CHAÚQUE, B., J. M., 2022. Issue 1, v 1 nº 7: 1 - 18 mjas, ISSN Online: 2790-2994
REVIEW PAPER
Published: 27 September 2022
https://doi.org/10.53224/mjas/ispg/2022v1n7

Efficacy of Solar Disinfection (SODIS) in Inactivating Viral Pathogens in Water, with Emphasis on Sars-Cov-2 - Review

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Received:
01 de Janeiro 2022
Accepted:
08 Agosto 2022
Published Online:
27 Setembro 2022

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Citation:
CHAÚQUE, B. J. M. Efficacy of solar disinfection (SODIS) in inactivating viral pathogens in water, with emphasis on Sars-Cov-2-Review

ABSTRACT

The detection of infectious viral particles in the excreta of infected people and the elucidation of the tropism of Sars-Cov-2 by other organs, including the digestive tract, raised health concerns, given the hypothesis of contagion via the fecal-oral route. While the debate on this hypothesis remains open and an increasing number of studies support this path of contagion, mainly through the ingestion of contaminated water, there is a growing concern about the health risk of poor communities, especially in developing countries. However, solar water disinfection (SODIS) can be an alternative for remediation of the contagion of Sars-Cov-2 through the water-mediated fecal-oral route. In this work, the effectiveness of SODIS as an alternative for remediation of Sars-Cov-2 contagion through water is critically reviewed. We found that the biological properties of Sars-Cov-2, namely, the stability of the genome, and the ability to remain infectious in environmental water matrices, with the precariousness of sanitation infrastructure and drinking water supply, make the chances of contamination by Sars-Cov-2 through drinking water to be high. SODIS is able to ensure the inactivation of Sars-Cov-2 in water, and can be effectively applied as an emergency and permanent measure to provide safe drinking water to underprivileged communities.

Keywords: Fecal-oral contagion through water; Ultraviolet radiation; Heat; Waterborne viruses.

INTRODUCTION

Covid-19, caused by (Severe Acute Respiratory Syndrome) Sars-Cov-2, known to be predominantly contracted by the mouth, nose and eyes (WHO 2020; PETRONIO; MARCO; COSTAGLIOLA, 2021) is by far the most infectious and devastating disease caused by a coronavirus, even compared to Sars-Cov-"1" (November 2002 to August 2003) and Mers-Cov (April 2012 to date) (MEO et al., 2020; XIE; CHEN, 2020).

It has been reported that the viral genome (CHEN et al., 2020; KIM et al., 2020; ZHENG et al., 2020; YANG et al., 2021) as well as viable and infectious viral units (XIAO et al., 2020b; ZHANG et al., 2020) of Sars-Cov-2 are present in the stools of symptomatic or asymptomatic infected persons (TIAN et al., 2020; YANG et al., 2021), including persons with negative results for nasopharyngeal swab tests (LING et al., 2020; XIAO et al., 2020b). Sars-Cov-2 has also been detected in different body fluids, including urine from infected people (KIM et al., 2020). All these facts and the detection of the Sars-Cov-2 genome in sewage (ARSLAN; XU; EL-DIN, 2020; AHMED et al., 2021; BALDOVIN et al., 2021) and in different bodies of fresh water such as rivers that receive sewage and groundwater reservoirs (GUERRERO-LATORRE et al., 2020; MAHLKNECHT et al., 2021) have triggered a global health alarm, given the real risk of fecal-oral transmission of Sars-Cov -2 (DING; LIANG, 2020; LANGONE et al., 2021; SUNKARI et al. 2021).

The hypothesis raised by the fecal-oral transmission of Sars-cov-2 remains an important matter of open debate, and requires further research to be performed for validation or discarding (ARSLAN; XU; EL-DIN, 2020; DONDE et al., 2021; GWUENZI, 2021; SUNKARI et al., 2021). The magnitude of concern associated with this hypothesis becomes high when considering the contexts of underprivileged communities, which lack adequate sanitation infrastructure capable of removing Sars-Cov-2 and other pathogens from the water cycle (ARSLAN; XU; EL-DIN, 2020; SUNKARI et al., 2021). In these societies, a waterborne disease attributed to the ingestion of water contaminated by fecal microorganisms remains a harsh and challenging reality (BAIN et al., 2014).

Although the concern about the ingestion of pathogenic viruses transmitted by water is based on the illness of the exposed people, the ingestion of water contaminated by Sars-Cov-2 still could not be associated with diseases or symptoms of Covid-19 (although the gastrointestinal manifestations were reported (CHEUNG et al., 2020; CHOLANKERIL et al., 2020). The main concern with the fecal-oral route of contamination by Sars-Cov-2 mediated by water is based on the fact that it can allow the maintenance of the circulation of the virus in the environment; since the virus can replicate in the cells of the digestive tract of infected people (DING; LIANG, 2020).

Although the risk of contagion by Sars-Cov-2 through water was considered low (WHO, 2020), based on the fact that sewage treatment systems have effectively removed Sars-Cov-2 from the water (RIMOLDI et al., 2020), as well as, because there are no reports of detection and isolation of infectious Sars-Cov-2 in sewage (ABOUBAKR; SHARAFELDIN; GOYAL, 2021; LANGONE et al., 2021) and also, because other coronaviruses have not been previously reported in groundwater (WHO, 2017). Although this position is correct, it is most assertive for urban contexts in developed countries with modern sanitation infrastructure and that function properly (GWENZI, 2021). The lack of reports of detection and isolation of infectious Sars-Cov-2 in sewage has been attributed to its rapid inactivation (BIVINS et al., 2020;

RIMOLDI et al., 2020; LANGONE et al., 2021) given the complex composition of sewage, which includes the presence of various chemical substances, such as detergents and disinfectant residues (CHAUDHARY et al., 2020). In developing countries, basic sanitation infrastructure, such as the sewage network, is scarce and, when present, is obsolete, works under pressure and far above its capacity, and is generally not connected to a sewage treatment plant (SUNKARI et al., 2021). These facts, combined with the problem of the precariousness of the drinking water treatment and distribution system, makes the probability of contagion by Sars-Cov-2 through the fecal-oral route to be high in developing countries, especially in suburban and rural areas. A practical example of conditions that favor waterborne transmission of Sars-Cov-2, including a water-mediated fecal-oral route in developing countries, is described by (SIDDIQUI et al., 2020).

Recent evidence consistently suggests that the less polluted the water matrix, the viral genome remains stable for a long time (AHMED et al., 2020) and remains infectious for longer, with low temperatures having a dilating effect in this period (OLIVEIRA et al. 2021) (Table 1). This leads to an obvious thought that the persistence time of viability of Sars-Cov-2 in untreated drinking water may be relatively longer and, therefore, the probability of contagion may be relatively greater than suggested. This probability increases if water is collected from rivers, springs, lakes and shallow wells located in areas where people use latrines, as underprivileged communities often consider this water ready for immediate consumption, provided it looks good and has an imperceptible or tolerable odor (VERHEYEN et al., 2009; BAIN et al., 2014; ISLAM, et al., 2016; CHAÚQUE et al., 2021b). It was pointed out that free-living amoebas (FLA) are normally present in these waters, and the interaction of viruses with AFL can result in greater viral persistence and environmental spread (CHAÚQUE; Rott, 2022).

Table 1 - Persistence of Sars-Cov in the aqueous matrix at different temperatures

TARGET	MEDIUM	TºC	DETECTION TIME (day)	REFERENCE
Sars-Cov-1 (Infectivity)	Dechlorinated tap water	20	2	WANG *et al*., 2005
		4	14	
	PBS	20	14	
		4	14	
	Urine	20	14	
	Sewage	20	3	
		4	14	
	Water	20 - 25	4	DUAN *et al*., 2003
	Urine	20 - 25	> 5	
Sars-Cov-2 (Infectivity)	Raw river water *	24	6.4[a]	OLIVEIRA *et al*., 2021
		4	18.7[a]	
	Filtered river water *	24	8[a]	
	Raw wastewater *	24	4[a]	
		4	17[a]	
	Filtered wastewater *	24	4.5[a]	
	Wastewater	20	1.6	BIVINS *et al*., 2020
	Tap water	20	2	
Sars-Cov-2 (RNA)	Raw wastewater	4	27.8[b]	AHMED *et al*., 2020
		15	20.4[b]	
		25	12.6[b]	
		37	8.4[b]	
	Raw wastewater *	4	43.2[b]	
		15	29.9[b]	
		25	13.5[b]	
		37	5.71[b]	
	Dechlorinated tap water	4	58.6[b]	
		15	51.2[b]	
		25	15.2[b]	
		37	9.4[b]	

(*) Autoclaved. (a) Time required reducing 2 log10 in Sars-Cov-2 viability. (b) Time required reducing 1 log10 in Sars-Cov-2 RNA stability. TºC: temperature.

This situation demands that measures to guarantee access to safe drinking water be included among the urgent and priority interventions in the fight against Covid-19. These measures need to be effective, accessible and affordable, especially when designed to be implemented in the contexts of developing countries and underserved communities, at a time when the Covid-19 pandemic is severely shaking the global economy and creating more barriers to investments in sanitation.

Solar water disinfection (SODIS) is a promising method that satisfies these requirements, as it is effective, accessible and cheap, as it essentially uses solar radiation, which is a free and abundant source of energy in most low-income countries (PICHEL; VIVAR; FUENTES, 2019). The inactivation of waterborne microorganisms belonging to all health interest groups, including viruses, has been widely reported through SODIS (GILL; PRICE, 2010; MCGUIGAN et al., 2012; PICHEL; VIVAR; FUENTES, 2019; SOBOKSA et al., 2020). Inactivation of environmental resistance structures of bacteria and protozoa (e.g. *Bacillus subtilis* spores, *Cryptosporidium parvum* oocysts, and *Acanthamoeba* spp. cysts) has also been reported (GÓMEZ-COUSO et al., 2009; HEASELGRAVE; KILVINGTON, 2011; CHAÚQUE et al., 2021a). Further more, the use of SODIS has been implicated in the considerable reduction of cases of waterborne diseases (BITEW et al., 2018; SOBOKSA et al., 2020) and in the induction of the state of immune resilience against gastrointestinal diseases (CONROY et al., 2001; SSEMAKALU et al., 2014; SSEMAKALU et al., 2020).

In the present article, the effectiveness of SODIS to inactivate viruses, focusing on Sars-Cov-2 in water is critically reviewed, in light of the available evidence on the stability and resistance of Sars-Cov in a liquid medium (focusing on water) under different conditions, with an emphasis on temperature and ultraviolet (UV) radiation. The feasibility of using SODIS as a remediation strategy for possible Sars-Cov-2 contagion via the fecal-oral route is discussed.

Lack of Basic Sanitation and Risk of Ingesting Sars-Cov-2 with Water

Basic sanitation is essential to people's health and is a qualifier for well-being in human settlements, and its accessibility is a minimum requirement of human dignity (EDITORIAL, 2018).

The detection of the Sars-Cov-2 genome in feces (LIN et al., 2015; LING et al., 2020; MARTÍNEZ; PÉREZ; MOYA, 2020), in sewage (AHMED et al., 2021) and in several freshwater bodies, including underground and surface reservoirs for drinking water, as well as river water, is well documented (GUERRERO-LATORRE et al., 2020; MAHLKNECHT et al., 2021). The presence of the Sars-Cov-2 genome in groundwater was correlated with the concentration of sucralose in the water, showing the infiltration of sewage into the soil (MAHLKNECHT et al., 2021). All of this, as well as the isolation of infectious viral particles from urine (SUN et al., 2020) and stools (XIAO et al., 2020a; ZHANG et al., 2020) has triggered a global health alarm given the hypothesis of fecal-oral transmission of Sars-Cov-2, and generated a great scientific debate (ARSLAN; XU; EL-DIN, 2020; DING; LIANG, 2020; GUERRERO-LATORRE et al., 2020; JONES et al., 2020; GWENZI, 2021; SUNKARI et al., 2021).

However, fecal-oral transmission of various waterborne pathogens, including viral enteropathogens, is endemic in developing countries (VERHEYEN et al., 2009; BAIN et al., 2014; UPFOLD; LUKE; KNOX, 2021). This is because about 2 billion people worldwide still draw water from a source contaminated by feces (WHO, 2019). Most of these people live in poor countries in Africa (53%) and Southeast Asia (35%) and, although this phenomenon also occurs in urban areas (12%), it is predominant in rural areas (41%) (BAIN et al., 2014). As a result, gastrointestinal diseases associated with the consumption of contaminated water cause about 829,000 deaths annually worldwide, and more than half of them (485,000) are caused by diarrhea (WHO, 2022a). It is important to note that in these countries the number of deaths are commonly underreported, as cases are generally underreported, as access to health services and technological resources to diagnose diseases, including Covid-19, remains problematic (OKEKE, 2011; ODIH et al., 2020). This finding is confirmed by the fact that most of the studies that reported the presence of Sars-Cov-2 in various environmental matrices including water were carried out in developed countries (PANDEY et al., 2021).

In developing countries, the precariousness or lack of infrastructure for sanitation and treatment and distribution of drinking water stands out among the main factors that favor the consumption of contaminated water. In the urban environment, the sewage network is generally obsolete (PANDEY et al., 2021) and spills raw sewage into surface waters (ANAKHASYAN et al., 2012; RIMOLDI et al., 2020; SUNKARI et al., 2021). Peri-urban environments are typically characterized by densely populated unplanned settlements, which lack adequate sanitation infrastructure including safe and sufficient water sources for everyone (KAYEMBE et al., 2018; GWENZI, 2021). In rural and especially peri-urban settlements, the main source of drinking water is predominantly shallow wells and surface waters are also used for potable purposes, mainly in rural areas. The water collected from these sources is commonly considered ready for immediate consumption (without treatment), as long as it has a good visual aspect and an imperceptible or tolerable odor. In addition, septic tanks (mainly in urban and peri-urban areas), as well as latrines (in peri-urban and rural areas) are the main sanitation strategies in place, used by communities and promoted by governments (DEEN, 2014; WHO, 2022b). In rural areas of many developing countries, open defecation remains a common practice (KAYEMBE et al., 2018; BHATT et al., 2019; SUN; HAN, 2021), with around 673 million people across the world still defecates outdoors (WHO, 2022b).

The discharge of raw sewage into surface waters has been largely implicated in severe contamination of rivers, lakes (GWENZI, 2021; UPFOLD; LUKE; KNOX, 2021) and groundwater (HUO et al., 2021). The presence of different microorganisms, including enteric viruses (LIN et al., 2015; POTGIETER et al., 2020), as well as the Sars-Cov-2 genome in river water has been attributed to fecal contamination (GUERRERO-LATORRE et al., 2020; RIMOLDI et al., 2020). The presence of different types of enteropathogenic viruses, including enteric viruses in water sources has been extensively reviewed (GIBSON, 2014; UPFOLD; LUKE; KNOX, 2021).

Although the use of septic tanks and mainly latrines is celebrated, as it considerably improves local sanitation and excrement management, compared to outdoor desertion, in addition to helping to meet the goals set out in UN objective 6. Their impact on improving health remains questionable (PUJARI et al., 2012). These have been seriously implicated in the contamination of groundwater accessed through wells (VERHEYEN et al., 2009; GRAHAM; POLIZZOTTO, 2013; KAYEMBE et al., 2018; LUTTERODT et al., 2018; HOUÉMÉNOU et al., 2020), and the prevalence of gastrointestinal diseases (BORCHARDT et al., 2003; FONG et al., 2007; CRAUN et al., 2010).

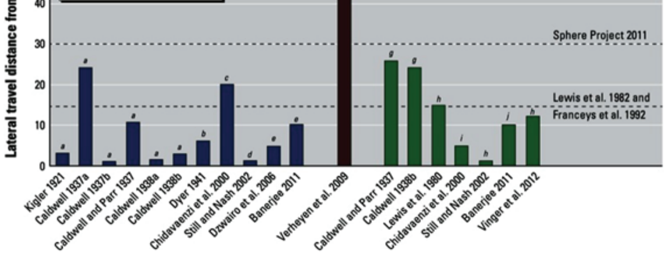
The distance between the well and a latrine or septic tank, as well as the depth and characteristics of the soil are determining factors for fecal contamination of water. In peri-urban settlements in developing countries, the vast majority of wells are less than 30 m from latrines (DZWAIRO et al., 2006; MARTÍNEZ-SANTOS et al., 2017; NGASALA; MASTEN; PHANIKUMAR, 2019; CHAÚQUE et al., 2021b). Martínez-Santos et al. (2017) found the following spatial distribution of wells and latrines: 86.5% (0-30 m), 11.8% (30-50 m) and only 1.7% (> 50 m). Ngasala; Masten; Phanikumar (2019) found that 65% of the wells were less than 15 m from a septic tank, and all wells at a mean distance of 13.4 m. Abebe et al. (2020) found that 51.8% of the wells were up to 15 m away and the rest (482%) were up to 25 m from the pit latrine, however Chaúque et al. (2021b) found that 100% of the wells were located between 7 and 25 m from the nearest pit latrine.

In general, the smaller the depth of the well and the lateral distance between the well and the latrine, as well as the less clayey the soil, the greater the likelihood that the water will have a high load of microbial contamination (ISLAM et al., 2016; CHAÚQUE et al., 2021b).

Although few countries have established in their legislation the minimum allowable distance between a groundwater source and a treatment or deposition point for faecal material (for example, latrine, aseptic tank, drain that receives feces, etc.) the standardized values are very varying from 3 to 100 m (PARKER; CARLIER, 2009). The tolerance of shorter distances by certain legislation suggests that these countries have a high degree of precarious sanitation and drinking water supply infrastructures.

The lateral distance between a well and a source of fecal contamination considered by the authors to be the most ideal varies from 30 to 50 m (GRAHAM; POLIZZOTTO 2013; MARTÍNEZ-SANTOS et al., 2017; OTAKI et al., 2021). The minimum distance of 30 m is suggested as safe against bacterial contamination (MARTÍNEZ-SANTOS et al., 2017; NGASALA; MASTEN; PHANIKUMAR, 2019) and chemical substances (CALDWELL; PARR, 1937; VINGER; HLOPHE; SELVARATNAM, 2012) and 50 m against viruses (VERHEYEN et al., 2009; OTAKI et al., 2021) (Figure 1). However, the implementation of these distances is practically impossible in the context of urban and peri-urban settlements in developing countries, which are often characterized by densely populated unplanned settlements, where each family occupies a small courtyard and has its own pit latrine and shallow well.

Figure 1 - Lateral distances traveled by microorganisms and chemicals from latrines in relation to the guidelines for separating latrines and water source. (a) *B. coli*, (b) total coliform, (c) coliforms, (d) fecal coliforms, (e) total and fecal coliforms, (f) adenovirus and rotavirus, (g) chemical stream (nitrate, nitrite, and chloride), (h) nitrate, (i) nitrogen, (j) salt tracer.



Source: GRAHAM; POLIZZOTTO (2013). Reproduced with permission from Environmental Health Perspectives.

The establishment of a minimum standard distance between a well and a source of contamination is based on the minimum travel time that the microorganism must spend to leave the source of fecal inoculum until reaching the groundwater source. The minimum desirable travel time is 25 days (PARKER; CARLIER, 2009) during which microorganisms are expected to lose viability before reaching the water source (ARGOSS, 2001; MARTÍNEZ-SANTOS et al., 2017). This time depends on the nature and granulometry of the soil, the time during which the microorganism can remain stable and viable, as well as the size of the microorganism to move through the soil pores (HERNANDEZ-CORTAZAR et al., 2017; MENA-RIVERA; QUIRÓS-VEGA, 2018; HOUÉMÉNOU et al., 2020). The fact that the diameter of the viral particle, including Sars-Cov-2 (about 60 to 140 nm) (ZHU et al., 2020) is much smaller than the bacterial indicators, for example *Escherichia coli* (about 500 nm of width and length 2,000 nm), the travel time will be much shorter, while the distance covered will be considerably longer than estimated based on bacteria. Thus, the frequency and burden of contamination of wells by viruses will be high, above expectations (OTAKI et al., 2021), since viruses are easier to move through soil pores due to their smaller size, and generally these are in greater numbers than bacteria in water contaminated by feces (ROSARIO et al., 2009).

The detection of the Sars-Cov-2 genome in samples of groundwater contaminated by feces (MAHLKNECHT et al., 2021) combined with all previous discussion answers positively to the question: Sars-Cov-2 from feces, can reach groundwater? In addition, the fact that the sludge in the latrines is normally free of disinfectants and soaps, as well as the fact that the temperature of the groundwater is low, increases the stability and viability of Sar-Cov-2 (OLIVEIRA et al., 2021) and the possibility of ingesting viable viruses when consuming untreated contaminated groundwater.

The ability of Sar-Cov-2 to remain viable for a considerably long time in a medium with a varied pH range, including very alkaline and acidic media (CHAN et al., 2020), similar to the gastric environment. In addition to the ability to multiply throughout the gastrointestinal tract (DING; LIANG, 2020; TIAN et al., 2020; XIAO et al., 2020b), associated with the consumption of untreated water collected from wells and rivers, greatly increases the chances contagion and persistence of the water-mediated fecal oral contamination cycle.

Taking into account the whole discussion so far, it is safe to say that the possibility of contagion by Sars-Cov-2 via water is very high, and probably has been occurring, and dramatically in contexts in developing countries where sanitation remains problematic, and coexistence of latrines and wells still persists (DEL BRUTTO et al., 2021; LIU et al., 2021). In these countries the situation is aggravated because the scarce infrastructures for the treatment and distribution of drinking water are often not able to adequately eliminate viruses from the water cycle (GIBSON et al., 2011; RIZK; ALLAYEH, 2018).

Characterization of SODIS and its Effect on Virus Viability

Solar disinfection (SODIS) is an effective, inexpensive and worldwide accessible method of microbiological water treatment, which can be used to provide drinking water to communities without access to safe managed drinking water sources (MCGUIGAN et al., 2012; MBONIMPA et al., 2018; CHU et al., 2019; PICHEL; VIVAR; FUENTES, 2019; MORENO-SANSEGUNDO et al., 2021). Conventional SODIS is a household method in which contaminated water is poured into a transparent container (usually PET bottles ~ 2 L) and exposed to direct sunlight for at least 6 or 12 hours on days with clear or partly cloudy skies (cloud of ~ 50 % of coverage), respectively (ASIIMWE et al., 2013; PICHEL; VIVAR; FUENTES, 2019).

Although SODIS involving batch disinfection using ± 2 L PET bottles is predominantly reported (FISHER; IRIARTE; NELSON, 2012; HARDING; SCHWAB, 2012; CARRATALÀ et al., 2015; POLO et al., 2015) approaches involving larger reactors (5-25 L) are also reported (UBOMBA-JASWA et al., 2010; KEOGH et al., 2015; POLO-LÓPEZ et al., 2019). Similarly, continuous flow disinfection prLocesses based on SODIS (GILL; PRICE, 2010; POLO-LÓPEZ et al., 2011), solar pasteurization (SOPAS) (DUFF; HODGSON, 2005; BIGONI et al., 2014; DOBROWSKY et al., 2015; CARIELO; TIBA; CALAZANS, 2016; AMARA et al., 2017; MANFRIDA; PETELA; ROSSI, 2017; DOMINGOS et al., 2019) or hybrid systems, are also reported (MONTEAGUDO et al., 2017; CHAÚQUE et al., 2021a).

The literature presents an abundant record of evidence of the effectiveness of SODIS in inactivating microorganisms belonging to all taxa, including bacteria (DEJUNG et al., 2007; HEASELGRAVE; KILVINGTON, 2010; MORENO-SANSEGUNDO et al., 2021), fungi (LONNEN et al., 2005, SICHEL et al., 2007), protozoa (LONNEN et al., 2005; HEASELGRAVE; KILVINGTON, 2010) and virus (HEASELGRAVE; KILVINGTON, 2012; CARRATALÀ et al., 2015; POLO et al., 2015). A considerable reduction in the viability or total inactivation of forms of environmental resistance has also been reported, including bacterial spores (LONNEN et al., 2005; DEJUNG et al., 2007; BOYLE et al., 2008) and protozoan (oo)cysts (MCGUIGAN et al., 2006; GÓMEZ-COUSO et al., 2009; HEASELGRAVE; KILVINGTON, 2011; GARCÍA-GIL et al., 2020a). Inactivation of several groups of pathogenic or surrogate viruses, including coxsackievirus-B5, poliovirus-2, hepatitis A virus, echovirus 11, adenovirus type 2, murine norovirus (MNV-1), as well as bacteriophages (MS2 and ϕX174) have been reported (HARDING; SCHWAB, 2012; HEASELGRAVE; KILVINGTON, 2012; CARRATALÀ et al., 2015; POLO et al., 2015). A summary of the viruses transmissible by ingesting contaminated water as well as their profile of inactivation by SODIS is shown in Table 2. Some phages are also included, because in addition to being better indicators of water contamination by enteric viruses than bacterial indicators (MCMINN; ASHBOLT; KORAJKIC, 2017; LIAN et al., 2018), their routine use in monitoring drinking water quality is appreciable, as it is less expensive and technically less demanding than other viruses.

Table 2 - Pathogenic waterborne viruses or surrogate and their profile of inactivation by SODIS

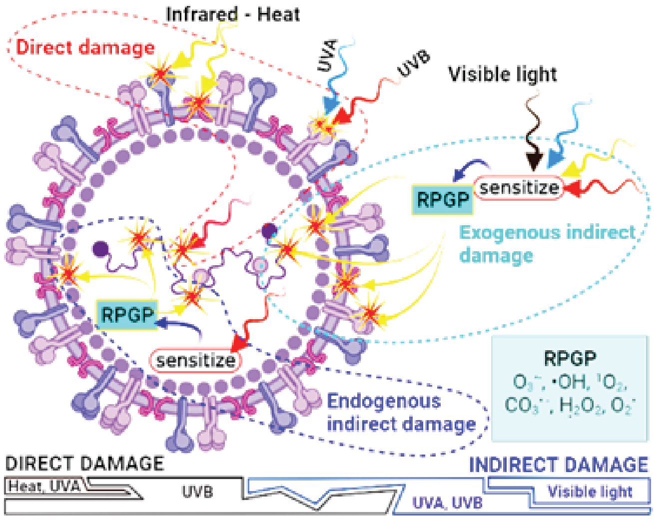
TARGET VIRUS	SUNLIGHT	CONTAINER	UV DOSE (w/m²)	T ºC	TIME (hours)	INACTIVATION log.	%	REFERENCE
Coxsackievirus B5	Simulated	Polystyrene dish	550	45	1	4.5	99.9	Heaselgrave; kilvington, 2012
Hepatitis A virus (HAV)	Simulated	Polystyrene dish	550	45	2	4	99.9	
	Natural	PET bottles	828	40 [b]	8	2.5	83.4	Polo *et al*., 2015
Poliovirus type 2 (NCPV 503)	Simulated	Polystyrene dish	550	45	1	4.2	99.9	Heaselgrave; Kilvington, 2012
	Simulated	Polystyrene dish	850	25	4	4.3	100	Heaselgrave *et al*., 2006
	Simulated	Polystyrene dish	850	40	6	3.6	100	
Poliovirus type 3 (PV3)	Simulated	Open reactor	6528 x 10^3	20	6	5.6	99.9	Love *et al*., 2010
	Simulated	Open reactor (UVB filter)	8173 x 10^3	20	8	0	0	
	Simulated	Open reactor	194	20	6	3	75	Silverman *et al*., 2013
Murine Norovirus (MNV-1)	Natural	PET bottles	828	40 [b]	8	2	66.7	Polo *et al*., 2015
	Natural	PET bottle	50	42.5 [b]	6	1.4	26.4	Harding; Schwab, 2012
	Natural + ([a])	PET bottle	50	42.5 [b]	6	1.7	32	
Rotavirus	Simulated	Quartz glass	6800 x 10^3	20	2.5	3	99.9	Wegelin *et al*., 1994
	Simulated	Quartz glass	5000 x 10^3	30	1.8	3	99.9	
	Simulated	Quartz glass	1900 x 10^3	40	0.7	3	99.9	
Adenovirus type 2 (HAdV2)	Simulated	Open reactor	13055 x 10^3	20	12	3.1	99.9	Love *et al*., 2010
	Simulated	Open reactor (UVB filter)	8173 x 10^3	20	8	0	0	
	Simulated UVA	Pyrex glass	26.9	20	24	2	40	Carratalà *et al*., 2013
	Simulated UVB	Pyrex glass	~ 13.9	7	5	~ 4	~ 80	
	Simulated	Open reactor	194	20	6	2.1	52.5	Silverman *et al*., 2013
	Simulated	PET bottle	1340	22	6	3	50	Carratalà *et al*., 2015
Echovirus 11 (EV)	Simulated	PET bottle	1340	22	6	1.5	30	Carratalà *et al*., 2015
Phage f2	Simulated	Quartz glass	9000 x 10^3	20	3.3	3	99.9	Wegelin *et al*., 1994
	Simulated	Quartz glass	5100 x 10^3	30	1.9	3	99.9	
	Simulated	Quartz glass	3500	50	1.3	3	99.9	
Phage ϕX174	Simulated	PET bottle	1340	22	6	0.25	4.1	Carratalà *et al*., 2015
Phage MS2	Simulated	PET bottle	1340	22	6	> 6	> 85	Carratalà *et al*., 2015
	Simulated	PET bottle	180	40	2	3	7	
	Simulated	Open reactor	8703 x 10^3	20	8	1.5	50	Love *et al*., 2010
	Simulated	Open reactor (UVB filter)	8173 x 10^3	20	8	0	0	
	Natural	PET bottle	50	42.5 [b]	6	5.5	88.7	Harding; Schwab, 2012
	Natural + ([a])	PET bottle	50	42.5 [b]	6	> 6.2 [c]	100	
	Natural	PET bottle	617	48 [b]	34.3	3	99.9	Fisher; Iriarte; Nelson, 2012
	Natural + ([d])	PET bottle	617	48 [b]	4.12	3	99.9	
	Simulated	Open reactor	194	20	6	2.2	55	Silverman *et al*., 2013
	Simulated	Open reactor	5580 x 10^3	25	2	0.5	8.3	Theitler *et al*., 2012
	Simulated	Glass reactor	0	59	2	1.23	20.5	
	Simulated	Open reactor (UVA+B)	5580 x 10^3	59	2	2.2	36.7	
Phage PRD1	Simulated	Open reactor	194	20	6	2.9	72.5	Silverman *et al*., 2013
Phages F-RNA	Natural	Open tank	685	14	39.9	3	99.9	Sinton *et al*., 2002
	Natural	Open tank	687	14	37.5	3	99.9	
Phage P22	Natural	UVB transparent	610	39 [b]	2	3	99.9	Davies *et al*., 2009

(a) Lemon juice (15 mL/L). (b) Maximum temperature. (c) Reached limit of detection for the assay. (d) Sodium Percarbonate (100 mg $Na_2CO_3 \cdot 1.5H_2O_2$) + Citric acid (100 mg $C_6H_8O_7$-).

Microbial inactivation during SODIS occurs due to the synergistic effect of UV radiation (UVA - 320-400 nm and UVB - 280-320 nm) and thermal energy (infrared 760 - 1400 nm) from the sun (CASTRO-ALFÉREZ; POLO-LÓPEZ; FERNÁNDEZ-IBÁÑEZ, 2016; CASTRO-ALFÉREZ et al., 2017; MBONIMPA et al., 2018; MORENO-SANSEGUNDO et al., 2021), and the speed of microbial inactivation increases with increasing water temperature, predominantly from 30 ºC to ~55 ºC (CASTRO-ALFÉREZ et al., 2017; VIVAR et al., 2017; NWANKWO; AGUNWAMBA; NNAJI, 2019; CHAÚQUE et al., 2021a). Heat above the optimum temperature for microbial growth compromises microbial integrity during SODIS, inducing the denaturation of structural and functional proteins (CASTRO-ALFÉREZ et al., 2017; VIVAR et al., 2017).

Optical inactivation of microorganisms occurs essentially in three different ways: both by direct action as well as by the indirect endogenous and indirect exogenous action of solar radiation in the UVA and UVB spectrum (Figure 2). Direct photoinactivation (caused mainly by UVB) occurs when a photon of radiation is absorbed by the photosensitive molecules of the microorganism (e.g., genome, flavins derived from porphyrins, NADH, proteins), compromising its chemical and functional structure, due to the damage that has occurred directly at the photon absorption site (SABINO et al., 2020). Indirect photoinactivation (mainly attributed to UVA and visible light (400 - 700 nm)) is that which occurs when the sensitizer (e.g., nitrate, nitrite, photocatalytic metal complexes) located within (endogenous) or outside the microorganism (exogenous) absorb a photon and sensitize the generation of reactive photogenerated products (RPGP) (e.g., $O_3^{•-}$, •OH, $^1O_2$, $CO_3^{•-}$, H_2O_2, $O_2^{•-}$) which in turn cause damage to microorganisms. UVB radiation is also involved in indirect mechanisms of microbial damage (LIU et al., 2015; MATTLE; VIONE; KOHN, 2015; WANG et al., 2015; NELSON et al., 2018). Details on the mechanisms of microbial photoinactivation are presented in the appropriate literature (NELSON et al., 2018).

Figure 2 - Solar photoinactivation model in viruses showing damage mechanisms and the contribution of different radiation components to the inactivation rate (Designed through BioRender).



Although viral inactivation during SODIS can be attributed to the indirect damage triggered by UVA radiation (DEJUNG et al., 2007; HARDING; SCHWAB, 2012), it results mainly from direct damage due to the absorption of photons from UVB radiation, as shown for the MS2 phage (CARRATALÀ et al., 2013; MATTLE; VIONE; KOHN, 2015; NELSON et al., 2018). Despite the increase in water temperature, considerably accelerating viral inactivation (WEGELIN et al., 1994; CARRATALÀ et al., 2015; POLO et al., 2015; LIAN et al., 2018; MORENO-SANSEGUNDO et al., 2021), ultraviolet radiation has greater importance in the synergy of inactivation during SODIS (THEITLER et al., 2012; POLO et al., 2015). In addition, the physical-chemical composition of water has a determining effect on the magnitude of the effectiveness of SODIS (SILVERMAN et al., 2013; LINDEN; MURPHY, 2017).

Inactivation of Sars-Cov-2 by Means of Heat

The literature shows that coronaviruses, mainly Sars-Cov, are very sensitive to the increase in the temperature of the medium (KIM et al., 2020a; BURTON et al., 2021; LOVEDAY et al., 2021; PARSA et al., 2021). The results of different studies show that the rate of thermal inactivation of Sars-Cov is influenced by the matrix (Table 3), as also reported for most groups of microorganisms, including viruses (ESPINOSA et al., 2020).

It has been reported that exposure to a temperature of 50-56 °C for 10-90 minutes is sufficient to reduce about 4-6 logs10 in Sars-Cov viability. (DARNELL et al., 2004; KARIWA; FUJII; TAKASHIMA, 2006; BIVINS et al., 2020; PASTORINO et al., 2020). While the rate of inactivation of Sars-Cov increases with increasing temperature, the exposure time required to inactivate more than 6 logs10 drops to about 2-30 minutes, when the temperature reaches 75 ºC (DUAN et al., 2003; DARNELL et al., 2004; RABENAU et al., 2005; BIVINS et al., 2020).

Table 3 - Sars-Cov heat inactivation profile

TARGET	MATRIX	TºC	EXPOSURE TIME (min)	REDUCTION (log_{10})	REFERENCE
		56	90	6	
	DMEM	65	60	6	DARNELL *et al.*, 2004
		75	30	6	
	PBS	56	20	4	DARNELL; TAYLOR, 2006
		65	10	4	
Sars-Cov-1	Culture medium	56	90	6	
		67	60	6	DUAN *et al.*, 2003
		75	30	6	
	MEM	60	30	5	RABENAU *et al.*, 2005
		56	60	7	KARIWA; FUJII; TAKASHIMA *et al.*, 2006
	Sewage	50	15	5	
		70	2	5	
		56	10	6.65	BIVINS *et al.*, 2020
		70	5	5.34	
Sars-Cov-2	Cell supernatant	56	30	> 5	
		60	60	> 5	
		95	15	> 6	PASTORINO *et al.*, 2020
	Serum	56	30	> 5	
		60	60	> 5	

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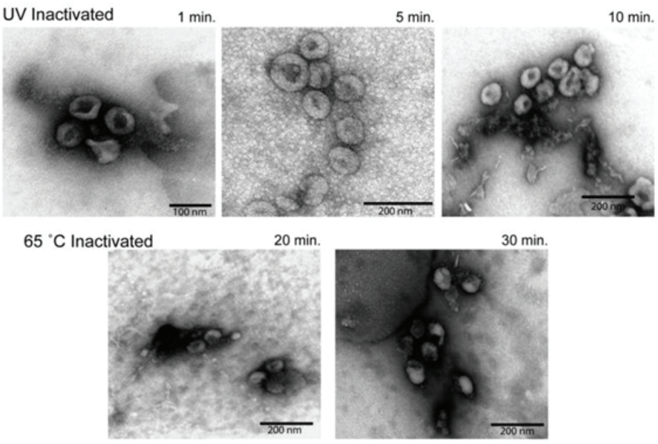
TºC: temperature. PBS: Phosphate Buffer Solution

The thermal inactivation of the virus occurs mainly due to the denaturation of the secondary structures of the proteins, which can alter the conformation of the virion proteins involved in binding and replication process (LELIE; REESINK; LUCAS, 1987; SCHLEGEL; IMMELMANN; KEMPF, 2001; POPAT; YATES; DESHUSSES, 2010). Although the morphological deformation of Sars-Cov-2 can occur due to exposure to UV radiation, especially if the exposure is long (≥ 10 min) it is more pronounced after thermal inactivation (65 ºC for ≥20 min), where the rupture of the virus can also be observed (Figure 3) (LOVEDAY et al., 2021).

Figure 3 - Electron microscopy image, showing the morphological changes (shape and size) of Sars-Cov-2 inactivated by UVC radiation (upper line) and by heat (lower line)



Source: LOVEDAY et al. (2021), with permission: http://creativecommons.org/licenses/by/4.0/.

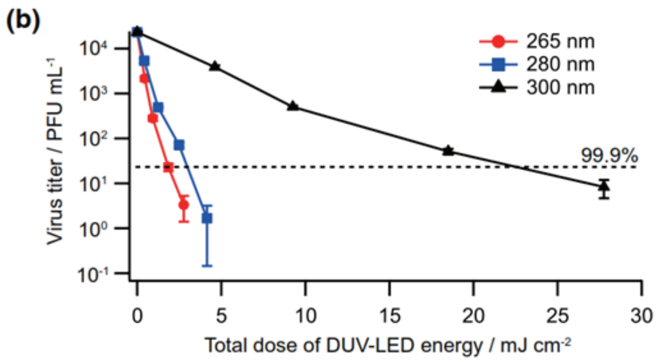
During conventional SODIS, where a transparent bottle (usually ~2 L PET bottle) is exposed to direct solar radiation, maximum temperatures ranging from 38 to 49 ºC are normally achieved (FISHER; IRIARTE; NELSON, 2012; HARDING; SCHWAB, 2012; POLO et al., 2015; VIVAR et al., 2017). When low-cost collectors are used, higher temperatures (45 - 55 ºC) are generally achieved in less exposure time, and larger volumes of water can be processed daily (UBOMBA-JASWA et al., 2010; BEATTIE et al., 2019). On the other hand, in medium-cost solar pasteurization systems (SOPAS), considerably higher temperatures ranging from 60 to 90 ºC are easily achieved, including in continuous or semi-continuous flow systems (BIGONI et al., 2014; DOBROWSKY et al., 2015; STRAUSS et al., 2016; CARIELO et al., 2017, CHAÚQUE et al., 2021a). In these systems, relatively large volumes of water (30 - 315 L) can be disinfected daily by each disinfection unit (DUFF; HODGSON, 2005; CARIELO; TIBA; CALAZANS, 2016; CARIELO et al., 2017; DOMINGOS et al., 2019).

Considering all this, it is safe to say that the inactivation of sars-cov-2 in water through SODIS and SOPAS is safely achieved, during the 6 hours of minimum recommended exposure time. The inactivation of the vast majority of other pathogenic viruses of oral fecal transmission can also be safely achieved in disinfection processes based on thermal radiation from the sun (LINDEN; MURPHY, 2017).

Inactivation of Sars-Cov-2 by UV Radiation

The literature shows that Sars-Cov is highly susceptible to UV radiation (KARIWA; FUJII; TAKASHIMA, 2006; WANG et al., 2015; NELSON et al., 2018; SABINO et al., 2020; MOHAN et al., 2021). Studies show that the Sars-Cov photoinactivation rate varies depending on the type of UV radiation (A, B or C). The rate of inactivation decreases as the wavelength increases, so that, as we move from UVC to UVA radiation, the longer the exposure time and the radiation dose required to achieve the same log10 reduction in viral viability (Figure 5) (DARNELL et al., 2004; HEILINGLOH et al., 2020; MINAMIKAWA et al., 2021).

Figure 4 - Sars-Cov-2 photoinactivation profile by different types of UV radiation (UVC - 265 nm, UVB - 280 nm and UVA - 300 nm)



Source: modified from MINAMIKAWA et al. (2021), with permission: http://creativecommons.org/licenses/by/4.0/.

Most studies that evaluated the effectiveness of UV radiation in inactivating Sars-Cov used UVC and showed that inactivating Sars-Cov-2 can be achieved by exposure to low UV doses, such as 0.016 mJ/cm², during exposure times ranging from fractions of seconds to minutes (Table 4). The number of inactivated log10 increases with increasing UVC dose and exposure time (BIASIN et al., 2021; PATTERSON et al., 2020; SABINO et al., 2020).

Nicastro et al. (2021) estimated that UV-B/A photons have a powerful virucidal effect on Sars-Cov-2, and that solar radiation in temperate regions at midday during the summer is able to inactivate about 63% of viral particles (1.5 x 10^3 TCID50/mL) in less than 2 minutes of exposure.

Table 4 - Sars-Cov inactivation profile by UV radiation

TARGET	UV NATURE (nm)	UV INTENSITY (mJ/cm²)	MATRIX	EXPOSURE TIME	Log_{10} REDUCTION	REDUCTION (%)	REFERENCE
Sars-Cov-1	UVA	2.133	DMEM	15 min	NA	0	DARNELL *et al.*, 2004
	UVC (254)	4.016		15 min	5	100	
	UVC	0.040	Saline solution	< 2 min	NI	100	ANSALDI *et al.*, 2004
	UVC (254)	4.016	PBS	40 min	5	100	DARNELL; TAYLOR, 2006
			Culture medium (DMEM)	15 min	3	100	
	UVC (260)	324	Culture medium	60 min	6	100	DUAN *et al.*, 2003
	UVC (254)	0.134	MEM	15 min	5.3	70.7	KARIWA; FUJII; TAKASHIMA *et al.*, 2006
				60 min	6.3	84	
Sars-Cov-2	UVC (254)	20	PBS	NI	3.9	55.7	PATTERSON *et al.*, 2020
		40			7	100	
	UVC (~280)	3.75	PBS	1 min	0.9	87.4	INAGAKI *et al.*, 2020
		37.5		10 min	3.1	99.9	
		75		20 min	3.3	100	
	UVC (254)	3.7	DMEM	NI	3	50	BIASIN *et al.*, 2021
		16.9			6	100	
		84.4			6	100	
	UVC (254)	0.016	DMEM-HG	0.01 s	1	90	SABINO *et al.*, 2020
		0.706		0.32 s	2	90	
		6.556		2.98 s	3	99.9	
		31.880		14.49 s	4	99.99	
		108.71		49.42 s	5	99.999	
	UVC	3.7	DMEM	NI	3	100	BIASIN *et al.*, 2021
		16.9	DMEM	NI	9	100	
	UVC (265)	1.8	EMEM-	30 s	5	99.9	MINAMIKAWA *et al.*, 2021
	UVB (280)	3.0	FBS 2% / PBS-FBS	30 s	5	99.9	
	UVA (300)	23.0	2%	30 s	5	99.9	
	UVC (254)	1.94	DMEM – 10% FBS	9	6	100	HEILINGLOH *et al.*, 2020
	UVA (365)	0.54	DMEM – 10% FBS	9	1	16.7	
	UV B (285)	480*	PBS	NI	2 [a]	100	WONDRAK *et al.*, 2021

DMEM: Dulbecco's Modified Eagle's Medium. DMEM-HG: DMEM High Glucose. EMEM: Eagle's Minimal Essential Medium. NA: not achieved. NI: not informed. FBS: Fetal bovine serum. PBS: Phosphate Buffer Solution. (*) Cumulative UV dose. (a) Plaque forming units.

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Few studies have evaluated the effectiveness of UVA and UVB radiation in inactivating Sar-Cov (DARNELL et al., 2004; HEILINGLOH et al., 2020; MINAMIKAWA et al., 2021). Darnell et al. (2004) reported 0 log10 of inactivation of Sars-Cov-1 suspended in Dulbecco's modified Eagle medium (DMEM) exposed to 2,133 mJ/cm² of UVA radiation for 15 minutes. Heilingloh et al. (2020) reported one log10 (16% of the initial dose) of inactivation of Sars-Cov-2 suspended in DMEM containing 10% fetal bovine serum (FBS), exposed to 0.54 mJ/cm² for 9 minutes. However, Minamikawa et al. (2021) reported the inactivation of 5 log10 (99.9% of the initial dose) of Sars-Cov-2 suspended in phosphate buffer solution with 2% FBS (PBS- 2% FBS) exposed to 23.0 mJ/cm² of UVA radiation for 30 seconds. Inactivation of 5 log10 (99.9%) of Sars-Cov-2 suspended in PBS-2% FBS was also reported when the viruses were exposed to 3.0 mJ/cm² of UVB radiation for 30 seconds (MINAMIKAWA et al., 2021). Wondrak et al. (2021) demonstrated that exposure of SARS-CoV-2 to simulated solar radiation (UVA - 5.34 mJ/cm² s, UVB - 0.28 mJ/cm² s) induces the loss of virus infectivity (2log10 of PFU - plaque forming units) for Vero and Calu-3 human epithelial lung cells. These authors also reported that SARS-CoV-2 exposed to simulated solar UV radiation (receiving a UVB dose of 480 mJ/cm²) does not trigger stress response gene expression caused by viral infection in human lung epithelial cells Calu-3.

The greater virucidal effect of UVC and UVB radiation is explained by the fact that they trigger direct damage to the genome and viral proteins (NELSON et al., 2018; SABINO et al., 2020).

The rate of viral inactivation also varies depending on the absorbance of the medium, the lower the absorbance the better the transmittance and consequently the rate of viral inactivation. Thus, a better rate of inactivation of Sars-Cov-2 is expected during SODIS, since water generally exhibits low absorbance (similar to PBS) than many test media used in the studies (NELSON et al., 2018; MINAMIKAWA et al., 2021). In natural conditions suitable for SODIS, high doses of UV radiation (UVA and UVB) are usually measured (Table 2). During conventional SODIS (using PET reactors), the inactivation of 5.5 and 3 log10 (88.7 and 99.9%) of Phage MS2 (which is an indicator of contamination by viruses of fecal origin (LECLERC et al., 2000)) in the water matrix was reported by exposure to 500 and 617,000 mJ/m² (FISHER; IRIARTE; NELSON, 2012; HARDING; SCHWAB, 2012). Considering all this, and also the synergy of heat and UV, as well as the exposure time of 6 hours (for conventional SODIS), it is safe to consider that the inactivation of Sars-Cov-2 can be achieved safely during SODIS, and thus provide safe drinking water for human consumption.

Use of SODIS in the Remediation of Contagion by Sars-Cov-2 Through Water

The use of SODIS is strongly recommended as an alternative to provide safe water to underprivileged populations, including in emergency situations as it is effective and cheap, since solar radiation is free, and PET bottles (normally used as reactors) can be collected in the local selective disposal without monetary cost and reused after proper cleaning. In rural areas where the availability of PET bottles is relatively low, supply of reactors may be necessary.

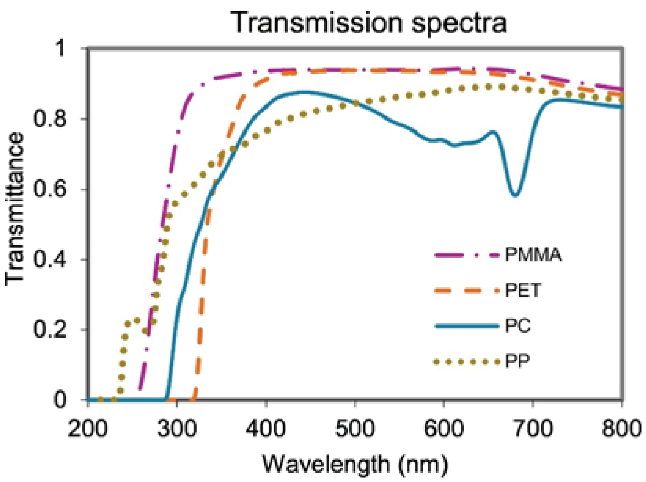
The implementation of SODIS can be done as previously described in the literature (MCGUIGAN et al., 2012; BUSSE et al., 2019; POLO-LÓPEZ et al., 2019). In summary, the water to be treated (including groundwater (MAHLKNECHT et al., 2021) will need to be poured until about 85% of a transparent PET bottle is filled, so the bottle must be closed tightly and shaken vigorously for at least 30 seconds. Then, the remaining volume must be completed and the bottle exposed (lying down, preferably on a reflecting surface) to direct solar radiation for at least 6 hours (preferably counted from 10 am) before being ingested. Polypropylene (PP) buckets of up to 20 L can be used as reactors to process relatively larger volumes of water, without prejudice to the effectiveness of SODIS.

These reactors can be used for up to 9 months before they need to be replaced with new buckets, but thinner-walled buckets (usually those with a capacity of up to 5 L) will need to be replaced within 5 months of use (POLO-LÓPEZ et al. 2019). The efficacy of PP buckets in disinfecting large volumes of water contaminated by viruses, bacteria and protozoa is explained by the fact that this material is permeable to UVA radiation, as well as UVB; PET bottles are practically impervious to UVB (Figure 6) (BUSSE et al., 2019; POLO-LÓPEZ et al., 2019).

Transparent polycarbonate (PC) bottles of up to 19 liters can also be used to disinfect large volumes of water, as these have proved to be as effective as 2-liter PET bottles in field conditions, in tests carried out on three different continents (KEOGH et al., 2015).

Reactors made of polymethylmethacrylate (PMMA) are also suitable to be used to disinfect the previously mentioned volumes, and a similar or relatively higher efficiency is expected, as this material exhibits high UV transmittance (about 97% for UVA and UVB) and relatively higher than PET, PP and PC (Figure 6) (GARCÍA-GIL et al. 2020b).

Figure 5 - Transmittance for solar radiation of the materials recommended for SODIS reactors. PMMA - polymethylmethacrylate, PET - polyethylene terephthalate, PC - polycarbonate, PP – polypropylene



Source: GARCÍA-GIL et al. (2020b), with permission: https://creativecommons.org/licenses/by/4.0/.

On slightly sunny days (with cloudiness up to 50%), it is recommended to add small doses of chlorine-based disinfectant before exposing the reactors to the sun. Although the ultraviolet radiation generally available under these conditions is relatively low, it is high enough to induce chlorine photolysis, resulting in the production of various reactive oxidants (e.g., O_3^-, OH^-, O_2^-) which in turn accelerates the inactivation of microorganisms (ZHOU et al., 2014; REMUCAL; MANLEY, 2016; CHAÚQUE; ROTT, 2021a). The acceleration of microbial inactivation by the generation of reactive oxidants in water during SODIS can also be achieved by the integration of solar disinfection methods based on photocatalytic nanomaterials (LEE et al., 2009; ALROUSAN et al., 2012; HELALI et al., 2014; SNOW; PARK, 2014; MAC-MAHON et al., 2017; RYBERG; CHU, 2018; SHEKOOHIYAN et al., 2019).

Water disinfection methods based on solar radiation can be used not only as a palliative alternative to combat contamination by waterborne pathogens, including in an emergency, such as the covid-19 pandemic. They can also be used to provide large-scale drinking water on a permanent basis or until the adoption and installation of systems based on other water treatment strategies becomes more appropriate. Readers interested in details on the mechanisms for applying SODIS as a large-scale public drinking water strategy are directed to the appropriate literature (CHAÚQUE; ROTT, 2021b; CHAÚQUE et al., 2022). Briefly, high-performance continuous-flow solar disinfection systems need to be built for this purpose, so disinfection technologies based on SODIS and SOPAS, as well as photothermal and photocatalytic nanomaterials will need to be combined to allow the processing of a large volume of water per unit of time. These systems can be used to install a solar water treatment plant, connected to a drinking water supply network.

Recommendations for Future Studies

Although most studies corroborate positively with the hypothesis of water-mediated fecal-oral contagion of Sars-Cov-2, this issue remains an open debate, therefore, further studies evidencing the presence of Sars-Cov-2 in freshwater rivers, lake and groundwater are still needed. The viability and infectivity of viruses in these water bodies also need to be characterized.

The implication of the spatial coexistence of pit latrines and shallow wells in relation to the presence of Sars-Cov-2 in water needs to be explored. Developing country contexts where fecal water contamination remains endemic is an ideal field for such studies.

The evidence for the effectiveness of solar disinfection of water contaminated with Sars-Cov-2 under real sunny conditions is invaluable.

CONCLUSIONS

This review aimed to evaluate the effectiveness of the application of solar water disinfection (SODIS) as a remediation strategy against Sars-Cov-2 contagion through the fecal-oral route mediated by drinking water.

The evidence available to date strongly suggests that there is a high possibility of contagion by Sars-Cov-2 through ingestion of contaminated water, especially in settlements with no access to adequate sanitation infrastructure and safely managed drinking water services.

SODIS is able to inactivate Sars-Cov-2 in water and is therefore an applicable strategy for remediation of possible contagion from ingestion of contaminated water.

Acknowledgments
The authors thank CAPES for the scholarship granted to Beni Chaúque.

Declaration of Interests
All authors report no conflicts of interest relevant to this article

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