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Solar desalination/purification (solar stills, humidification-dehumidification, solar disinfection) in high altitude during COVID19: Insights of gastrointestinal manifestations and systems' mechanism

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ABSTRACT

From the starting of the pandemic different transmission routes of the pathogen was brought into the spotlight by researchers from different disciplines. This matter in high-altitudes was more boosted as the main parameters were not exactly realized. In this review we are about to highlight the possibility of consuming contaminated water generated form solar water desalination/disinfection systems in highlands. Three systems including solar still, solar disinfection (which experimented by the authors in 2019 in high altitude) and humidification-dehumidification were consider in this context. Ascribe to the risks of pathogens transmission in solar desalination/disinfection systems where the water resources are heavily polluted in every corner of the world, highlighting the risk of consuming water in high-altitude where there are many other parameters associated with spread of pathogen is of great importance. As it was reported, reliability of solar desalination and solar water disinfections systems against contaminated water by the novel coronavirus remained on the question because the virus can be transmitted by vapor in solar stills due to tiny particle size (60–140 nm) and would not be killed by solar disinfections due to low-temperature of operation <40 °C while for HDH contamination of both water and air by sars-cov-2 could be a concern. Although the SARS-CoV-2 is not a waterborne pathogen, its capability to replicate in stomach and infection of gastrointestinal glandular suggested the potential of transmission *via* fecal-oral. Eventually, it was concluded that using solar-based water treatment as drinking water in high altitude regions should be cautiously consider and recommendations and considerations are presented. Importantly, this critical review not only about the ongoing pandemic, but it aims is to highlight the importance of produced drinking water by systems for future epidemic/pandemic to prevent spread and entering a pathogen particularly in high-altitude regions *via* a new routes.

1. Broader context

Plagues and pandemics have ravaged humanity throughout its existence, often changing the course of history. There are a number devastating bacterium-based and virus-based plagues and pandemics respectively, such as the Justinian Plague, the Black Death, the Spanish flu, and the Swine flu. A bacterium-based disaster like The Justinian Plague was swept away the whole world and killed nearly half of the world's population at the time while a virus-based pandemic such as the Spanish flu killed nearly 50 million people just about in two years. Epidemics and pandemics in the modern times (i.e., twenty-one century) were continually occurred with various agents and different rate of deaths (Kaur et al., 2020).

The world has been struggled with an unpleasant surprise since the end of 2019 with the advent of severe acute respiratory syndrome originated by the coronavirus type 2 (SARS-CoV-2). However, the scientific community was not unfamiliar with coronavirus family because of the outbreaks of SARS-CoV-1 and MERS in 2003 and 2012 respectively, but both previous outbreaks have been controlled by the governments and medical communities. However, in the case of the SARS-CoV-2, the

Abbreviation: CSO, Combined Sewer Overflows; HDH, Humidification-Dehumidification; LED, Light Emitted Diode; PCM, Phase Change Materials; SODIS, Solar Water Disinfection; WBE, Wastewater based epidemiology; WWTP, Wastewater Treatment Plant.

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rapid spread of the virus is so fast that massive contagium, diseases and death have been recorded in less than 40 months more than 750 million infections with 6.8 million deaths are reported (20 of the worst epidemics and pandemics in history | Live Science January 25, 2023). The concern about these numbers can be elucidated when we consider that these statistics are in the present era while the world has high standards of public health. The novel coronavirus results in multi-facet problems in many different sectors from leisure centers, airlines, and restaurants to oil and gas drilling. But the first and important sector is the public health services of countries which extremely suffer in the last 3 years. Because, the public health of countries simultaneously standing at the first and the last lines of this battle. Thus, other sectors should be assisted the public health to prevent more pressure on the shoulders of this sector and carry a part of burden that forced to the public health services. Therefore, each sector in any industry, whether in tourism industry or entertainment services can stand side by side to fight against the pandemic. In the meantime the scientific community plays one of the vital roles in confronting with the novel coronavirus. Biologists, genetics, epidemiologists, vaccine experts, microbiologists, virologists, etc. all of them worked in the concept of medical scientists to encounter with the virus by producing effective vaccines, proposing preventive methods for spread of the virus in the society, determining the new mutations of the virus (which some of them are highly contagious), developing frameworks for other scenarios that may occur in the future.

However, medical experts are not the only scientific communities that play an important role in the ongoing pandemic, but there are other scientists from different disciplines such as environmental specialists that have important role in various aspects. Environmental experts have extensive knowledge in a broad range from applied microbiology to water science. Experts in each section of the environmental engineering during the COVID19 pandemic played a part in facing the virus. For example, wastewater-based epidemiologists (WBEs) worked on the surveillance of the virus based on the wastewater sample in each month and estimating the number of infections by measuring the concentration of the SARS-CoV-2 RNA in samples (Kitajima et al., 2020; Kumar et al., 2020; Buonerba et al., 2021). The importance of environmental experts can be enlighten when we consider that WBE experts found the SARS-CoV-2 RNA months before the starting of the pandemic in different locations not in China but other countries such as Spain and Brazil (Chavarria-Miró et al., 2020; Fongaro et al., 2020). The other important sector of environmental engineers is the water science and technologies that mainly focused on the contamination of water bodies by various sources, wastewater treatment plants (WWTP) technologies, and water purification and desalination units (Parsa, 2021). In this regards contamination of water bodies by the novel coronavirus that could be subjected treatment to use by people in regions that rely on the solar desalination and solar disinfection systems should be of great concern of environmental experts. This can be more important when these systems are about to operate in a particular area such as high altitude regions.

2. Motivation and objective of the present study

The concept of solar desalination and disinfection to provide safe drinking water for people in high altitude regions was experimented for the first time in 2019 (Parsa et al., 2020a, 2019a, 2020b, 2020c). Furthermore, effectiveness of the solar still and solar disinfection during the ongoing pandemic were discussed in 2021 (Parsa, 2021; Parsa et al., 2021a) (Fig. 1). On the other side of the coin, during the COVID19 pandemic, controversial arguments have been emerged about the positive or negative effects of the altitude on the spread of the SARS-CoV-2. Therefore, it is of great importance to inhibit any other possibility that might be considered as a portal to enter SARS-CoV-2 to human body in high altitude regions which could results in further arguments about disease transmission. Thus, the main objective of the present review is to highlight the effectiveness of solar water desalination (solar stills) and solar water disinfections (SODIS) in high altitude regions when the feed water of the systems not only has mineral impurities but also biologically contaminated by the SARS-CoV-2 since the water resources throughout the world have been contaminated by the novel coronavirus (Fig. 2). Importantly, reliability of humidification-dehumidification (HDH) system which vastly emerged in recent years also briefly was discussed in this context. Although the SARS-CoV-2 is not a waterborne pathogen, its capability to replicate in stomach as well as infection of gastrointestinal glandular suggested the potential of transmission *via* fecal-oral. Therefore, it is of great significance to highlight the possibility of transmission of the novel coronavirus through solar-based water treatment systems to drinking water (generated water); even if the presence of the virus would not lead to disease. In other words, the present review would not limited to the ongoing pandemic, but it has a broader prospect which is the efficacy of systems against biological contaminated water in high latitude regions which has specific conditions particularly higher UV and lower temperature of operation. However, we are mostly highlighted the novel coronavirus in our discussion because it during the last three years it results in biologically-contamination of water resources. The study organized in several steps to easily follow by readers to comprehend the bigger picture. In the first step application of solar water desalination and disinfection systems in high altitude regions briefly discussed and it followed by the prevalence of the virus in high altitude regions which is a controversial between researchers, as effect of altitude (positive or negative) on the spread of the virus is not clear yet. In the next step important common parameters that have effect on systems and the viability of the virus which are UV and temperature are discussed (Fig. 3). In the next section the off-centered routes of pathogens transmission with some example from previous epidemics are brought to show that the dominant route of transmitting a disease is not the only way of spread but other routes –in this case waterborne route- is also a possibility. In the next step impact of the novel coronavirus not only on the respiratory system but on other systems like cardiovascular system, hematological system, neurological system, ophthalmological system, and more important that gastrointestinal system was discussed. The influence of the SARS-CoV-2 on the gastrointestinal system has been further explained and some of the new findings are brought into the spotlight. Importantly, recent studies that proved the novel coronavirus not only infected the gastrointestinal tract but it also can replicate in stomach has been highlighted. Finally reliability of the solar desalination and solar water disinfection systems based on previous studies has been thoroughly elucidated and recommendations and considerations are summarized.

3. Solar water treatment

Solar water treatment can be applied to various water media including seawater, groundwater, surface water, contaminated water, and different types of wastewater (including pharmaceutical, industrial, and urban). In this section we succinctly discussed about the three types of water desalination/purification systems which are solar stills, solar water disinfection (SODIS) and humidification-dehumidification (HDH).

3.1. Solar still

Since ancient times, purifying impure water by distillation is one of the easiest ways for producing hygiene and drinkable water (Manokar et al., 2014). Principle of operation in solar stills which is based on the evaporation and condensation process has been extensively discussed in the previous studies (Omara et al., 2017; Arunkumar et al., 2019; Panchal et al., 2020; Kumar et al., 2020b). Furthermore, solar stills due to their simple structure and easy maintenance, still consider as one of the pioneer method not only for the developing world but also in industrialized countries. Previous studies proved that solar stills are capable to separate a wide range of organic and inorganic impurities from pharmaceutical and chemical compounds to biological contaminations. Various approaches also applied to increase the efficiency of solar stills including using different solar collectors

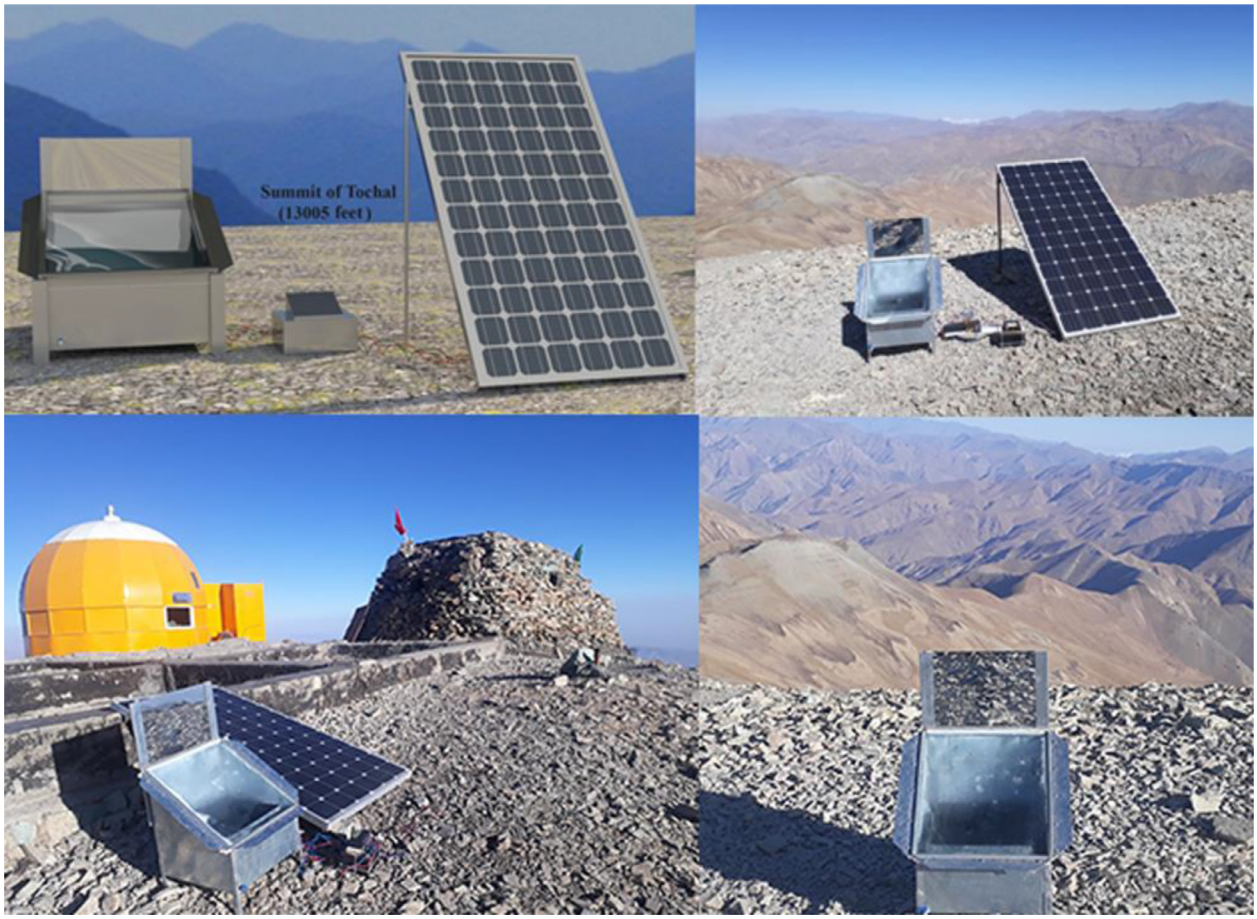


Fig. 1. Schematic of the two active and passive solar desalination systems at high altitude (Parsa et al., 2020a, 2019a).

(Manokar et al., 2017; Kumar et al., 2021; Muthu Manokar et al., 2020), reflectors (Omara et al., 2017), wick materials (Elsheikh et al., 2022), low-cost energy storage (Panchal et al., 2022), heat localized materials (Sharshir et al., 2020) thermoelectric (Yanbolagh et al., 2020; Shoeibi et al., 2020), phase change materials (PCM) (Dsilva Winfred Rufuss et al., 2018; Thalib et al., 2020; Essa et al., 2022), and nanoparticles (Mahian et al., 2017; Parsa et al., 2021b; Shoeibi et al., 2022; Thakur et al., 2021). Interestingly, nanoparticles in solar stills have been attracted huge attentions of researchers due to their antibacterial characteristics against pathogens (Sadeghi and Nazari, 2021; Parsa et al., 2020d; Shoeibi et al., 2021). Accordingly, recent studies showed that solar stills can be consider as one of the most important future's solutions of the providing potable water when it showed that by controlling the mechanism of heat and mass transfer and reducing the heat loss through the environment the efficiency of systems theoretically and experimentally can reach up to 700% and 400% respectively (Xu et al., 2020; Zhang et al., 2020). However such approaches are in laboratory scales and are in their infancy stages.

3.2. Humidification-dehumidification (HDH)

The principle of the HDH system is based on the fact that dry air can carry certain amount of vapor content. HDH systems consist of humidifiers, dehumidifiers, and renewable and/or non-renewable heaters and pumps. Principle of the HDH is extensively discussed in the previous studies (Rahimi-Ahar et al., 2020). Briefly, HDH systems worked on humidifying (water spray) and dehumidifying air (by entering the cold feed water at 15–25 to the condenser) through direct/indirect contact of water and air in a humidification and dehumidification chambers, respectively. HDH systems have various configurations such as close air open water (CAOW), open air close water (OACW,) open air open water (OAOW), and close air close water (CACW) with water and/or air heating (Narayan et al., 2010). However, some of these configurations, such as OAOW and CACW, are not appropriate for practical applications but the CAOW with water heating reported as the highest effective HDH configurations with superior gain output ratio (GOR) (Gholizadeh et al., 2020). An external heater usually assists HDHs to increase water and/or air temperature and a fan to circulate air through the unit. It is worth being reminded that using a separate air heater in HDH in the recent years was not energetically and economically rational because high efficient configurations by water heating are proposed. HDH system is also constructed by virtually simple and moderate-cost of materials, easy maintenance, and high productivity, but it cannot work as a passive system because it always needs electricity to derive pumps, fans, and electrical heaters (or solar heaters). It should be noted that the productivity in HDH systems is higher than solar stills, but solar still has easier maintenance and lower capital cost rather than HDH systems. Generally, the working temperature of HDH system is between 60 and 80 °C.

3.3. Solar water disinfection

Solar water disinfections (SODIS) systems proposed as one of the easiest and low-cost passive water treatment particularly in developing world against contaminated water by biological species (McGuigan et al., 2012; Gomez-Couso et al., 2009). In this method contaminated water is poured into plastic bottle (mostly PETs) and expose to sunlight for definite time (normally between 4 and 12 h) to eliminate pathogens through thermal inactivation by increasing the temperature, UV wavelength by denaturation of Pathogen's cell structure and destroying pathogens cells through generation of re-

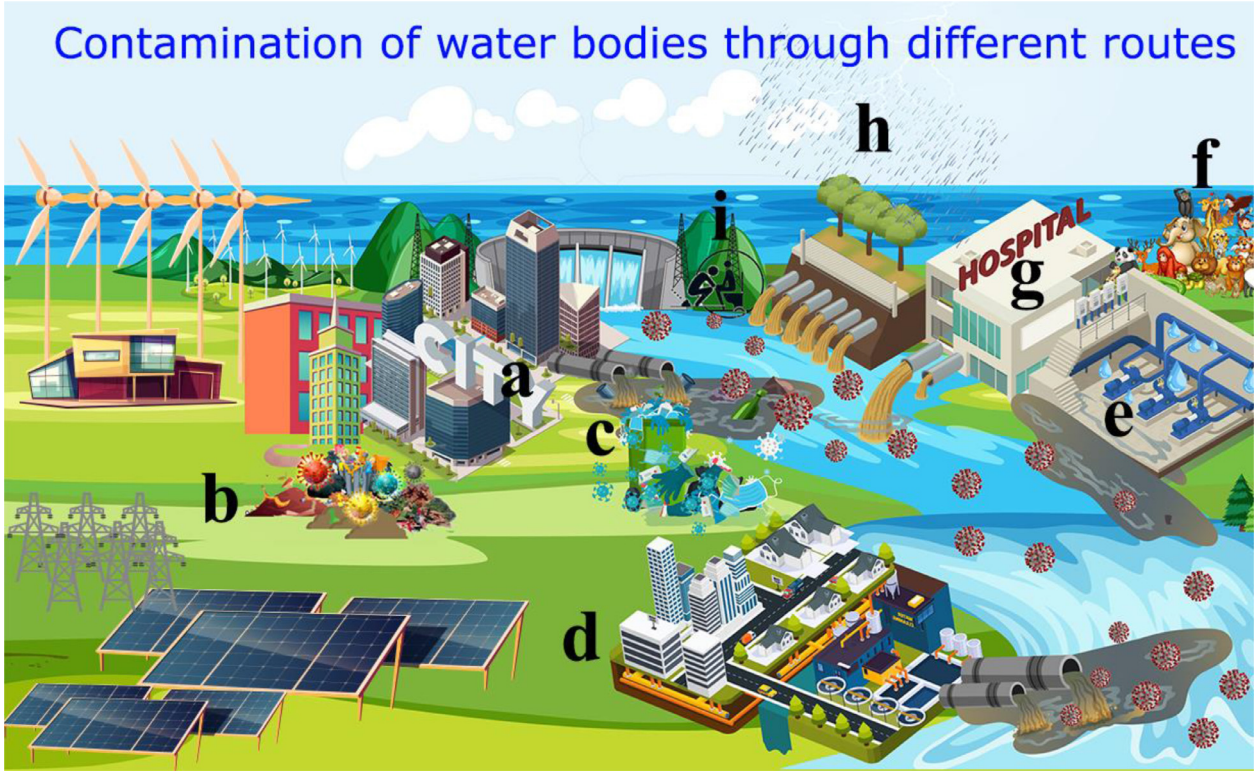


Fig. 2. Possible routes of contamination of water bodies (Parsa, 2021; Parsa et al., 2021a). Some routes such as wastewater discharge (a) and WWTPs have significant contribution on the contamination of water bodies while some routes such as secondary host (animals). Some routes such as open defecation and pit toilet mainly happened in developing countries and poor communities. the possible routes can be mentioned as: (a) discharging cities wastewater, (b) contaminated wastes, (c) improper disposing personal protective equipment(PPE), (d) wastewater treatment plants (WWTPs), (e) sewer leakage, (f) Secondary hosts(animals), (g) hospital sewage, (h) combined sewer overflows (CSOs), (i) open defecation and pit toilets (Parsa et al., 2021a).

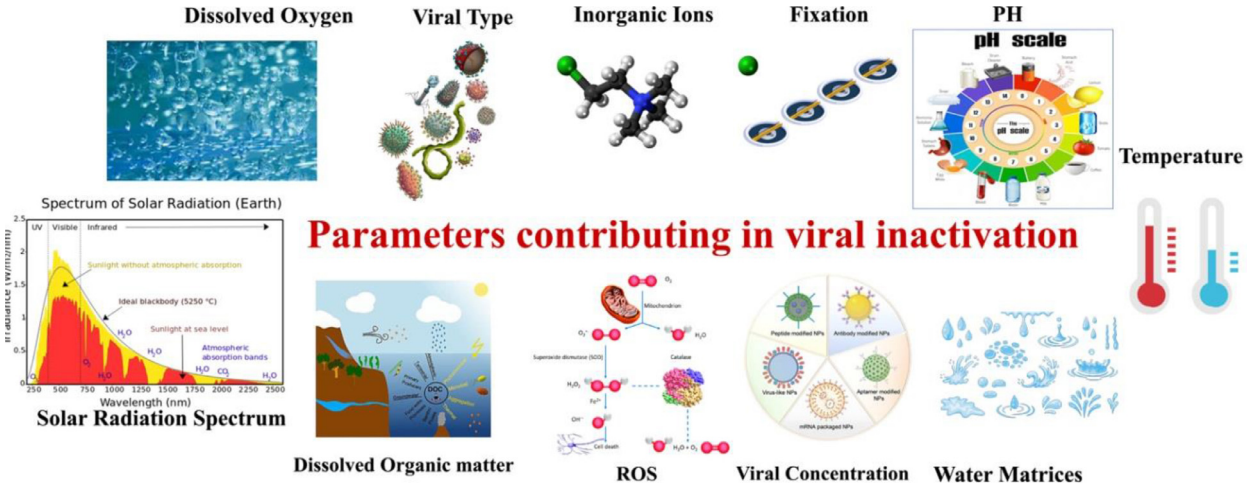


Fig. 3. Inactivation of viral *via* environmental parameters.

active oxygen species (Parsa et al., 2021a; García-Gil et al., 2020). So far, various pathogens including bacteria such as Campylobacter jejuni, Escherichia coli, Salmonella spp (Wegelin et al., 1994; Boyle et al., 2008), Staphylococcus aureus, Shigella, Bacillus subtilis (Kehoe et al., 2004; Lonnen et al., 2005; Al-Gheethi et al., 2019) as well as viruses like Bovine Rotavirus, Bacteriophage f2, Encephalomyocarditis (Wegelin et al., 1994), Poliovirus (Heaselgrave et al., 2006), Hepatitis A virus, Murine norovirus (MNV-1) (Polo et al., 2015), MS2, PhiX174, and Adenovirus (Angeler et al., 2019). Besides, elimination of various protozoa such as Acanthamoeba castellanii, Naegleria gruberi, Entamoeba invadens, Giardia lamblia, Cryptosporidium parvum, and Acanthamoeba polyphaga (Heaselgrave et al., 2006) as well as some fungus like Candida albicans and Fusarium solani (Lonnen et al., 2005) are evaluated.

4. Solar water desalination and disinfection in high altitude

Regarding the huge body of impure water in high altitude regions and presence of nearly 150,000,000 people in highlands in more than 120 cities and towns (Cohen and small, 1998), the concept of water desalination in such areas has not brought in spot light in any study before. In 2018, the first studies on solar water purification systems by using

solar stills performed by Parsa et al. (2020b). Series of experiments for various modifications of solar stills in high altitude at the peak of Mount Tochal in 3964 m height during several days are performed. To show the performance of systems in high altitude regions a similar system at the same time was tested in the city of Tehran. In the first scenario a passive solar still with external reflector was tested and reported 56% augmented in productivity compare to Tehran-located system (Parsa et al., 2019b). In the second scenario solar stills used thermoelectric module heating that powered by photovoltaic and reported highest hourly efficiency of 66.5% at the summit with improvement of 42.5% in productivity rather than solar still in Tehran (Parsa et al., 2020a). They also evaluated the effect of altitude on various thermodynamic parameters such exergoeconomic, energy-matrices, and CO2 emission/mitigation. In another study Parsa et al. performed series of experiments in solar stills that used silver nanofluid for double purpose which are increasing the rate of heat and mass transfer while it act as an antibacterial agent (Parsa et al., 2020c). The results showed that energy and exergy efficiency of the nanofluid-based system in high altitude was increased by around 106% and 196% respectively. In this study for the first time they propose to collect the produced water in PET bottle to use the advantage of solar water disinfection because the available UV summit of Tochal is nearly 30% higher than Tehran. Thus, the collected water of solar stills during experiments expose under sunlight for 8 h. In this regard, they declared that by taking the advantage of two disinfection methods of using silver nanoparticle and SODIS the produce water is highly hygiene, specifically, for biological contamination.

5. Prevalence of the SARS-CoV-2 in high altitude regions

Arias-Reyes and co-workers was the first researchers that discussed about the spread of the novel coronavirus in high latitude regions. The epidemiological data of the SARS-CoV-2 for three high altitude regions in Tibet, Bolivia and Ecuador indicated a significant reduction in rate of infection by increasing the altitude. The findings revealed that by increasing the altitude the rate of infections in Bolivia and Ecuador diminished by about 3 and 4 fold less than low-altitude regions respectively (Arias-reyes et al., 2020). Beside altitude effect, Escalante et al. (Intimayta-Escalante et al., 2020) claim that density of population also has effect on low rate of the infection. Segovia-Juarez et al. (2020) statistically investigate the effect of altitude on COVID infections and reported that altitude reduces COVID cases but not the rate of mortality. However Burtscher et al. (2020) have commented on the theory of Arias-Reyes et al. about the inverse relation of altitude with SARS-CoV-2 infections in high altitude by bringing some instances on the higher risk of respiratory disease associated with high altitude. Moreover, it was found that high altitude dwellers were more likely to report persisting symptoms (71.7%) compare those living at lower altitudes (Izquierdo-Condoy et al., 2022). Accinelli and Leon-abarca (2020) in Peruvian context reported the lower infection of the SARS-CoV-2 in high-latitude (higher than 4300 m) inhabitants by about 6.4 fold lower than those inhibited in sea level. Importantly, it was found that viral load has not significant correlation with altitude (Ortiz-Prado et al., 2022; Ortiz-Prado et al., 2022). Furthermore, Huamaní et al. (2020) also commented on the hypothesis of Arias-reyes et al. (2020) and argue that while the hypothesis in general is corrected there are other factors associated with a low prevalence of the disease in high latitude regions such as natural social distance due to low density of population and lower obesity in highlands. Rodrigo et al. quantitatively correlated the high altitude with COVID-19 cases and declared that the high altitude inhabitants have stronger immunity system against the SARS-CoV-2 due to high and longer-lasting titers of anti-receptor binding domain (RBD) antibodies in their body which lead to lower infection rat (Rodrigo et al., 2021). Cano-Perez et al. (2020) also reported from Columbian prospective that the rate of infection, especially, rate of fatality in high altitude (up to 3180 m) regions is substantially lower than lowlands but Janice et al., brought this hypothesis into question by developing a model that is not only based on altitude but also consider the density of population (Janice, 2021). Fernandes et al. (2021) investigate the effect of altitude on COVID-19 incidences in 154 cities of Brazil. The results elucidated that altitude relative humidity has an inverse relation with COVID-19. On the contrary, Woolcott and Bergman (2020) found that altitude has a direct effect on the rate of COVID-19 fatality in 567 and 1016 counties in Mexico and the United State. Their statistical findings exhibited that people living in altitude over than 2000 m above sea level has higher risk of infections as well as fatality rather than those lived in altitude lower than 1500 m. Conversely, Stephens et al. (2021) reported that based on the infection cases with respect to the altitude, the rate of infections in high altitude is significantly lower than those in low-altitude in the US counties. Similarly, low rate of mortality in high altitude (Ortiz-Prado et al., 2021a, 2021b) and higher rate of survival amongst people admitted to the high-altitude ICU in Ecuador (Simba et al., 2022). Cascetta et al. (2021) also brought the hypothesis of altitude inverse relation with COVID cases into the question by reporting the higher case of infections in high altitude regions of Italy.

The pros and cons of altitude in spreading of the novel coronavirus is a controversial between scientists. Researchers in several studies concluded that in high altitude regions there are some important factors that may associate with low rate of the infections. These factors mentioned as high UV irradiance, high level of Ozone, natural social distance, dry air, lower ACE2 receptor in body of high altitude inhabitants. However, in below some of the most important studies in the following is presented. However, there too many controversial arguments between researchers about the positive or negative effect of altitude during the ongoing pandemic

6. Common parameters contribution on the SARS-CoV-2 and solar purification

Different parameters are impacted the viability of the viruses in the environment. From beginning of the pandemic researchers from different disciplines have been proposed numerous methods such as ozonation (Martins et al., 2020), heating (Chan et al., 2020), plasma (Guo et al., 2021), bio-based methods (Das, 2020), reagents/disinfectants/sanitizers (or generally called chemical compounds) (Castaño et al., 2020), UV (Raeiszadeh and Adeli, 2020), Gamma rays (Leung et al., 2020), metal organic frameworks (MOF) (Ornstein et al., 2020) and nanomaterial (Sportelli et al., 2020) for inactivation of the novel coronavirus in different environment from aqueous solutions to surfaces. However, we particularly focus on the effect of UV and heating on the eradication of the virus because these parameters are associated on the performance of solar stills and SODIS as well as inactivation of the virus.

6.1. UV effect

Rathnasinghe et al. (2021) proposed to use germicidal UVC (254 nm) for eliminating the SARS-CoV-2 on N95 mask. They designed an experiment to inoculate 2.5 cm^2 of the mask in 10^6 plaque-forming units (PFU) of SARS-CoV-2. Distance of the UV lamp with the mask remain constant during experiment while the exposure time of UV irradiance was variable between 0 and 164 s. The findings revealed that the at just 2 s exposure, 1 $\log_{10}$ reduction was observed while complete elimination of the virus (3.65 $\log_{10}$) was obtain at 240 s. Jennifer L et al. (2020) used four different pathogens (Bacteriophage Phi X174, Bacteriophage Phi6, Bacteriophage MS2, Methicillin-resistant *Staphylococcus aureus*) with different characteristics (single-stranded RNA, double-stranded DNA and gram-positive bacteria) as a surrogate of the SARS-CoV-2 to evaluate the effectiveness of the UVC for decontaminating novel coronavirus in bins of airport security. The expose time were varied between 10 and 30 s. The results showed that all of the pathogens are completely inactivated during 30 s cycles (3 $\log_{10}$ reduction) suggesting UVC as an appropriate option for airport security bins decontamination. However it should be mentioned that the Bacteriophage MS2 just reduce by about

2 $\log_{10}$. Ruetalo et al. (2020) simulate the inactivation of SARS-CoV-2 originated by droplets/aerosols of an infected person on surface by utilizing UVC. They examined that under different regime of movements (slow and fast) the sample of the SARS-CoV-2 with concentration of 3×10^6 infectious unit (IU) per μL can be completely eliminated while they realized that drying for 120 min has an insignificant effect on inactivation of the virus. Drph et al. (2020) experimented the effectiveness of xenon-pulsed UV source for producing UVC in highest viruicidal spectrum in the range of 200–280 nm for eliminating the SARS-CoV-2 in hard surface and N95 mask. The results revealed that in 2 and 5 min exposure time for hard surface and N95 mask more than 4.54 $\log_{10}$ and 4.79 $\log_{10}$ reductions in viral concentration were achieved respectively. (It should be mentioned that the highest wavelength for which absorbed by the nucleic acid is between 250 and 270 nm). Inagaki et al. (2020) reported that by producing UVC by an LED in 280 nm wavelength on sample with 3.7×10^4 PFU/mL complete deactivation of the SARS-CoV-2 virus with 3.3 $\log_{10}$ is achieved. Luzzatto-Fegiz et al. (2020) modeled the effect of available UVA in sunlight alongside with UVB for inactivating the SARS-CoV-2 in different mediums which are stainless steel and aerosols. They declare that in contrast with previous studies which stand bsed on UVB inactivation; the UVA have contribution, in inactivating based on valid data. However, this effective ness on stainless steel is more apparent than aerosols. Biasin et al. (2021) reported reduction of > 3 $\log_{10}$ the minimum dosage of UVC by about 3.7 mJ/cm^2 was achieved. However, using minimum dosage of UVC results to the virus remains viable and be able for replication until sufficient infection dose. Fischer et al. (2020) examined the effectiveness of the UVC (260–285 nm) light for deactivation of the SARS-CoV-2 virus on N95 masks up to three times. Heilingloh et al. (2020) examined the effectuality of the different UV light on viability of the SARS-CoV-2 and reported that UVA (365 nm) has insignificant effect for eliminating the virus but UVC (254 nm) is strong enough for complete inactivation of the virus after nine minutes. Ragan et al. (2020) utilized UVC irradiance at different doses incorporate with riboflavin to inactivate the SARS-CoV-2 in blood and plasma. Their findings revealed more than 3 log reduction in viral titer were obtained by using just 60% of UVC dosage. Ozog et al. (2020) chose 1.5 J/cm^2 of virucidal UVC as an effective dose based on previous viral inactivation on different Influenza viruses (i.e., H1N1, H5N1, and H7N9) as well as various coronaviruses (MERS and SARS-CoV-1) for eliminating the SARS-CoV-2 on five different model of N95 respirators. They reported that while top edges of the respirators may receive higher dosage around 3 J/cm^2 but 1 J/cm^2 is as the minimum dose inactivation for masks. A study on sensitivity of the SARS-CoV-1 before the beginning of the pandemic is conducted by researcher and reported that by applying 0.5–0.75 dose UVC source the SARS-CoV-1 concentration reduced by about 3.4log. Pendyala et al. (2020) developed a mathematical model for predicting the effective dose of the UVC for inactivation of the SARS-CoV-2 to assist researchers on experimental validation. The findings indicated that the model has a good agreement with available experimental results published before. The effective dose for the based on the model examine by about 21.5 J/cm^2. Smith et al. (2020) compared the effectiveness of the UVC on decontaminating of in two N95 respirators. The outcomes showed that the UV irradiance showed germicidal effect on just one of the masks. They declared that this may be as a result of an insufficient dose of the UV. (for table/exposure and extended exposure to UV significantly impaired mask integrity(From/the/paper). Dose of the UV is 0.5 J/cm^2). Sagripanti and Lytle (2020) examined the effectiveness of the solar UV on inactivation of the SARS-CoV-2 in different seasons and different locations. The finding revealed that maximum inactivation of the SARS-CoV-2 is obtained under ideal conditions where in cold seasons the viability of the virus increases.

Herman et al. (2021) examined the effect of available UVB in solar radiation based the data of ozone monitoring instrument regarding two experimental laboratory results. The results of the model showed that the available UVB at higher latitude regions (>60°) results in inactivation time of the virus higher than 120 min. Also they concluded that however, the available UVB in mid-day is strong for inactivation of the SARS-CoV-2 in aerosols, but due to the high time (7–20 min) of inactivation (i.e., slow time for eliminating the SARS-CoV-2) it cannot be consider as a solution against transmitting the virus in crowd places. Keil et al. (2020) realized that the concentration of the SARS-CoV-2 in platelet and the plasma by exposing to the UVC can drastically decrease by about 4.53 $\log_{10}$ and 3.4 $\log_{10}$, respectively. Tang et al. reported that solar UV has an inverse relation with five different human coronaviruses including the SARS-CoV-2. Their results showed that according to the data from 2018, the viability of the coronaviruses in the US by increasing the dosage of the solar UV is decrease. However since the SARS-CoV-2 is new the more research recommended. Schuit et al. (2020) investigated the effectiveness of simulated sunlight (UVA&UVB; 280–400 nm) against inactivation of the SARS-CoV-2 in aerosols. Their results (based on solar intensity in different season) showed that the T_{90} for the virus during fall/winter and summer is 19 and 8 min Similarly, Shumate et al. reported that the available solar UV (UVA & UVB) in a simulated sunlight can inactivate the SARS-CoV-2 up to 90% in simulated saliva and culture media on a surface (stainless steel) around 6.8 and 14 min respectively which are virtually absolutely in line with the results of Herman et al. UVC wavelength is effective enough to inactivate the novel coronavirus in different medium. One of the advantages of UV is that it maintains the integrity of the structures such as face masks compare to other method like using ethanol. However, the time of exposure to UV irradiance should be carefully considered because extra exposure results in integrity if the N95 masks. Although it was reported that simulated sunlight may have a contribution in the SARS-CoV-2 deactivation (Schuit et al., 2020; Ratnesar-shumate et al., 2020), but researchers should be cautious about the effectiveness of sunlight because UVC is known as dominant type of UV that have germicidal effect which is rational because of the fact that The effective UV irradiance is directly damaged to the genome of pathogens while the effectual wavelength for this phenomenon is below 280 nm (somewhere in 260–265 nm which is the highest UV absorption of nucleic acid (Kowalski, 2010).

6.2. *Thermal inactivation*

Utilizing temperature as one of the effective methods for inactivation of various pathogens have been suggested in plenty of studies by many researchers. All living systems are sensitive to alters in temperature, as temperature impacted the rate at which biochemical reactions begin. Aboubakr et al. (2021) comprehensively discussed on the effect of temperature on the six types of coronavirus family on different surfaces such as metals, plastics, glass, ceramic, rubber and porous surfaces. Also persistence of coronavirus family in various types of water (i.e., deionize water, tap water, lake water, reagent water) and human body fluid have been reviewed. Abraham and Plourde (2020) in series experiments proposed a range of temperature and time of expose for complete eradication of the novel coronavirus. Their finding revealed for temperatures >65 °C, 55–60 °C and 50–55 °C around 3, 5 and 20 min are needed for obtaining 5–7 log reduction. Furthermore, Hessling et al. (2020) by reviewing the existing literature on the heat inactivation of the various types of coronavirus reported that at 60 °C, 80 °C and 100 °C for 37.5, 3.7 and 0.5 min, 5log reduction is obtained. During the ongoing pandemic also many researchers examine the impact of the temperature on the survival of the SARS-CoV-2. Pastorino et al. (2020) scrutinized three heat inactivation scenarios at temperature 56 °C, 60 °C, and 92 °C for 30, 60 and 15 min in three different samples, respectively. Their findings revealed that in all scenarios a 4log reduction were observed while for scenario of 92 °C for 15 min the detection of the virus in sample is tremendously reduced which should be avoided for elimination in laboratory ahead of molecular diagnostics. Similarly, in a preprint Pastorino et al. (2020) indicated that for 6log reduction temperature of 92 °C for 15 min is needed. Pere et al. (2020) carried out a trial study on the forty samples of COVID19 patients and used heat

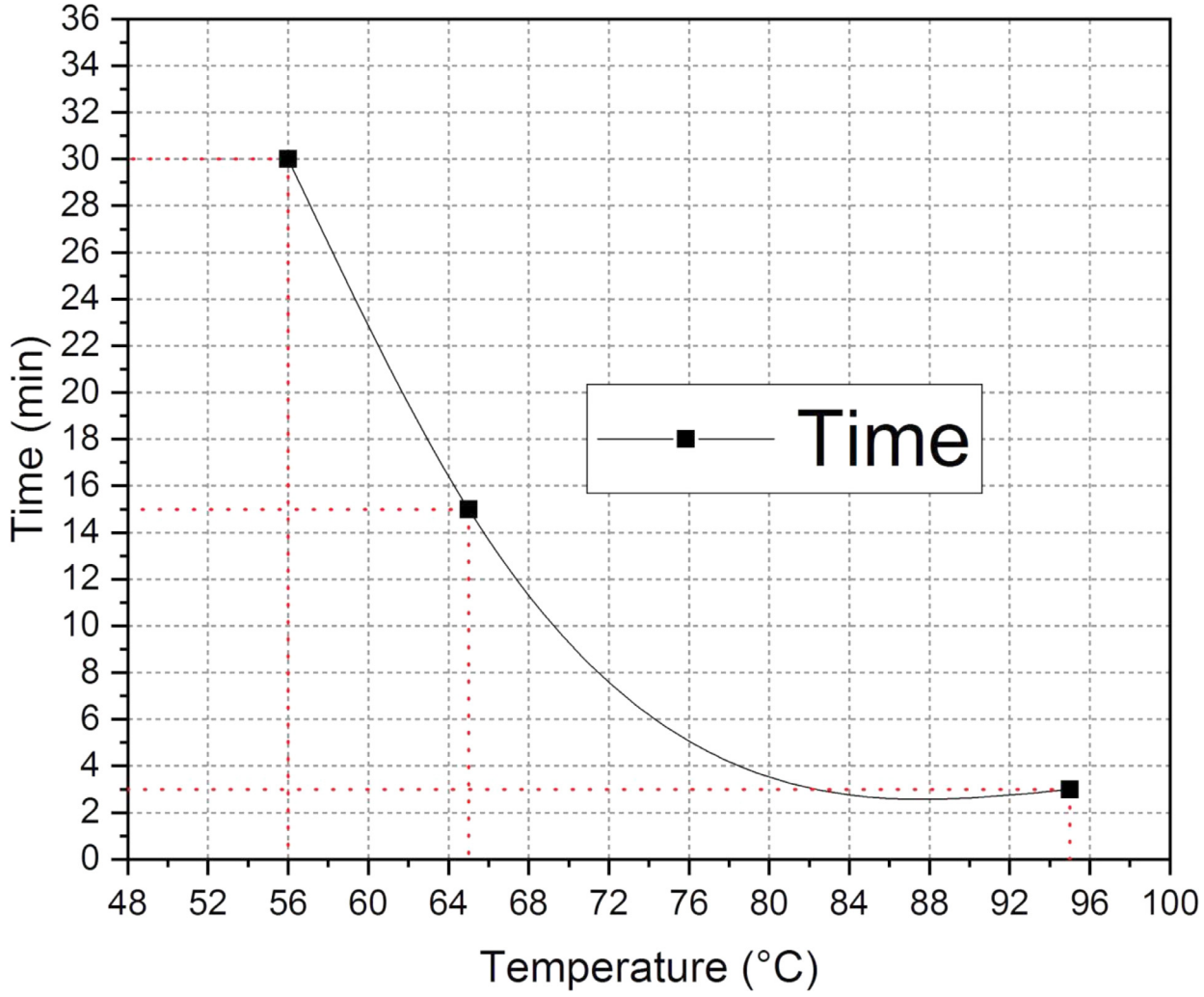


Fig. 4. Time for Inactivation of the novel coronavirus by increasing temperature (Batéjat et al., 2021).

inactivation protocol at 56 ˚C for 30 min of and reported that heating is an appropriate bio-safe method for elimination of the SARS-CoV-2. Using heat as thermal disinfectant for eradication of the novel coronavirus on the surface of mask shows promising results (Daeschler et al., 2020). For instance, it was proposed to immersed the contaminated face masks in water at temperature 56 ˚C for 30 min to deactivate the virus while the mask's functionality remains constant (Wang et al., 2020a). Campos et al. (2020) examined heat treatment of the N95 face mask on various enveloped viruses including the SARS-CoV-2 at different ranges of temperature and humidity from 60 to 95 ˚C and ambient-100% respectively. Their findings elucidated that the viral inactivation at temperatures 75 ˚C and 85 ˚C for 30 and 20 min when humidity is 100% is obtained while the integrity and face mask fabric without significant changes remained intact. Wang et al. (2020) reported the viral RNA at 37 ˚C remains stable at least for one day and further heat treatment is needed for elimination of the virus. However, based on the concrete pieces of evidence it was realized that by raising temperature (as it illustrated in Fig. 4) elimination of the SARS-CoV-2 exponentially increases (Parsa, 2023).

7. Pathogens transmission and uncommon routes

Generally, each pathogen has a specific and dominant route for transmission. A great example is the novel coronavirus, which is considered a pathogen that enters the body through the respiratory system. Although it was imagined that the novel coronavirus severely infected the respiratory system and transmitted only by the respiratory system, numerous studies (see Fig. 5) showed that the other human body systems' such as cardiovascular system, hematological system, neurological system, ophthalmological system, and more important that gastrointestinal system also infected by the virus and have potential to be a possible route of transmission (Gavriatopoulou et al., 2020).

During the pandemic the number of infections increases exponentially, all the possible transmission routes should consider which means new research and approaches should be embraced. It means researchers should not rely just upon the old data (The Lancet Respiratory Medicine, 2020). Although the main transmission route of novel coronavirus is *via* the respiratory system by droplets originating due to sneeze, cough, and breathing of an infected person, there are still many concerns about other paths in the transmission of SARS-CoV-2 to humans. The concerns about an off-centered route like wastewater aerosols are reasonable because during the SARS-CoV-1 outbreak in 2003, malfunctioning in the sewer network of a building led to the spread of the virus *via* wastewater aerosols, which results in dissemination of the virus in a building with more than 300 infections and 40 death (Sun et al., 2020). Also, transmission of the virus *via* wildlife and domestic animals to human is another possibility but if the virus is transmitted from animal to human, it is extremely hard to confirm the animal-human route, as

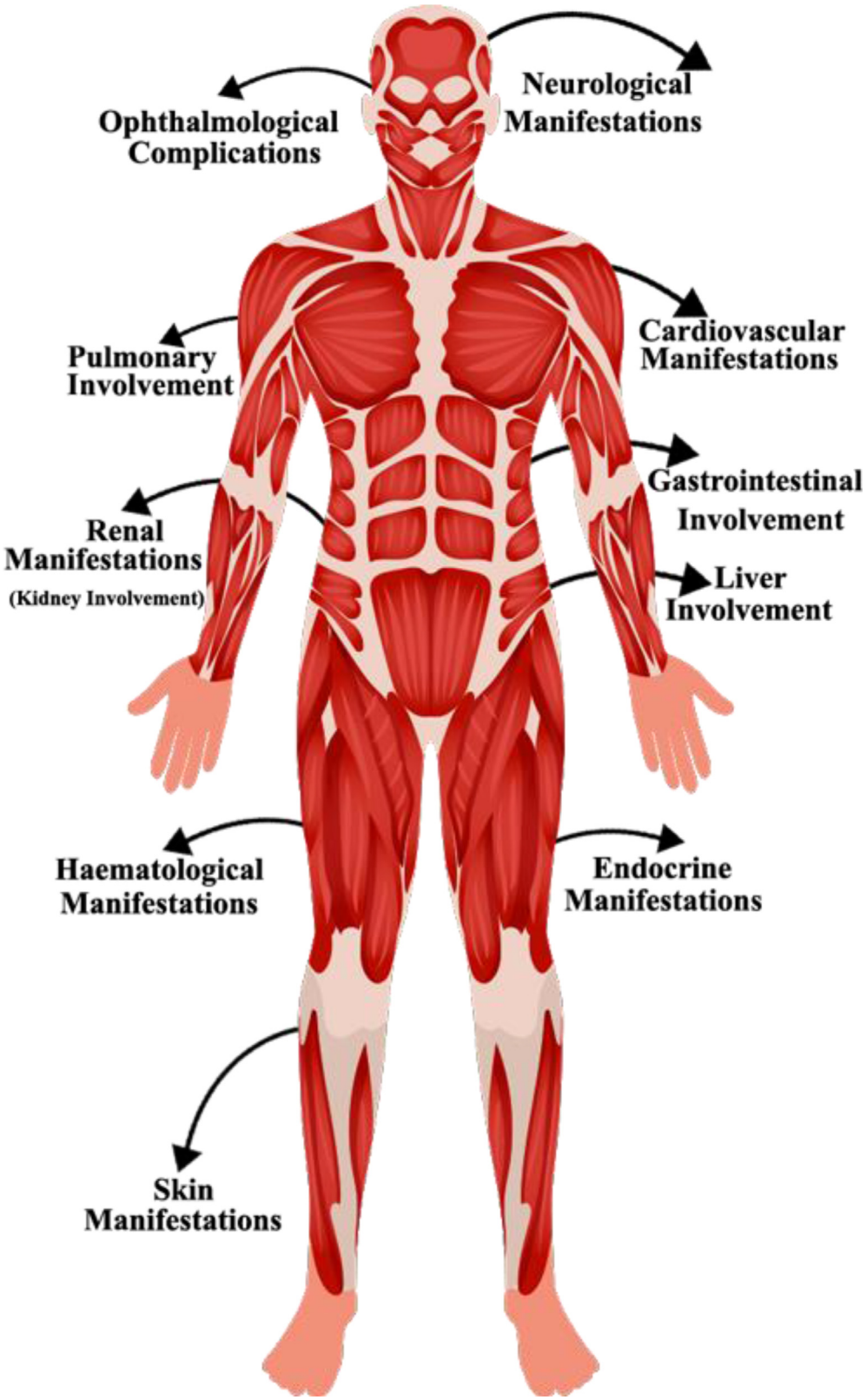


Fig. 5. Schematic overview of the systemic manifestations of SARS-CoV-2 infection in different parts of human body (Gavriatopoulou et al., 2020).

it will be disguised with the human-human transmission which is the dominant routes of spreading the disease (Sharun et al., 2020). Interestingly, the transmission of the novel coronavirus *via* foodborne is another concern that the researchers suggested but the lack of experimental data and conclusive reports make it impossible to draw any conclusion. For instance, while some scientists believed that the risk of transmission of the SARS-CoV-2 *via* foods is tremendously low because of strong treatment methods during food preparation (Thippareddi et al., 2020), others suggest that the food can be a transmission route for the virus (Han et al., 2020). Recently, Jensen et al. (Kjær et al., 2020) sug-

gested the possibility of different routes of the SARS-CoV-2 transmission by comparing the COVID-19 pandemic with an outbreak of cholera outbreak in 1853 (with 4663 deaths) in Copenhagen which showed the drinking water was not the only route of bacteria transmission. Furthermore, it was declared that while transmission of the Ebola virus is known by the body fluid but recent evidence argued that the pulmonary is also involved during the infection even after the blood of patient was clear of the virus (Petrosillo et al., 2015; Vetter et al., 2016). Based on Italian and US experience heavy load of the viral concentration (i.e., Ebola) in respiratory system (mainly lungs) in several patients observed which force hospital experts in some cases to use mechanical ventilator whilst it was always assumed that the Ebola is in body fluids of patients (Lalle et al., 2019). Even a well-known disease like the Influenza A (various subtypes including H1N1) virus that frequently lead to some epidemics and pandemic since 1900s' and mainly known to be transmitted by aerosols, droplets and in some rare cases direct contact (Killingley and Nguyen-van-tam, 2013), easily can be transmitted by contaminated water (Hinshaw et al., 1979). Moreover, in the context of COVID 19, numerous studies elucidated the existence of the SARS-CoV-2 virus in gastrointestinal samples, which raises the probability of transmission *via* fecal-oral route (Mohapatra et al., 2020). It will further discussed in the next section. Collectively, these are just some examples among numerous diseases that their main route is not the only path of spreading but off-centered routes is completely plausible. Thus, waterborne route (in aforementioned cases) is not only a possibility but a serious concern. Importantly, for antimicrobial resistance pathogens that less studied in this context and rapidly disseminate in the environment, possible routes of transmission should realized- particularly as waterborne pathogens- and new researches are needed as this type of pathogen is candidate for the next pandemic. Meanwhile, from the prospect of environmental engineering, realizing the effectiveness of solar-based water desalination/purification systems against all types of above-mentioned pathogens should be carefully and thoroughly evaluated.

8. Organs impacted by the SARS-CoV-2

Even though from commencing of the pandemic the respiratory system subjected as the dominant route of transmitting the virus, it was reported that the virus also has affected other organs too. As it mentioned in numerous studies, the SRS-CoV-2 (and also the SARS-CoV-1) bind to angiotensin-converting enzyme (ACE2) receptor which is ubiquitously found in cardiovascular, gut, kidney and lung (Wang et al., 2020c). Fig. 5 illustrated manifestations of COVID-19 infection and the underlying pathophysiology which evidence of for some of them are briefly discussed. Evidence of the novel coronavirus on the cardiovascular system can be highlighted when the injuries of myocardial in patients with positive tests were observed (Inciardi et al., 2020; Hu, 2020; Doyen et al., 2020; Hui et al., 2020), supporting the hypothesis that injury of the myocardial straightly is associated with the SARS-CoV-2 in those cases. Hematological system is another example where organs may impact by the SARS-CoV-2 as it has ACE2 receptors on Lymphocytes surface suggested direct infection by the virus (Luo et al., 2020). Furthermore, it has been reported that the novel coronavirus may have complication in central/ peripheral nervous systems (CNS/PNS) (Needham et al., 2020; Commission et al., 2020). In a big observational investigation in china in more than 214 hospitalized persons more than one third (36.4%) showed neurological manifestations (Branch, 2020). In a recent study kidney dysfunction of the patients with positive tests of the novel coronavirus is observed (Zarychanski et al., 2020) while skin abnormality in more than 20% of patients is another example that an organ impacted by the SARS-CoV-2 (Brien, 2021). Although the direct transmitting of the SARS-CoV-2 *via* eye conjunctiva had not been proved yet but in China a study showed that nearly 31% of the patients has ocular manifestation (Wu et al., 2020). Gastrointestinal system is also reported to be affected by the novel coronavirus which thoroughly discuss in the next section.

8.1. Gastrointestinal system and symptoms of the COVID-19 patients

The impact of the novel coronavirus on the gastrointestinal system have been showed in a number of studies. Gastrointestinal symptoms in infected persons demonstrated in a wide range from anorexia, nausea, vomiting, diarrhea, abdominal pain, and abnormal liver function (Talley et al., 2020). Mao et al. (2020) in a meta-analysis on the findings of 35 studies that conducted on more than 6600 patients concluded that the patients with severe illness of COVID19 have higher rate of gastrointestinal symptoms while in 10% of patients the gastrointestinal symptoms may not concurrent with respiratory symptoms- results in late diagnosis of this group of patients.

8.2. Gastrointestinal tract as the source of transmission

It is widely accepted that the respiratory systems is the dominant routes of transmission of the SARS-CoV-2. However, as it mentioned in the previous sections due to the high level of ACE2 in gastrointestinal system it may be an off-center routes for entering the virus even if this is very unlike possibility. Previously, Kotfis and Skonieczna-żydecka (2020) pointed out the gastrointestinal tract would be considered as an alternative path for infection of the person to person by the SARS-CoV-2. Simsek et al. (2021) in a meta-analysis on the findings of the all studies on gastrointestinal transmission concluded that the fecal-oral transmission should not be underestimated. Jiao et al. (2021) in a non-human model proved that the gastrointestinal tract can be considered as a transmission route of the SARS-CoV-2. Importantly, by Giobbe et al. (2021) in a recent study published in Nature Communication, showed that SARS-CoV-2 virus can efficiently replicated in stomach of persons and leading to infections. Conclusively, due to the effective infection of gastric epithelium they concluded that the virus play an important role in fecal-oral transmission. Collectively, the number of studies in this context are limited and it would not be possible to draw any conclusion that show the virus can be consider as waterborne, however, these results also could not be ignored and further investigations is critical in this context.

9. Solar stills and solar disinfection in high altitude against SARS-CoV-2

Utilizing solar water desalination (solar stills) and solar disinfections (SODIS) against biological contamination water in high altitude have several issues. Contamination of water bodies in high altitude regions due to the human wastewaters is one the main concerns. In previous studies some of the high altitude water bodies introduced which many of them are close bodies regardless of their huge volume. This means the concentration of pathogens in such water bodies will not be subjected to dilution. Even with an effective wastewater treatment system, the novel coronavirus (and many other pathogens) can be detected in water bodies in high altitude regions. This can be proved by the fact that during the ongoing pandemic the SARS-CoV-2 in many industrialized countries such as US, Japan, France, UK, to name a few (Teymoorian et al., 2021), which have advance water treatment infrastructures as well as pretreatment and post-treatment methods (Fig. 6) have been detected due to numerous reasons such as colossal number of infections and tiny size of pathogens. Regarding this, we can take solar stills as the first example for biological water treatment. Mechanism of transmitting pathogens in solar stills consider as one of the major concerns. In previous studies it has been proved that some bacteria with can transmitted *via* droplet of water in solar stills. Importantly, any particle with a specific size can remain airborne for an indefinite time if there is no air current such an indoor environment like the evaporation chamber of solar stills. On the other, particle size of the novel coronavirus estimated to be between 60 and 140 nm which is multiple times smaller than previous particle, resulting to transmit the virus to purified water. Furthermore, the SODIS system work based on the synergistic effect of temperature and UV can

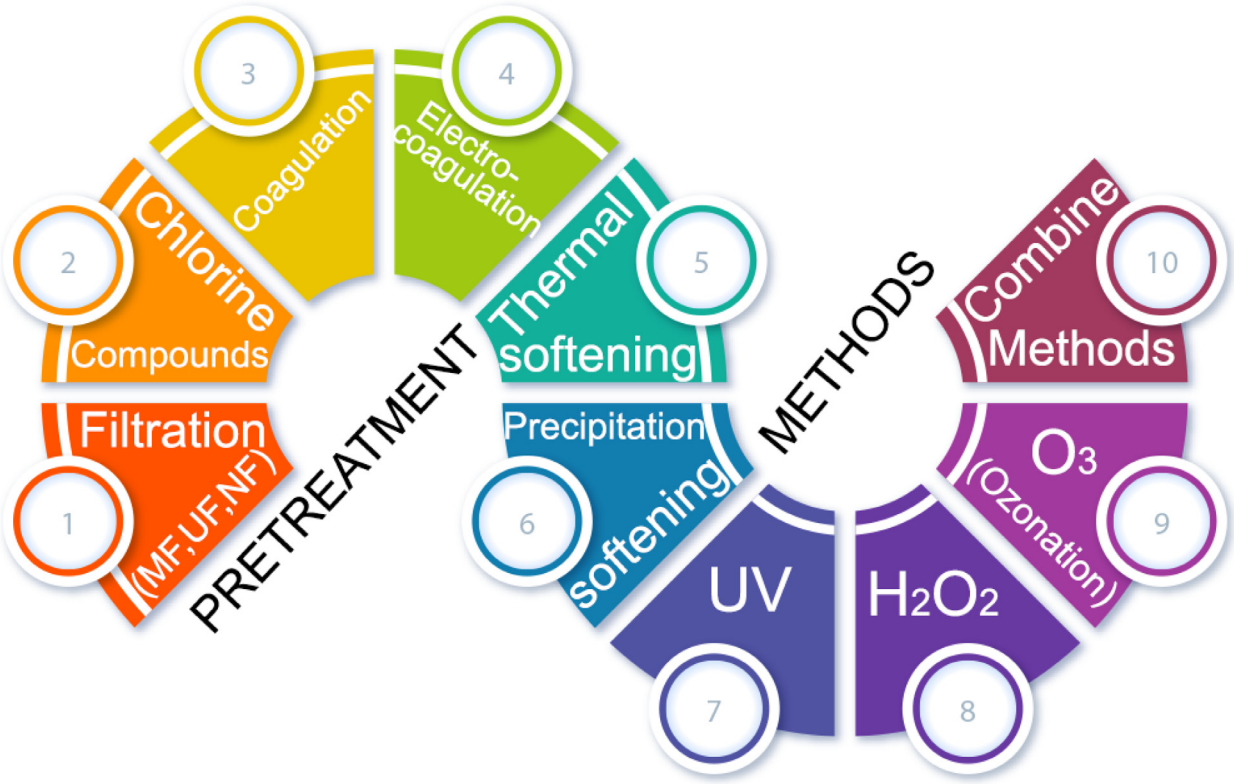


Fig. 6. Various pretreatment methods in the industrialized countries.

consider as an effective method for purifying contaminated water. Since the intensity of UV dose by increasing each 1000 m augmented around 12% in high altitude regions high level of UV dose may associated to improve the performance of SODIS systems. But most wavelength of UV that reaches to the surface is in UVA. As it mentioned before the effective wavelength for viral inactivation is in UVC wavelengths which is not available on the surface earth and completely absorb by the atmosphere. On the other temperature of operation in SODIS systems mainly placed between 30 and 40 ˚C which is not critical for the novel coronavirus neither for other dangerous pathogens that can be lead to start an epidemic or pandemic. The same is true for solar stills. Temperature of operation for solar stills (particularly passive systems) is not critical for most of pathogens. Also in active solar stills that work in higher temperature, a part of productivity collected at low temperatures which may carry pathogen through vapor. Collectively, both parameters of UV and temperature that have contributed in viral inactivation even in high altitude region where higher rate of solar intensity and UV is available may not enough for producing complete hygiene water. Subsequently using drinking water that produced by solar stills and solar disinfections in high altitude regions might have risk for viral transmission and preventive methods as mentioned before should be consider by consumers. However, it may have low risk but any possible routes and new approaches during the ongoing pandemic by the scientific communities should be taken seriously. In this regards, using produced water of solar desalination and disinfection systems in high-altitude regions should be cautiously considered.

9.1. Humidification-dehumidification against the SARS-CoV-2

Unlike solar stills and SODIS which experiments are conin high-altitude, the HDH has not experimented in such regions before, however, their importance as one of the most emerging small-scale desalination which commercially available makes them worthy to be evaluate in this context. Generally, temperature operation of water in HDH systems is between 60 and 80 ˚C and increasing temperature beyond this range negatively affected system's performance and led to reduction of gain output ratio (GOR) (Narayan et al., 2010). It should be mentioned that among different configurations the CAOW with conventional air heating has the lowest GOR (almost equal to solar stills), thus, air heating is not suitable option for practical application. In this regards, the CAOW and CWOA layouts with water heating brought into the spotlight since these configurations have an acceptable GOR (between 2.5 and 2.6) and frequently proposed rather than other configurations for practical applications. Since process in HDH, generally, starts at the temperature of 60 ˚C, some pathogens would be eliminated. These pathogens that previously lead to some epidemic/pandemic can be mentioned as Ebola virus, Influenza A (H1N1), SARS-CoV-1, MERS-CoV, and SARS-CoV-2. Temperature has an inverse relationship with viability of these pathogens whilst by increasing the temperature the survival of pathogens drastically decreased but at temperature of 60 ˚C, different ranges of time are needed for complete inactivation of pathogens. For example, the novel coronavirus at 56 ˚C eradicated in 30 min while at 95 ˚C it inactivated in 3 min but Ebola virus is eliminated at 60 ˚C after 60 min. This means, at lower temperatures, the complete eradication of pathogens takes time (for example between 3 and 60 min) for those that previously lead to some outbreaks/pandemics. As mentioned above, the temperature range of HDH (i.e. 60–80 ˚C) for most dangerous GCBR pathogens (those with risk of originating an outbreak/pandemic) is critical and most of them are removed in less than 60 min. Therefore, one thing that should be reminded is to prevent water circulation at least for an hour at 60 ˚C in the HDH. This can be considered as a thermally-based biological pretreatment that eliminated most dangerous viruses, bacteria, and protozoa but such strategies should not affected the performance of HDH. However, the Achilles' heel of HDH systems is the temperature of feed water. As it mentioned in Section 3.2 the feed water enters into the HDH from condensation chamber to decrease the dehumidifier tubes temperature for higher condensation of vapor while at the same time it use the latent heat of the vaporization of vapor to preheat the feed temperature.

The entering temperature of feed water is almost equal to seawater in the range of 15–25 ˚C (Rostamzadeh, 2021). This temperature range is not critical for most pathogens, including those leading to previous outbreaks/pandemics and those mentioned as high risk of starting another epidemic/pandemic. Therefore, biological contamination fouling can originate in the dehumidifier tubes, which might make the tubes to the source of contamination with the capability of polluting the entering feed water. Subsequently, pollution in dehumidifier leads to contamination of humidifier, specifically packed bed of humidifier. The other important parameter is the entering air into HDH systems, particularly the open-air HDH systems can be a possible source of pathogens entering the system's cycle. Generally, in an appropriate condition (i.e. there is no air removing/diluting system or wind) a droplet with particle size <5 μm, can remain suspended in air for an unlimited time (Fennelly, 2020). Importantly, most of the dangerous pathogens with GCBRs characteristics and those that previously led to outbreaks/pandemics due to their tiny size (less than 1000 nm) can be airborne. On the other hand, preheating the air is not an option as HDH systems with air heater have very low efficiency. However, it should be reminded that many parameters are involved in transmitting pathogens from air such as the temperature of the environment, the concentration of pathogens, viability of virus in an outdoor and/or indoor environment, minimum infection doses etc. but we should consider every nuance possible route cautiously to avoid any risk of contamination in produced water. From these viewpoints, the produced water in HDH system with possible dual-routes of pathogens entrance to systems (even with air and/or water heating) has some risks.

10. Concluding remarks and recommendations

- Regarding the specific conditions in high altitude regions, several factors are negatively/positively associated in spreading the novel coronavirus.
- Although the SARS-CoV-2 the dominant route is the respiratory system, it is important to consider other off-center routes.
- Even though the SARS-CoV-2 is not waterborne pathogen, and it may not lead to disease or infection *via* fecal-oral route it is vitally important to prevent any portals for entering the virus to the human body particularly in high altitude regions.
- The novel coronavirus with a tiny size 60–140 nm (and many other pathogens) can transmit *via* the vapor in solar stills.
- The common parameters in high altitude regions during the operation of systems and the SARS-CoV-2 are UV and temperature.
- As the temperature of operation of water in solar desalination systems in high altitude regions is lower than low-altitude this factor is not critical for eliminating the SARS-CoV-2 as well as many other pathogens.
- Since the temperature of operation for solar water disinfection systems in high altitude regions is not as high as low altitude it (less than 40 ˚C)
- Even though, the intensity of UV in high-altitude regions is drastically high (almost ~30% at 4000 m), it is not effective to completely inactivate the SARS-CoV-2.
- Using active solar stills in high altitude that integrated with thermoelectric, evacuated tube collectors, flat plate collectors, parabolic concentrators, etc. which have high temperature of operation can lead to eliminating pathogens during operation.
- HDH systems have higher working temperature (water temperature at 60–80 ˚C) but water and air are associated as working fluids and pathogens can carry by the feed water and air injected to the system. Since feed water preheated up to a certain temperature pathogens can be eliminated but based on the principle of HDH, the feed water first inter into the condenser tubes at temperature between 15 and 25 ˚C to increase the rate of condensation and in the same time use the latent heat of evaporation and enhancing the feed temperature. Therefore, when the feed water is biologically contaminated, the cold environment of condenser tubes could be a high risk place for growth of pathogens. No need to mention that the air in HDH also can be a source of contaminations as the most of aforementioned pathogens can remain airborne. Thus, HDH systems with air heater are more reliable in terms of confronting by airborne biological contamination.
- As the passive solar stills working temperature in high-altitude regions is low using antibacterial nanofluids such as Ag can be an effective method against any type of pathogens including the novel coronavirus.
- Although the effect of nano-coated absorber of solar stills has not proven to be an anti-pathogen strategy, using some antibacterial nanomaterial in absorber such as silver, gold, iron, and titanium might be an impact on the pathogens in contaminated water.
- Heating the produced water of systems in high altitude regions can be an effective thermal inactivation method.

11. Conclusion

The ongoing pandemic from the 2019 have been a huge public health challenge in front of the world. Many lives have lost and economy of all countries has been impacted. The pandemic severely affected the environment, thus a huge part of its devastating burden is on the shoulders of environmental experts. Therefore environmental experts should propose novel strategies to prevent the further spread of the disease. Herein we reviewed the impact of the pandemic in high altitude regions and a possible route of viral prevalence through purified water. Even if the SARS-CoV-2 would not lead to disease or infection *via* fecal-oral route it is critically important to inhibit any portals for entering the virus to the human body particularly in high altitude regions. Furthermore, it is of great significance to consider all possible routes of transmission and be cautious for plausible upcoming epidemic/pandemic that may already walk into the shadows such the antimicrobial resistance pathogens. Last but not least, it is of great importance to emphasize that our main purpose in this critical review was not to draw any conclusion on a new transmission route of novel coronavirus *via* drinking water neither a significant impact of virus transmission in high altitude by use of solar desalination and disinfection systems, but the most important thing that brought into the spotlight is that using solar-driven water desalination and disinfection in high altitude regions could be possible route of entering pathogens to human body when the water resources are heavily contaminated by biological species.

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Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

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