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Desalination 512 (2021) 115106

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Reliability of thermal desalination (solar stills) for water/wastewater treatment in light of COVID-19 (novel coronavirus “SARS-CoV-2”) pandemic: What should consider?

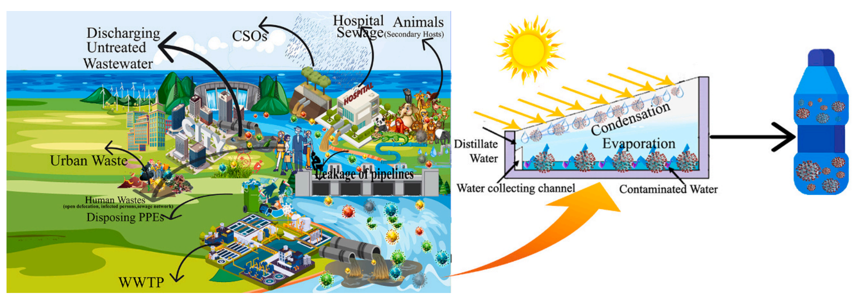
Seyed Masoud Parsa

Department of Energy Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

HIGHLIGHTS

- First study on feasibility and risks of solar thermal desalination during COVID-19 pandemic
- Pathogens such *E. coli*, *K. pneumoniae*, *E. faecalis* that several times larger than coronavirus transmit by vapor in solar still.
- Working temperature for most solar stills is not critical for the novel SARS-CoV-2 to remain viable.
- Increasing the viral load in water bodies can result to contaminate the feed water and structure of solar stills.
- Experiments on viability of the virus as post-pandemic researches should conduct in cold/warm seasons.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Solar desalination
Environmental contamination
Wastewater treatment
COVID-19
Waterborne disease
Pathogens

ABSTRACT

The COVID-19 pandemic disturbed the world from the beginning of 2020. The high excessive number of patients and the presence of the SARS-CoV-2 in human excreta and urine even after the infected person's respiratory tests were negative, results in a heavy load of viral in various water bodies and mostly untreated wastewaters. In the present study, the reliability of using small-scale solar thermal desalination systems (solar stills) during a situation like the COVID-19 pandemic is discussed. Pollution of water bodies through the SARS-CoV-2 via numerous routes increases the risk of contaminating the feed water and subsequently the whole structure of solar stills. Since the transmission of pathogens (particle size: 0.5–3 μm) via droplets of water in solar still is reported before, transmitting of SARS-CoV-2 via droplets of water which multiple times smaller (particle size: 60–140 nm) than those pathogens is a concern. The most important issue which must be highlighted is that solar stills worked at low-temperature while the viability and survival of the SARS-CoV-2 in various water matrices in the temperature range (4–37 °C) for several days is reported. In this regard, using solar stills during the COVID-19 pandemic need further consideration by all researchers and people around the world.

E-mail address: masood.parsa1988@gmail.com.

https://doi.org/10.1016/j.desal.2021.115106
Received 19 February 2021; Received in revised form 9 April 2021; Accepted 13 April 2021
Available online 4 May 2021
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1. Introduction

"Be fast, have no regrets; you must be the first mover… If you need to be right before you move, you will never win" –Dr. Michael Joseph Ryan, Epidemiologist. Executive Director of WHO Health Emergencies Programme.

1.1. Broader context

"June 2021: until now about 250 million people are infected and 1.75 million are dead [1]." Such prognostications certainly make anyone's heart collapse, but these statements are not unexpected now. Indeed, the numbers are far from such predictions now. The year 2020 is commenced with an unpleasant surprise that warned people around the world about the advent of a virus from the family of the *Coronaviridae*; (severe acute respiratory syndrome coronavirus 2 "SARS-CoV-2") or as it was briefly called later "the COVID-19". The world is not unfamiliar with the family of coronaviruses. In 2003, medical communities were faced with the severe acute respiratory syndrome 1 (the SARS-CoV-1) epidemic which started in Guangdong, China [2]. Nine years later in 2012, Middle East Respiratory Syndrome (MERS) with lower infection cases but a higher rate of fatality (2562 infected cases with 37% rate of fatality) rather than the SARS-CoV-1 (8098 infected cases with 9.5% rate of fatality [3]) was emerged in Saudi Arabia [4]. In the last days of December 2019, Chinese officials reported the first case of the SARS-CoV-2. Even though, more than 2000 scientific papers brings Wuhan in their abstract/introduction and plenty of these researches stated that the coronavirus is started in Wuhan, China [5] but some investigations have contradiction results with these statements.

Analyzing wastewater samples in the city of Barcelona revealed the presence of the SARS-CoV-2 in the middle of March 2019 while the first case in Spain was announced eleven months later by officials on 25 February 2020 [6]. Similarly, in Brazil, the sample of sewer network from the city of Florianopolis in the state of Santa Catarina in November 2019 confirmed the existence of the SARS-CoV-2 while the first reported case in Brazil was on 21, January 2020 [7]. In this regard, plenty of uncertainties were associated with the COVID-19 which is not completely realized yet. Even the exact location that the pandemic was started remains unknown. These findings are emphasized on the crucial role of wastewater/water bodies for detecting viral diseases before it becomes an epidemic or a devastating pandemic like the COVID-19. Before March 11 of 2020 that the COVID-19 outbreak announced a pandemic by the World Health Organization (WHO) [8], the presence of the virus in the water bodies is not thoroughly and significantly considered by all researchers. But after that when the pandemic become a global catastrophe, all the pathways that may lead to the prevalence of the virus is considered as a possible route because the COVID-19 threatens all human beings and it is exceedingly contagious and the rate of infection increases day by day in the absence of any reliable solution for a cure.

While the COVID-19 is recognized as a respiratory disease that spread rapidly, there are many concerns about the possibility of other transmission pathways whereas infected gastrointestinal glandular suggested the potential of transmission via fecal-oral [9]. These concerns about an off-center route are reasonable because, during the SARS-CoV-1 epidemic in 2003, the probability of transmission of the virus in a building in Hong Kong via wastewater aerosols (which results in more than 300 infections and 42 deaths in the location) brought new assumption into the spotlight for transmitting the virus via a new route [10]. Further studies verified and validated the heavy load of viral aerosols in the building because of the malfunction in the sewer system (which lead to the floor drains) when the exhausting fans of the bathrooms were run. Then, the presence of the virus about 200 m far away from the building was also detected [11]. The presence of viral aerosols in the environment as well as traveling the viral (as it happened before in the SARS-CoV-1) disturb scientific communities and governments as the possibility for opening a new window for spreading the viral via water bodies. Even though, the viability of the SARS-CoV-2 in water bodies compared to other viruses (specifically non-envelope viruses) is lower [12,13] but the presence of this virus (i.e., the SARS-CoV-2) is drastically increased because of the colossal volume of the SARS-CoV-2 influx via human urine and excreta that lead to presences of the viral in numerous wastewaters [14–16].

In this regard, it is predicted that the contamination of water supplies/bodies/reservoirs has the potential to infect the whole communities [17]. In the past few years, the transmission of the Influenza virus and coronavirus via drinking water is highlighted, but there is no conclusive evidence [18]. Recently, the possibility of transmitting the novel coronavirus via various water matrices arose many questions [19]. The SARS-CoV-2 virus is closely threatening humanity and human lives and the situation in the future can be much worse than today is. We should keep in mind that besides saving human lives which is the most important aspect for confronting the novel coronavirus, the bad side-effects of the COVID19 pandemic make the economy of many countries suffer while it can shatter the small economies such as local businesses. In a word, the novel coronavirus has affected all human beings around the world and all people struggling in this tough situation. Any possibility and new approaches whether it is implausible or most likely should be considered and embraced by all researchers, governments, and people to prevent the rapid spreading of the virus [20].

1.2. The objective of the present study

Considering the possible routes of transmission, there is a concern about the transmission of the novel coronavirus via small-scale solar desalination systems (solar stills). This approach has not been before considered in any other study. Therefore, the main purpose of the present study is to elucidate the possibility of the contamination and transmission of the virus in solar stills structure and particularly distillate water droplets respectively. The study is planned in a way to propose some recommendations and consideration for researchers as well as other people who used small-scale solar desalination systems (solar stills) during the COVID-19 pandemic. This paper is organized in several steps for enlightening readers about the concept which should be carefully followed to realize the main points of the paper. In the first step, various types of pathogens with a focus on their environment and the important parameters that affected their viability are succinctly presented. In the second step, the principle of solar stills, their applications, the temperature of operation, and productivity are briefly reviewed. Since water temperature and productivity of solar stills at low temperature is crucial in the present study this section is very important. The paper in the third step continued by introducing contamination of water bodies and some of the well-known routes are concisely clarified. In the fourth step, the presence of the SARS-CoV-2 in water bodies is reviewed and the survival and fate of various coronavirus families (specifically novel coronavirus) with a focus on temperature is elucidated. In the fifth step, some of the environmental factors that affected the survival of the coronavirus family are presented. In the sixth step, the effect of temperature on the survival of the SARS-CoV-2 in solutions is discussed since the temperature plays a critical role in the inactivation of the novel coronavirus. In the seventh step, the risks of using solar stills during a situation like the pandemic are comprehensively argued. The seventh step is very important since it discussed the effect of temperature on pathogens in solar stills. Emphatically, in this section transmission of pathogens through vapors in solar stills is also presented. It should be noted that sections sixth and seventh are crucially important since the viability of the virus in solutions regarding the temperature as well as transmission of the pathogens by the vapor in solar still are presented in these sections. Eventually, in the eighth step, some recommendations and remarks for using solar stills during the ongoing pandemic are proposed while future studies as post-pandemic researches are also discussed. It should be noted that the approach of the present study is not limited to the situation like the ongoing pandemic (the COVID-19) but it has a wider prospect that is the reliability of the using solar stills when the feed water has biological contamination.

2. Pathogens

2.1. Types of pathogens

Various types of pathogens in the environment can be categorized as viruses, bacteria, fungi, protozoa, cyanobacteria. The source of each pathogen is different. Some of these sources can be mentioned such as humans, domestic/wild animals, and water. These pathogens in the environment have risks for living organs and specifically the human body and they can lead to various diseases such as Meningitis, Hepatitis, respiratory disorders, Typhoid, etc. The period of incubation and survival of each pathogen can be varied from several hours to several weeks based on their structure and their susceptibility to their environment [21]. Interestingly, the environment can have a huge impact on the survival of the pathogens. For example, *Escherichia coli* has a longer rate of survival in soil rather than in water [21]. In the present study, we focus specifically on the viruses since the context of the present study is in the ongoing pandemic.

2.2. Viruses in water environment

While bacteria consider as an indicator for examining the quality of the drinking water but there are numerous viruses which are existed in treated and untreated water. In the next sections, the presence of different viruses is thoroughly discussed. Briefly, some of these viruses can be mentioned such as astrovirus, rotavirus, adenovirus, norovirus, hepatitis A and E viruses, caliciviruses, and enteroviruses, including coxsackieviruses and polioviruses. It should be pointed out that infection by viruses can result in a higher rate of morbidity for vulnerable groups such as children, elderlies, immunocompromised people, and pregnant women [22]. For instance, rotavirus plays a leading role in diarrhea for children (less than 5 years old) which leads to 500,000 deaths each year [23]. Generally, water treatment facilities are not designed to detect or completely eliminate viruses in wastewater because it's has a huge cost and time-consuming process [24]. Thus, the presence of various types of viruses even in drinking water is not an unlikely possibility.

2.3. Parameters affecting the survival of viruses in water

There are plenty of factors that can influence the viability of viruses in the water environment. Some of these parameters can be mentioned such as light characteristics (source of light, intensity, and wavelength), viral concentration, temperature, organic matters, dissolved oxygen, free radicals, and PH. Among all of these parameters, the effect of temperature is well-studied rather than others and its inverse relationship with the survival of viruses is elucidated in numerous studies [25]. We shed light on the effect of temperature on the viability of viruses in the present study because in solar thermal desalination systems and viruses; temperature is in common as an important factor on the performance of the systems and viability of the viruses respectively.

3. Solar still

3.1. Concept, principle, and types

Solar stills as one of the simplest methods for producing hygiene water were used long ago from ancient eras. Since the principle of this method is simple, it is always introduced as one of the first methods for water treatment in remote and off-grid regions. The principle operation of solar stills is based on the evaporation and condensation process. A basin (or bed) filled with waste/contaminated/impure/saline water. A transparent inclined cover is mounted on the basin. Solar radiation enters into a transparent cover and increases the temperature of water in the basin. Subsequently, the evaporation process is started. As the water is heated the condensation process also begins on the surface of the inclined transparent cover. Finally, the droplets of distillate water are accumulated in a channel and collected by a valve [26]. Generally, there are two kinds of solar distillation systems named active and passive systems. In passive systems, the sun is the only source of energy that drives the whole system while in active types, besides the energy of the sun, another external heat source of energy also assisted the system [27]. The type of various modifications employed to improve the low efficiency of solar stills is determined by the type of the system (i.e. active or passive). In some cases researchers uses specific geometry for solar still such as double-slope [28,29], tubular [30,31], pyramid [32,33], hemispherical [34,35], spherical [36,37], stepped [38,39], and asymmetrical [40,41] to make an improvement on system. The most prominent passive techniques can be mentioned such as using energy absorbing/storing materials (sands, cement, and marble pieces) [42–44], porous media [45,46], utilizing phase change materials (PCMs) [47–50], using wicks [51–53], fins [54,55], internal/external reflectors [56–58], film cooling [59–61], increase the rate of heat and mass transfer by utilizing different nanoparticles in absorber/fluid/cover of solar stills [62–70]. Meanwhile, integration with humidification-dehumidification systems [71,72], thermoelectric modules (for heating and cooling) [73,74], and external/internal condensers [75,76] are another modifications for enhancing the performance of system. Furthermore, utilizing various solar collectors such as flat plate collector (FPC) [77–80], solar dish concentrator (SDC) [81,82], parabolic trough concentrator(PTC) [83,84], Fresnel lens (FL) [85,86], evacuated tube collector (ETC) [87–90], mini/shallow solar pond [91,92], and photovoltaic (PV) and photovoltaic/thermal (PV/T) [93–96] are other methods to improve the performance of solar stills. Fig. 1 demonstrated the schematic of single slope solar still.

Solar stills are used in different regions throughout the world for water purification which most of them are in developing countries (See Supplementary 1. Section 1.1 "*Solar stills around the world*"). Furthermore, solar stills are utilized for the separation of different impurities of the water. Fig. 2 exhibited various types of impurities that separate by solar stills. (Also see Supplementary 1, Section 1.2 "*Solar stills for separation and purification*").

3.2. Temperature of operation

The temperature of operation for various types of solar stills (i.e. active and passive) places in a specific range. Generally, passive systems have a lower working temperature than the active type because the system receives less energy input. The starting point of temperature for experiments for active and passive types is different but the initial temperature is usually determined by the opinion of the research team and it is usually found between 20 and 30 °C [97]. For passive solar stills

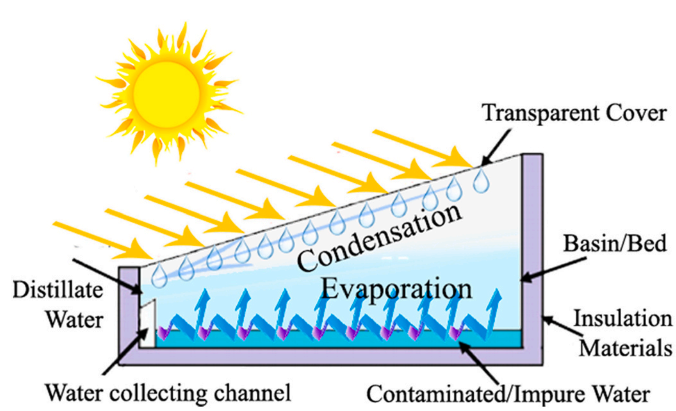

Fig. 1. Schematic of solar still.

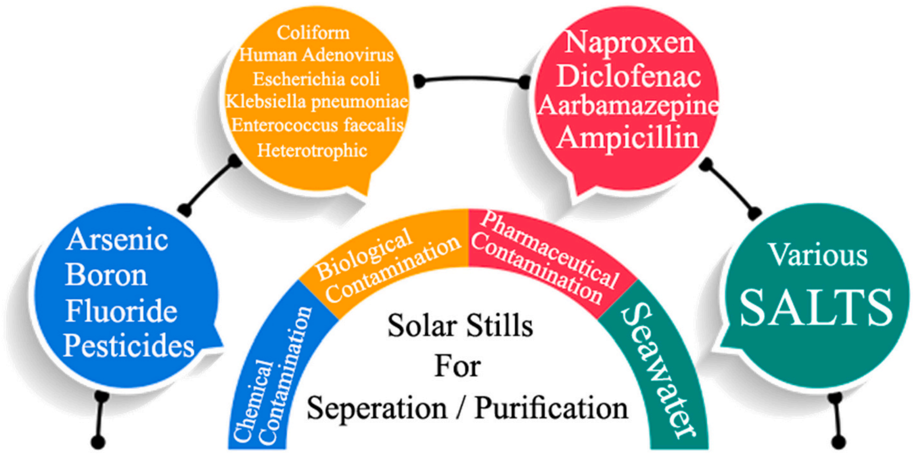

Fig. 2. application of solar still for separation of various impurities.

with various modifications as mentioned before, the maximum temperature of the system reaches up to 70 °C [98]. However in the case of active systems temperature is drastically higher because of using various collectors or pre-heaters and external heat sources such as FPC, PTC, SDC, ETC.

3.3. Productivity of solar stills

Likewise, the temperature, the productivity usually for active systems is higher than passive types because in active types of solar stills higher temperatures of water were obtained. Productivity of active solar stills placed in a range of 0.5 Liter/day for passive systems to more than 10 Liter/day. In solar stills, productivity was expressed with terms which are the Hourly/ instantaneous productivity and total/daily/overall productivity. The first term is the productivity of the system in a specific time interval (usually an hour) and the second term as it seems obvious is the summation of the hourly productivity. Furthermore, instantaneous and overall efficiency calculated based on the hourly and total productivity respectively. It should be noted that the instantaneous efficiency is defined as the productivity of the system at 1 h (Kg) multiply by latent heat vaporization of water (KJ/Kg) divided by the amount of solar radiation (Watt/ m^2) reached to the system multiply by area of solar still (m^2). Eqs. (1) and (2) express the instantaneous and overall efficiency of solar still.

$$\eta_{hourly} = \frac{\dot{m}_{evap} L}{I(t) A_b} \tag{1}$$

where, $\dot{m}_{evap}$, L, $I(t)$, and A_b represent the amount of distilled water, latent heat of vaporization, solar intensity, and the effective area of the basin respectively.

$$\eta_{Daily} = \frac{\Sigma\left(\dot{m}_{evap} L\right)}{\Sigma(I(t) A_b)} \tag{2}$$

There is an important point about the productivity of solar stills. Water has vapor at a broad range of temperatures. This means that in a close environment like solar stills which water temperature gradually increases the vapor on the condensation surface generated and collected at any temperature. Table 1 gives various types of systems with productivity at different working temperatures. Although, the graph of water temperature and productivity of various systems mentioned in the previous section clearly showed that solar stills have productivity even at a lower temperature but in Table 1 we mentioned some of the studies that explicitly reported the productivity of the system regarding to the temperature of operation. Furthermore, it should be mention that the critical temperature for the survival of the novel coronavirus is up to a certain temperature (56 °C), and upon this temperature, the viability of the virus is drastically decreases. Therefore, the higher temperature of operation (55–80 °C) and their productivity are not brought in Table 1. In the next sections, the viability of the virus with respect to the temperature is comprehensively discussed. Fig. 3 presents different productivity of the solar stills corresponds with different temperatures reported in Table 1.

4. Contamination of rivers, groundwater, and surface water

Big rivers and their banks and floodplains are virtually the home of a huge part of civilization on the blue planet. Almost 2.7 billion people live in these areas but in recent years the anthropogenic barriers are a force on big rivers and subsequently to these regions too [113]. The source of the pollution that mainly stresses water bodies is generally divided into two categories which are nutrients and pathogens produced by human wastes [113]. The source of pollution that boosted these two main sources of contamination is different. For instance, wastewaters are one of the main sources that directly and indirectly contaminated water bodies and aquatic environments. Some of the well-known huge transboundary rivers and basins that are polluted by pathogens of wastewaters are Ganges, Amazon, Congo, Parana, Nile, Yenisey, Lena, Zambezi, Niger, Amur, Indus, Mekong, and Salween rivers, to name a few [114]. Although the presence of the SARS-CoV-2 in the aquatic environment is thoroughly proved [17], in the next section a concise discussion about the possibility for contamination of water bodies by the SARS-CoV-2 is presented. Fig. 4 illustrated the possible routes for contamination of water bodies. Some sources of water body's contaminations can be mention as, urban wastes, wastewater discharges, human wastes, open defecation, improper disposing of personal protecting equipment (PPE), wastewater treatment plants (WWTPs), an infected person, poor sanitation, fault in sewage network, human enteric viruses in different routes, combine sewer overflows (CSOs), to name a few. Pollution of rivers and groundwater by wastewater has numerous instances throughout the world. Discharging sewage and industrial wastes to the river of Marimba in Zimbabwe resulted in heavy pollution of the river and plenty of environmental hazards [115]. Furthermore, discharging hospital wastewater into rivers is one of the sources of environmental pollution in developing countries [116] whereas in Nigeria more than 90% of hospital wastes directly discharge into the environment without any treatment [117]. Lack of a proper wastewater treatment plant (WWTP) and draining landfills and leachate into the environment also leads to pollution of the "Sai Dong Nai" River and groundwater which provided about 0.77 and 0.5 million m^3/day of water of Ho Chi Minh City people respectively [118]. Furthermore, municipal solid wastes are readily contaminated the surface water and

Table 1
Productivity of various solar stills at different temperature range.

Type	Modified/ integrate by	Productivity/ T_{Water} "for 15–20 °C"	Productivity/ T_{Water} "for 20–25 °C"	Productivity/ T_{Water} "for 25–30 °C"	Productivity/ T_{Water} "for 30–35 °C"	Productivity/ T_{Water} "for 35–40 °C"	Productivity/ T_{Water} "for 40–45 °C"	Productivity/ T_{Water} "for 45–50 °C"	Productivity/ T_{Water} "for 50–55 °C"	Ref
Stepped/ Passive	Wick & Reflector	–	–	–	–	–	–	–	54 °C/180 mL	[99] [99]
Single slope/ Passive	–	–	–	–	–	37 °C/40 mL	41 °C/48 mL 44 °C/72 mL	46 °C/80 mL	50.5 °C/100 mL 53 °C/112 mL	[100]
Single slope/ Passive	Carbon foam & porous absorber	–	–	–	–	–	–	49.2 °C/100 mL 48.6 °C/ 40 mL 47.6 °C/40 mL	54.2 °C/136 mL 54 °C/ 180 mL51.6 °C/ 64 mL	[100]
Double slope/ Passive	Multi Wicks	19 °C/77 mL 19 °C/56 mL 18 °C/37 mL 17 °C/56 mL 16 °C/22 mL 15 °C/23 mL	24 °C/162 mL 23 °C/214 mL 21 °C/144 mL 20 °C/182 mL	29 °C/445 mL 28 °C/415 mL 25 °C/611 mL	33 °C/623 mL 32 °C/566 mL	37 °C/743 mL 35 °C/669 mL	–	–	–	[101]
Double slope/ Passive	Multi Wicks	18 °C/62 mL 18 °C/65 mL 17 °C/74 mL 16 °C/20 mL 16 °C/22 mL 15 °C/23 mL 12–14 °C /9 mL	24 °C/234 mL 23 °C/136 mL 22 °C/179 mL 20 °C/189 mL	27 °C/398 mL 27 °C/366 mL 25 °C/297 mL	31 °C/563 mL 34 °C/608 mL 31 °C/518 mL	35 °C/688 mL	–	–	–	[101]
Single slope/ Active	PV/T	–	24 °C/50 mL	27.7 °C/60 mL	30.9 °C/89 mL	37.7 °C/99 mL	42.5 °C/123 mL	48.2 °C/208 mL	54.4 °C/311 mL	[93]
Single slope/ Active	PV/T	–	–	26 °C/80 mL	30.7 °C/90 mL	36.5 °C 152 mL	42.5 °C/353 mL	47.5 °C/523 mL	–	[93]
Single slope/ Passive	–	15 °C/40 mL 18.5 °C/34 mL	20.1 °C/37 mL 21.3 °C/32 mL 24.8 °C/16 mL 24 °C/44 mL	29.5 °C/15 mL -	32.3 °C/5 mL 30.1 °C/12 mL 34.9 °C/6 mL °C/mL	39.2 °C/5 mL -	40.1 °C/5 mL 41.4 °C/4 mL	46.2 °C/22 mL 48.3 °C/45 mL 47.4 °C/14 mL 48.3 °C/33 mL	50.3 °C/58 mL 53 °C/70 mL 51.5 °C/58 mL	[102]
Single slope/ active	PV/T	19.4 °C/62 mL 18.7 °C/26 mL 16.1 °C/50 mL	–	27.7 °C/22 mL	30.3 °C/20 mL	–	40.7 °C/16 mL 41.2 °C/10 mL 42.3 °C/8 mL °C/mL	45.7 °C/255 mL	–	[102]
Single slope/ active	FPC	–	–	–	–	–	41.84 °C/40 mL	–	–	[103]
Single slope/ passive	–	–	-	-	-	-	49.9 °C/75 mL 49.2 °C/46 mL	45 °C/10 mL	51 °C/30 mL 53.5 °C/130 mL	[104]
Single slope/ passive	Inverted absorber	–	–	–	34.6 °C/60 mL 31.9 °C/50 mL 40.1 °C/5 mL 40.1 °C/5 mL	–	42.3 °C/30 mL 43.5 °C/130 mL	46.4 °C/60 mL 49.8 °C/22 mL	52.3 °C/22 mL	[104]
Single slope/ Active	PVT-FPC & Heat Exchanger (Experimental)	9.25 °C/1.4 mL 11.55 °C/2.7 mL 19.62 °C/6.5 mL	–	28.46 °C/ 18.9 mL	–	37.57 °C/ 39.2 mL	44.4 °C/ 110.5 mL	49.26 °C/ 149.5 mL	52.25 °C/ 168.6 mL	[105]
Single slope/ Active	PVT-FPC & Heat Exchanger (Theoretical)	9.31 °C/1.5 mL 11.74 °C/2.9 mL	20.16 °C/7.3 mL	29.4 °C/21.1 mL	–	38.84 °C/ 44.5 mL	–	45.89 °C/ 124.3 mL	50.89 °C/ 166.4 mL 53.93 °C/ 186.9 mL	
	–	18.9 °C/80 mL	21.8 °C/90 mL	27.9 °C/110 mL	34.7 °C/120 mL	38.9 °C/150 mL	–	45.8 °C/250 mL	54.9 °C/300 mL	[94]

(*continued on next page*)

Table 1 (*continued*)

Type	Modified/ integrate by	Productivity/ T_{Water} "for 15–20 °C"	Productivity/ T_{Water} "for 20–25 °C"	Productivity/ T_{Water} "for 25–30 °C"	Productivity/ T_{Water} "for 30–35 °C"	Productivity/ T_{Water} "for 35–40 °C"	Productivity/ T_{Water} "for 40–45 °C"	Productivity/ T_{Water} "for 45–50 °C"	Productivity/ T_{Water} "for 50–55 °C"	Ref
Single slope/ passive										
Single slope/ Active	PV/T & Peltier Cooling	18.4 °C/95 mL	21.8 °C/110 mL	28.3 °C/150 mL	°C/mL	35.7 °C/220 mL 39.3 °C/250 mL	-	46.7 °C/350 mL	54.4 °C/450 mL	[94]
Single slope/ Active	PV/T & Peltier Heating	-	24.8 °C/120 mL	28.9 °C/150 mL	-	35.7 °C/280 mL	43.6 °C/350 mL	48.8 °C/500 mL	-	[94]
Single slope/ Active	PV/T & Peltier Cooling/ heating	-	-	25.3 °C/230 mL 29.1 °C/260 mL	-	36.3 °C/350 mL	44.2 °C/480 mL	49.1 °C/650 mL	-	[94]
Single slope/ Active	ETC & heat pipe	-	-	-	-	-	-	–	54.41 °C/ 320 mL	[106]
Single slope/ Passive	With/without Reflectors & sun tracking (for 8 configurations)	–	21.6 °C/1.7 mL 21.4 °C/1.8 mL	26.5 °C/16.9 mL 29.1 °C/91 mL 28.2 °C/2.1 mL 28.1 °C/33.4 mL 27.5 °C/2.4 mL	32.9 °C/21.3 mL 32.7 °C/98.9 mL 31.7 °C/44.2 mL 34.2 °C/ 131.3 mL	36.8 °C/172 mL 37.2 °C/123 mL 37.4 °C/225 mL 36.5 °C/6.1 mL 35.2 °C/6.7 mL 36.6 °C/6.5 mL 39 °C/7.5 mL	42.9 °C/ 242.8 mL 43.5 °C/234 mL 41.2 °C/225 mL 40.9 °C/190 mL 42.7 °C/333 mL 42.8 °C/166 mL 41.5 °C/166 mL 44.1 °C/353 mL	45 °C/248 mL 49.9 °C/299 mL 45.7 °C/356 mL	54.5 °C/290 mL 53.8 °C/367 mL 51.4 °C/641 mL 51.5 °C/685 mL	[107]
Single slope/ Passive	–	19.3 °C/30 mL	-	25.1 °C/38.5 mL 26.2 °C/30 mL 27.4 °C/88.5 mL	33.1 °C/54.5 mL	–	40.9 °C/22.5 mL 43.05 °C/ 112 mL	47.05 °C/ 133.5 mL 48.7 °C/390 mL	52.1 °C/490 mL 54.75 °C/ 205 mL	[108]
Single slope/ Active	FPC	–	–	26.75C/30 mL	30 °C/22.5 mL 30.85 °C/ 32.5 mL	39.65 °C/ 59.5 mL	44.95 °C/ 115 mL	–	51.87 °C/ 137 mL	[108]
Double slope/ Active	FPC	–	–	–	–	–	40.7 °C/40 mL 42.7 °C/65 mL	48.7 °C/226 mL	53.4 °C/389 mL	[109]
Single slope/ Passive	–	12.2 °C/7 mL °C/mL 15.4 °C/10 mL 17.5 °C/8 mL	24 °C/20 mL 22.2 °C/16 mL 20 °C/14 mL	25.1 °C/10 mL 27.4 °C/26 mL 28 °C/28 mL	33.2 °C/21 mL 32 °C/33 mL 32.9 °C/36 mL	36.2 °C/41 mL 37.3 °C/42 mL	40.4 °C/56 mL 43.9 °C/50 mL 42.5 °C/45 mL	-	-	[110]
Single slope/ Active	FPC	-	-	25 °C/16 mL	32.6 °C/29 mL 34 °C/32 mL	-	42.6 °C/72 mL 41 °C/40 mL 40.6 °C/68 mL	46.4 °C/80 mL 47.6 °C/100 mL	52.3 °C/250 mL 50 °C/281 mL	[110]
Double slope/ Active	FPC	–	–	26.6 °C/32 mL 25.9 °C/34 mL	34.8 °C/37 mL	35.5 °C/40 mL	44.1 °C/208 mL 42.4 °C/121 mL	-	53.1 °C/479 mL 51.6 °C/252 mL	[111]
Single slope/ Passive	–	–	–	–	34 °C/33 mL	39 °C/56 mL 37 °C/51 mL 36.3 °C/65 mL 39.5 °C/94 mL	41 °C/93 mL 44 °C/89 mL	45.9 °C/134 mL 49 °C/134 mL	52 °C/232 mL	[112]
Single slope/ Passive	Utilizing Fe_2O_3 micro particle	–	-	–	-	39 °C/130 mL 38 °C/94 mL 36 °C/80 mL	44 °C/161 mL 42 °C/114 mL 41 °C/124 mL	48 °C/194 mL	50 °C/260 mL 53 °C/250 mL	[112]

(continued on next page)

Table 1 (*continued*)

Type	Modified/ integrate by	Productivity/ T_{Water} "for 15–20 °C"	Productivity/ T_{Water} "for 20–25 °C"	Productivity/ T_{Water} "for 25–30 °C"	Productivity/ T_{Water} "for 30–35 °C"	Productivity/ T_{Water} "for 35–40 °C"	Productivity/ T_{Water} "for 40–45 °C"	Productivity/ T_{Water} "for 45–50 °C"	Productivity/ T_{Water} "for 50–55 °C"	Ref
Single slope/ Passive	Utilizing Fe_2O_3 nanoparticle	–	–	–	-	38 °C/80 mL	44 °C/179 mL 42 °C/130 mL 40 °C/119 mL	45 °C/169 mL 47 °C/227 mL	52 °C/210 mL	[112]

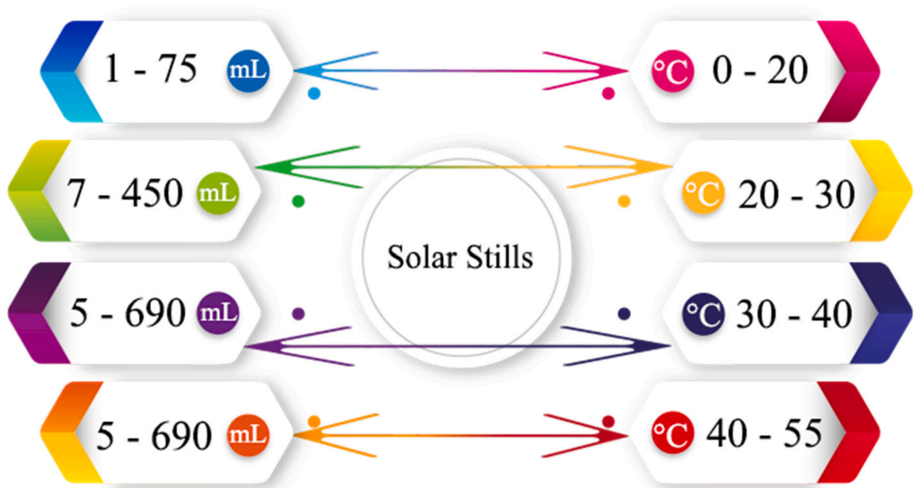

Fig. 3. Productivity of various solar stills with respect to the temperature.

groundwater in Kenya because of open dumping without any regulation [119]. Municipal waste (which usually contains various pathogens) has a great potential to be the source of pollution of water bodies whereas in some cases slum people may play a significant role in contamination of potable water that stems from a dam [120]. On the other hand, in some of the developing countries, farmers exploited human waste and sewer as fertilizer. In Ghana, Mali, and Benin some farmers bribe drivers of septic tanks to discharge the sludge on the agricultural lands [121,122]. It should be reminded that in the former times, return of some disease epidemics has been connected to the direct exploitation of sludge in some communities [123,124]. The lack of tight regulations and strict action of officials especially in developing countries and lack of laboratory experiments makes many water bodies in developing countries as the source of pathogens which can remain infective under proper environmental conditions over days. Proximity of water bodies and groundwater resources to WWTPs also can be another reason for the pollution of water bodies [125]. In a huge city such as Mexico City and the valley next to it about ¾ of wastewater of the city (the volume of produced wastewater is 45,000 Liter/s) is reused without any formal wastewater treatment. Down et al. compared biological contaminations such as Vibrio Cholera, Salmonella, and *E. coli* with chemical pollution and concluded that pathogens are the main agents of surface and groundwater contamination that results in diarrheal and gastrointestinal diseases in residents [126]. Nevertheless, rivers contamination in urbanized and industrialized countries is completely apparent. While the government of China just in 2016 the expending more than 21 billion dollars in water treatment infrastructure [127], but it was reported that about 9% of China's rivers are heavily polluted [128]. Moreover, rivers in India are one of the sources of contamination and disease because of the lack of efficient WWTP and sewer system. For example, bacteriological characteristics of a river like the Gomti makes it completely dangerous and unsafe for any purpose [129]. Ganges River is a famous example of an unsafe river because of many reasons such as doing religious traditions during year and discharging wastes (human waste, wastewater, sewage) into the river. It was elucidated that about 0.2 billion Liter/day of human sewage just discharge to the river from Varanasi which is directly related to many water-borne diseases in the region [130]. (For more discussion about the contamination of water bodies, see supplementary 1. Sections 1.3, 1.4, and 1.5 "*Contamination by wastewater, Contamination by sewer leakage, Contamination by Human enteric viruses*" respectively).

5. The SARS-COV-2 (COVID-19) in wastewater

Wastewater can be considered as one of the high risks routes for transmission of the novel coronavirus [131]. Analyzing wastewater considers one of the effective tools to detect the presence of the COVID-19 in any region [132]. Hence, wastewater-based epidemiology (WBE) for determining the SARS-CoV-2 in various regions in recent months was performed by many researchers [133–138]. Nevertheless, the presence of the SARS-CoV-2 in water bodies and wastewater in many industrialized and developing countries such as the Netherland [139], Czech Republic [140], Ecuador [141], India [142], Nicaragua [143], and the US [144] are observed too.

Unfortunately, in many cities (mostly in developing countries) sewage and wastewater without any treatment are directly drained into the natural water. Although it was declared that due to the shutting down of business, the quality of surface water and a huge lake such as Vembanad Lake is improved [145], but Hou et al. reported that the presence of the SRAS-CoV-2 in the stool of patients led to contamination of groundwater [146]. Moreover, in many countries in Latin America, virtually 60–70% of wastewaters without any treatment are directly drained into the aquatic environment whereas 40% of the people are not connected to the sewage system [147]. In some cases, a huge city like the Quito city with 3 million populations treated only 3% of its wastewater [141]. Laura et al. quantitatively reported presence of the SARS-CoV-2

Fig. 4. Possible routes for contamination of water bodies.

in high concentrations in three natural rivers. They declared that a high concentration of virus in such regions with weak sanitation systems in the future could result in many health risks as well as numerous environmental barriers. Furthermore, an insufficient sanitation system can be a potential for soil, groundwater, surface water to be highly contaminated [148]. This is important because in numerous countries in the world (mostly developing countries) there is no adequate sanitation system. It should be emphasized that highly polluted soil indirectly leads to contamination of surface water and groundwater. Ineffective sanitation system especially in developing countries and places where the healthcare buildings wastes is not disposed properly is potential risk of water contamination during the ongoing pandemic. A good example is the healthcare facilities in Palestinian West Bank which just treated 2% of their wastewater whereas the healthcare facilities consider as one of the high risk source of the SARS-CoV-2 RNA in their wastewater [149]. This can be even worse for the countries that have dense population with low waste/sewer/sewage/water treatment systems such as India [150]. A poor sanitation system also increases the potential for contamination of water bodies by human excreta. The presence of the SARS-CoV-2 in the stool of patients was reported positive even though their respiratory tests were negative [9,151–157]. Moreover, the presence of viral in human feces can be prolonged between 11 and 35 days [158]. This indicated that the viability of the virus is not limited to an infected person which means that after patients get treated and healed, the human feces that contains the SARS-CoV-2 virus still increases the viral load to water bodies due to poor sanitation system or WWTPs in the developing world as well as industrialized countries respectively. However, the infectivity of the viral in the wastewater is not certainly examined yet [158–161], but the huge amount of wastewater (including human feces) that discharge into the aquatic environment in some cases like the city of Quito (with 3 million population) that treated only 3% of its wastewater results in a greater load of viral and subsequently higher contamination in water bodies like the River of Gomti [141]. A similar situation like the city of Quito exists in plenty of cities in developing countries with a poor sanitation and sewage network. Numerous researches reported the presence of the SARS-CoV-2 in treated (or untreated) wastewater as well as rivers. (See supplementary 1, section 1.6 “*Detection of the SARS-CoV-2 in wastewater*”).

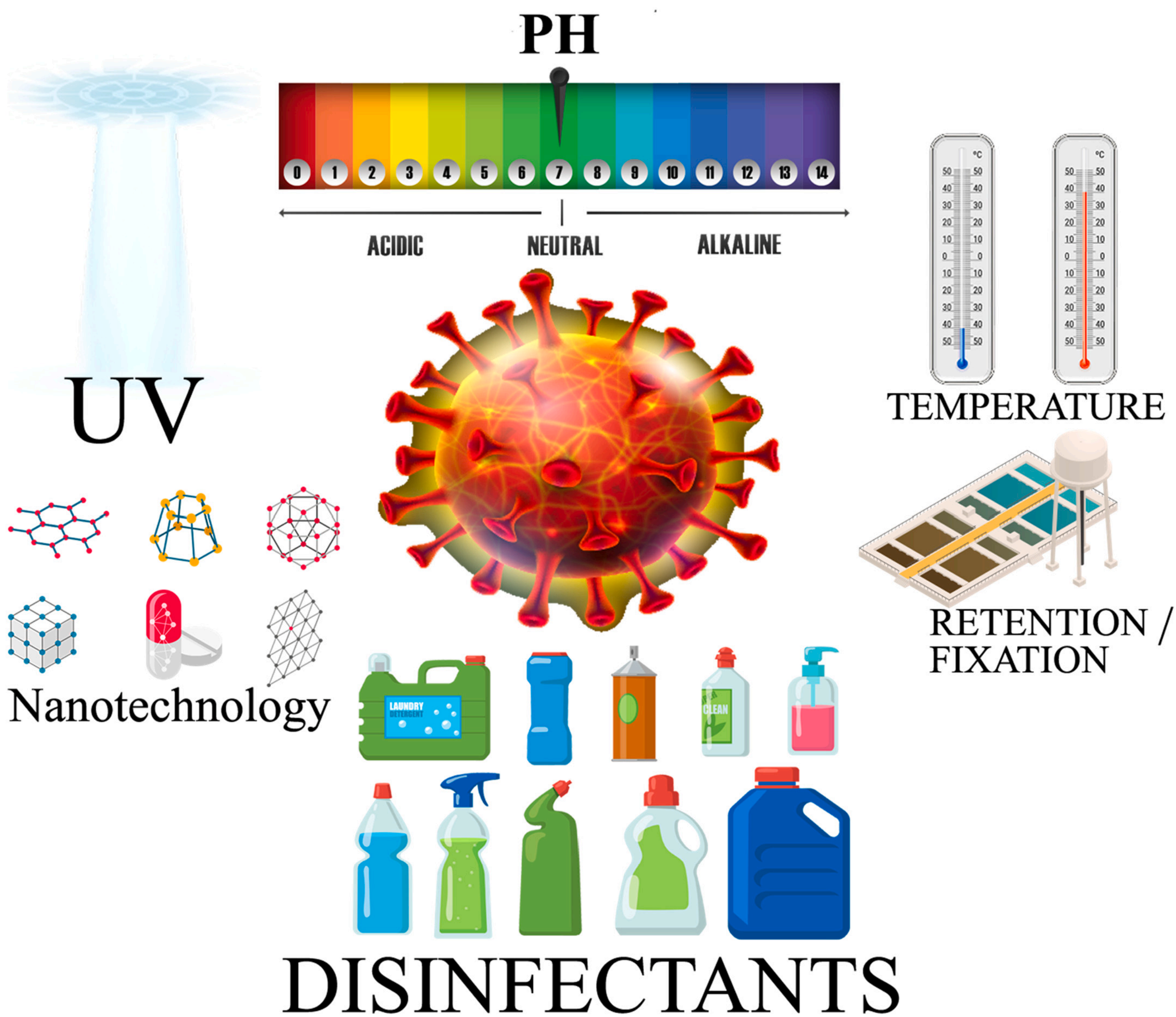

Fig. 5. Some parameters and methods that affecting the viability of the SARS-CoV-2.

6. Survival and fate of the family of coronavirus in the environment

The number of studies on the important parameters that may result in inactivating the SARS-CoV-2 in various environments is almost diverse. In fact, the actual and exact effect of parameters such as PH, retention time, exposure under sunlight, UV content, proper disinfectant (see Fig. 5) is not completely realized yet. In this regard, researchers may force to use previous studies that performed on a similar family of the coronavirus. Several factors that may help to have an insignificant/significant effect on the inactivation of the virus are presented by researchers. For instance, it was found that PH in a wide range (i.e. PH = 3–10) has no significant effect on the survival of the virus [162] while at extreme PHs (2–3 and 11–12) the infectivity of the virus was lost within one day [163]. After the SARS-CoV-1 epidemic, Wang et al. in 2005 [164]examine that the SARS-CoV-1 virus by chlorination (i.e. Cl) at 0.5 mg/Liter concentration in 30 min thoroughly inactivated. On the other hand, using a disinfectant in inappropriate dosage may have some environmental hazardous by producing DBPs in water. Also, it is revealed that temperature has a direct effect on the inactivation of the *coronaviridae* family and mostly the SARS-CoV-2. The reason that the virus is intolerant when it expose to heat is that the *coronaviridae* family is covered by a lipid layer that readily breaks down when the temperature is enhanced [165–167]. The effect of various parameters (specifically temperature) on the viability of the *coronaviridae* family is extensively discussed in previous studies. (See Supplementary 1, Section 1.7 "*Effect of temperature on different coronaviridae family*").

Even though researchers may have to use the experience from the previous epidemic related to the family of *coronaviridae (*i.e. *the SARS-CoV-1, the HCoV-the 229E, the MERS,* etc.*)* [148] because of the lack of studies, but due to difference between the SARS-CoV-2 and those mentioned above; researchers may not be able to draw a comprehensive-conclusion for predicting the exact behavior of the virus under different conditions or proposing an effective method against it. Nguyan et al. [168] theoretically showed that the SARS-CoV-2 binds more strongly to the angiotensin-converting enzyme 2 (ACE2) of their receptor rather than the SARS-CoV-1. Furthermore, Tian et al. [169] concluded that the effectiveness of the broad range of antibodies like the *m396* and the *CR3014* is binding to the SARS-CoV-1 but not to the SARS-CoV-2. Hence, more investigation that explicitly focuses on the SARS-CoV-2 should be conducted.

7. Effect of temperature on the viability of the SARS-CoV-2

As discussed above the family of coronavirus is susceptible to an increase in the environmental temperature. In fact, by increasing the temperature the structure of the SARS-CoV-2 RNA is damaged and the viability of the virus is extremely decreased. In this regard, researchers proposed to enhance the environment temperature for eliminating the SARS-CoV-2 aerosols in the indoor environment [170]. Wang et al. [171] proposed to reuse the face masks by the method of hot water decontamination to heat the immersed mask in the water at 56 °C for half an hour (30 min) for eradicating the SARS-CoV-2 in the mask. They reported that by utilizing this method in a company during a period (around 40 days); the number of masks used by employees is decreased by about 122,500. Chan et al. [163] reported that the SARS-CoV-2 is highly sensitive to temperature in which the virus in solution at low temperature (4 °C), room temperature (20–25 °C), and hot temperature (33–37 °C) retain up to 14 days, 7 days, and 1–2 days respectively. Fig. 6 exhibited the viability of the virus with respect to a range of temperature in the water reported by Chan et al. [163].

Chin et al. [162] reported that the SARS-CoV-2 is greatly sensitive to increasing temperature in which at 4 °C the virus remains thoroughly stable after 14 days (only 0.7 $\log_{10}$ reduction) while increasing the

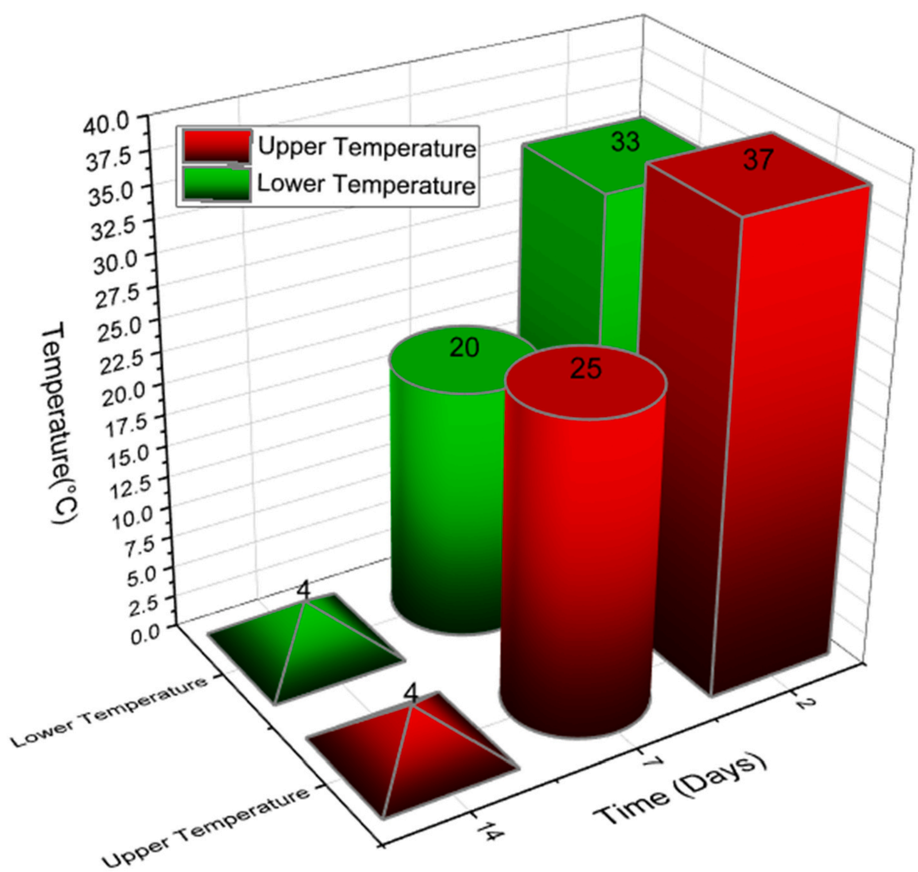

Fig. 6. Viability of the SARS-CoV-2 in solution with respect to temperature [163].

temperature up to 70 °C the virus is inactivated in 5 min. In a recent study, Ahmed et al. [172] experimented with the viability of the SARS-CoV-2 and Murine Hepatitis Virus in three different solutions which are: tap water, autoclaved wastewater, and untreated wastewater in a range between refrigerator temperature to hot temperature (i.e., 4 °C, 15 °C, 25 °C, and 37 °C). Their findings revealed that T_{90} for the SARS-CoV-2 in tap water, autoclaved wastewater, and untreated wastewater, takes between 9.4 and 58.6 days, 5.71–43.2 days, and 8.04–27.8 days respectively. Figs. 7–9 demonstrate the T_{90} for tap water, autoclaved wastewater, and untreated wastewater. It should be mentioned that in Figs. 7–9 the lower and upper boundary (i.e., minimum and maximum days) is based on the standard deviation presented in [172]. Nevertheless, it should be pointed out that the number of studies on the viability of the SARS-CoV-2 with respect to the temperature in various water matrices is limited. Therefore, the number of days that the virus can remain viable in various water matrices may be diverse case by case. It should be noted that the viability of the virus in Fig. 6 is different in comparison with those reported in Figs. 7–9. Because in Fig. 6 Chan et al. [163] is discussed on maximum viability (based on days) of the virus regarding temperature while Ahmed et al. [172] reported the T_{90} of the SARS-CoV-2 in different solutions.

8. What is the risk of solar distillation during the pandemic?

As discussed above, the SARS-CoV-2 widely exists in various types of water bodies and its presence will be more day by day due to the tremendous prevalence of the virus throughout the world. Currently, more than 99 million people were infected by the novel coronavirus and 2.1 million of them lost their lives [173] while it was anticipated that until June 2021, about 250 million people were infected and 1.75 million are dead but the number of deaths is higher and it is disturbing. It should be mentioned that the number of infected people from the beginning of the pandemic during the month of February – May 2020 is drastically lower than in the future; numerous studies (that discussed above) were reported the presence of the SARS-CoV-2 in various water bodies, in the future by increasing the number of the infected people throughout the world, the concentration of the viral in water bodies staggeringly is enhanced which means more water bodies will be contaminated.

The problem arises when we stepped the fact into the spotlight that, various pathogens can be transmitted through vapor droplets [174]. Not to mention that solar stills worked based on the collecting water droplet. The quality of produced water is crucial from chemical compounds, bacteriological, and pharmaceutical characteristics. Some researchers were conducted studies to evaluate the transmission of various pathogens through vapor and droplets in solar distillation units. Balladin et al. [175] found that the concentration of biological colonies in produce water from stepped solar still is exceedingly high. However, the type of pathogens is not examined in this study. Moreover, Ahsan et al. [176] pointed out that the presence of *E. coli* in distilled water of a solar still and declared that the presence of bacteria could be related to cross-contamination. Also, Kikuchi et al. noted the presence of *E. coli* in the distillate water of a plastic-type solar distillation unit [177]. Further, accumulating microorganisms such as algal or micro-flora particles on brine could increase the vulnerability of supply water by microbial contamination which directly/indirectly can result in contamination of distilled water [178]. Ayoub et al. [179] have been performed a series of indoor and outdoor experiments on the feasibility of solar stills in

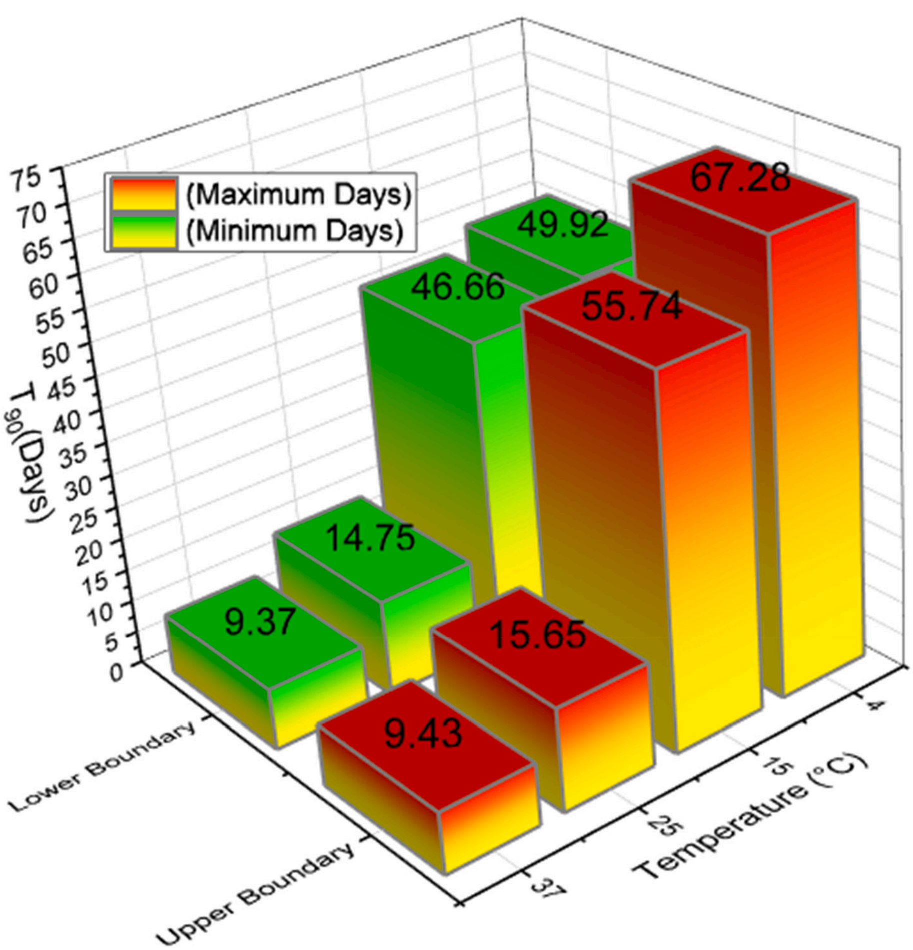

Fig. 7. The average T_{90} for the SARS-CoV-2 in tap water [172].

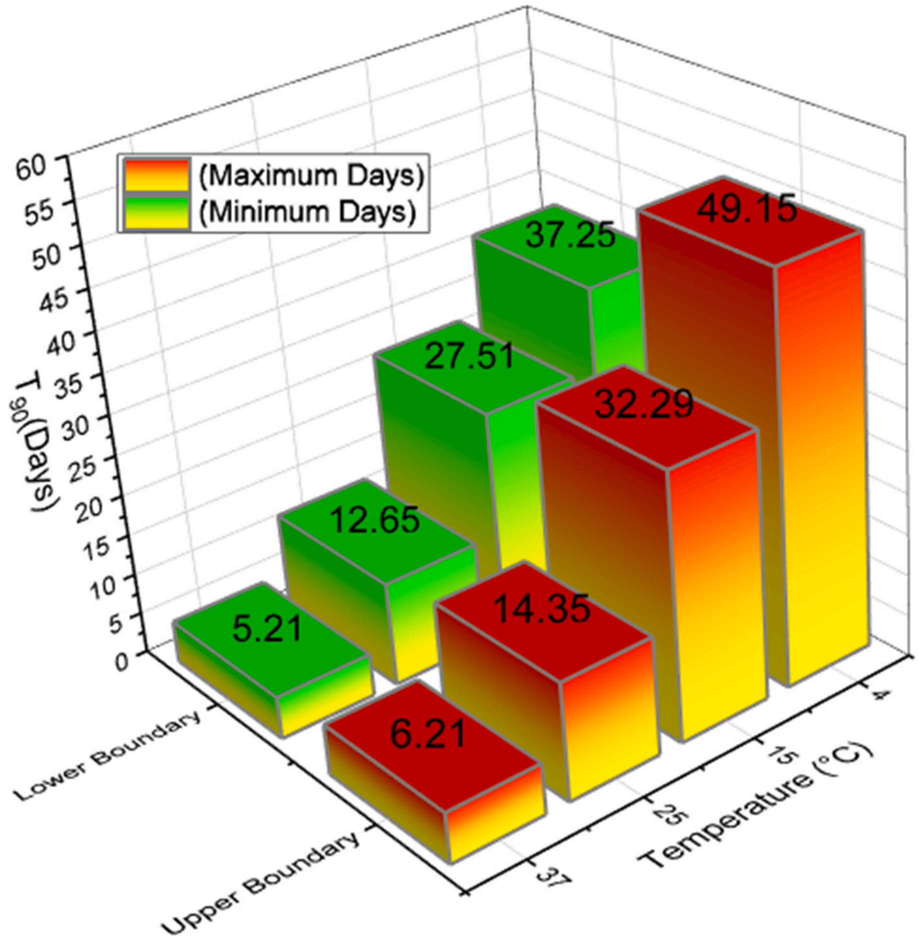

Fig. 8. The average T_{90} for the SARS-CoV-2 in Autoclaved wastewater [172].

removing three different pathogens which are: E. coli, *Klebsiella pneumoniae*, and *Enterococcus faecalis*. Their findings revealed that all pathogens are capable to transfer via vapor in a solar distiller unit and the rate of transmission for *Enterococcus faecalis* through vapor at a temperature between 40 and 45 °C and 50–55 °C compare to two other pathogens is greater. However, the outdoor experiment showed that solar UV has a significant role in the inactivation of pathogens in distillate water, but they emphasize that the effect of solar UV can be significant only at the optimum condition which is the availability of strong solar radiation. This means that under non-optimal/sub-optimal conditions effect of UV can be decreased or eliminated. Similarly, in another study [180] performance of solar still for eliminating E. coli and *Enterococcus faecalis* is performed. Findings revealed that the rate of transfer for *Enterococcus faecalis* via vapor at temperature ranges 40–45 °C and 50–55 °C is higher than *E. coli* while at the temperature 30–35 °C the rate of transfer for *E. coli* is higher. Since the number of studies is not sufficient for examining the behavior of pathogens transmission through vapor there is no definite explanation about this phenomenon. One possibility that can be concluded is that *Enterococcus faecalis* is a thermally resistant pathogen and can survive at a higher temperature, even up to 65 °C. Furthermore, another important factor is the availability of reaching sunlight (mainly UV) to all parts of the solar still. It was reported that all constituents of solar stills should be exposed to the sun to prevent the growth of bacteria and pathogens which can contaminate the distillate water [181]. However, this is not completely plausible, because sunlight may not reach some parts of solar stills (under basins or collecting channels) and the presence of pathogens seems to be inevitable. Further, another important factor is the fact that the rate of solar radiation transmitted through transparent cover to derive solar stills is decreased because the droplet of water on the transparent cover reflected some part of solar radiation [182]. This meticulous factor is crucial since it was realized that for the elimination or reduction of pathogens in distillate water as well as the whole structure of the system; solar stills should access the high intensity of sunshine [179,180]. Moreover, it should be mentioned that the distillate water produced in the early hours of the experiment (i.e. morning) is at hours that solar intensity is low and subsequently the solar UV is low too. It is worthy to be noted that among three types of UV which are UVA (315–399 nm), UVB (280–314 nm), and UVC (100–279 nm); UVA is the most abundant type of UV while just around 5% of UVB reaches to the surface and UVC is completely absorbed by the atmosphere and ozone layer [183,184]. Generally, the UVC wavelength is effective and strong enough for waterborne viral rather than UVB and UVA [185]. Nevertheless, it was reported that there are viruses such as RoVs and AdVs that prone to chlorine compounds but not UV light [186–188]. However, it should be mentioned that in recent studies, researchers focus on the feasibility of eliminating the SARS-CoV-2 by UV [189–191]. The results showed that UVC is strong enough to damage and eliminate the SARS-CoV-2. But the problem is that UVC is not available on the surface of the earth. Thus, we cannot rely on the effect of UV (besides temperature) as an effective factor to inactivate the novel coronavirus. On the other hand, it was revealed that at higher relative humidity the viability of the virus in droplets is increased [192]. Thus, in an environment such as solar still which in most times of experiments the relative humidity is higher than 95% the viability of the pathogens in generated droplets is certainly increased too. However, the impact of simultaneously higher temperature and relative humidity in the absence of wind (this is the conditions inside of the solar still) is unclear and did not realize yet.

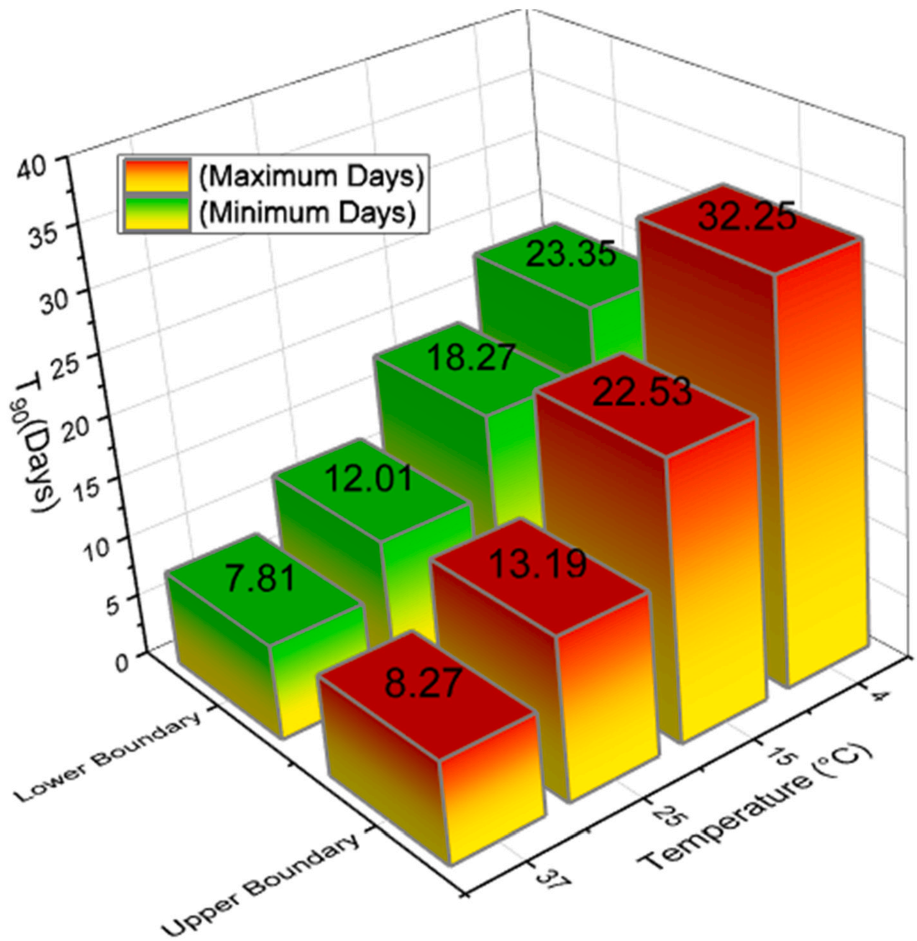

Fig. 9. The average T_{90} for the SARS-CoV-2 in untreated wastewater [172].

Thus, the risks of transferring pathogens are not an unlikely possibility and they can be transmitted in any condition. Since now there is no research on the transmission of the SARS-CoV-2 virus via vapors of contaminated water. This makes the uncertainties even more complicated. The problem can arise when we consider that solar stills generated droplets of water at various temperatures. We shed light specifically on the productivity of solar stills at low temperatures because at the higher temperature the viability of the virus is drastically low. As given in Table 1 and also investigations by numerous researchers in plenty of experimental studies most solar stills (whether active or passive type) have productivity in temperature less than 40 °C and some of the studies it researchers reported the distillate water produced in the temperature range of 20–30° [93,107,111] and even in temperature less than 20° [94,101,102,105,108,110]. Moreover, the inside temperature (evaporation chamber) of solar stills is always lower than the water temperature (around1–5 °C) [100]. This is a very important point because if a pathogen that is sensitive to temperature can survive at a higher temperature (i.e., water temperature inside the basin of solar still), the viability and survival of the pathogen at a lower temperature (in this case environment temperature inside the solar still) certainly is higher. However, the survival of the virus in such an environment (low temperature and high relative humidity) is not recognized. The survival of the novel coronavirus in higher temperature like 50–70 °C examined that is less than 30 min [162,163]. Moreover, it is also declared that at 22 °C the virus can survive up to 7 days. Regarding Table 1, solar stills among this wide range of temperature (20–50 °C) can be operated and at each hour produce distillate water (droplets of vapor) which collected and keep in containers or channel. The risk of transmission can be elucidated more by considering the fact that coronavirus can survive at room temperature (20–25 °C) up to 7 days and this temperature is not critical to damage viral structure while at this temperature solar stills produce distillate water and the viability of the virus in the temperature range between 33 and 37 °C is examined around 1 to 2 days. Since the temperature is one of the most important factors that can critically affect the viability of the SARS-CoV-2, the risk of transmission can be more arisen when we consider the fact that solar stills have productivity at all of the aforementioned temperatures (i.e., 20–25 °C and 33–37 °C). This means that while at a temperature such as 33–37 °C the virus can survive at least for 24 h; a solar still can easily produce distillate water at this temperature just in an hour. For enlightening this statement we bring a brief explanation. It means that while the virus remains viable at this temperature between 24 and 48 h; a solar still which uses contaminated water can produce droplets of water during one day of an experiment at this temperature range without damaging to the SARS-CoV-2 and transmission of the pathogen via vapor can occur. The viability of the virus at this temperature is more dangerous for systems that have a low temperature of operation such as Pal et al. [101] which reported that the maximum temperature of operation during the experiment reaches 37 °C. However, the risk for other systems that work at a higher temperature (i.e., >70 °C)remains, because during the experiments when water temperature increases to reach a maximum temperature like 70 °C; the system at this temperature range (i.e., 20–25 °C and 33–37 °C) has productivity and in this way, the virus can be transmitted via droplets of distillate water.

Besides studies that conducted on the transmission of the pathogens via vapor in the solar still, it should be noted that the transmission of pathogens via vapor is directly related to the size of their particle. Interestingly, until there is no current air, wind, air ventilator, air condition system, or any parameter that remove/dilute air; in most indoor environment for a particle (droplet) size equal or smaller than 5 μm, particle (droplet) can remain airborne for an indefinite time [193]. This means that tiny droplets due to their drastic small size can be evaporated into droplet nuclei and remain suspended in air or even exhale [194]. Moreover, it should be mentioned that the transmission of viruses by droplet nuclei is plausible while it was reported that the measles virus can be transmitted via droplet nuclei [195]. Hence, by considering the fact that pathogens such as *E. coli*, *Klebsiella pneumoniae*, and *Enterococcus faecalis* with the size around 0.5–3 μm [196–198] can be transmitted via vapor in solar stills, the transmission of coronavirus with 60–140 nm which more than 10 times is smaller than theses pathogens are a complete possibility. In this regard, the risk of transmission of coronavirus from contaminated water is high. Furthermore, the collecting channels and containers also have a high potential for contamination. From this prospect, not only the produced water but the whole setup will be contaminated and the solar still may become a source of contamination. Although, there are no factual pieces of evidence about the transmission of the virus because of contamination of drinking water via the SARS-CoV-2, there is anxiety on the side effects of the current pandemic wave on the underprivileged communities/societies [199].

9. Concluding remarks, recommendations, considerations, and future studies

1. Poor sanitation system and insufficient access to sewage network in a whole continent like Latin America which more than 50% of wastewater without any treatment discharged to the environment drastically contaminated water bodies.
2. The SARS-CoV-2 is extremely susceptible to temperature in which at low temperatures (4 °C), room temperature (20–25 °C), and hot temperature (33–37 °C) the viability of virus examined about 14, 7, and 1–2 days respectively but at 56 °C and 70 °C it decreases to less than an hour (30 min and 5 min respectively) on its environment.
3. The SARS-CoV-2 can remain viable in a wide range of temperatures for several days where the average T_{90} of the virus in various solutions such as tap water for a temperature range of 4 to 37 °C is examined between 9 and 58 days.
4. The risk for transmitting of the SARS-CoV-2 via vapor in solar still is completely possible because of the small particle size of the SARS-CoV-2 (60–140 nm) while transmission of pathogens such as *E. coli, Klebsiella pneumoniae,* and *Enterococcus faecalis* with the particle size of 0.5–3 μm (more ten times larger than the SARS-CoV-2) is proved before.
5. At a temperature range of 22–37 °C, all solar stills produced droplets of water, while the viability and survival time of the virus at this temperature range is for several days. This means that during any experiments, solar stills at this temperature range can transmit the virus without any damage to the RNA structure.
6. However, at a higher temperature range 37–50 °C time of inactivation and damage to the virus structure is not recognized yet, but regarding Figs. 6–9 and also several reports on the effect of temperature; it is not an irrational assumption if considering that the structure of virus at least can be undamaged for an hour (or several hours) which is long enough for transmitting the virus via droplets of water.
7. The temperature operation of some solar stills is very low (<40 °C) throughout the whole experiment. This can result in increasing the viability of the virus in distillate water as well as the body of solar still. Such systems have higher risks compared to systems with higher working temperatures.
8. Using solar stills throughout the night with energy-storing materials such as PCM that is widely utilized in solar distiller units is not a reliable and safe method because the distillate water is produced in the absence of Solar UV whereas solar UV has a vital role in preventing the transmission of pathogens through vapor. Also, the temperature of operation at night is lower than a day. However, many studies are also conducted during nighttime
9. After each experiment, the body of solar stills should wash with an effective and strong disinfectant to remove any pathogens (specifically the SARS-CoV-2) because at the end of the experiments usually the night falls and in a dark environment there is more possibility for the growth of any survived (remained) pathogens in the basin as well as the body of solar still.
10. It is recommended that computational physicists alongside medical science experts developed a framework based on computational fluid dynamics to examine the survival of the virus in such an environment. However, a similar study was recently performed for the outdoor condition.
11. With the arrival of cold seasons in the northern hemisphere the viability of the virus will be increased since the temperature is drastically decreased and the relative humidity increased. Thus, the presence of the virus in water bodies would be more prevalent.
12. Using an external condenser in solar stills is not a safe way since the condenser chamber/reservoir usually is a dark place (usually close space) which is a proper condition for growing transmitted pathogens through vapor droplets. Therefore, it is recommended to avoid using a condenser and in the case of using a condenser, researchers should use a condenser made of transparent materials (such as Plexiglass) to allow the solar radiation reach to the produced water.
13. The produced water via solar distiller unit can be heated by heating source (such as fire as the simplest method) for 2 min in a container to increase the water temperature up to 70 °C to eliminate the huge part of the virus up to 90% [200].
14. In the case that there is no heating source to heat the produced water; collected distilled can be exposed under sunlight to use the advantage of solar water disinfection (SODIS). However, the effect of SODIS on eliminating the SARS-CoV-2 is not understood yet by researchers but SODIS is a well-known method to reduce the concentration of pathogens in contaminated water.
15. During a pandemic like the COVID-19 when the individual's infections have exponentially raised, the concentration of the viral in water bodies (mainly in wastewater) tremendously enhanced, and any deficiency in reducing/eliminating viral loads (due to using an improper dose of disinfectants or ineffective wastewater plants) may lead to viral transferring to feed or reuse water.
16. Distillate water generated in the early hours of experiments is more prone to carry pathogens via vapor because the water temperature is not critical for the pathogen and the rate of solar UV (which is an important factor to prohibit the growing and survival of pathogens) is lower too.
17. Reflection of solar intensity by droplets of distillate water reduces the rate of solar radiation reach to the inside of the solar still while the availability of a high rate of solar radiation is an important factor for preventing the transmission of pathogens through vapor.
18. Since the rate of solar UV in cold seasons (specifically winter) is lower than warm seasons and the presence of sufficient UV is critical for preventing the transmission of the pathogens via vapor and also pathogens growth inside of solar still, using solar still is not suitable for these seasons.
19. The effective wavelength of UV for inactivating the SARS-CoV-2 is in the regions 100–279 nm which is considered as UVC.
20. Availability of solar UV consider as an important factor in the survival of pathogens in solar stills but it should be reminded that the wavelength of UVC is effective and strong enough to damage the virus while the most available solar UV (UVA) on the surface of the earth has not a significant effect on damaging viruses.

21. The temperature of operation in solar still during cold seasons is substantially lower than summer because of lower ambient temperature and solar intensity and therefore the system's temperature of operation is considerably lower than summer. Thus, using solar stills during autumn and winter is not recommended.
22. In passive solar stills, the possibility of transmitting pathogens via vapor is higher because the temperature of operation is lower than active and the maximum temperature generally is placed around 60 °C (in some rare cases it may reach around 70 °C)
23. Using a renewable or non-renewable preheater to increase the temperature of feed water can assist the system in eliminating pathogens that susceptible to temperature.

Because of the fact that the SARS-CoV-2 is rapidly spread and highly contagious; future investigations to experimentally examine the various parameters on the viability and the fate of the SARS-CoV-2 under real conditions in small-scale solar desalination systems should be conducted under protected conditions by strict protocols [201] alongside direct supervision of an expert medical team. However, it recommends to all researchers to perform these studies as post-pandemic studies because the situation is critical during these days. In this regard for future studies following can be suggested:

24. Viability and survival of the virus in solar stills environment and the collected water.
25. The concentration of the virus in the presence and absence of solar UV (mainly UVA and UVB) under laboratory condition
26. Effect of exposing the distillate water under sunlight to take the advantages of methods such as SODIS
27. Constructing new geometry of solar stills to divide the distilled water into lower temperatures (lower than 40 °C) and higher temperatures (i.e. higher than 50 °C) and collect the distilled water at each temperature range separately.
28. Realizing the synergistic effect of UV and temperature on the viability of the SARS-CoV-2 in basin water as well as distillate water.
29. Examining the presence of the virus in the basin water after the experiments were finished, especially in the passive systems in which the temperature of operation is low.
30. Since seawater is one of the sources of the solar still's feed-water; realizing the survival and fate of the SARS-CoV-2 virus under conditions of seawater is crucial because it was reported that some viruses can be long-lasting even after months in seawater.
31. Evaluating effect of the COVID-19 on the performance of large-scale thermal desalination systems such as MED and MSF is an interesting topic worth to be realized.
32. A comprehensive study to elucidate characteristics of waterborne pathogens, their presence in water bodies that lead to death of people (especially children) in developing countries and introducing the available methods to eradicate them from the produced distillated water and body of solar stills is highly recommended.
33. Engaging water science experts (Mechanical/chemical/environmental engineers) with medical scientists (especially applied microbiology and environmental microbiology experts) to develop a framework for realizing the feasibility transmission of various waterborne/airborne pathogens through solar stills is also recommended.

Once again it should be emphasized that any experimental study on the viability of the virus in solar desalination systems is required multidisciplinary insight and the engineering researchers and experts should work alongside an expert medical team.

10. Conclusion

The ongoing pandemic becomes a catastrophe that threatens all human beings. The side effects of this undesirable phenomenon on the environment are inevitable. Contamination of water bodies by the SARS-CoV-2 is one of those numerous impacts of the pandemic. The situation in developing countries which most of them have not a proper WWTP and sewage network is certainly inferior to it expected. On the other hand, each year hundreds of papers are published in the field of solar stills and their application for water treatment under various conditions in different regions of the world. Transmission of pathogens via vapor and the low-temperature operation of solar stills can turn to a concern about the feasibility of transmitting the SARS-CoV-2 via vapor because of the small size of the virus and its resistance against water temperature in a wide range (4–37°) for several days. Since solar stills proposed as an affordable method to provide potable water by separating impurities (whether chemical or biological) for people who have not accessed safe drinking water, it is critical to consider their applicability during a pandemic. As mentioned in numerous studies any possibility about the transmission of the virus and opening a new route should not be overlooked. More studies are urgently needed to clarify the implications of virion stability and its transferring on the solar stills. Once again, it should be reminded that while the rate of death in the world is more than it was expected so far [1], any possibility of transmitting the SARS-CoV-2 virus should consider which means new approaches should be embraced [20]. As a word, it should be reminded that the present study is not limited to the situation like the ongoing pandemic but it has a broader prospect about using solar stills in regions that the feed-water may be polluted by biological contamination that most of which are in developing countries.

Declaration of competing interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.desal.2021.115106.

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