample (from a car with COVID-19 patient)	Centrifugation; rRT-PCR and Vero E6 cells	N-gene	0.25–0.50 μm	Lednický et al. (2021)
Aerosol (Rooms in hospital wards)	rRT-PCR and Vero E6 cells	E-gene	20 TCID ₅₀ /mL	Santarpija et al. (2020)
Plastic	End-point titration on Vero E6 cells	NA	3.2 TCID ₅₀ /mL (3–4 days)	van Doremalen et al. (2020)
Food material (Salmon)	Vero E6 cells	NA	10 ² TCID ₅₀ /mL	Dai et al. (2021)

ORF refers to an Open Reading Frame. NA refers to not available.

Table 2

Presence and persistence of coronavirus in water-food-environment media

Matrix	Samples	Location	Virus type	Persistence	Main findings	Reference
Water/ wastewater/ sewage/river	Pasteurized and Unpasteurized wastewater	Michigan, USA	MHV, ϕ 6, and MS2 and T3	MHV and ϕ 6 persisted ($T_{90\%}$) for 13 and 7 h, respectively, at 25 °C in unpasteurized wastewater with lesser persistent in pasteurized wastewater at 10 °C, while MS2 persisted for 121 h. T3 persisted much longer than other surrogate viruses considered.	The persistence of enveloped viruses in wastewater indicated concerns for their inactivation in wastewater treatment facilities.	Ye et al. (2016)
	Water (reagent grade), lake water, and pasteurized settled sewage	Chapel Hill, NC, USA	TGEV and MHV	TGEV and MHV persisted for 22 ($T_{90\%}$) and 17 days, respectively, at 25 °C in water (reagent grade). However, TGEV and MHV persisted for 9 ($T_{99\%}$) and 7 days, respectively, at 25 °C in pasteurized settled sewage. The infectivity decreases by $<1 \log_{10}$ for both viruses after 4 weeks at 4 °C.	The coronaviruses (based on surrogates TGEV and MHV) could remain infectious for long period in water and sewage matrices at low and ambient temperatures of 4 and 25 °C, respectively.	Casanova et al. (2009)
	Hospital wastewater, dechlorinated tap water, domestic sewage	Beijing City, China	SARS-CoV	SARS-CoV persisted for 2 days at 20 °C and 14 days at 4 °C in hospital wastewater, dechlorinated tap water, and domestic sewage. However, the persistence was extended for 14 days in wastewater at 4 °C.	Conventional disinfectant like chorine is highly effective to inactive SARS-CoV	Wang et al. (2005)
	Tap water, primary and activated sludge (secondary) effluents	Tucson, AZ, USA.	SARS-CoV	10–12 days at 23 °C in dechlorinated tap water and >100 days at 4 °C. 2–3 days 23 °C in primary sewage. 3 days 23 °C in secondary sewage.	The persistence of SARS-CoV is longer in primary wastewater than secondary wastewater due to the presence of organic material and suspended solids.	Gundy et al. (2009)
	Untreated wastewater, autoclaved wastewater, and dechlorinated tap water	Brisbane, Australia	SARS-CoV-2 and MHV	SARS-CoV-2 RNA: 8–28 days in untreated wastewater, 6–43 days in autoclaved wastewater, and 9–59 days in dechlorinated tap water, all at 4–37 °C. MHV RNA: 7–57 days in untreated wastewater, 6–43 days in autoclaved wastewater, and 11–44 days in tap water, all at 4–37 °C.	The difference in persistence of both SARS-CoV-2 RNA and MHV RNA is not statistically significant. The persistence of SARS-CoV-2 RNA in untreated wastewater was less sensitive to high temperature compared to other sample matrices at other temperature values.	Ahmed et al. (2020b)
	Tap water and untreated primary influent	Northern Indiana, USA	SARS-CoV-2	2 days in tap water and 2 days for wastewater, both at room temperature of 20 °C. SARS-CoV-2 infectivity significantly decreased to 15 and 2 min at 50 °C and 70 °C, respectively. The higher starting titer of $10^5 \text{ TCID}_{50} \text{ mL}^{-1}$ showed longer persistence of the entire sampling time course (7 days).	The genetic material of the SARS-CoV-2 was found to be more persistent than the infectious virus.	Bivins et al. (2020)
	Wastewater influent	Helsinki, Finland	SARS-CoV, SARS-CoV-2, and Norovirus GII	Both SARS-CoV and SARS-CoV-2 RNAs persisted for 84 days at temperatures of 4 to –75 °C. Norovirus GII RNA indicated a 1-log ₁₀ reduction in persistence by between 29 and 84 days during storage.	The persistence of non-envelop viruses like norovirus is not better than enveloping viruses like SAR-CoV-2 in cold environmental conditions as against the existing belief.	Hokajärvi et al. (2021)
	Wastewater	Paris, France	SARS-CoV-2 RNA, – Coxsackievirus B5	Both SARS-CoV-2 RNA and protected viral RNA persisted for up to 7 and 12 days, respectively at 4 °C but showed less stability at 20 °C.	Both SARS-CoV-2 RNA, – Coxsackievirus B5 RNA have closely similar persistence levels to temperature changes. The infectivity of both viruses	Wurtzer et al. (2021)

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Table 2 (continued)

Matrix	Samples	Location	Virus type	Persistence	Main findings	Reference
	River water and wastewater	Minas Gerais State, Brazil	SARS-CoV-2	Coxsackievirus B5 RNA maintained its infectivity at 10 min up to 42 °C. SARS-CoV-2 persisted for 7.7 and 5.5 days in rain water and wastewater, respectively at 4 °C. However, the viable virus persisted more (4–4.5 times) at 24 °C in both samples.	was preserved up to 24 h in wastewater samples. The temperature had a strong correlation with the persistence of SARS-CoV-2 in river water and wastewater	de Oliveira et al. (2021)
Food/food package/food handlings	Plastic carrier (simulating contaminated food packages) and wipes	Czech Republic	Alphacoronavirus 1	The virus persisted to a detectable limit for up to 5 days at 4 °C. Wet wipes significantly inactivated the virus from the surface of the plastic package, with no detectable of the virus after 96 h when using disinfectant wipes.	The persistence and possible transmission of SARS-CoV-2 through plastic packaging for food can be sufficiently mitigated using wet-wiping, especially with disinfectant wet wipes.	Malenovská (2020)
	Salmon		SARS-CoV-2	SARS-CoV-2 maintained viability when attached with the salmon for 8 days at 4 °C and 2 days at 25 °C.	Infectivity is associated with temperature in the salmon.	Dai et al. (2021)
	Romaine lettuce		Bovine coronavirus (strain 88)	Infectious Bovine coronavirus persisted for up to 25 days on romaine lettuce surface under refrigerated condition.	Coronavirus maintaining its viability on the lettuce surface demonstrates the possibility of zoonotic transmission to humans.	Mullis et al. (2012)
	Dromedary camel milk, goat milk, and cow milk	Saudi Arabia	MERS-CoV	7 h under 4 °C refrigerated conditions. No infectious virus present in the Dromedary milk samples within 48 min at 22 °C storage.	Heat treatment (pasteurization) decreased the infectivity of the MERS-CoV in milk samples below the detectable limit.	van Doremalen et al. (2014)
	Lettuce, and strawberries		SARS-CoV (Strain 229E)	At 4 °C, SARS-CoV persisted for 2 days on lettuce, while the virus did not survive on strawberries. SARS-CoV persisted less on the produce at –20 °C.	Respiratory virus-like SARS-CoV could persist for a while on fresh fruits under refrigeration conditions (temperature) commonly used to store them in the household.	Yépiz-Gómez et al. (2013)
Environmental compartments	Aerosols	New Orleans, Fort Detrick, and Pittsburgh, in the USA.	SARS-CoV-2, SARS-CoV, and MERS-CoV	At prevailing environmental conditions of 23 °C and 53% RH, the SARS-CoV-2 maintained its infectivity up to 16 h, more than SARS-CoV and MERS-CoV.	SARS-CoV-2 could persist very long in aerosol and indicates the possibility of serving as an airborne pathogen.	Fears et al. (2020)
	Aerosols, plastic, stainless steel, copper, cardboard	NA	Infectious SARS-CoV-2, and SARS-CoV	At 21–23 °C and 40% RH, both viable SARS-CoV-2 and SARS-CoV persisted for 72 h on plastic, and stainless steel with a significant reduction on stainless steel after 48 h and plastic after 72 h. Viable SARS-CoV-2 and SARS-CoV persisted for only 4 and 8 h, respectively, on copper, while they persisted for 24 and 8, respectively, on cardboard. Viable SARS-CoV-2 persisted for 2.64 h in aerosol (the experimental duration was 3 h) while SARS-CoV persisted for up to 2.43 h	Both viable SARS-CoV-2 and SARS-CoV demonstrated similar persistence on surfaces and aerosols under the same environmental conditions.	van Doremalen et al. (2020)
	Glass, wood, mask (inner and outer surface), stainless steel, paper, tissue paper, banknote paper	NA	SARS-CoV-2	At environmental conditions of 22 °C, pH of 3–10, and 65% RH, SARS-CoV-2 was viable up to 2 days on glass, 1 day on wood, 7 days on mask (outside surface), 4 days on mask (inner surface), 4 days on stainless steel, 30 min on paper and tissue paper, and 2 days on banknote paper.	SARS-CoV-2 is highly stable under favorable environmental conditions but very susceptible to disinfectants.	Chin et al. (2020)

(continued on next page)

Table 2 (continued)

Matrix	Samples	Location	Virus type	Persistence	Main findings	Reference
	Polytetrafluoroethylene, polyvinyl chloride, Ceramic tiles, glass, silicone rubber, and stainless steel.	United Kingdom	SARS-CoV (Strain 229E)	The virus persisted for 5 days in all the materials at 21 °C.	While SARS-CoV was able to remain viable on different surfaces, the virus was inactivated quickly on copper alloy materials.	Warnes et al. (2015)
	Paper, disposable gown (impervious), and cotton gown.		SARS-CoV (Strain GUV6109)	At 20 °C, SARS-CoV persisted for less than 2 h on the disposable gown, and less than 1 day on the cotton gown, and paper,	There is an unlikely transmission of the virus via droplets on paper and cotton materials, especially when it is dried. Detergents can serve as a decontaminant agent of SARS-CoV.	Lai et al. (2005)
	Wood boards, paper (press and filter), cloth, plastic, metal, and mosaic.	Beijing, China	SARS-CoV (Strain CoV-P9)	At 21–25 °C, SARS-CoV persisted for 4 days on wood board, 4 on press paper, 5 days on filter paper and cloth, 4 days on plastic, 4 days on glass, and 3 days on the mosaic.	The persistence of SARS-CoV in the environment is strong but highly susceptible to heating and Ultraviolet irradiation.	Duan et al. (2003)
	Steel, plastic, and aerosol		MERS-CoV	For steel and plastic, MERS-CoV persisted for 48 h at 20 °C and 40% RH, 24 h at 30 °C and 30% RH, and 8 h at 30 °C and 80% RH. For aerosol, MERS-CoV maintained its viability at 20 °C and 40% RH.	The prolonged presence of MERS-CoV under conducive environmental conditions could aid its transmission in such an environment.	van Doremalen et al. (2013)

water-food-environment media.

Where MHV is Murine hepatitis virus, $\phi 6$ is *Pseudomonas* phage (human enveloped virus surrogate), PEG is Polyethylene Glycol, TGEV is Transmissible Gastroenteritis Virus, RH is Relative humidity, *Alphacoronavirus 1* is SARS-CoV-2 surrogate (strain M 42, CAPM V-126), MS2 and T3 (*Enterobacteria* phage) are non-enveloped virus surrogates. Meanwhile, current studies have indicated that the extended survival of SARS-CoV-2 in water environments is constricted due to some environmental variables such as pH, relative humidity (RH), UV ozone, and temperature, and disinfectants like bleach or chlorine were found to significantly influence the SARS-CoV-2 survival outside the living hosts (Bivins et al., 2020; Chin et al., 2020; Bilal et al., 2020; Kampf et al., 2020; Chan et al., 2020). Ratnesar-Shumate et al. (2020) demonstrated the inactivation of SARS-CoV-2 on different surfaces using simulated sunlight, with an observed slower rate of inactivation under lower simulated sunlight levels. The authors concluded that there might be significant varying persistent and exposure risk to SARS-CoV-2 between indoor and outdoor environments depending on the level of exposure to sunlight. Chan et al. (2020) also demonstrated the infectivity of SARS-CoV-2 in different environmental conditions after fecal shedding to the external environment. The results showed that the virus remained infectious for 7 days while in solution at a temperature of 25 °C but rapidly lost its infectivity within 1 day when the temperature increased to 37 °C. Also, the SARS-CoV-2 was unable to survive at pH of 2 and 3, however, remained infectious for 1 day when the pH increased to 4 and 11.

Nevertheless, the existing studies on other coronaviruses like SARS-CoV and MERS-CoV suggest that the infectivity persists for 2–14 days in the water environment under favorable conditions of temperature and humidity (Wang et al., 2005; van Doremalen et al., 2013). van Doremalen et al. (2020) compared the environmental stability of both SARS-CoV and SARS-CoV-2 on different material surfaces such as copper, plastic, cardboard, stainless steel, and aerosol. They confirmed little differences in half-lives for both SARS-CoV and SARS-CoV-2 in all the surfaces except for the cardboard.

While the presence and persistence of SARS-CoV-2 in the water environment have received considerable attention, the food environment has received less attention with few publications available on the presence and persistence of SARS-CoV-2 on food and food materials (Zuber and Brüssow, 2020). Meanwhile, the emergence of SARS-CoV-2

linked to Huanan Seafood Wholesale Market in Wuhan, China, where food items of both plant and animal origins are sold, among which are bats and pangolins that are considered possible natural and intermediate hosts of SARS-CoV-2 and other mammalian viruses (Li et al., 2020; Minhas, 2020; Cyranoski, 2020). The ability of the virus hosts to infect other livestock and the contact of saliva, urine, or feces with fruits and other food items meant for human consumption from these hosts could lead to spillover zoonotic transmission to humans (Minhas, 2020). The selling of these animals serving as potential SARS-CoV-2 hosts along with other agricultural products in such a big environment could possibly lead to the presence of the virus and likewise its substantial contamination of both other food items and the environment (Duda-Chodak et al., 2020; Yadav et al., 2021).

The previous studies of other coronaviruses demonstrated their stability in a frosty condition, leading to rising concerns on the potential of the SARS-CoV-2 to persist on raw or uncooked foods of animal source and even vegetables, which are often preserved through refrigeration. For instance, Dai et al. (2021) demonstrated prolonged infectivity of SARS-CoV-2 in a salmon up to 8 days at 4 °C. Similarly, infectious Bovine coronavirus was reported to persist on the romaine lettuce under refrigeration conditions for not less than 14 days (Mullis et al., 2012). MERS-CoV could persist in dairy products like milk for at least 72 h under 4 °C refrigerated conditions (van Doremalen et al., 2014). Also, some strains of SARS-CoV and MERS-CoV similar to SARS-CoV-2 could maintain their infectivity for almost 2 years at a temperature of –20 °C (WHO, 2020b). Different studies conducted on coronavirus also suggested that these viruses have varying degrees of persistence as regards surfaces, ranging from few hours to several days depending on various factors such as temperature, humidity, and light. Moreover, since coronaviruses are known to be thermolabile, their persistence decreases significantly with the increase in temperature. This was substantiated by Leclercq et al. (2014) and Darnell et al. (2004) where they reported the inactivation of MERS-CoV at 65 °C for 1 min, and SARS-CoV at > 75 °C for 15 min, respectively. Similarly, Chin et al. (2020) reported the inactivation of SARS-CoV-2 at least 5 min under 70 °C incubation. Thus, Rizou et al. (2020) posited that cooking food items above 70 °C could inactivate the virus, while care should be taken when handling frozen food as this condition could serve as a haven for the viruses. Meanwhile, no study has demonstrated the persistence of SARS-CoV-2 on food.

The research and data gathering is ongoing concerning the possible presence and persistence of SARS-CoV-2 on food and food packaging, especially as a new variant of the virus with rapid transmission potential emerges, leaving room for spillover transmission through fomite. The potential of SARS-CoV-2 transmission through fomite is no longer mere speculation with some reported pieces of evidence confirming the presence of the virus on material surfaces (van Doremalen et al., 2020; Ren et al., 2020). The evidence of fomite transmission through shared food was suggested in cluster cases during a company conference in Singapore (Pung et al., 2020).

Similarly, the soil environment has gained little attention with few reports on the presence and survival of the viruses in the soil or any connection (Conde-Cid et al., 2020; Khan et al., 2021). Often, the wastewater and sewage sludge are disposed into the soil without proper treatment, while the sludge has the potential of harboring viruses if not properly treated. The soil samples were taken about 2-m away from three hospitals with COVID-19 patients and wastewater plants were found to contain between 205 and 505 copies per gram of SARS-CoV-2 RNA (Zhang et al., 2020b). Gundy et al. (2009) demonstrated that the survival of human coronavirus (HCoV-229E) for 2 days at 23 °C in activated sludge. Alpaslan Kocamemi et al. (2020) confirmed the presence of SARS-CoV-2 RNA in all the activated sludge samples taken from major municipal wastewater treatment plants in Istanbul. Peccia et al. (2020) also confirmed the presence of SARS-CoV-2 RNA in primary sewage sludge collected from a metropolitan area of New Haven, Connecticut, USA. The sludge has been found to harbor envelop virus due to the hydrophobic nature of the virus and organic matter present in the sludge, thereby making the magnitude of the virus concentration higher than those found in wastewater. This hydrophobic interaction has been reported to be largely responsible for virus attachment to solid materials like sludge (Mohapatra et al., 2020). Chin et al. (2020) also reported the persistence of SARS-CoV-2 on smooth surfaces, be it artificial or treated, such as plastic and steel than the rough surfaces such as paper, cloth, or wood. Although sludge samples were found to contain a high concentration of SARS-CoV-2 genetic material, the transmission of the virus through this matrix has not been verified, considering that further treatments of the sludge before its final disposal into the soil are expected to inactivate the virus (Bogler et al., 2020). The only risk of virus contamination, especially to the wastewater workers or sludge handlers could be where the sludge is not properly treated before its disposal or

use as a soil amendment as often done in developing and less developed countries (Adelodun et al., 2021a,b).

Considering the limited data on the presence and persistence of the SARS-CoV-2 in water-food-environment media; thus it is safe to rely on the existing information on similar viruses in these regards, while the investigation continues on the presence, persistence, and possible transmission of SARS-CoV-2 in water-food-environmental compartments under varying attributed environmental variables.

4. Water-food-environmental compartments associated SARS-CoV-2 transmission

4.1. The connection between water/wastewater and SARS-CoV-2 transmission

While the presence of SARS-CoV-2 in the water environment including water and wastewater has been established, the probable transmission of the virus through these media is yet to be ratified. The knowledge of the transmission pathways of the SARS-CoV-2 is very critical to providing the appropriate measures that can discontinue the further spreading of the virus to protect public health. The hypothesized pathways of SARS-CoV-2 in the water-food-environment are illustrated in Fig. 1.

As it stands, the only argument against the transmission of the virus through the water environment is its infectivity and inability to persist for a very long time outside the intermediate animal hosts or novel living hosts (see Fig. 2). There is still inadequate information on the transmission of the virus due to different testing protocols currently employed which do not target assessing the viability or infectivity of the virus (Bogler et al., 2020), thereby leading to controversies on the possible alternative transmission pathways. The real-time polymerase chain reaction (RT-PCR) of nucleic acid testing technology combining with varying concentration procedures is the popular method for detecting the presence of SARS-CoV-2. Bogler et al. (2020) opined that the lack of evidence so far on the infectious SARS-CoV-2 in wastewater could be attributed to the difficulty in the isolation of viable envelope virions rather than its absence in the media.

Furthermore, the aerosolization of water and wastewater contaminated with SARS-CoV-2 via airborne particles could increase the potential risk of SARS-CoV-2 transmission in an indoor environment even

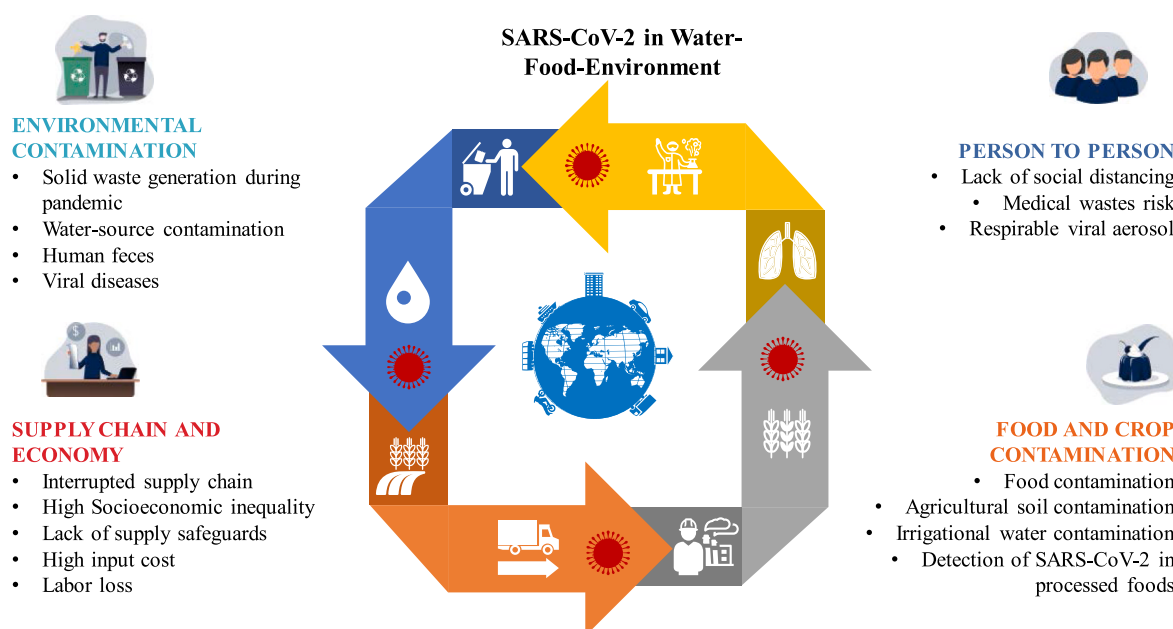


Fig. 1. The hypothesized pathways of SARS-CoV-2 in the water-food-environment.

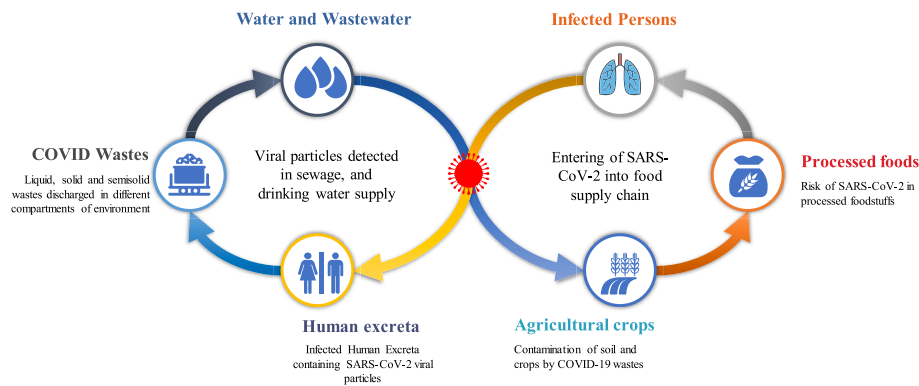


Fig. 2. Nexus of water-food-environment as impacted by SARS-CoV-2.

when observing the social distancing measure, as was evident during the earlier coronavirus outbreak (Anand et al., 2021; Lai et al., 2020; La Rosa et al., 2020; Yu et al., 2004). The presence of both the rigid outer shell and low shell disorder on the SARS-CoV-2 enhances its resilience and virulence in the environment including water and indicating the potential fecal-oral transmission (Gwenzi, 2021). Some researchers also opined that SARS-CoV-2 could maintain its stability and virulence under harsh environmental conditions of temperature, absolute and relative humidity, and sunlight than other coronaviruses (van Doremalen et al., 2020; Aboubakr et al., 2020; Chin et al., 2020). While the transmission of the SARS-CoV-2 in the water environment remains inconclusive due to lack of substantial evidence, the conditions of the water environment such as temperature, sunlight, and organic compounds that the virus can adsorb to and get shielded from sunlight. Balboa et al. (2021) confirmed the affinity of SARS-CoV-2 as an enveloped virus to biosolids, making the fate of the virus in the treatment plants and environmental matrices unhindered due to the protection of the protein capsids from damage in the sludge line. This could play significant roles in the persistence and virulence of SARS-CoV-2 in such media, which could further lead to any potential health risk on the human being, especially wastewater workers (Zhang et al., 2020; Foladori et al., 2020; Heller et al., 2020; Gwenzi, 2021; Yadav et al., 2018b; Zhang et al., 2020a). Nevertheless, the possible transmission in a public bath was reported by Luo et al., (2020), where a cluster spreading was confirmed by 8 individuals who had their bath in a public bath center in Huai'an, Jiangsu Province, China.

The assessment of potential risks of SARS-CoV-2 transmission in the water environment has also been receiving attention (Bogler et al., 2020). The potential health risks of COVID-19 on wastewater workers via contaminated sewage and wastewater treatment plant was reported by Kitajima et al. (2020). Yang et al. (2020) conducted a potential risk assessment of SARS-CoV-2 in the three rivers including Yangtze, Han, and Fu Rivers in Hubei province, China. They found that the Yangtze River basin had a lower risk index of 10^{-12} for the possible spread of the virus in the water media due to the large flow despite an increase in the number of reported cases in this area during this period compared to Han and Fu River Basins with risk indexes of 10^{-10} and 10^{-8} , respectively. Similarly, Zaneti et al. (2021) conducted a quantitative microbial risk assessment study, which indicated that aggressive and extreme scenarios of 2.6×10^{-3} and 1.3×10^{-2} , respectively, were higher than the tolerable SARS-CoV-2 infection risks of 5.5×10^{-4} per patient per year; thus, further demonstrates the concern of possible transmission through water environment. The large number of infected people in a community sharing the same sewer system is an inherent factor that could increase the transmission risks and potential of COVID-19 outbreaks (Adelodun et al., 2020). The possible transmission of SARS-CoV-2 from feces to wastewater routes has great implications in low-income countries with inadequate wastewater treatment and poor infrastructural sanitation facilities (Adelodun et al., 2020, 2021). The likely events such as floods and leakages of sewer carrying the wastewater

containing the SARS-CoV-2 laden feces can lead to transmission of the virus or other pathogens into the water bodies such as lakes and rivers (Gormley et al., 2020). The wastewater has been regarded as a sustainable freshwater source for both domestic and irrigation purposes for the majority of the rural areas in low-income and developing countries while the sewage sludge has been recognized for use as fertilizer, especially by rural farmers (Lamastra et al., 2018), thus creating an avenue for potential transmission of SARS-CoV-2 through uptake in crops and entering into the food chain (Usman et al., 2020). Although many of the available studies concluded that the risk of transmission through water or wastewater is not substantial with no existing study to demonstrating the SARS-CoV-2 infection through these routes; still the presence of the stable virus in the selected water environment cannot be ignored especially as the knowledge of the SARS-CoV-2 virulence is still evolving.

4.2. The connection between food, food packages, food handlers, and SARS-CoV-2 transmission

Kinds of seafood have been suggested as a possible hotspot of SARS-CoV-2 transmission since the Huanan seafood Wholesale Market in Wuhan, China was suspected to be among the first transmission origins of the virus (Li et al., 2020). Also, the resurgence of the virus was recorded in the Xinfadi Market, the largest Agricultural Market in Asia with the largest wholesale in vegetables, located in Beijing, where the virus was detected on the chopping boards used for cutting imported salmon (Zhao, 2020; Gupta et al., 2021; Kumar et al., 2019). Dai et al. (2021) pointed out the possibility of international transporting and transmission of SARS-CoV-2 through food products, especially fish and seafood that are required to be stored at a very low-temperature environment under which these food items can maintain their infectivity for more than a week. van Doremalen et al. (2014) demonstrated that MERS-CoV could survive for a prolonged period in milk, which suggested the possibility of viral contamination of dairy products. Moreover, the consumption of raw or undercooked animal products, such as raw milk, raw meat, or raw animal organs as a tradition in some parts of Asia, suggests the possible contamination of foods with SARS-CoV-2 and also regarded as the first respiratory virus that could be foodborne (Duda-Chodak et al., 2020). As earlier noted, no study or reliable evidence has reported the transmission of the SARS-CoV-2 virus through food consumption (EFSA, 2020; Duda-Chodak et al., 2020). Since low temperature favors the survival of the virus, this might explain the reason why the seafood markets could be a source of outbreaks of the SARS-CoV-2. Moreover, the risk of transmission through fresh produce that might not be able to undergo heat treatment before consumption is very high (Han et al., 2021). Hence, the general rule that extra care should be ensured as regards the consumption of raw food items that are preserved under a low temperature while also ensuring proper cooking of fish and seafood before they are consumed. Moreover, the indirect

transmission through food packages (fomite) from COVID-19 patients, especially the asymptomatic ones, can inadvertently result in spillover transmission.

In promoting food safety, the European Food Safety Authority (EFSA) and the United States Food and Drug Administration (FDA) have been maintaining close examination on the transmission of COVID-19. Although enteric viruses have been reported to show some level of persistence and stability in different food matrices (Bosch et al., 2018), no evidence has indicated that food or food materials serve as the transmission route of the previous outbreaks of other coronaviruses of SARS-CoV and MERS-CoV (EFSA, 2020), and there is no substantiation to prove that SARS-CoV-2 is dissimilar in this regard as of 3rd of January 2021. Nonetheless, the indirect transmission by smear infection through foods or food packages that were lately contaminated with viruses or by infected persons and shortly afterward collected by another healthy person who touches his eyes or mucous membrane of his mouth or throat (BfR, 2020).

The shopping attitude of inspecting many food items such as bakery products, fruits, and vegetables for either ripening or spoilage before finally settled for the desired ones could be an avenue for indirect SARS-CoV-2 transmission if such a shopper is infected and without any appropriate protection measure. However, this is to be expected within a short period after the contamination and it is also not concluded to be the main means of spreading the virus as scientists are still seeking more reliable knowledge about how this virus spreads in the environment apart from person-to-person (EFSA, 2020; CDC, 2020). Galanakis (2020) affirmed that fresh foods may be made prone to SARS-CoV-2 before being frozen, and by that way, the transmission may occur. The possible contamination of food items through non-sanitized hands during the harvesting, processing, and preparation have also been stressed (Duda-Chodak et al., 2020). It should be equally noted that the relevant correlated MERS-CoV and SARS-CoV have been confirmed to be infectious for up to 2 years in a frozen state (BfR, 2020). The food as a transmission route of SARS-CoV-2 is, for now, speculation which no study or test has been conducted to ascertain (EFSA, 2020).

4.3. Relationship between environmental compartments and SARS-CoV-2 transmission

The potential transmission of SARS-CoV-2 and its probable pathways in the environment has continued to receive attention due to the threat it portends in escalating the risk of the virus spread. Unlike other transmission routes such as water and air, the soil compartment of the environment has received relatively low attention (Anand et al., 2021b; Núñez-Delgado, 2020b). Despite this, the soil ecosystem serves as the destination for all the contaminants including the ones from the COVID-19 pandemic (Ajibade et al., 2021a, 2021b; Zand and Heir, 2020). In fact, D. Zhang et al. (2020b) reported that soil could serve as a viral sink for a possible secondary source of SARS-CoV-2 transmission. The increasing use of personal protective equipment like face masks and tons of medical wastes from personnel tending to the infected patients creates a potential pathway for the virus proliferation into the soil compartment if such contaminated materials are wrongly disposed of without proper decontamination. The presence of SARS-CoV-2 on material surfaces may trigger an influx of the virus from soil to water, food materials, and other environmental media due to the interplay that exists among them. Recently, Núñez-Delgado (2020) and Kumar et al. (2020) raised a concern about SARS-CoV-2 presence in the environmental compartments and the potential risks of transmission through water-soil media while extending to the groundwater sources. A recent study by Mahlkecht et al. (2021) reported the presence of SARS-CoV-2 RNA in different freshwater environments in an urban setting including groundwater samples, which demonstrates the ability of the virus to leach and infiltrate from surface water or leakage sewer to underground water resources. A review study by Bradford et al. (2013) had earlier described the fate and transport of viruses in the environmental

compartment, while a study by Ogorzaly et al. (2010) demonstrated the transport of enteric viruses through the aquifer into groundwater.

However, no studies are yet to demonstrate the transmission of SARS-CoV-2 between and within any environmental compartments. Nevertheless, the presence of infectious SARS-CoV-2 in wastewater from feces of infected patients and evidence of contaminated environmental materials, and the possibility of being infectious under the conducive environment pose a threat of possible transmission pathway. A close relationship that was readily established on virus migration to the soil is through water, air, and surfaces (clothes, metals, paper, wood, plastic) (Ren et al., 2020; Gupta et al., 2019). To further explain the current complex virus transmission to a different environment, a framework for the fecal-oral transmission of the virus was proposed by Heller et al. (2020). It was reported that based on the recent publications of the presence of the virus in stool, saliva, wastewater, and sewage systems, the routes at which the virus can transmit from stool are through water, on surfaces, and via vectors; thereby creating two additional routes via water from surface cleaning and direct access to contaminated waters (rivers, ponds, and streams) (Ajibade et al., 2021b). Marquès and Domingo (2021) also suggested the possibility of indirect transmission due to available evidence of contamination of inert and inanimate surfaces. The contraction of the virus can then be through contact or ingestion and causing respiratory and intestinal tract infections. The aerosolization during sludge handling or treatment could serve as an avenue for virus transmission. However, this is only a hypothesis that has not been tested or any study conducted to prove it.

Similarly, a built environment which is the collection of smaller environments constructed by men such as public buildings, cruise ships, cars, public transport, and other man-made spaces (Horve et al., 2020), is also another environmental aspect to be considered as regards to SARS-CoV-2 transmission. Lednicky et al. (2021) isolated viable SARS-CoV-2 from a car driven by a COVID-19 patient with mild symptoms and further demonstrated the transmission potential of the virus to an occupant of the vehicle. Dietz et al. (2020) asserted that it is worthwhile to understand the possible transmission means of SARS-CoV-2 within the built environmental ecosystem and the behavior of man, spatial dynamics, and building operational factors that possibly enhance and lessen the spread and transmission of SARS-CoV-2, as a greater number of the human population spends more than 90% of their daily lives within the built environment. Considering that both fomites and aerosols have been strongly considered as potential pathways for the SARS-CoV-2 transmission (Al Huraimel et al., 2020; van Doremalen et al., 2020; Prather et al., 2020; Morawska and Milton, 2020; Lednicky et al., 2021), the built environment could aid possible transmitting vectors for the circulation of COVID-19 by stimulating close interactions between individuals in a confined environment via viral transfer through the aerosols and fomites.

The population density of occupants in buildings, predisposed by building type and program, occupancy schedule, and indoor activities, enhances the growth of human-related microorganisms (Horve et al., 2020). The lack of cross-ventilation was allegedly responsible for the recent clustered aerosol transmission among the bus riders in China (Shen et al., 2020). The confined space of the built environment has a high range value of R_0 (5–14) (Dietz et al., 2020), indicating a greater risk of SARS-CoV-2 transmission in such a confined environment. It is common that greater occupant density and rise in indoor activity level usually leads to a greater degree of social contact and connectivity by direct and indirect interaction amongst persons (Andrews et al., 2014) and also environmentally facilitated with fomites (Dietz et al., 2020).

An investigation on a group of hospitalized patients who suffered respiratory distress in December 2019 in Wuhan, China showed that about 10 days later, the hospital facility was detecting patients that were not in the initial group with COVID-19 (Dietz et al., 2020). It was deduced that the upsurge in the number of infected patients must have possibly occurred with the built environment of the hospital (Rothan and Byrareddy, 2020). Similarly, the rise in exposure risk in connection

to high occupant density and constant interaction was demonstrated in the COVID-19 epidemic that occurred on the Diamond Princess cruise in January 2020 (Mizumoto et al., 2020). Out of the 3711 passengers on board the Diamond Princess during their 2-week quarantine on the ship, about 700 (i.e. ~19%) of them contracted COVID-19 (Zhao et al., 2020). These instances suggest the high transmissibility level of SARS-CoV-2 as facilitated by confined spaces in the built environments, like proximity to one another, especially infected and uninfected persons, remains a factor in the spread of SARS-CoV-2 (Mizumoto et al., 2020). To address the potential spread of the SARS-CoV-2 infections through airborne in a built environment, Morawska et al. (2020) suggested some measures which include the provision of adequate ventilation, reduction in the use of air recirculation within the built environment as the recirculated air could contain infectious virus, the use of air cleaner and disinfection devices such as germicidal ultraviolet, and avoidance of overcrowding in an indoor environment.

There are environmental variables that favor the thriving of SARS-CoV-2 in the environment. Eslami and Jalili (2020) examined the connection between the numbers of positive daily cases of SARS-CoV-2 with three environmental factors, namely: high relative humidity, temperature, and wind speed in four Chinese cities and five Italian cities. In the study, the connection between the predominance of COVID-19 with high air humidity and wind speed was trivial and statistically insignificant. However, the reductions in most cases are due to rising humidity and wind speed. Also, the connection associated with the predominance and maximum ambient temperature was negligible to moderate; and the predominance of the disease was surveyed to have decreased in most cities where the studies were carried out (Bhattacharjee, 2020). Chin et al. (2020) affirmed that SARS-CoV-2 offers high resistance and stability at a temperature of 4 °C, while its resistance was recorded to have lasted for 5 min at a temperature of 70 °C, suggesting its sensitivity to heat.

Generally, heat, high or low pH, and sunlight have been identified to enhance inhibition and killing of the coronavirus (WHO, 2020c). Though, a study has equally shown that at room temperature, and a pH range of 3–10, the virus can be found stable (Chin et al., 2020). Moreover, Wang et al. (2020) affirmed in their work carried out in 26 counties of China which involved a survey of 24,139 positive SARS-CoV-2 cases that with a 1 °C rise of the lowest ambient air temperature, the cumulative number of cases declined by 0.86%. The fact that the novel coronavirus pandemic broke out in the seafood and animal market in Wuhan, breathing in the viral particle comprising environment may have contributed to the spread of the virus (Shahbaz et al., 2020).

5. Preventive measures for SARS-CoV-2 infection through the water-food-environment media

Looking at the huge research and developmental contributions from the science community, there is a need to aggressively come up with a lasting approach and detailed strategy to understand, report, and solve the problems of viruses diffusing through nature. The idea of handling chemical contaminants in the environment and relating with the specific property of virus transport and inactivation on surfaces, in solution, and air can be further explored (Gheraout and Elboughdiri, 2020). Moreover, the high mutation rate of SARS-CoV-2 and its subsequent adaptation in different environmental media is a cause of concern (Rehman et al., 2020). Adelodun et al. (2020) proposed some mitigation approaches targeting developing and low-income countries where access to water and sanitation is limited, which include decentralization of wastewater systems, provision of adequate water and sanitation infrastructure, and adequate policy interventions. These measures are essential to mitigate the introduction of SARS-CoV-2 into environmental media such as sewage via handwashing, vomit, urine, feces, or sputum (Bhowmick et al., 2020; Adelodun et al., 2020). Furthermore, considering that the SARS-CoV-2 is an enveloped virus, the use of soap to wash

hands in running water for at least 20 s is sufficient enough to inactivate the virus. The proper hygiene practice is essential to prevent indirect transmission of the virus, especially through the possible fecal-oral route. The use of sustainable materials like biosorbent and other recyclable materials that can inactivate the virus in the environment should also be employed. This approach is to avoid using any materials that would create any further menace to the environment.

Due to the non-existence of a standard method specifically for sampling and characterizing SARS-CoV-2 in environmental compartments, the early detection of the virus in various environmental media has become a challenging task. The development of a monitoring protocol for the novel coronavirus based on the existing wastewater-based epidemiology model and the adoption of such on other environmental samples such as the sampling and characterizing SARS-CoV-2 in a built environment can expedite the actions on mitigating the spread of the virus in the environment. Meanwhile, adequate ventilation and avoiding crowded enclosed environments could greatly minimize the transmission of the virus in a built environment. Ensuring cross ventilation and adequate ventilation rate, avoiding air-recirculation, regular cleaning and disinfecting air circulation sources, minimizing close contact, avoiding unnecessary touching of surfaces and face, and hand hygiene are some of the proposed preventive measures to observe in a semi-closed space or build environment (Morawska et al., 2020) (Fig. 3).

Since the substantiating evidence for the transmission of SARS-CoV-2 through food, food packages, and food handlers is still a topic of debate, sanitary recommendations that can ensure food safety are suggested while relocating and preparing food, namely: regular and proper washing of hands, avoiding contact of raw meat with other foods, cooking at high temperatures and preserving food in the refrigerator. In addition, staff involved in food preparation and distribution are strongly recommended to adhere to adequate personal hygiene practices. These include covering of mouth and nose with the elbow when sneezing and coughing, isolation of employees that show symptoms of COVID-19 or have contact with patients, maintaining at least a distance of 6 feet or 1.8 m between employers, and the use of appropriate personal equipment such as facemask and hand gloves during food preparation and handlings (WHO, 2020b). Several disinfecting or sanitizing spots as well as washing and disinfecting surfaces with high contact using diluted sodium hypochlorite should also be made adequately available (Eslami and Jalili, 2020; Duda-Chodak et al., 2020).

6. Research needs and policy recommendations

No doubt, there has been increasing research on the SARS-CoV-2. However, still, we have a significant knowledge gap on the persistence and fate of SARS-CoV-2 in the environmental media vis-à-vis water-food-environmental compartments interactions. Although the current information shows that the presence of virus varied among the environmental media and by extension in food and food materials. Also, the virus was reported to lose its infectivity quickly in many of these environmental media devoid of living hosts. The detection of viruses in various media, especially in water and sludge samples that requires prior concentration, is a challenging task due to difficulty in virus recovery (Farkas et al., 2020). Moreover, investigating the potential transmission of the virus via water-food-environment interactions requires detailed information on the reference quantity of the virions that could pose transmission risk, which is critical to uncover appropriate inactivation mechanisms. Research in this line will in no doubt create valuable knowledge for the current and future pandemics.

The hypothesis on the fecal-oral transmission of SARS-CoV-2 needs to expedite attention by considering some of the environmental conditions that might favor the thriving of SARS-CoV-2 outside the living hosts. Furthermore, the potential health risk of ingestion of SARS-CoV-2 RNA contaminated water and food materials, especially in high concentrations, begs for further research since there is a significant number of studies that reported high shedding of SARS-CoV-2 RNA in stools and



Fig. 3. Methods of preventing SARS-CoV-2 transmission through water-food-environment compartments.

its presence in both wastewaters, rivers, and other environmental compartments. Although the current knowledge indicates the genetic material of the virus is non-infectious and harmless while also demonstrated more stability than the infectious virus, especially under lower temperature (Hokajärvi et al., 2021), the health implication of ingesting SARS-CoV-2 RNA excessively should be thoroughly investigated. Besides, a study had proposed the infectivity and transmission potential of these RNAs (Xu, 2020), since the viable proportions from the measured viral load of the SARS-CoV-2 RNA are often not measured.

The present studies rely on speculation of SARS-CoV-2 transmission through environmental routes. However, considering the prolonged shedding of SARS-CoV-2 RNA from infected patients even after tested negative for respiratory samples (Wu et al., 2020), and the existing knowledge of environmental persistence and transmission of SARS-CoV and MERS-CoV (Aboubakr et al., 2020), the possibility of environmental, fecal-oral, and fomite transmission routes cannot be entirely ruled out and further extensive research is a need in this regard. The investigation on the relative contributions of these transmission routes will clear several assumptions and uncertainties regarding the spread of the SARS-CoV-2 and thereby promoting appropriate mitigation strategies for the current and similar future pandemics.

Furthermore, the current SARS-CoV-2 detection and quantification techniques and methods are still evolving and need further validations, especially for easy adoption to other potential viral contamination samples such as food and food materials, and aerosol. The lack of reliable, cheap, and readily available SARS-CoV-2 detection tools specifically for foods has been a challenge for the food industry. The food sector would benefit immensely from the research and policy interventions on appropriate virus detections and inactivation to ensure food safety along the food supply chain, especially in this era of SARS-CoV-2 and future pandemics.

For SARS-CoV-2 inactivation and decontamination, significant efforts have been made on the development of different approaches and tools to inactivate the viruses, including SARS-CoV-2 in water and other environmental samples. However, the existing technologies or techniques for the virus inactivation are either inaccessible or too expensive for the majority of people living in rural communities, especially in developing and less developed countries. The unhygienic and environmental living conditions of these groups of the population make them vulnerable to potential virus infection (Adelodun et al., 2021a,b). The research and policy intervention on the development and large-scale production of simple, low-cost, easy-to-use, and accessible facilities and technologies for virus inactivation and decontamination are greatly required, targeting a highly vulnerable population group.

7. Conclusion

The current state of knowledge regarding the presence and persistence of SARS-CoV-2 in water-food-environmental compartments and the possible transmission pathways with associated risks through these media based on the available literature was reviewed. The recent emergence of new variants of the virus that are found to be recalcitrant and highly transmissible has raised more concern on the need to safeguard the alternative pathways through which the virus can be transmitted including water-food-environmental media. The current study explored the available information in the literature on these alternative pathways through which the SARS-CoV-2 could be transmitted based on the cause-and-effect relationships of environmental samples in various media rather than considering each transmission pathway in isolation. The identification and isolation of infectious SARS-CoV-2 in some environmental samples have dictated the possible transmission through alternative pathways, especially when considers the mystery of a soaring number of confirmed cases despite strictly following the recommended outdoor face masking and social distancing, among others. The emerging methodologies and technologies have shown that environmental samples could contain viable SARS-CoV-2 with a relatively high level of persistence. However, no study has yet to demonstrate or confirm the transmission of SARS-CoV-2 via water, food, and/or other environmental compartments. Moreover, the available studies on the detection and quantification of the viable SARS-CoV-2 in water-food-environment media are limited, with fewer data from the regions with sanitation and hygiene challenges that could promote indirect transmission of the virus. There is a need for further investigation and data gathering to unravel the complete mechanism for the novel SARS-CoV-2, especially regarding the different pathways of transmission. The following recommendations are thereby suggested for further research.

Development of protocols for analyzing the infectious SARS-CoV-2 from all forms of environmental samples, although this would require a high level of safety to conduct. This is very important to mitigate the probable cause-and-effect transmission of the virus in different environmental matrices due to the existing interplay of human activities among them.

The health risks and implications of consuming a high quantity of genetic materials of SARS-CoV-2 should be conducted as a significant number of studies have demonstrated the presence and extended persistence of these materials on the environmental samples and food material and package surfaces. Also, the investigation needs to be extended to the infectivity of the genetic materials of the recently emerged highly transmissible variants of the virus.

Furthermore, the research and policy interventions on the virus inactivation and decontamination tools and methods targeting vulnerable population groups in rural areas, especially in the developing and

less developed countries due to their state of sanitation and hygiene challenges are highly encouraged.

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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.

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