Advanced nanostructured materials in solar interfacial steam generation and desalination against pathogens: Combatting microbial-contaminants in water– A critical review

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Abstract

The consumption of biologically-contaminated water annually leads to hundreds of thousands of deaths, most of which occur among children in developing countries. Solar-based water desalination systems are emerging as a promising, low-cost, and environmentally friendly solution to provide safe drinking water. The use of nanostructured materials in solar stills and solar interfacial evaporation systems is considered a highly effective method for performance improvement. These nanomaterial-assisted solar desalination systems can eliminate biological contaminants in water through various mechanisms. This paper presents, for the first time, an extensive review of the effectiveness of solar stills and solar interfacial evaporators aided by various forms of nanomaterials in combating biological contamination, including viruses, bacteria, protozoa, fungi, and antimicrobial resistance (AMR) pathogens. We specifically focus on pathogens with global catastrophic biological risk (GCBR) characteristics, particularly viruses and AMR pathogens. Special attention is given to the role of AMR pathogens and their potential transmission routes in the environment and water bodies, as they pose significant potential for future pandemics. The effectiveness of solar stills and solar interfacial steam generation methods is examined in light of their inactivation mechanisms, operational principles, crucial environmental parameters, and pathogen characteristics. Challenges and potential directions for future research are also discussed and proposed.

Keywords: Solar Desalination; Water contamination; Water microbiology; Antimicrobial-resistance (AMR); Interfacial evaporation; Developing World

1. Introduction

1.1 Broader context

As the Nobel Prize winner Albert Szent-Gyorgyi (Discoverer of Vitamin C) stated: "Water is life's matter and matrix, mother and medium. There is no life without water"; providing safe drinking water for people is of great importance and a global task for governments, global organizations, private sectors, NGOs, researchers, and stakeholders. Numerous statistical reports by researchers and organizations declared that if providing safe drinking water is now considered a problem, it will become a crisis in the near future. Nearly half of the world's population, at least one month of each year, experienced extreme water shortage [1]. By now, around 2.2 billion people have no access to safe drinking water, while 785 million people do not have access to basic water needs [2]. This is 3why from the beginning of the 21st century, the United Nations (UN) in the action plan called Millennium Development Goals (MDGs, 2000-2015), assigned a specific target to the problem of water [3] which was not completely realized. In the second action plan of the UN, called Sustainable Development Goals (SDGs "2015-2030") contain 17 goals; goal 6 (SDG6) is explicitly focused on providing safe drinking water for all people [4]. Indeed, the freshwater crisis hampered realization of the several of SDGs [5]. Currently, unsafe water sources are responsible for more than 1.2 million deaths (Fig. 1) [6]. Although the lack of drinkable water is usually reported in the regions with the high stress of potable water resources and poor communities -particularly in the Middle East, North Africa and South East Asia- this problematic issue is no longer considered as a matter of concern just for developing countries but it start to become a global crisis even for some of the most industrialized countries. For instance, the US water shortage is inevitable in the near future between 2021-2046 [7] and some states like California, Arizona, Colorado, New Mexico, Utah, Wyoming, and Nevada will be suffer from extreme water shortage [8], indeed, the crisis is already started. However, in developing countries with no proper drinking water infrastructures, sanitation systems, and wastewater treatment plants (WWTP) the situation is worse than imagine and the water resources would be heavily polluted by biological contamination. This fact would be more elucidated when we consider that more than 670 million people (mostly in poor communities and undeveloped countries) practice open defecation [2] which adversely contaminated water bodies by dangerous pathogens from different families of bacteria, viruses, protozoa, and antimicrobial-resistance (AMR) pathogens. The other important factor is the contamination of water bodies via wastewater originating by human wastes, which negatively affects countries with the developed economy, such as the US, France, England, and Japan, to name a few [9,10]. Unfortunately, these pathogens cannot only infect human by their main route but other routes are also possible, which means an airborne pathogen might be waterborne too. Numerous examples on uncommon routes of pathogens – particularly viruses- transmission have been realized [11], indeed, the most recently findings is on SARS-CoV-2 during the COVID-19 pandemic [12]. This means that any pathogen in water bodies, no matter the dominant transmission route, has potential to become waterborne. Last but not least, the importance of providing safe drinking water can be more highlighted when we know that every 2 minutes, a child under 5 is dying due to diarrhea diseases that are related to unsafe water [2] meaning that each year, more than 250,000 children would not live to celebrate their fifth birthday because of diarrhea. It means "**More children are killed by unsafe water, than by bullet**" said Henrietta Fore - UNICEF Executive Director.

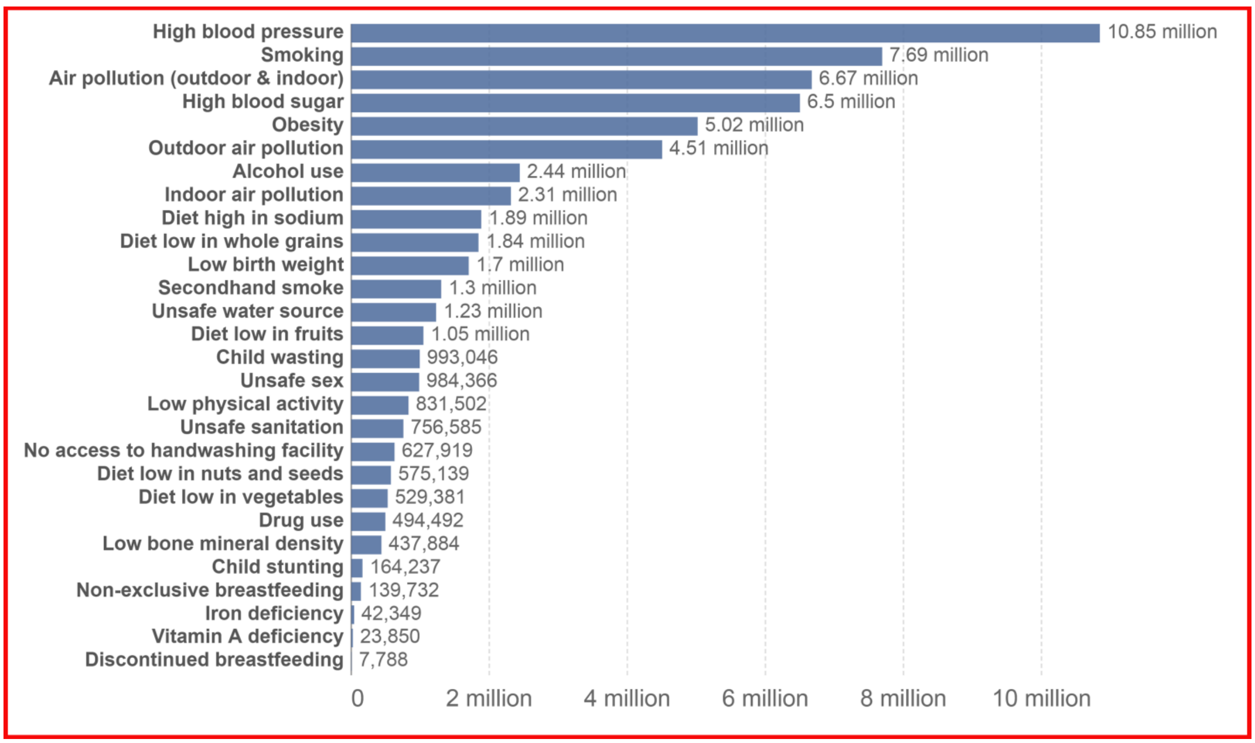

Figure 1. Total annual number of deaths by risk factor, measured across all age groups and both sexes throughout the world in 2019. Reproduced with permission from open source reference [6], copyright 2019. As it can be observe, contribution of unsafe water sources is nearly 1.23 million deaths, making it as the 13th cause of death.

1.2 Motivation and objective of the present review

As two-thirds of our blue planet is covered by water, solar-based water desalination and purification systems (in this review, solar stills and solar interfacial evaporators) have become a topic of ever-fast-growing interest. However, contamination of water bodies by dangerous biological species in recent years is exponentially on the rise (contamination of water bodies in every corner of the world by the SARS-CoV-2 during COVID-19 is a good example), which makes it obligatory to determine systems' effectiveness against biological species. We consider these two solar systems in our review since solar still is the oldest method to provide drinking water and currently used in many communities throughout the world. In contrast, solar interfacial evaporators is a novel approach starting from 2014 [12] with exceptional performance. It is considered the next-generation of small-scale solar desalination to provide drinking water, maybe as an alternative for replacing solar stills in the future.

Most reviews in both systems focused on the type of material, as the materials are the cornerstone of fabricating a highly efficient structure. In recent years innumerable studies have reviewed solar stills in terms of the type of materials [13–19], cooling and heating methods [20–24], designs and geometries [25–32], modeling and optimization [33–35], economic and cost analysis [36–38], thermodynamic parameters [39–42], integration with different collectors and heat exchanger [43–49] and effect of climate parameters [50,51]. Moreover, in the last decade, countless studies in solar interfacial evaporators reviewed the use of different types of materials [52–61], strategies for salt management [62–67], energy utilization and management [68–70], applications and integration [71–74], sterilization [75], examining the light effect intensity [76], design and fabrication methods [77–80] and simultaneous photocatalytic activity [81–83].

However, till now, there is no review study to comprehensively and explicitly focus on the effectiveness of solar stills and solar interfacial steam generators (based on the systems' mechanism and microorganism characteristics) against biologically contaminated water. Thus, the present review for the first time would open new insights and research gaps for researchers working on solar stills and solar interfacial evaporations through contaminated water against different types of dangerous biological contamination -with the risk of starting an epidemic or pandemic- including viruses, bacteria, protozoa, fungi and more important that, antimicrobial-resistance (AMR) pathogens. Importantly, we highlighted all of the possible mechanisms for elimination of pathogens based on operating conditions of both systems. Figure 2 shows a graphical illustration of previous reviews on solar stills and solar interfacial evaporations and highlights the focus of this review.

This review is structured into two sections. In the first part, characteristics of particular dangerous pathogens and contamination of water bodies by biological contamination is presented to show the heavy pollution of water bodies while clarifying the importance of solar-based water desalination systems against pathogens for practical real world applications. Importantly, this part presented instead of discussing system operating principles which is repeatedly discussed in previous reviews, because of the fact that knowing the pathogens characteristics and their contamination in water bodies is the cornerstone at the context of this review. In the second part, mechanisms of nanomaterials and environmental parameters (which are crucial for the performance of both systems) against biological species are brought into the spotlight. Eventually, effectiveness of systems with nanomaterials through different mechanisms against each type of pathogen based on previous studies is thoroughly scrutinized. At the end of this critical review, recommendations, research gaps and new directions for future researches were suggested.

It is worth noting that a particular emphasis is placed on antimicrobial resistant (AMR) pathogens in the environment and their presence in water media. This focus is due to their rapid spread in aqueous environments through various routes, since it was anticipated that the next pandemic which silently walk in the shadows and is more terrifying that the COVID-19 pandemic is as the results of AMR pathogens which annually could lead to 10 million deaths.

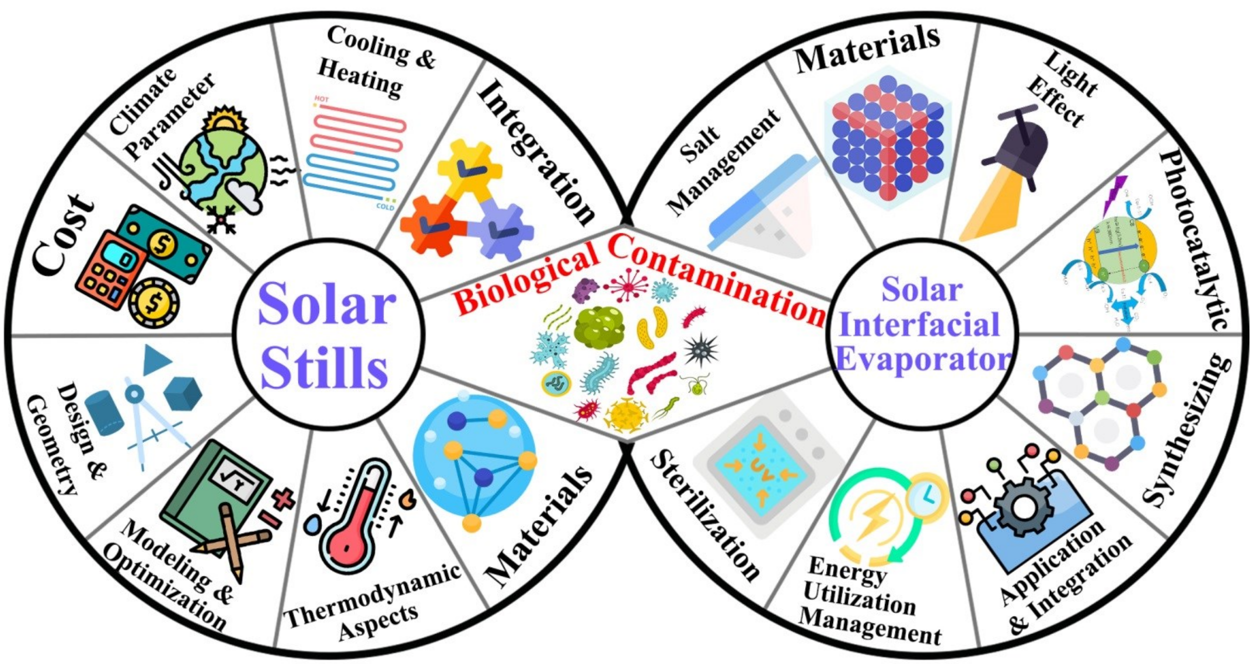

Figure 2. Major contributions of recent reviews on solar still and solar interfacial evaporators. The reliability of solar still and solar interfacial evaporators against biologically-contaminated water has not been realized.

2. Pathogens and global catastrophic biological risks (GCBRs)

Global catastrophic biological risks (GCBRs) are events in which biological agents can cause significant damage to human civilization. Pathogens that fall into the GCBR-level category pose some specific characteristics in transmissibility between humans, the time needed for transmission, fatality, virulence factors empowering immune system evasion, and human immunity against them [84,85]. These are essential categories of biological threats that should be carefully considered to prevent and respond appropriately before biological catastrophes become unmanageable. The GCBRs are usually sudden and not sensitive to medical countermeasures; thus, handling them in time is important. Although most pathogens can be placed in this category, the ones with the ability of respiratory transmission that have a longer incubation period and no preexisting host immunity are more hazardous and capable of causing pandemics [84]. Some of the most devastating epidemics and pandemics in the last half-century are presented in Table 1. Although microbes with fecal-oral and waterborne pathogens like vibrio cholera are lethal, their danger would generally be preventable through an effective sanitation system [84]. However, it should be pointed out that due to low-sanitation networks and lack of wastewater treatment infrastructures in developing countries, vibrio cholera is among the most hazardous pathogens that annually cause (directly and indirectly) the death of thousands of people, especially children.

The World Health Organization (WHO) states: “The best time to prevent the next pandemic is now”; thus, a new term called "Disease X" is introduced. Disease X is a name, adopted by the WHO, which refers to a disease caused by an unknown pathogen that affects public health globally. We should identify and study different conditions to be well-prepared enough to deal with any unknown pathogen. In fact, it’s not technically a "diseases", It's an area of research for scientists to develop roadmaps for any possible condition to respond to unforeseen strains. Among different types of pathogens we shed the light on three important organisms of viruses, bacteria, and protozoa as all of them previously and currently lead to some calamitous epidemics and pandemics. Importantly, we extensively discuss about antimicrobial-resistance pathogens (AMR) that alarmingly consider as the next pandemic and continuously emerge in the shadows.

Table 1. Some of the most important epidemics and pandemics in the last 50 years

Pathogen	Family	Genome	Important ways of transmission	Case fatality rate (%)	Median incubation period (day)	Particle size	Year of epidemic/ pandemic	Location of first reported case	Sensitivity to temperature
Ebolavirus	Filoviridae	Negative sense, single stranded RNA	Direct contact	50-63	2-21	80 nm	1976-present	Zaire	60 °C for 60 minutes
HIV	Retroviridae	Positive sense, single stranded RNA	Sexual contact, injection equipments	80-90	5-70	90-160 nm	1981 – present	West Central Africa	Above 60 °C
SARS-CoV-1	Coronaviridae	Negative sense, single stranded RNA	Respiratory secretions	10	5	78 nm	2003	China	56 °C for 90 minutes
Influenza A (H1N1)	Orthomyxoviridae	Negative sense, single stranded RNA	Respiratory secretions	0.02-0.4	1-7	80-120 nm	2009	North America	70-90 °C for 1-5 minutes
MERS-CoV	Coronaviridae	Positive sense, single stranded RNA	Respiratory secretions	34.4-37	5		2012	Saudi Arabia	Above 40 °C
Ebolavirus	Filoviridae	Negative sense, single stranded RNA	Direct contact	70-71	2-21	80 nm	2013-2016	West Africa	60 °C for 60 minutes
SARS-CoV-2	Coronaviridae	Positive sense, single stranded RNA	Respiratory secretions	at least 2-3	5,2	60-140 nm	2019-present	China	56-95 °C for 3-30 minutes

2.1 Viruses

Viruses are the most likely pathogens to cause pandemics [84]. They have a higher replication and mutation rate, giving them the potential to adapt to host cells and even zoonotic [85]. On the other hand, there are no broad-spectrum antiviral agents and no certain vaccines [85], making this group of pathogens more important. A new subtype or strain of viruses that can be transmitted easily among human, or the one's that we have no immunity against, and also the ones that become zoonotic after mutations, like swine flu and avian flu (which were common among pigs and birds before the antigenic shift) can lead to starting pandemics. Among viruses, the ones with RNA as a genome are more likely to cause pandemics [86]. They are less stable and have no proofreading system like DNA replication. Viruses that replicate in a host cell's cytoplasm are more capable of becoming widespread [87,88]. DNA viruses, unlike RNA viruses, tend to have nuclear replication, which limits their zoonotic ability, but it's not a rule [84]. As an exception, smallpox is a DNA virus with cytoplasmic replication and Influenza A, is a RNA virus with nuclear replication but historically, the highest pandemic risks are happened by RNA viruses [89,90]. Respiratory droplet transmissibility is another factor that augmented viral pandemic potential, as breathing is happening worldwide every single second and is more difficult to protect definitely [84]. Orthomyxoviruses (like Influenza virus), coronaviruses, paramyxoviruses (especially these three genera: respirovirus, henipavirus, and rubulavirus), pneumoviruses and picornaviruses (especially the two genera of enterovirus and rhinovirus), are some of RNA viruses with the respiratory route of transmission, which are significant as GCBR-level threat for public health [84] and some of them have been the reason of life-threatening pandemics. Table 2 presents some of the most dangerous viruses in the GCBR level.

Table 2. Important viruses categorized in the GCBR level

Family	Important genera	Genome	Envelope	Particle size	Site of replication	Important diseases	Sensitive to	Critical temperature	Ref
Orthomyxoviridae	*Influenza A*	Segmented, negative sense, ssRNA	+	80-120 nm	Nucleus	Respiratory diseases	(Influenza A:) sodium hypochlorite, 60-95% ethanol, aldehydes, phenol	70-90°C for 1-5 min	84,91
Coronaviridae	Coronavirus (*SARS-CoV-1; MERS; SARS-CoV-2*)	Non segmented, positive sense, single stranded RNA	+	50-200 nm	Cytoplasm	Respiratory tract infections, common cold, SARS, MERS, COVID 19	Temperature, chlorine, UVC	56-75°C For 15-45 min	87,88,92
Filoviridae	Ebolavirus	Negative sense, single stranded RNA		80 nm	Cytoplasm	Direct contact	Bleach, Alcohol	60 °C for 60 minutes	93
Paramyxoviridae	Respirovirus, Henipavirus, Rubulavirus	Non segmented, Negative sense, ssRNA	+	50-540 nm	Cytoplasm	Respiratory tract infections, measles, mumps	Soap, alcohol, ether, sodium hypochlorite, temperature	37 - 72°C	94–97
Pneumoviridae	HMPV, RSV	Non segmented, Negative sense, ssRNA	+	100-1000 nm	Cytoplasm	Respiratory tract infections	Ethanol, bleach		98,99

Picornaviridae	Enterovirus, Rhinovirus	Non segmented, positive sense, ssRNA	-	27-30 nm	Cytoplasm	Common cold, Hepatitis, meningitis	Pyroligneous acid		100–102

2.2 Protozoa

Protozoa organisms are less important in pandemics but are the second most frequent cause of mortality among children under 5 [84]. Generally, they can cause disasters in undeveloped and poor communities. Detection of cysts and oocysts of pathogenic enteric protozoa is expensive, low probable, and usually absent in a small treatment facility, so they may be missed in sanitation [84]. The portrait of protozoa could seem like a serial killer when we know that half of all humans who have lived died of malaria [103]. However, it is still manageable through antimalarial agents and vector-limiting strategies, but there is also a concern of artemisinin-resistant forms spreading, which can cause many troubles [104]. Among parasitic protozoa, *Toxoplasma gondii*, *Entamoeba histolytica*, *Cyclospora cayetanensis*, *Isospora belli, Blastocystis hominis, Balantidium coli, Acanthamoeba spp., Sarcocystis spp.* and *Naegleria spp* are waterborne and can cause infections in humans.

Importantly, *Giardia* and *Cryptosporidium* are zoonotic agents and the most common protozoa in waterborne outbreaks [85,105] as they are less sensitive to conventional treatment methods [84], and they can cause acute diarrheal disease, especially among children in developing countries [86–90]. *Cryptosporidium parvum* and *Giardia lamblia* are chlorine-resistant protozoa that can survive in common wastewater treatment systems [106–108]. Table 3 presents their characteristics and sensitivity to UV and temperature. The other reason for their importance is the small size of *Giardia cysts* and *Cryptosporidium oocysts* (1–17 µm), enabling them to pass through filters at water treatment systems [109] and transmit via water vapor. They have high stability in the aquatic environment up to 6-12 months [84], and also survive in cold water for a long time [84].

Table 3. Characteristics of two of the most important waterborne protozoa

Pathogen	Parameters	Value	Time of expose	reduction	reference
Giardia	Temperature	56 °C 70 °C	600 s 600 s	>2 log >2 log	110,111
	UV	550 w/m2	1 h 2 h 4 h 6 h	0.94 log 1.96 log 1.96 log 1.96 log	112
Cryptosporidium parvum	Temperature	60 °C 72 °C	300 s 5-15 s	3.4 log > 3 log	113,114
	UV	550 w/m2	1 h 2 h 4 h 6 h	0.02 log 0.07 log 0.15 log 0.32 log	112

2.3 Bacteria

Compared with viruses, bacteria are basically less important in causing pandemics. The reason is that their replication and mutation speed is relatively slower, and antibacterial therapies also have limited the ability of bacterial pandemics [84].

Most fecal-oral transmissible bacteria, such as vibrio cholera, can be eliminated through effective sanitation [84]. Cholera and plague disasters in Yemen [106] and Madagascar [107] had been more a result of the bad condition of societies in war or lack of supplies rather than the Pathogen's characteristics. Table 4 represents some of the most dangerous bacteria that can be considered in the GCBR category with their characteristics and results of experiments conducted on their inactivation. Notwithstanding of the medical advancements and public health developments in recent years, it was still reported in 2020 that *vibrio cholera* and typhoid fever yearly infected nearly 3 and 11 million people through the world and lead to 95,000 and 117,000 deaths respectively, most of them are among children [115].

Table 4. Characteristics of the most dangerous and important bacteria in recent experiments

Bacteria	Temperature (°C)	Inactivation time(s)	Log10 reduction	Particle size	REFs
Campylobacter spp.	60 62	300 15	3.9 log 3.5-5 log	0.2–0.5 µm	116,117
Coxiella burnetii	79.4	25		0.2–0.7 µm	117
Escherichia coli 0157	60	300	1.5 log	1–2 µm	116
Enterococcus faecalis	65	7-19		0.6–2.5 µm	118
Klebsiella pneumoniae	72	23	Per log	12.6-27.4 nm	119
Legionella pneumophila	58	360	Per log	2-20 µm	120
Mycobacterium paratuberculosis	72	15	> 4 log	NA	117
Pseudomonas aeruginosa	65	5	Per log	0.5–1.5 µm	118
Salmonella typhimurium	65	< 2	Per log	68-72 nm	118
Shigella sonnei	65	3	Per log	0.3-1 µm	118
Vibrio cholerae	55	22.5	Per log	0.36-0.4 µm	121
Yersinia enterocolitica	72	0.5	Per log	19.2-22.5 µm	119

2.4 Antimicrobial-resistance (AMR) pathogens

Imagine the world where a routine surgery or chemotherapy be considered too dangerous because there are no drugs to prevent or treat infections [122]. Indeed, antibiotics are no more effective enough. Nothing can give us a clearer picture of the terrifying dangers of antimicrobial resistance (AMR) pathogens than this statement. Each year AMRs results in 600 thousands of death throughout the world. These AMR pathogens can inure treatments by 2050, leading to 10 million deaths each year and forcing the global economy to around $100 trillion (Figure 3-a) [123]. This number means that AMRs potentially will be a bigger murderer than cancer. Currently, the rate of infections by AMR in the Euro region is equal to all infections by Influenza, Tuberculosis, and HIV/AIDS (Figure 3-c). The devastating problem of AMR spreading is elucidated when we consider that antibiotics are used for human infections, animals, fishes, and agriculture industries. Unfortunately, the rate of deaths attributed to the cephalosporin-resistant Escherichia coli and carbapenems-resistant Klebsiella pneumonia from 2008 to 2015 drastically have been increased by about 4 and 6 folds, respectively (Figure 3-b). Thus, the possibility of spreading AMR pathogens is high since it has multiple routes to the environment [124]. We will briefly discuss the routes in the next sections. However, their dissemination, enrichment, prevalence, adaptability, and interaction with the environment have a complex matrix, which is not the topic of this review.

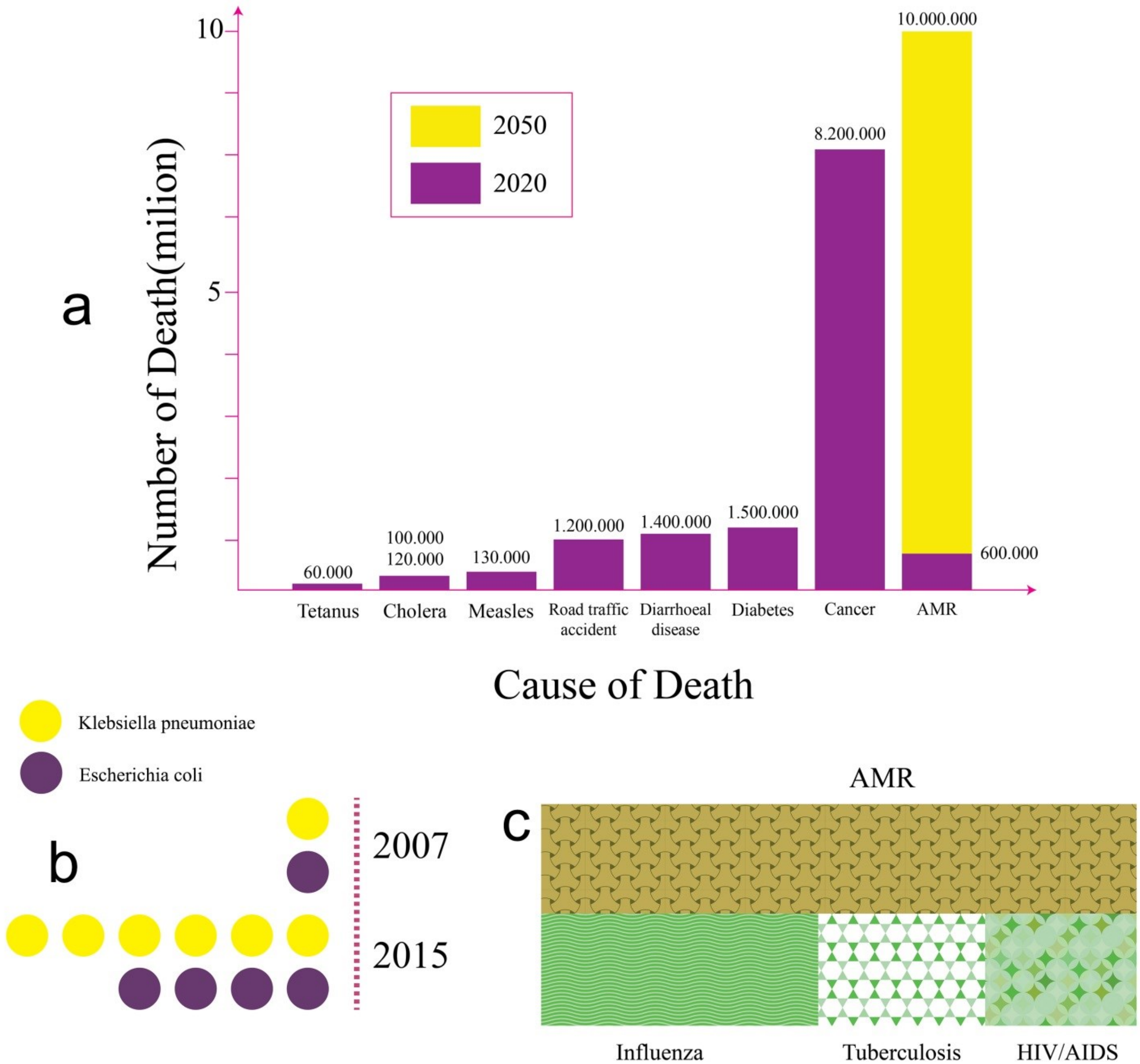

Figure 3. a) The number of deaths attributed to AMR in comparison with other main causes of death. b) The number of deaths due to the infections by Klebsiella pneumonia resistant to carbapenems (yellow circle) and Escherichia coli resistant resistant to cephalosporin (purple circle) which augmented from 2007 to 2015 by around six folds and fuor folds respectively. c) The burden of infections by AMR on the European population is equal to total infections by Influenza, Tuberculosis and HIV/AIDS. Reproduced from reference [125] with permission (open source) from European Centre for Disease Prevention and Control (ECDC), copyright 2022

Importantly, AMR pathogens are also a serious concern in terms of the possibility of causing bacterial pandemics. It's a slow-growing pandemic due to more speed of bacterial resistance to antibiotics compared to new antibiotic development [108]. As it can see in figure 4, the CDC has classified 18 types of antibiotic-resistant bacteria into 3 groups based on their threat to human health. Accordingly, the role of AMRs during the ongoing pandemic have alarmingly brought into the spotlight as it has the potential to escalate the impact of the pandemic not only from the direct effects but due to their side effects of leading co-infections. Table 5 presents two categories of AMRs characteristics classified as urgent and serious threats to humans.

Table 5. AMR characteristics in the groups of the urgent and serious threat

species	Type of pathogen	Important complications	Major route of transmission	Particle size	temperature
Carbapenem-resistant Acinetobacter baumannii	gram-negative bacteria	pneumonia urinary tract infections bloodstream infections	contact with contaminated surface or person	1.0–1.5 μm by 1.5–2.5 μm[1]	A. baumannii successfully survived at −20 to 44 °. At 50 to 80 °C the survival ranged from 5 days to 5 min.
Drug-resistant Candida auris	fungus	bloodstream infections wound infections	contact with contaminated surface or person	2.5-5.0 μm	C. auris is sensitive to the stress combinations imposed by hospital laundering protocol (pH > 12 plus heat shock at >80°C)
Drug-resistant Clostridium difficile	gram-positive bacteria	dehydration Severe diarrhea Colitis sepsis	fecal-oral route	3-4 μm	Temperatures over 85°C are needed to completely eliminate all C. difficile spores in an aqueous environment
Carbapenem-resistant Klebsiella pneumoniae	gram-negative bacteria	pneumonia bloodstream infections wound infections meningitis	direct person-to-person contact	0.5-2 μm	NA

Extended-spectrum beta-lactamase (ESBL) producing Escherichia coli	gram-negative bacteria	diarrhea	Fecal-oral route	0.25–1.0 µm	NA
Drug-resistant Neisseria gonorrhoeae	gram-negative bacteria	pelvic inflammatory disease (PID) urethral infections	Sexual transmission Transmission of via fecal oral	0.6 to 1.0 µm	NA
Drug-Resistant Candida glabrata	fungus	bloodstream infections urinary tract infections	direct person to person contact	2-3 µm in diameter	
Vancomycin-resistant Enterococcus faecalis	gram-positive bacteria	urinary tract infections endocarditis bacteremia	contact with contaminated surface or person	1 µm	NA
Multidrug-resistant Pseudomonas aeruginosa	gram-negative bacteria	pneumonia bloodstream infections	contact with contaminated surface	0.5 to 0.8 µm by 1.5 to 3.0 µm	NA
Drug-resistant Salmonella enterica Serovar nontyphoidal	gram-negative bacteria	gastroenteritis bacteremia	consumption of contaminated food of animal origin	2–5 µm long by 0.5–1.5 µm wide[2]	NA
Multidrug-resistant Shigella flexneri	gram-negative bacteria	diarrhea	fecal-oral route	0.4-0.6 µm	sensitivity to mild heat was observed above a temperature of 45 ºC
Methicillin-resistant Staphylococcus aureus (MRSA)	gram-positive bacteria	skin infections bloodstream infections pneumonia endocarditis	contact with contaminated surface or person	diameters of 0.5 – 1.5 µm	S. aureus died within 20 minutes at 80 ºC
Drug-resistant Streptococcus pneumoniae	gram-positive bacteria	pneumonia meningitis bloodstream infections	direct person-to-person contact via respiratory droplets	0.5 - 1.25	
Drug-resistant Mycobacterium tuberculosis	gram-positive bacteria	Attack different parts of body especially lungs	direct person-to-person contact via respiratory droplets	2-4 µm in length and 0.2-0.5 µm in width	heat inactivation happens at 80°C for 20 minutes

Figure 4. Antimicrobial-resistant threats based on the level of risks according to the CDC. Reproduced from (open source) reference [126] permission from Centre for Disease Control, copyright 2022

It should be point out that a separate section has not been discussed on fungi since they have a low possibility to start biological catastrophic in this context, however, they still can cause disease in human. In this regard, a thorough discussion on application of solar interfacial evaporators against fungi is discussed at the end of the paper.

3. Contamination of natural water resources

In the face of the rapid technological development of the human race in the 21st century, contamination barriers via multiple routes have become a burden on the shoulders of the environment, specifically, natural water resources. Indeed, human activity is one of the two important factors that contaminate water bodies with untreated/treated wastewater [127]. The size of contaminating water resources can be illustrated by considering the fact that some of the longest and huge water bodies (i.e, transboundary rivers) with thousands of kilometers in length, such as Nile, Ganga, Congo, Lena, Amazon, etc., are biologically-contaminated by human wastewater [128]. Pollution by microorganisms affected the above-mentioned rivers while anthropogenic activities resulted in biological contamination of oceans and seawater, mainly (but not limited) by wastewater. The level of water stress is has a meaningful relation for areas with high death rates due to waterborne diseases. Figure 5 (a-d) shows global solar irradiance, global water stress, global deaths associated with waterborne pathogens and antimicrobial resistance (AMR) distribution worldwide. Surprisingly, those regions with a higher rate of solar intensity are confronted with severe water shortage and higher rates of mortality due to waterborne pathogens, while the distribution of AMR pathogens is corresponds with these areas.

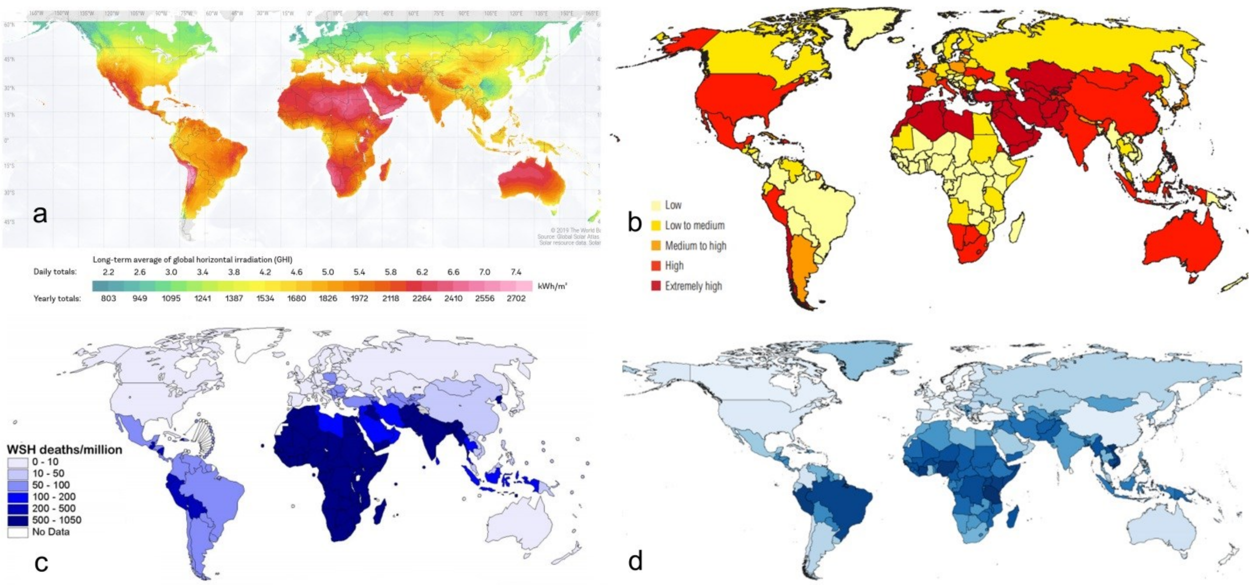

Figure 5. (a). Global solar irradiance through the world. Reproduced from open source reference [129] with permission from SolarGIS, copyright 2022. (b). Country-Level water stress in 2040. Reproduced from open source reference [130] with permission from World Resources Institute, copyright 2015. (c). Estimation of the worldwide mortality impacts of waterborne pathogens. Reproduced from open source reference [131] with permission from Elsevier, copyright 2015. (d). Global predictions of antimicrobial resistance (AMR) abundance in all countries and territories in the world. Map colored according to the predicted abundance of AMR from light blue (low AMR abundance) to dark blue (high AMR abundance). Reproduced from open source reference [132], with permission from Springer-Nature, copyright 2019.

3.1 AMR pathogens in water media

In contrast to other environmental contamination (at the top of them, chemical contaminations), which may be subjected to dilution, sorption and degradation in the environment; antimicrobial resistance can persist under harsh conditions and can replicate and spread in the environment [133]. The complex process of expanding AMR pathogens and their interrelation with the environment might be highlighted when it was declared that environmental pollution such as microplastics increases the survival rate of AMR pathogens [134]. Some of the most important environmental activities that lead to spreading and increasing AMR pathogens in water bodies are presented in Figure 6 [135] which can be highlighted that how vast is the number of parameters that contribute to AMR dissemination to water bodies.

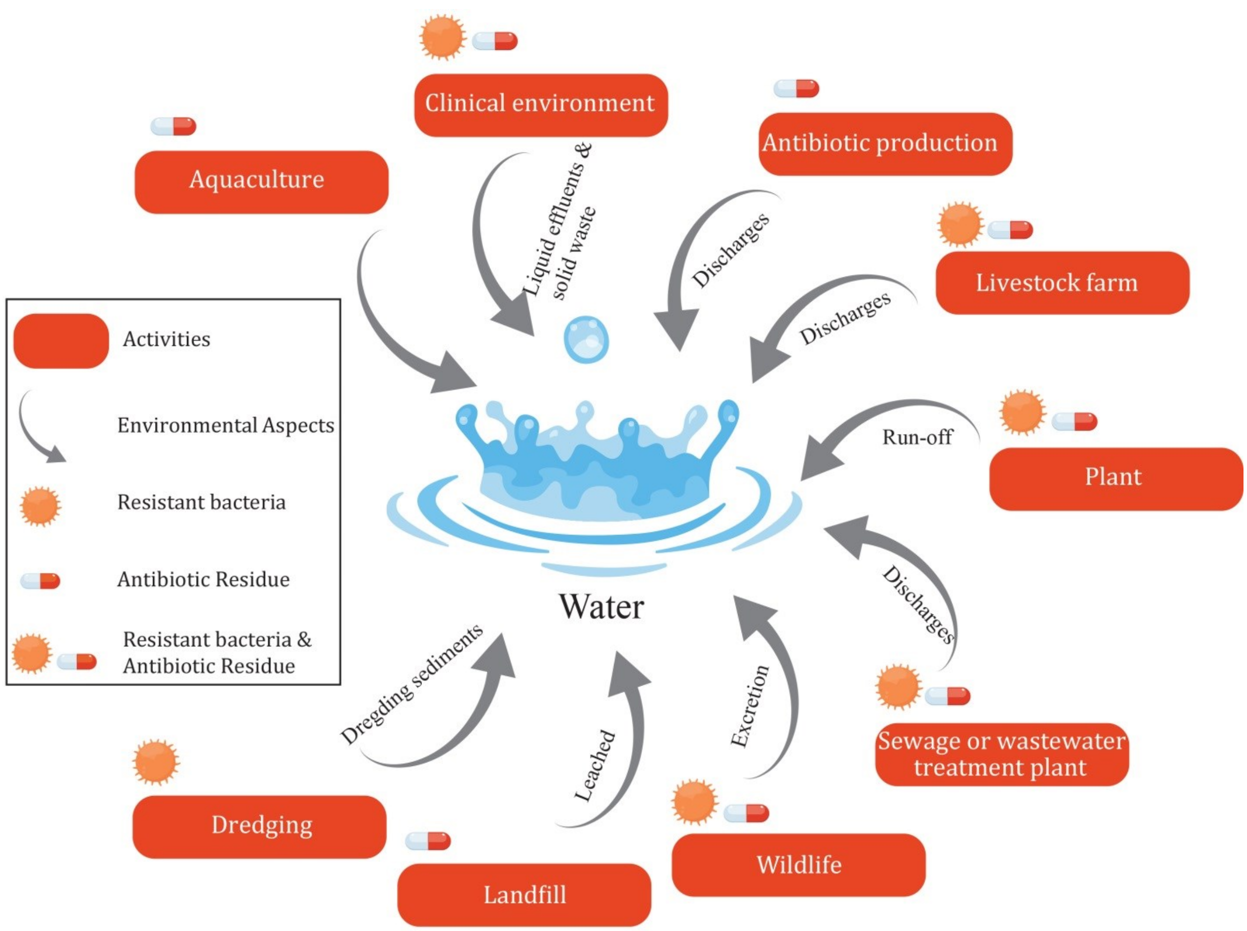

Figure 6. Some of the important routes of environmental activities leading to augment AMRs' presence to water bodies. Reproduced from open source reference [135] with permission from the United Nation Environment Programme (UNEP), copyright 2022

Recently, *methicillin-resistant Staphylococcus (MRSA)* and *methicillin-susceptible Staphylococcus (MSSA)* AMRs are detected in WWTP of the US in high concentrations [136]. When these kinds of AMRs are found in water samples of the one of the most industrialized countries in the world, the situation in the developing world and poor communities is certainly worsened than it can be imagined because of the fact that these regions, basically have not sufficient sewage network and sanitation system, lacks of WWTP, and contamination of their water bodies due to lack of a tight regulation is more common. A good example of the lack of tight regulations is the Ganga river in India which heavily contaminated by hazardous biological species.

Among the most concerning AMR pathogens, which are known as urgent threats, *carbapenem-resistant enterobacteriaceae* (CREs), already pose a major concern for healthcare professionals [109], and according to CDC estimation, the mortality due to CRE infection is about 40-50%.

India has the highest consumption of antibiotics worldwide, especially β-lactam antibiotics [137], as it has a large crowd, but only around 40% of its wastewater is adequately treated [138], so hospital sewage can have an important role in antibiotic resistance spread [108]. Some AMR pathogens, including CREs have been quantified in 12 hospital wastewater outfalls over 2 seasons in New Delhi. It is proven that hospitals can have an important role in AMR spread [108]. Figure 7 illustrates the abundance of CRE in hospital wastewaters across New Delhi. Extended-spectrum *β-lactamase Enterobacteriaceae* (ESBL) are another group of antibiotic-resistant bacteria classified as serious-threat pathogens detected in Lebanese hospital sewage [139]. Therefore, AMR dissemination through hospital wastes in water resources can cause a big challenge worldwide, if not treated [133,140,141]. As it mentioned above contamination of water bodies through different pathogens would important when it consider that the feed water of small-scale solar desalination systems (in this context solar still and solar interfacial evaporation) could be contaminated by various dangerous pathogens, at the top of them are AMRs. Accordingly, the interrelation between biologically-contaminated water and the importance of antimicrobial mechanisms and structures of solar evaporators would be more elucidated. It should be point out that the significance of feed water's quality in terms of biological species in the solar still and solar interfacial evaporators has not attracted attention rather than other terms such photothermal efficiency and productivity.

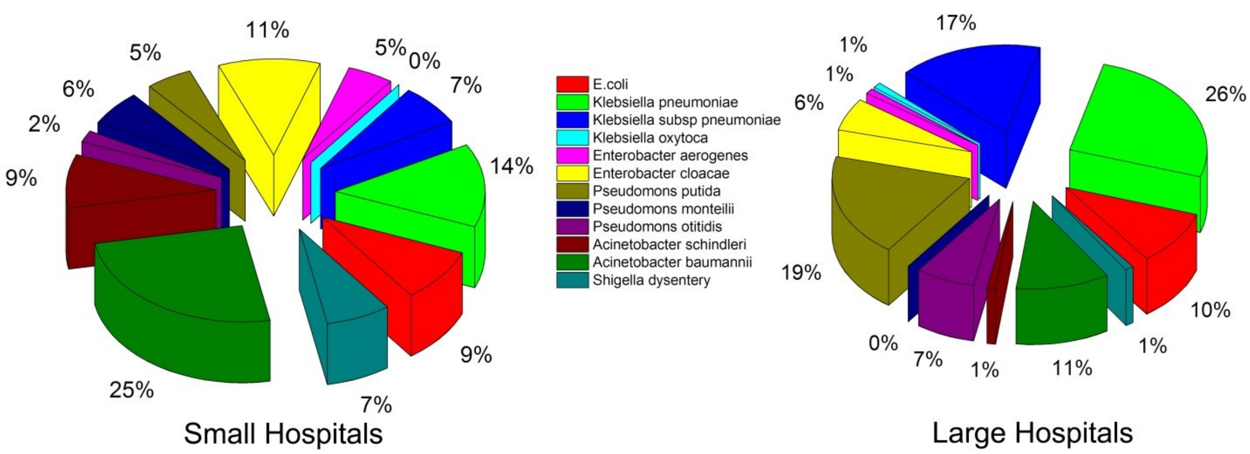

Figure 7. Proportional abundance of CRE AMR as a function of genus and hospital sizes in hospital wastewaters across New Delhi. Reproduced from reference [108] with permission from American Chemical Society, copyright 2017

As the importance of various pathogens and contamination of water bodies is briefly highlighted, we take the next step to realize the application of nanomaterial-assisted two solar-based water desalination systems against pathogens.

4. Small-scale solar desalination systems

Solar water desalination/purification is proposed as one of the best environmental-friendly renewable energy-based systems to address drinking water shortage throughout our blue plant. From a capacity viewpoint, these systems were divided into mega-scale and small-scale. Mega-scales with tens of thousands of liter water are suitable for big cities and any regions with a highly dense population, while small-scales are appropriate for remote regions, small communities, and low-income areas [142,143]. Interestingly, many theoretical studies on renewable-based mega-scale systems were performed but most of them, particularly, solar-driven large-scale desalination from an economic standpoint, is not feasible since plenty of them driven by fossil fuels such as natural gas. Nevertheless, small-scale solar-based systems for decades used to provide safe drinking water for small communities. We divided these systems into two categories as illustrated in figure 8, based on their development time. In this regard, solar still is the first system because it has been utilized since ancient times. It is followed by the recently developed approach of solar interfacial steam generators (SISG) presented in 2014 by Professor Gang Chen group at MIT, which takes advantage of advanced materials science. As it can be seen in Figure 8 a-b, the process for both systems is similar and it stands based on evaporation and condensations process. However, the huge difference between the operational mechanism of solar still and SISG came from the mechanism that the impure water heated. In solar stills the whole water inside the basin is heated which called bulk heating while in SISGs the a part available liquid that transfer through the (micro/nano) channels at the top of the solar absorber heated. The first problem of bulk heating is the heat loss through absorber and walls of basin to the environment through different heat transfer mechanisms. The second issue is the amount of energy needed to increase the temperature of impure water ascribe to its extraordinary specific heat capacity

(4184 J·kg^{-1}·K^{-1}) compare to most substances. The high specific heat capacity would be the reason for difference between photothermal efficiency and productivity between solar stills and SISGs. A good example to manifest the difference can bring in this context. For the interfacial evaporation process, a thin layer of (which has a small portion of whole liquid) water should heated that results in fast rate of temperature enhancement as well as evaporation while in solar stills the temperature of whole liquid should increase. Accordingly, for SISGs the rate of evaporation and efficient use of available solar energy with minimizing the heat loss augmented significantly.

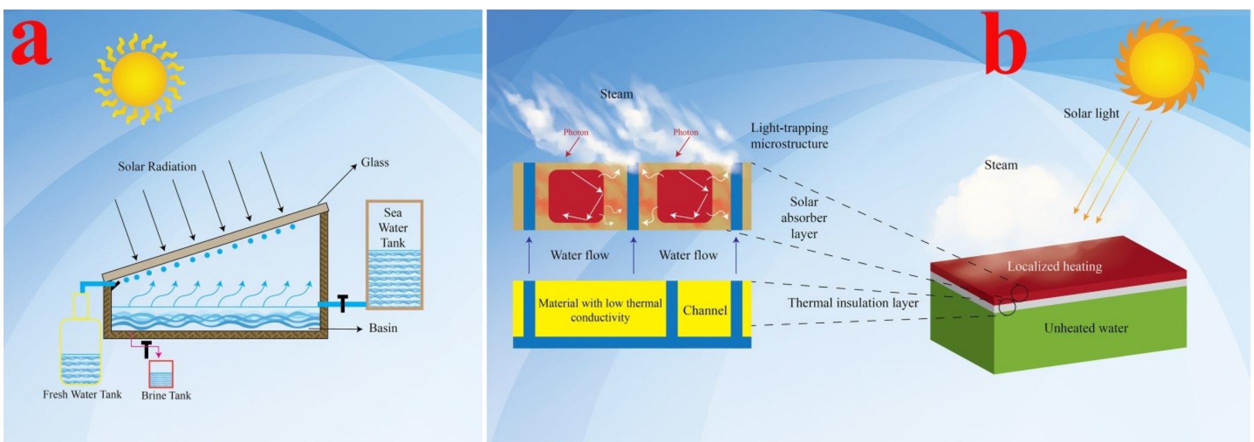

Figure 8. Schematic diagram of solar-based water desalination/purification systems. a) Single slope solar still. b) Solar interfacial steam generation.

5. Nanomaterial at different dimensions in solar-driven interfacial evaporation and desalination

5.1 Solar stills

Generally speaking, nanostructures in solar stills are utilized in zero and one dimensional (0D and 1D) as core-shell structures and nanospheres in two forms of nanofluids and nano-coating absorbers as well as condenser surfaces, respectively. Various nanofluids such as Al_2O_3 [144], TiO_2 [145], MWCNT, Ag [146,147], Cu [148], Cu_2O [149], CuO [150], ZnO [151], SiO_2 [148], SnO_2 [151], MgO [152], Au [153] and Fe_2O_3 [154] have been employed by researchers in solar stills. It is important to point out that these nanofluids (in most cases) utilized, not as an antimicrobial agent but as a passive improvement method of solar stills via increasing the rate of heat and mass transfer. There are two important issues associated with using nanofluids in solar still. The first one is the type of solar still utilized by nanofluid and the second is the long-term stability of nanofluid for practical -real-world- application. Evidently, nanofluids in most of solar stills are utilized as the passive method where there is no moving part in basin of solar still or any connected solar collector to agitate the fluid, thus, the agglomeration phenomenon is not a possibility but a certainty. Notably, in all previous studies, there is no evidence that solar stills continuously work with nanofluid through several regular cycles in long-term. On the other side of the coin, the long-term stability of nanofluids still remains a big question as it has a long way and confronts numerous obstacles [155] to be commercialized for real-world application. Notably, stability of nanofluids in saline solutions is another problem [156] since the feed water of desalination -regardless of biological contamination- always has a certain amount of salinity. Last but not least, almost in all of previous studies the zeta potential of nanofluids before and after experiments has not been measured to realize the stability.

5.2 Solar interfacial steam generators

In contrast to solar stills, nanomaterial in solar interfacial steam generators used in a broad range from zero to three dimensional materials (including 2.5D) such as core-shell, nanospheres, nanorods, nanosheets, and monolithic structures [61,157,158]. In recent years various types of materials including carbon families such as carbon dots[159], CNTs [160,161], graphene[162,163], reduced graphene oxide, graphite foam, carbon black, carbon fabrics, carbon foam [74,164]; semiconductor familes such as copper sulphides, copper phosphate, titanium-based semiconductors [53], hybrid (polymer-biomass-metal) structures [165,166] and noble metal family including gold, silver and palladium have been extensively used as high efficient photo-thermal materials in solar steam generators. Notably, combining nanomaterial with hydrogels, aerogels and polymer structures further boosted the performance of structure. Unlike the use of nanomaterial in solar stills, for utilizing nanostructures in solar interfacial evaporators many factors including facile synthesizing method, long-term mechanical/chemical stability, high number of cycles, precise and desirable architect for salt-resisting, organic/inorganic fouling, insulation, water path channels, structure alignments are considered. Moreover, utilizing different preparation methods for nanostructures by combing chemistry and material science would realize to manipulate and engineered the structure for the desired purposes. Furthermore, various material characterizations would be scrutinized, including SEM images, high-resolution TEM images, XPS, XRD, UV-Vis-NIR, and EDS on nanostructure before and after the operation. These precise measurements result in excellent mechanical/chemical/environmental stability, durability, reliability, high efficiency and cost-effectiveness, making solar interfacial evaporators an exceptional option for providing safe drinking water.

6. Mechanisms of nanomaterial and environmental parameters against biological species

The possible mechanisms of biological elimination by nanomaterials in solar-driven desalination systems would be via six ways which are: direct contact of nanomaterial, generation of reactive oxygen species (ROS), temperature of operation (and thermo-mechanical effect), surface engineering, ultraviolet content and other unconventional methods. A limited number of these methods are in solar stills. At the same time, all of them are directly or indirectly realized in solar interfacial evaporator structures thanks to the precise architecture of nanomaterials for specific purposes.

6.1 Direct contact effect of nanomaterial

One of the hazardous of engineering nanomaterials that are repeatedly reported is their environmental toxicity through cellular uptake in biological systems. The amount of nanoparticles reaching the living cell would be associated with the exposure and concentration of nanoparticles in the medium, including water, food, and air while it would be multiplied by increasing contact time [167]. Moreover, physicochemical characteristics of nanoparticles, such as size, particle shape, surface chemistry, and surface smoothness/roughness have greatly impacted the interaction between cell structure and nanomaterial [168,169]. As a good example, nanoparticle size is crucially important as the interaction between nanoparticle and biological system occur at nanostructure's surface. By decreasing particle size, the surface area of nanoparticle extraordinarily increases (i.e., more atoms/molecules would be displayed in surface), which leads to highly surface reactive of nanoparticle, subsequently, destructive chemical reactions increases [169]. On the other side, the inactivation mechanism of pathogens with the size of nanoparticle has another interesting relation. Taking the interaction between bacteria and nanoparticle as a good example where large nanoparticles aggregate at particular site to dissolve bacteria while smaller particles can dissolved single cell membrane of bacteria not double cells membrane [170]. Moreover, different families of nanomaterial with different shapes such as ZnO, Ag, CNTs, graphene oxide, TiO_2 and chitosan through various mechanisms including aggregation and cell membrane damaging, metal chelation, disrupting membrane integrity, internalization, destructing DNA, ROS generation, etc. (Figure 9) against a wide range of microbes as antimicrobial agents have been employed [171–173]. For instance, graphene has powerful antibacterial capacity due to the sharp edges that break cells membrane integrity [174] while superior oxidation level of graphene augmented the microbicidal efficacy [175]. Moreover, the direct effect of various nanofluids such as

ZnO, Ag, Fe, CNT, Co, Cu etc. against different pathogens including, *escherichia coli, pseudomonas aeruginosa, enterococcus faecalis, staphylococcus aureus, salmonella typhimurium, yeast* and *vibrio cholera* in previous studies have been realized [176–178]. Further, metal ions penetrate cell membrane and directly interact with -SH, -NH and -COOH groups of nucleic acids and proteins to reduce protein saturation and destroy intracellular metabolism [179].

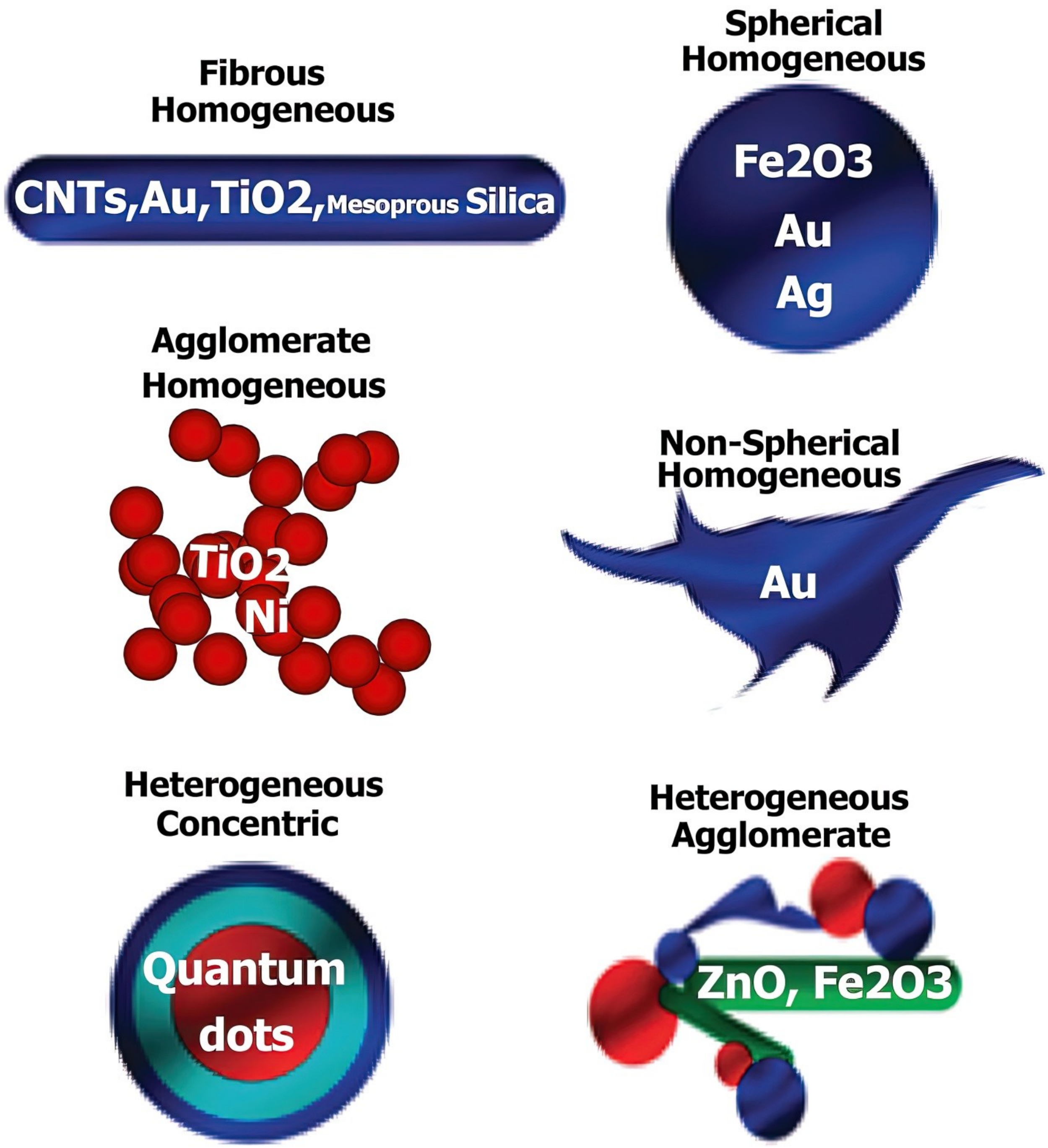

Figure 9. Nanomaterials at different shapes through different mechanisms affected living cells. These mechanisms are Internalization and membrane disruption (for spherical homogenous and heterogeneous concentric shapes), Internalization, membrane disruption, adverse effect on initiating of phagocytosis and blocking transport channels (for fibrous homogeneous shape), disrupting membrane integrity (for non-spherical homogenous), aggregation/agglomeration and membrane disruption (for agglomerate homogeneous and heterogeneous agglomerate). Reproduced from reference [169] with permission from Royal Society of Chemistry, copyright 2012.

6.2 Reactive oxygen species (ROSs) generation

ROSs called as “double-edged swords of life” [180]. It is important to remember that while ROSs in this context are usually pronounced as destructive to living cells, the moderate levels of ROS in biological systems is crucial for the functionality while higher levels damage living cells [168]. Indeed, a basal degree of ROS in cells is vital for life [180]. On the other side of the coin, it was mentioned that ROSs (H_2O_2, OH-,$^1O_2$ and $\cdot O^{2-}$) generation could be consider as one the most important mechanism of pathogens elimination in water as it can directly generate through a structure that particularly aim to produce ROSs or indirectly through other parameters such as UV and direct interaction of nanoparticles to cells. In essence, ROSs can boost pathogens deactivation directly and indirectly via different mechanisms such as protein denaturation, amino acid oxidation, damaging on RNA/DNA chromosomal, membrane lipid peroxidation, damaging plasmid DNA and oxidative stress (Figure 10) [181]. Importantly, novel nano-biocide strategies incorporated nanomaterials by ROS generation against AMR and multi-drug resistance (MDR) pathogens, presenting them as a powerful weapon in the coming battle against AMRs and MDRs [182].

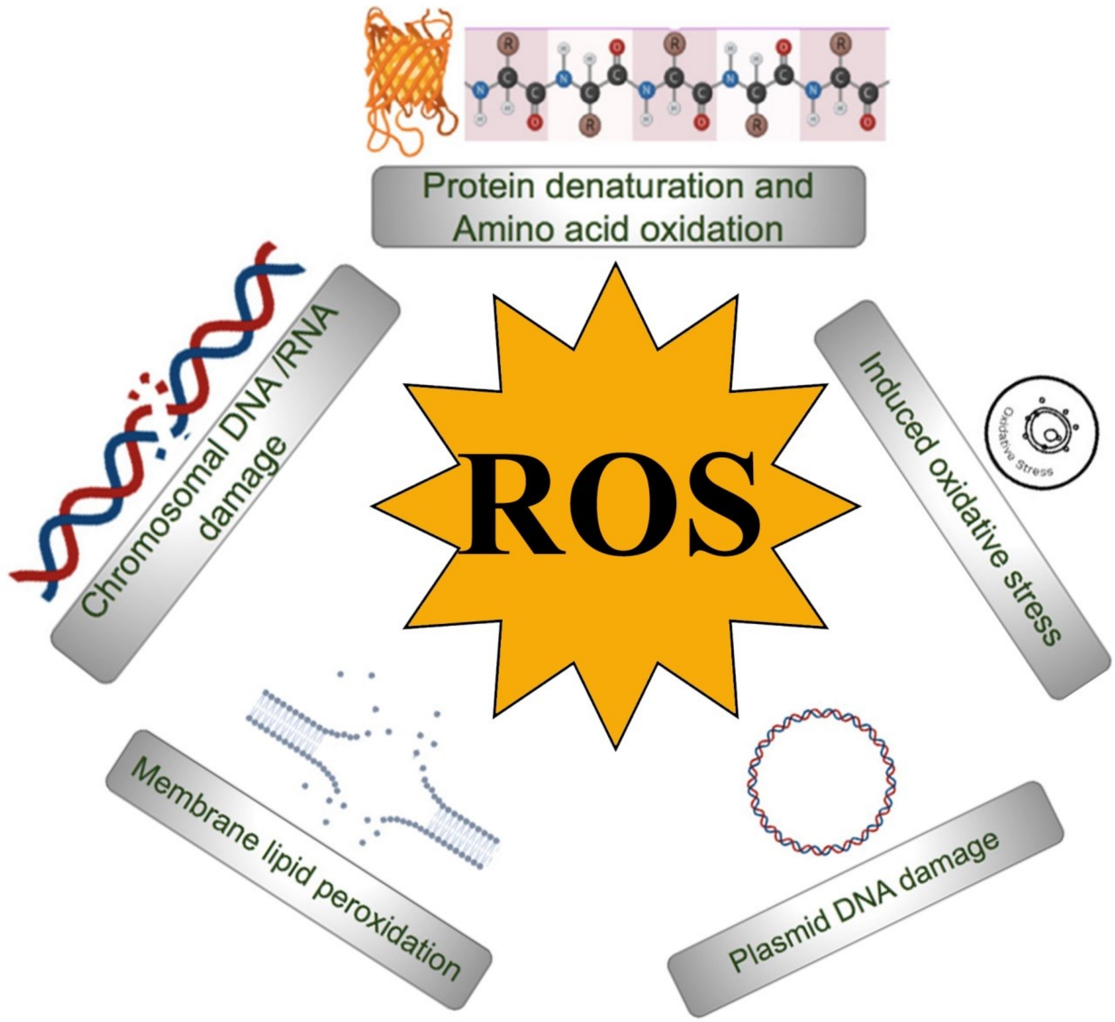

Figure 10. Five of the main mechanisms of pathogens elimination through ROSs generation. Reproduced with permission from open source reference [181] with permission from Elsevier, copyright 2023

6.3 Temperature of operation

High temperature has a negative effect on the microorganisms. Generally speaking, high-temperature results in greater decay level of microorganisms ascribed to the activated metabolism, fast nutrition reduction, overmuch competition between microbial communities and waste toxicity generation [183,184]. The direct/indirect damage on protein would define the mechanism of heat inactivation via hyperthermia on living cells. While for direct effect, the high temperature leading to direct damage of protein; for indirect mechanism, higher temperature leads to an increase the metabolic rate which results in augmenting the rate of ROS generation that damage protein via oxidation, aggregation, and denaturation (Figure 11) [185]. It was reported that the rate of bacterial deterioration would be twice when the temperature of the medium increase from 10ºC to 20ºC [186]. Indeed, this is the reason why *Salmonella enterica* and *Campylobacter jejuni* displayed rapid degradation in warmer environments [187]. For viruses, although numerous studies showed high temperature consider as a form of viral sterilization, that is not generally designated by viral temperature sensitivity [188]. In light of the COVID-19 pandemic, the temperature sensitivity of the coronavirus family (MERS, SARS-CoV-1, HCoV, MCoV) in water was reviewed, and it was found in a temperature range of 4-25 ºC the persistence of virus is between 2-25 days [189], however, enhancing the temperature exponentially increases the rate of reduction [190,191]. In pursuing the mechanism of viral inactivation due to temperature sensitivity, the later findings were in accordance with Murphy and Richman's previous findings in 1979 that stated “attenuation can result from a temperature-sensitive mutation in any gene”[192]. In a nutshell, even though the exact mechanism of viral inactivation as the temperature sensitivity may not realize, one possible explanation is that micro/nano changes in the structure of key viral enzymes influence folding of the enzyme as well as tertiary structure [193]. For instance, Loeb et al. decorated carbon black and gold nanorods on a thin film polymer for pathogen elimination through heat treatment. The reactor was designed to inactive pathogen when water flowed on the thin film. The results indicate that the surface temperature can swiftly excessed 75ºC which can ensure to inactive of the most heat-resistance pathogens, even viruses [194].

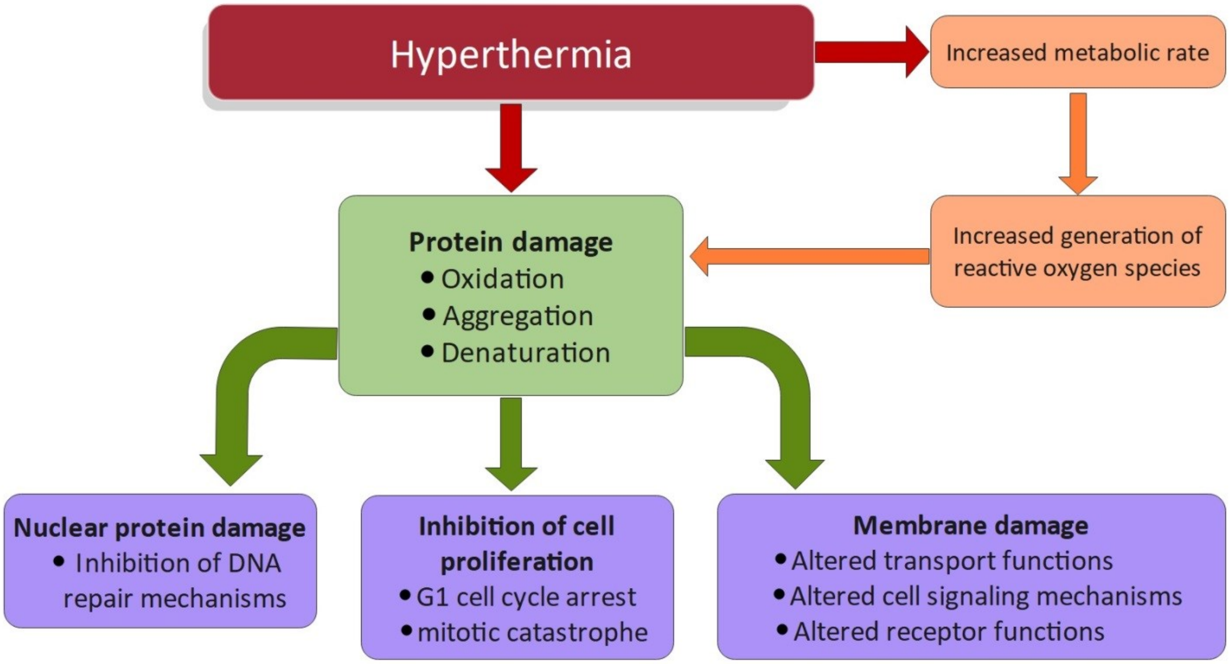

Figure 11. Possible mechanism of pathogen elimination thorough hyperthermia. Reproduced from open source reference [185] with permission from Intechopen, copyright 2013.

6.3.1 Thermo-mechanical effect

Thermo-mechanical damages indicated to the mechanical damage caused by pressure/sound waves that result in destruct to pathogen's structure through bubble generation and vapor explosion process. Accordingly, during the photothermal heating of nanoparticles in water media, a rapid thermal expansion of liquid in vicinity of them would lead to producing acoustic waves [75]. In such condition, if the generated temperature as the results of nanoparticle heating exceeds the critical temperature, the water nearby the surface of nanoparticle will start an explosive boiling, hence a vapor layer (bubble) formed around the particles [195]. Subsequently, the generated bubbles swiftly expand pressure waves, which disseminates into tissues and damage cell's membrane permeability barrier. Thus, cell's structure and functional parts are destroyed, leading to death of pathogen. Meticulously, the heat transfer analysis elucidates bubble production and cavitation damage is the cause of killing cells. Furthermore, temperature of nanoparticles as the results of isolating by the formed bubbles from surrounded liquid would increases [196]. This step accompanied by phase transition while certain mechanical, activation and thermal effect also occur during the collapse of bubble [197]. Thereafter, mechanical action damaging the permeability of cell membrane and destroys cell structure and function.

6.4 Surface engineering toward antimicrobial activity

Antimicrobial characteristics of tissues and textures has become a subject of growing interest, especially in the field of biomedical engineering via different health care scenarios from wound healing to body's internal protez, particularly (but not limited) medical implants [198,199]. In the earlier efforts in this context the focus of researchers was to minimize cell attachment however, recent endeavors mainly aimed to develop microbicidal surface [200]. Generally, three strategies are employed to develop antimicrobial surfaces which are the resistance approach, biocide approach and integration of resistance and biocide (Figure 12a,i-iii) [201]. Interestingly, many of antimicrobial surfaces are nature-inspired (particularly animal skins) because it is vital to maintain a biological system's surface clean (Figure 12b,i-iv). To attain each of these scenarios various nanomaterials including metallic biocides (Ag, Au, Cu), hydrophobic/hydrophilic structures, organic biocides (triclosan and econea), biological biocides (enzymes and peptides) and releasing active agents have been employed [201,202]. Nevertheless, graphene, TiO_2 and ZnO are well-established materials which extensively discussed for surface coating ascribe to their microbicidal activity [203,204]. Notably, carbon family (graphene oxide, CNTs, fullerenes), metallic and metal oxides nanomaterials and various polymers are among antimicrobial/antifouling structures that tremendously used for high performance membranes of reverse osmosis desalination [205]. Although the exact mechanism of each method is not the topic of this review, a brief example seems necessary. Carbon-based material such as graphene and CNTs suppress biofilm generation by mechanically splitting cells of biological species. Chemical feature of the nanomaterial with amine groups which are recognize to lyse bacterial cells further increase the microbicidal activity of the composite [206,207]. Interestingly, Ivanova and co-workers evaluated the antimicrobial efficacy of black silicon and dragonfly wing thorough their mechano-responsive surfaces against four type of gram-negative and gram-positive bacteria of *P. aeruginosa, S. aureus*, *B. subtilis vegetative* cells and *B. subtilis* (Figure 12c,i-viii) and reported ~450,000 cells $min^{-1}cm^{-2}$ elimination due to the superiority of black silicon and dragonfly wings capillarity over the elasticity of cells membrane [208].

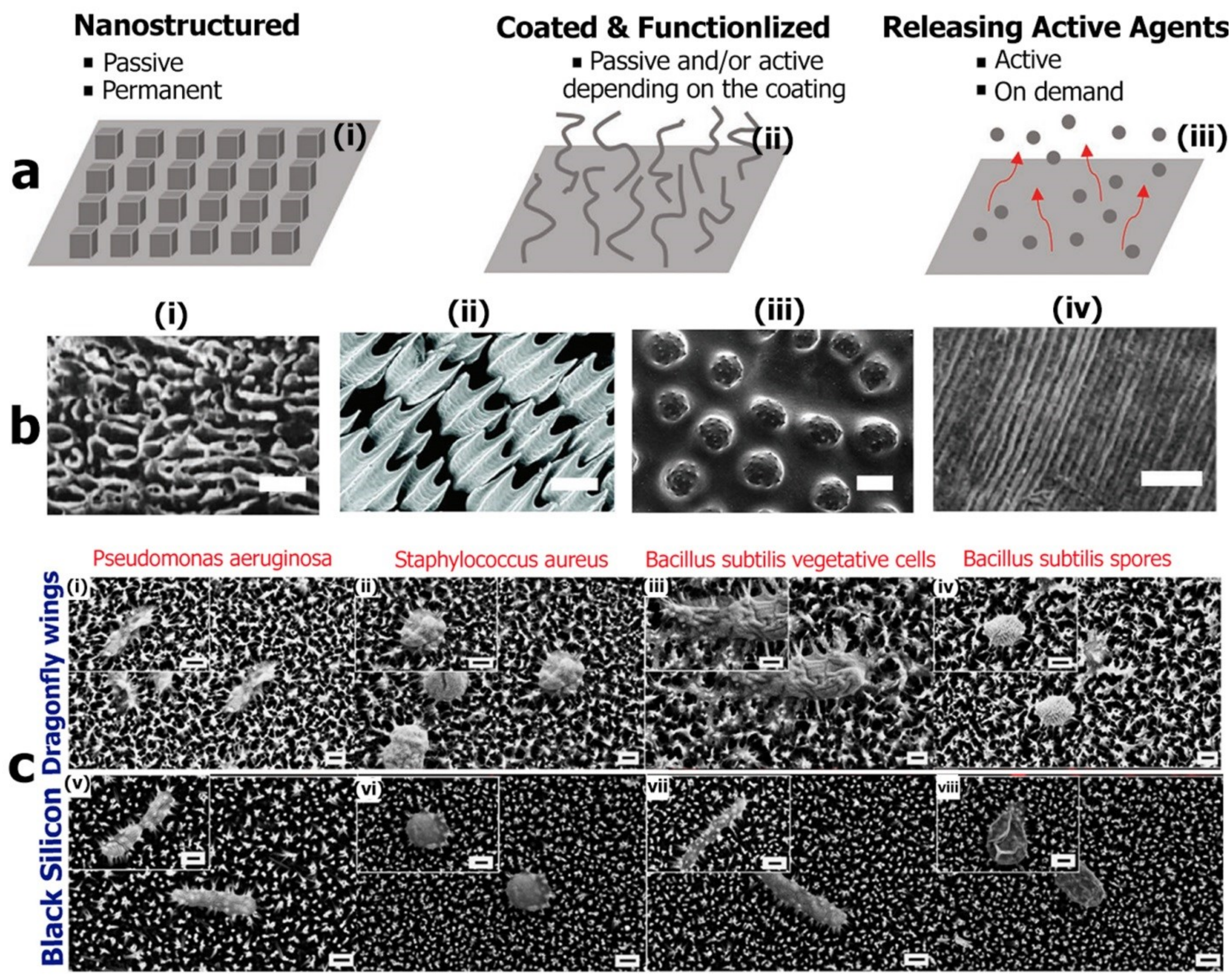

Figure 12. Surface engineering for antimicrobial activity. a) i-iii Main strategies adopted for passive and active antimicrobial surface Reproduced from reference [201] with permission from American Chemical Society, copyright 2022. B) i-iv, Nature-

based surfaces for designing antifouling surfaces inspired from pilot whale, shark, sea stars and mussels with scales 1, 100, 100, and 10 µm respectively. Reproduced from reference [202] with permission from Wiley-VCH, copyright 2017. C) i-iv and v-viii antimicrobial activity of dragonfly wings and black silicon against four gram negative/positive bacteria for 30 hours. The rate of cells elimination at both surfaces for the first 3 hours is almost constant by around 450,000 cells $min^{-1}cm^{-2}$ while for the rest of experiment it declined to 50,000 cells $min^{-1}cm^{-2}$. Reproduced from open source reference [208] with permission from Springer Nature, copyright 2013.

6.5 UV and visible light effect on pathogens

The negative effect of the ultraviolet on living cells is a broad field that should be carefully discussed. In general, the available ultraviolet wavelengths (i.e., UVA and UVB) on earth would be formed several types of DNA lesions. Microbicidal impact of ultraviolet may occur through two mechanisms of direct and indirect effect. The most frequent direct UVB-induced damage of DNA is by formation of cyclobutane pyrimidine dimers (CPDs) and pyrimidine (6–4) pyrimidone photoproducts - (6–4)PPs-. However, through an indirect process, UVA and UVB can raise the generation of oxidized DNA bases (Figure 13-a) such as 8-oxo-7,8-dihydro-2¢-deoxyguanosine (8-oxo-dG) [209]. The type of ultraviolet content categorized based on their wavelengths which was thoroughly discussed in previous studies [190]. Notably, UVC wavelengths (100-280 nm) are known as the most well-established germicidial method against pathogens. Its practicality during the pandemic for different purposes, from surfaces disinfection to air purification against the SARS-CoV-2, has been realized [210]. A conceptual framework on Photon-induced cellular damage in viruses and bacteria via direct and indirect pathways is presented in figure 13-b [211]. In direct pathway, photons affect chromophores at different sites of cells and subsequently cause damage in those specific points. In indirect pathway, photons affect sensitizers (*Sens*), which are endogenous or exogenous molecules that generate photo-produced reactive intermediates (PPRI). Importantly, endogenous *Sens* are apart of the cellular structure, while exogenous *Sens* are outside of cells, and as viruses have simple structures, we can overlook their indirect endogenous pathway. PPRI can cause damage in different parts of cells apart from their generation sites. While direct effect of UV on pathogens mainly occur at UVC wavelengths ascribe to the highest rate of absorption by nucleic acid which fall the ranges of 260-265 nm, the indirect effect of UV by generating ROSs would be derived by UVB (280-320 nm) and UVA (320-400 nm) wavelengths too. This is a very common phenomenon that utilize for solar water disinfection. Notably, the effect of sunlight would not limited to the UV wavelengths, but visible light wavelengths as the visible-light-driven photocatalysts by producing ROSs for water disinfection for a wide range of pathogens including E. coli, Bacteriophage MS2, S. aureus, B. subtilis, Salmonella, etc. have been proved to be effective enough in the context of photocatalytic disinfection [212]. Hence, pathogens' visible-light-driven disinfection can be considered as the sub-category of ROS mechanism. Interestingly, another method to directly eliminate pathogens in water media is to utilize upconverting materials [213]. Briefly, in this approach turning visible light photons into UVC wavelengths using lanthanide elements [214] has been proposed as powerful method against pathogens, however, regarding highly reactivity and low quantum yield this approach remain in the lab scale.

6.5.1 Direct effect of UV content on pathogens in aqueous media

In conventional solar desalination systems, black paint usually used to augment the rate of solar energy absorption (~ 400-700 nm), but in a number of researches, absorbing the full spectrum of solar energy (from 250-2500 nm) from far UV to near infrared wavelengths for SISGs are reported [215,216]. To do this, various materials by researchers such as silver nanoparticle (Ag) [217], reduced graphene oxides (rGO) [218,219], carbon nanotubes [220], carbonized paper-based materials [221], and mushrooms [222] have been adopted. Some of these structures can absorb all types of UV (i.e., full wavelengths of UVA and UVB and some parts of UVC) content and some of them absorb just parts of UV content (i.e., all UVA and some parts of UVB). Since our discussion here is for practical application of SISGs, we should not consider the absorption of UVC wavelengths by SISGs as it completely absorb by the Ozone layer, subsequently, it is logical only to consider the UVB and UVA wavelengths (Figure 13-a). The higher energy of UVB wavelengths leads to higher rate of microbicidal effect than UVA. The mechanism of the photo-inactivation of pathogens in water by UVB occurs through direct/indirect endogenous and indirect exogenous effect [223]. Indirect endogenous inactivation by UVB plays the main role while UVA and visible light effect are considered insignificant compared to UVB in this context. The number of studies on the germicidal effect of UVB on viruses, bacteria and protozoa is limited. However, it was reported that two bacteria (*Salmonella typhimurium LT2* and *Vibrio harveyi*) and one protozoan (*Cryptosporidium parvum*) effectively deactivated under UVB wavelengths [224]. Maraccini et al.[225] elucidated the impact of the simulated UVB sunlight on eight waterborne bacteria (*Bacteroides thetaiotaomicron, Campylobacter jejuni, Enterococcus faecalis, E. coli K12, E. coli O157:H7, Salmonella enterica serovar Typhimurium LT2, Staphylococcus aureus* and *Streptococcus bovis*) and reported the exogenous-induce photo-inactivation through the UVB has the main contribution in pathogens inactivation. On the other hand, inactivation of the aforementioned pathogens is under normal conditions with natural (or simulated) UVB with normal rate of absorption while in SISGs the rate of UVB wavelengths absorption is higher than 90% due to the use of modified nanostructured materials at different dimensions. Furthermore, it was reported that the synergy between UVA and UVB leading to induce faster inactivation of pathogens than the sum of UVA and UVB separately [226]. Hence, it can be concluded that the UVA and UVB wavelengths have contribution in pathogens elimination in water environment synergistically. Even though the impact of UV wavelengths absorption in SISGs structure on pathogens vulnerability was not the matter of researchers' concerns, previous studies showed that UVB wavelengths and their synergistic effect with

UVA can damage pathogens cells. However, behavior of different pathogens in aqueous environment at various UV wavelengths range could be varied case by case, subsequently, type of microorganism is of great importance.

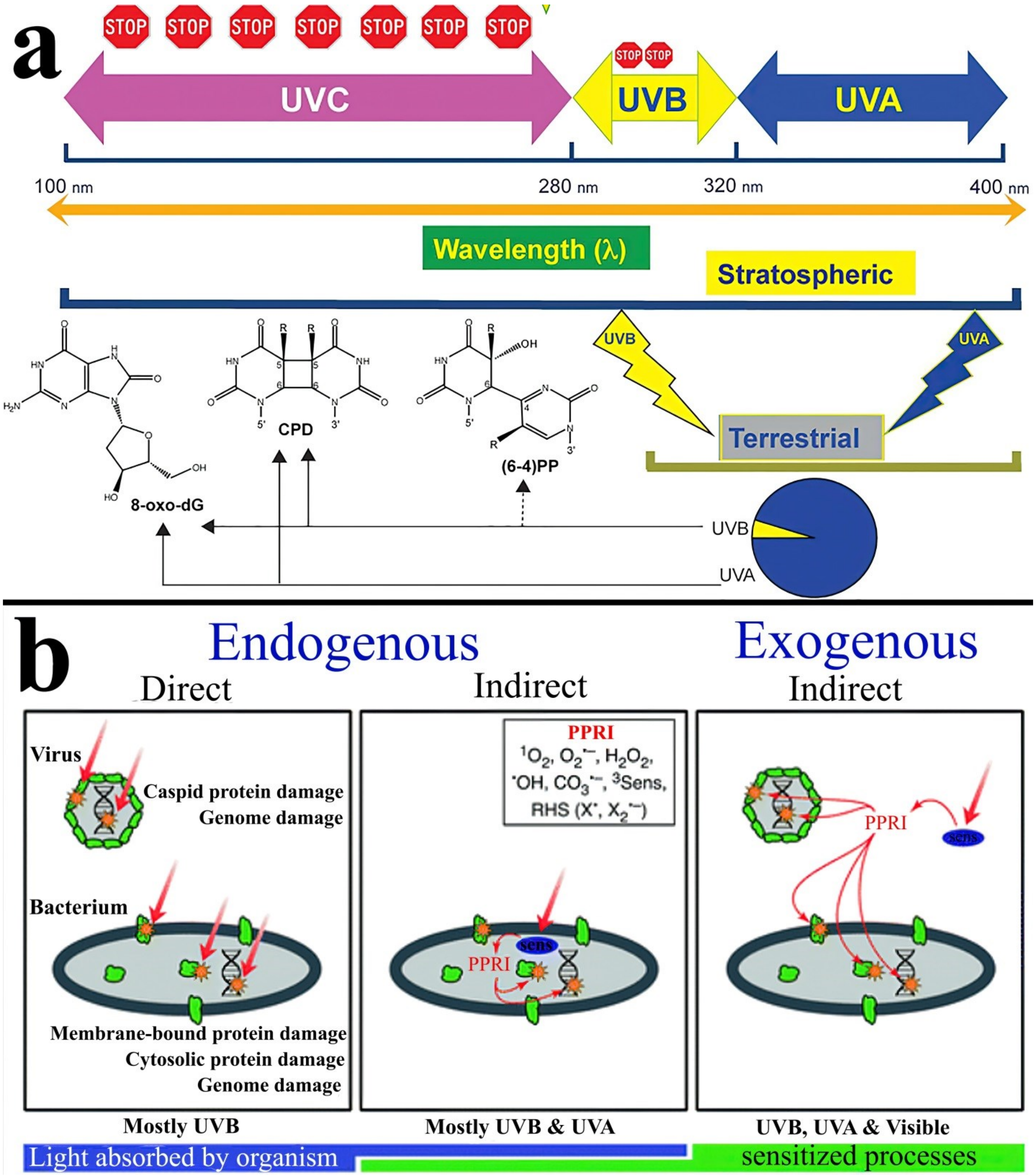

Figure 13. a) Solar UV spectrum incident on earth surface across 100-400 nm wavelengths, the UVC is completely absorbed by the ozone layer while a limited part of UVB and all UVA reaches on surface. UVA/UVB-induced DNA photoproducts are induced. Reproduced from open source reference [209] with permission from Royal Society of Chemistry, copyright 2012. b) A conceptual model of the solar inactivation mechanism in viruses and bacteria. In the direct mechanism, photons are absorbed by the chromophore at the damage site (orange star). In an indirect mechanism, photons are absorbed by the sensitizer (Sens) and results in damage (orange star) on different sites. Green shape represents protein. Reproduced from open source reference [211] with permission from Royal Society of Chemistry, copyright 2018.

6.6 Other antimicrobial approach

Several other approaches are not among the above-mentioned methods. Generally, these approaches are either the combination of the previous methods or could be structures that specifically designed as antimicrobial structures materials such as anti biofouling hydrogels, aerogels and foams. Importantly, some structures like polymers (in the context of SISGs) intrinsically have anti-biofouling features (such as microbial anti-adhesion structures [227]) while providing unique features for high-performance SISGs, making them as an excellent candidate for simultaneous desalination and disinfection. Moreover, some structures are fabricated to generate a hydration layer to increase the hydrophilicity of absorber and simultaneously weakening the interaction between microorganisms and surface of SISG, resulting in an anti-adhesion-biofouling nanostructure [228]. Furthermore, by removing the nutrients needed of biological species (i.e., fungi) such as starch and monosacharide form structures [229,230] (i.e., biomass-based such as wood etc.) growth of microorganism would be inhibited due to the cutting their energy needs for survival.

7. Effectiveness of solar interfacial evaporation and desalination against pathogens

As all parts of the puzzle are located in the right place, it is the time to pick the final pieces and putting them in the appropriate place. So far, systems mechanisms, pathogens' characteristics with great emphasized on AMR pathogens and their ways to contaminate water bodies are elucidated. Various mechanisms of nanomaterial and strategies against biological species are discussed. The next section discusses the effectiveness of systems for providing safe drinking water characteristics.

7.1 Solar stills against pathogens

Application of solar stills for separating various impurities including pharmaceutical [231], wastewater impurities [232,233], mineral impurities [234], pesticides [235] etc. have been performed in several studies, however, limited studies brought the biological species removal by solar stills into the spotlight, however, the bacterial transmission through vapor to distilled water were reported [236–238]. Recently, Parsa [191] in a theoretical study stated that if the feed water of solar stills would be contaminated by SARS-CoV-2 during the COVID-19 pandemic the system might not be capable to remove the virus ascribe to pathogens transmission through vapor due to extremely small size (60-140 nm) of novel coronavirus. Importantly, the use of nanomaterial to with this purpose to explicitly inactive pathogens in solar stills has not been performed yet. In this regard, the practicality of nanomaterials for eliminating pathogens remains a question. Although several researchers utilized antimicrobial nanomaterial in solar stills to purify biological contaminated water, biological species were not in the feed water. Indeed, researchers assumed that since the utilized nanoparticles have well-known antimicrobial characteristics, utilizing them would results in pathogens elimination. Sadeghi et al. utilized $Ag@Fe_3O_4$ hybrid nanofluid as an antibacterial agent in solar still and reported 218% improvement in productivity. Parsa and co-workers. [4,146] employed silver nanofluid in a single-slope solar still for simultaneous desalination and disinfection of biologically contaminated water. Even though, the feed water of solar still was not infected by microbial community, they concluded that the system is efficient against biological contaminated water regarding the presence of silver nanoparticles ascribe to the antimicrobial characteristics of Ag. It should be mentioned that the mechanism of nanomaterial for pathogen elimination is based on the direct intervention of nanomaterial by damaging to different parts of structure. However, the practical application of nanomaterials against pathogens in solar stills is not clearly realized yet.

7.2 Solar interfacial evaporation against pathogens

Studies on SISGs against pathogen communities mainly focused on the bacteria but other pathogens are examined in this context. The reason for more use of bacteria to evaluate the antimicrobial characteristics of structure could be associated with bacteria being more manageable for experiments, and detecting them in different media, including aqueous media, is simpler and cheaper than other pathogens. Importantly, studies on SISGs against biologically contaminated water have two avenues. The first one is purifying water from pathogens in order to be drinkable for human consumption, which is the main focus of our study. Secondly, SISGs were used as a low-cost sterilization system to produce high-temperature steam for medical sterilization. In the following, application of SISGs against pathogens and microorganisms is thoroughly discussed, however, at the end of this section a brief discussion on solar steam sterilization is also presented. It is important to note that some studies do not directly evaluate SISG's performance against pathogens; however, the structure intrinsically is powerful for eliminating pathogens. For instance, Fan et al. [239] fabricated a hybrid hydrogel nanostructure consisting of perovskite oxide and MXene for photocatalytic-photothermal steam generation and purification. They reported that perovskite oxide due to the absorption of shortwave photon and producing active oxidative species has high photocatalytic activity where 97.2% tetracycline hydrochloride degradation by breaking functional groups, ring-opening and oxidize reactions, and decomposing pollutants into harmless chemicals such as CO_2, H_2O and NH_3 obtained while high photo-thermal efficiency of 92.3 % was recorded.

7.2.1 SISGs vs. Bacterial

Chen et al. [240] presented a copper-based ploy-shells nanocomposite multifunctional SISG for simultaneous desalination and disinfection of contaminated water. They used E. coli as the bacteria sample in impure water to evaluate the microbicidal efficiency of the structure. Findings revealed that the proposed CuO/Cu_2O structure has an extraordinary microbicidal performance due to the continuous generation of hydroxyl (HO•) and superoxide ($O^-{}_2$) radicals which results in complete inactivation of the *E.coli.* Xu et al. [241] showed a multifunctional copper oxide nanowire mesh (Fig 14a-i) by activating potassium monopersulfate for solar steam generation is capable of purifying water from methyl orange while eliminate pathogens, including *staphylococcus aureus* and *E. coli* (Fig14a-ii). The antibacterial mechanism of the system was realized by damaging the intracellular structure of the pathogens due to the releasing positive copper ions into cell membrane. Noureen et al. [242] proposed a nanocomposite structure based on Trisilver phosphate and reduced graphene oxide (Ag_3PO_4/rGO) coated on textile (Fig14b-i) for desalination and disinfection of seawater contaminated by *staphylococcus aureus* and *E. coli*. The antibacterial activity of fabrics for different scenarios with/without Ag and rGO (Fig14b-ii) was compared. It was revealed that the bactericidal activity of the nanocomposite through formation of ROS by silver ions is highly effective through denaturation and oxidation of microorganism structure, leading to 99% inhibition of pathogens in contaminated water (Fig14b-iii). Qiao and co-workers fabricated an all polymer polyacrylonitrile-bisphenol A (PAN-BPA) 2D membrane and turn it into a 3D structure by gas foaming for highly efficient SISG (Fig14c-i). The finding showed that PAN-BPA has 3.7 fold reduction (Fig14c-ii,iii) on bacterial community due to intrinsic anti-biofouling characteristic of PAN-BPA polymer foam compare to bare PAN [243]. Xia and co-workers fabricated a TpPa covalent organic framework wrapped by in-situ growth of flower-like MoS_2 for highly efficient SISG. The effect of antimicrobial activity of structure by four marine bacteria of *E. coli, S. aureus, P.Aeruginosa,* and *VP* was examined (Fig14d-ii). The results indicated that due to high-temperature operation at the surface by around 67.8 ºC and 78.5ºC in 20 and 120 seconds respectively (Fig14d-i), the structure has superior effectiveness for complete removal of most pathogens [244]. Huang et al. evaluated the antibacterial activity of a laser-engineered graphene on natural wood in solar steam evaporator and reported antibacterial activity against E.coli. It was found that simultaneously damaging pathogen's cell and electrostatic repulsion between the negative charged surfaces of hydrophilic laser-engineered graphene and pathogen [245] were led to antimicrobial activity. Wen and co-workers coated polyurethane and polystyrene foam on surface of zwitterionic (Fig15a-i,ii) hydrogel for efficient solar steam evaporation and anti-adhesion of biological species. Their findings illustrated that the structure maintains superior productivity of 2.2 $kg.m^{-2}h^{-1}$ while reduce the pathogens *E.coli, S. aureus* and algal ditaom by around 96.2%, 86.5% and 100% respectively (Fig15b-c) [228].

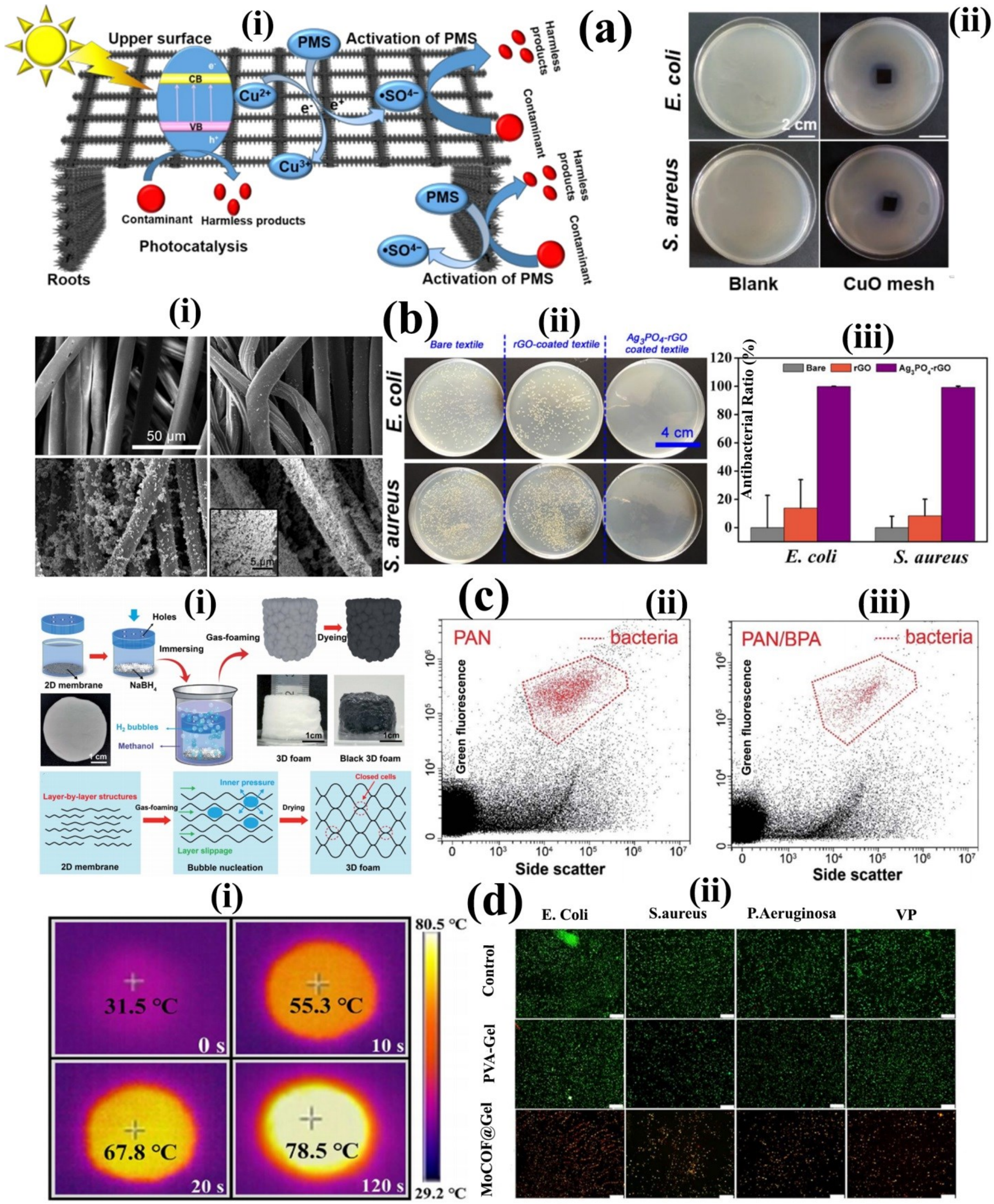

Figure 14. a-i) Schematic of multi-purpose CuO nanowire mesh in pollutant decomposition by solar interfacial evaporation. a-ii) Diffusion inhibition test of E. coli and S. aureus. Reproduced from reference [241] with permission from American Chemical Society, copyright 2019. b-i) SEM images of Ag_3PO_4-rGO coated on textiles at different concentrations from 2-24 mg/cm^2. b,ii-iii) biological test of bare textile, rGO and Ag_3PO_4-rGO for E. coli and S. aureus and their antibacterial ratio respectively. Reproduced from reference [242] with permission from American Chemical Society, copyright 2020. c-i) Fabrication process of

3D polymer foam through the gas-foaming method and the bubbling process. c,ii-iii) The flow cytometric results in 2D dot-plots. Red dots in the cluster illustrate bacterial cells from the foam for polyacrylonitrile (PAN) and bis-phenol A (BPA), respectively. Reproduced form reference [243] with permission from Royal Society of Chemistry, copyright 2021. d-i) IR images of MoCOF under one sun at various exposure times. d-ii) PVA-Gel and control groups display strong green fluorescence, showing high bacteria survival. The MoCOF@Gel group displays strong red fluorescence, indicating that huge amounts of bacteria have been eliminated. Reproduced from reference [244] with permission from Elsevier, copyright 2022.

Moreover, Zhang et al. reported over 95% removal of S. aureus bacteria and Nitzschia algae in monolithic Mxene-graphene oxide on PVDF membrane as the results of the anti-adhesion feature of structure and electrostatic repulsion effect [246]. To investigate the antibacterial effect of a graphene-chitosan/ZnO structure (Fig15d and e-i), Xiang and co-workers [247] cultivated *E.coli and S. aureus* in water for three days and measured the photothermal efficiency of the system. The results showed that the photothermal efficiency of the system in the presence of *E.coli* and *S. aureus* stand at 89.4% and 89.7%, which has a marginal reduction by around 1.4% and 1.1% compared to the original efficiency (90.8%) (Fig15d-ii) that attained without presence of microbial community ascribe to inhibitive bio-fouling nature of the structure. Wang et al. constructed a light-weight ethyl cellulose microspheres-based aerogel with polypyrrole as solar evaporator (Fig15h-i) and sprayed poly ionic liquid for antibacterial activity of the structure. The evaporator located in *Staphylococcus aureus* medium for 20 hours and no bacterial activity was observed as the results of electrostatic repulsion between the negatively charged surface and pathogen (Fig15h-ii) [248]. Hou et al. developed a vanadium oxide-based thin film for solar steam generation and disinfection by assisting haloperoxidase catalyze. Findings exhibit that in the presence of H_2O_2, oxygen-rich V_6O_{13} prompts conversion of Br^- to HbrO, leading to inactivate *E.coli* as the results of acidic activity of HbrO [249]. One important thing that should be highlighted in this context is that while SISGs is capable to produce high-temperature steam for sterilization and pathogens elimination, when the system aims to produce clean water, the generated steam is produced at lower temperature ranges even as low as ~40°C (Fig15g-i). Therefore, it may become a concern about transferring pathogens via steam -just like it happens in solar stills- since pathogens at low temperatures remain viable. Interestingly, Higgins et al. [250] explicitly focused on this problem and conducted experiments with biologically contaminated water to examine whether pathogens in SISGs can transmit in low temperatures via steam or not. They proposed a low-cost structure consisting of coated candle soot on the surface of cotton cloth and used polystyrene as the floating structure. Findings revealed that the produced water is free of bacteria which verified the effectiveness of the SISGs against bacteria (Fig15g-ii). While, this study can assure us about the effectiveness of SISGs when contaminated water used as the feed water the authors have not mentioned the type of pathogen, and its characteristics such as the size of particle.

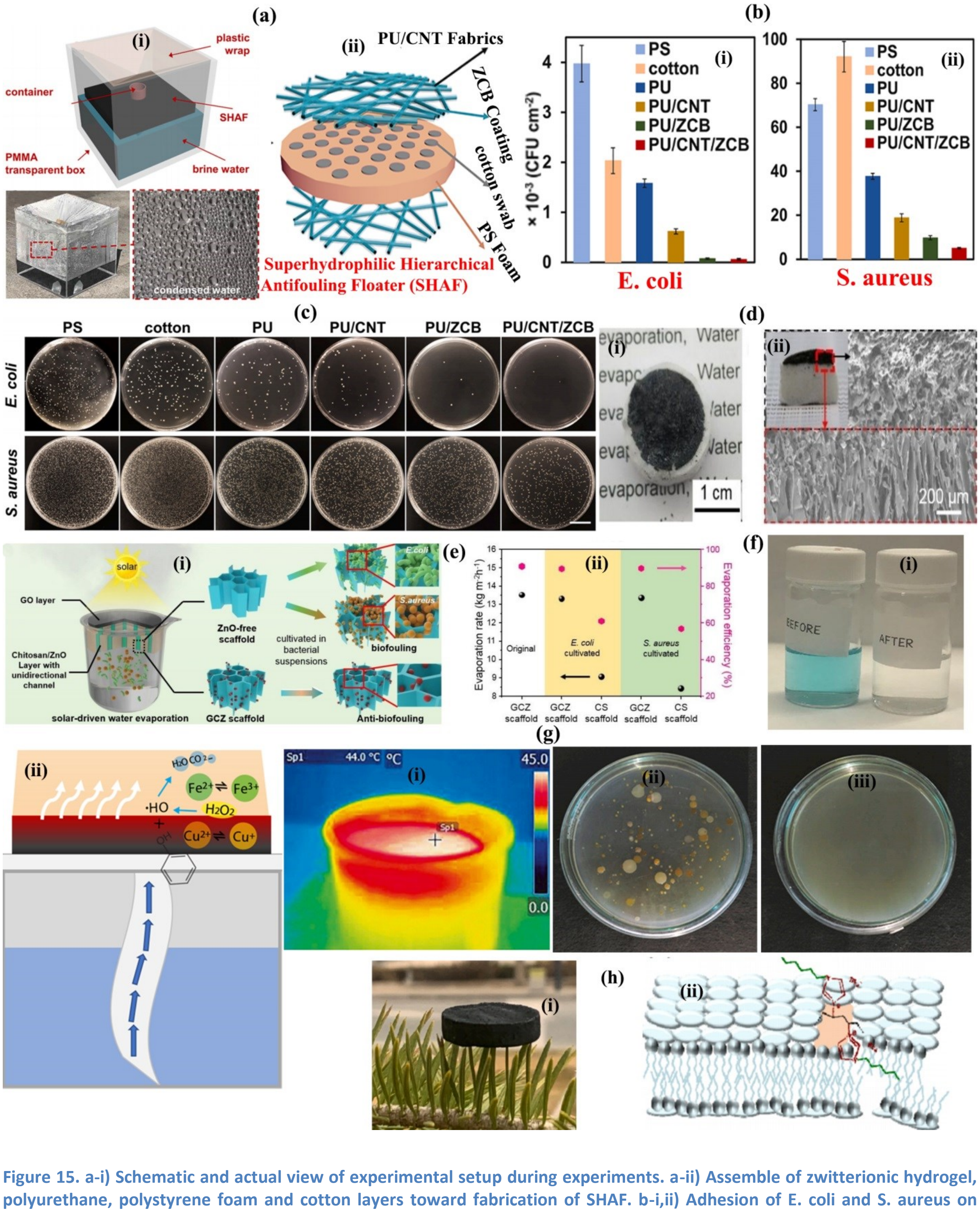

Figure 15. a-i) Schematic and actual view of experimental setup during experiments. a-ii) Assemble of zwitterionic hydrogel, polyurethane, polystyrene foam and cotton layers toward fabrication of SHAF. b-i,ii) Adhesion of E. coli and S. aureus on different fabrics including SHAF. c) The actual image of E. coli and S. aureus on different fabrics showed that the SHAF tremendously inhibited bacterial growth. Reproduced from reference [228] with permission from Elsevier, copyright 2021. d-i) Optical image from the top of GCZ structure and (d-ii) the longitudinal section of the GCZ structure with SEM image. e-i) Schematic of a solar interfacial evaporation based on GCZ scaffolds with a double-layer structure: the graphene oxide top layer act as solar thermal transvector and the chitosan/Zinc-oxide in the beneath layer act as water channel. Compared with

the Zinc-oxide-free GC scaffold that suffers from channel clogging ascribed to bio-fouling phenomenon, the GCZ maintained a one-way porous structure for transporting water after several days of culture in bacterial suspension. e-ii) Evaporation rate and photothermal efficiency of GCZ and CS with E, coli and S. aureus. Reproduced from reference [247] with permission from Royal Society of Chemistry, copyright 2019. f-i,ii) Optical image of methylene blue before and after purification and integration of solar steam generation with photo-Fenton device respectively. Reproduced from reference [251] with permission from Elsevier, copyright 2019. g-i) IR image of candle soot coated modified system after 30 min. g-ii,iii) Optical image of biological colonies in sewage and treated water respectively. Reproduced from reference [250] with permission from Elsevier, copyright 2019. h-i) Schematic of light-weight polypyrrole modification of the crosslinked ethyl cellulose microspheres. h-ii) S. aureus membrane disintegration and leakage of bacterial cytoplasm through electrostatic interaction. Reproduced from reference [248] with permission from Elsevier, copyright 2022.

7.2.2 SISG vs Protozoa

The application of SISGs against protozoa has not been realized in any study. However, several other researches have been conducted on other approaches, that might not directly relate to SISGs but indirectly lead to their effectiveness against protozoa. We focus on *cryptosporidium parvum* since a considerable portion of the protozoa-based water-related outbreaks were because of this protozoa [252]. Photo-Fenton is one of the well-established oxidation-based processes that is widely used for disinfection of different pathogens in ground water, drinking water, wastewater treatment plant [253] and VOCs [254]. Lamiero et al. applied the photo-Fenton process to realize sensitivity of *cryptosporidium parvum* under different conditions and reported higher concentration rate of Fe^{2+}/H_2O_2, lowest pH and longest exposure time results in inactivation of *cryptosporidium parvum* by around 91 ± 3.63% [255]. The other parameter in inactivation of protozoa is the available solar UV (i.e., UVA and UVB). Busse and co-workers conducted series of experiment to realize the effectiveness of available UVB at sea level on inactivation of two bacteria of *salmonella typhimurium LT2, Vibrio harveyi* and *cryptosporidium parvum* protozoa and reported high rate of pathogens inactivation in range of 318-330 nm (i.e., upper-UVB or lower-UVA) because of damaging DNA [224]. Furthermore, Liu et al. examined the mechanism of *cryptosporidium parvum* inactivation by solar UV and visible light and stated that the UVA and visible light effect on inactivation of pathogen results in endogenous ROS generation while UVB directly damages the genome of pathogen [256]. Interestingly, Shi et al. [251] integrated a 3D evaporator ceramic-like $CuFeMnO_4$ with photo-Fenton reaction (Fig. 15f-ii) for organic degradation from contaminated water resource and solar steam generation. Their findings showed that the highest removal of phenol (>99%) and methylene blue (Fig. 15f-i) obtained at highest concentration of H_2O_2 (0.15 M) while the evaporation rate and photothermal efficiency examined around 1.45 $kg.m^{-2}h^{-1}$ and 91% respectively. Similarly Lei et al. [257] in a preprint presented a polypyrrole/1T-2H MoS_2 structure for simultaneous solar water evaporation and organic degradation by photo-Fenton process and reported >99% removal of methylene blue. As can be see, the SISGs with the capability of photo-Fenton process is a novel but promising method which can be effective against pathogens - particularly protozoa and viruses- in this context; however, there is no study to explicitly focused on solar interfacial steam generation with photo-Fenton process for pathogens elimination.

7.2.3 SISGs vs. Viruses

The number of studies on the effectiveness of SISGs against viruses is rare. Chen et al. [258] fabricated an amorphous hollow fiber tantalum pentoxide carbon nanocomposite as an all-in-one ultra-high efficient solar steam generator (Fig. 16a-i). The proposed structure showed exceptional efficiency in removing different organic and inorganic contamination even radioactive contaminated water. Importantly, in response of the COVID-19 leading to contaminate water bodies, the authors examined the performance of structure for purifying water containing *pseudovirus SC2-P* (expressing the SARS-CoV-2 S protein) and reported 6log reduction of the pathogen (Fig. 16a-ii) which means the proposed system is strong enough to eradicate the novel coronavirus in an aqueous environment.

7.2.4 SISGs vs. Antimicrobial resistance (AMR)

Interestingly, Li et al.[259] in a novel approach presented an all-fiber porous foam containing aggregation-induced emission luminogens (AIEgens) 3D solar evaporator with bactericidal activity through the generation of ROS. By taking advantage of the plasma treatment and gas foaming method the 2D mat fiber turn into 3D structure and the height of the evaporator in 10, 30, 60 minutes was increased to 1, 3 and 5 cm respectively (Fig. 16d-i,ii). Performance of the structure after 5 cycles of bacterial activity revealed that the proposed structure can completely eliminate three bacteria of *E. coli, Staphylococcus epidermidis, S. aureus*, and more importantly, one type of AMR, *methicillin-resistant Staphylococcus aureus (MRSA)* (Fig. 16d-iii). Impressively, this was the first study that evaluated SISGs' effectiveness against an AMR pathogen. Moreover, Ebrahmi and co-workers [260] decorated single and double-layer Ag@rGO on natural wood (Fig. 16b-i,ii) as the substrate for highly efficient solar interfacial evaporation as well as antibacterial structure. The experiments were performed for different scenarios where rGO act as the bottom layer and top layer under 3 Suns. It was reported that rGO as the bottom layer has better performance than the upper due to lower thermal conductivity and hydrophobicity feature compared to Ag. Moreover, their biological test elucidates that the structure could effectively eliminate MRSA pathogen (Fig. 16c, i-iv).

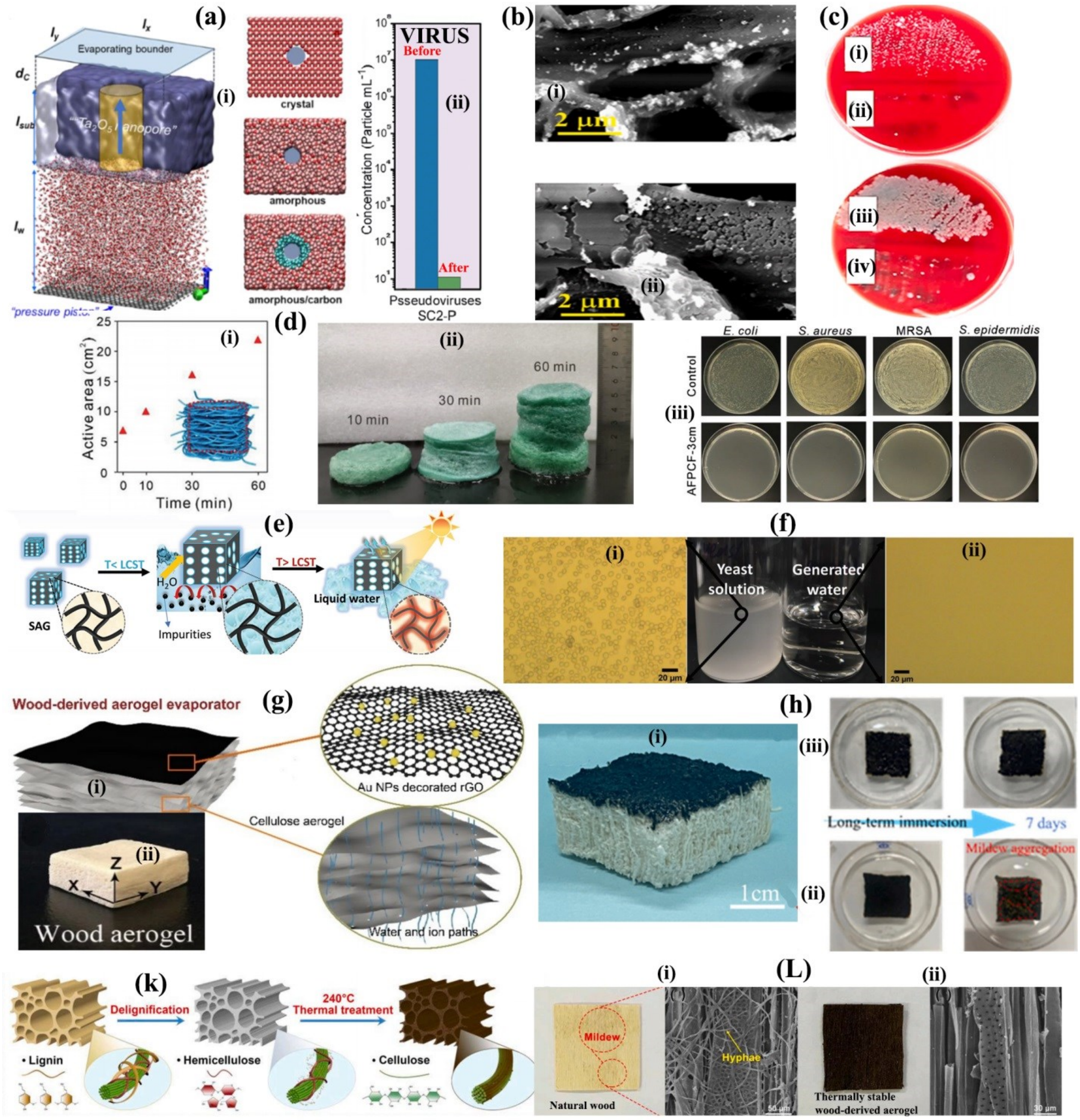

Figure 16. a-i,) Schematic of tantalum pentoxide solar evaporator (left side) and atomic structure of three substrates (right side). a-ii) Concentration of pseudovirus SC2-P (presenting the SARS-CoV-2 S protein) before and after evaporation process. Reproduced from reference [258] with permission from Wiley-VCH, copyright 2022. b-i,ii) Wood coating by silver and rGO nanoparticles respectively. c-i,ii) growth of S. aureus on bare wood and wood-based silver coated solar evaporator after 4 hours. c-iii,iv) growth of S. aureus on bare wood and wood-based silver coated solar evaporator after 24 hours. Reproduced from reference [260] with permission from Elsevier, copyright 2022. d-i) Active solar steam generator structure area after treatment with 1 m NaBH4 solution for 10, 30, and 60 min. d-ii) Photograph of the nanofibrous structure mat after different treatment times. d-iii) Photograph for selected pathogens including MRSA cultured on agar plate supplemented with solar evaporator structure under for 10 min. Reproduced from reference [259] with permission from Wiley-VCH, copyright 2021. e) Stages of nature-inspired gel-based solar absorber for purification of contaminated water by phase transforming. f-i,ii) evaluating the presence of yeast before and after purification. Reproduced from reference [261] with permission from Wiley-VCH, copyright 2021. g-i) Evaporator structure with an Au nanoparticle decorated rGO layer and a wood aerogel substrate

which preparing by drop coating and the chemical treatment. g-ii) Optical image of wood aerogel. Reproduced from reference [262] with permission from American Chemical Society, copyright 2020. h-i) Actual image of Ag-doped bamboo shoot porous carbon. h-ii,iii) Bactericidal test of bamboo shoot porous carbon and Ag-doped bamboo shoot porous carbon in pure water for 7 consecutive days. Reproduced from reference [263] with permission from Elsevier, copyright 2022. k) Schematic process of removing lignin and hemicellulose of wood. L-i,ii) Morphology of the natural wood and thermally wood aerogel surface regarding formation of mildew after floating on the river for 60 h, respectively. Reproduced from reference [264] with permission from Elsevier, copyright 2021.

7.2.5 SISGs vs. Fungi

A monolithic nature-inspired (by pufferfish mechanism) based on the phase transformation (swelling/de-swelling) consist of thermo-responsive poly $(C_6H_{11}NO)_n$ hydrogel, polydopamine layer, and sodium alginate (Fig. 16e) was fabricated by Xu and co-workers [261] for high efficient solar evaporator. The microbicidal efficiency of structure was evaluated by placing it in contaminated water containing 0.1% *yeast* and it was found that the produced water is free of any microorganism (Fig. 16f-i,ii). However, the exact mechanism of antimicrobial activity was not explained. Since forming mildew on biomass surfaces contacting with natural rich-nutrient water bodies is commonly phenomenon, several researches focus on the mildew-resistance SISGs. Zhang et al.[262] compared the performance of wood-based solar evaporator for continuous operation and reported that after 60 hours the evaporation rate and photothermal efficiency due to mildew film formation reduced by around 31.5% and 33.6% respectively. By modifying the internal structure of wood with Au-rGO mildew-resistance (Fig. 16g-i,ii), the evaporator reached 1.394 $kg.m^{-2}h^{-1}$ for 120 hours operation whereas neither mildew formation nor significant changes in performance was observed. Similarly, Chen et al. [263] impregnated Ag microspheres in bamboo shoot carbon porous to take the advantage of silver microbicidal activity for long-term application of double-layered SISGs (Fig. 16h-i). The continuous 24 hour test with and without silver indicated the severe effect of mildew formation on diminishing evaporation rate by around 25.7% while for structure with Ag no mildew was detected (Fig. 16h-ii,iii). Meng and co-workers [264] fabricated a wood-based aerogel mildew-resistance 3D solar evaporator for long-term stability via two steps methods which was treating by $NaClO_2$ aqueous and thermally-treatment to remove lignin and hemicellulose respectively (Fig. 16-k). A comparison between natural wood and modified evaporator for 60 hours in natural seawater showed that natural wood was severely infected by mildew while no mildew plaques were observed for modified evaporator (Fig. 16L,i-ii).

Table 6. Summary of different types of SISG structures through inactivation of microorganism-contaminants in water

Type of biological species	Name of pathogen	Type of materials	Solar Intensity (kW/m^2)	Productivity (kg/m^2)	Efficiency (%)	Number of cycles	Mechanism of inactivation/elimination	Ref
Bacteria	*E. coli*	Multi-shell CuO-Cu_2O		3.2	77	-	Continuous ROS generation (hydroxyl "HO•" and superoxide "$O^-{}_2$" superoxide)	240
Bacteria	*staphylococcus aureus and E. coli*	CuO Nanowires	1	1.42	84.4	5	damaging the intracellular structure of the pathogens by releasing positive Cu ions into cell membrane	241
Bacteria	*staphylococcus aureus and E. coli*	Ag_3PO_4-rGO coated on textile	1	1.31	86.8	7	ROS generation through Ag ions	242
Bacteria	-	polyacrylonitrile and bis-phenol A epoxy polymer foam	1	2.69	-	5	Intrinsic antimicrobial activity ascribe to formation of hydrophilic polymers by the nanofibrous walls of the closed cells	243
Bacteria	*E. coli, staphylococcus aureus, P. Aeruginosa, and VP*	Encapsulated TpPa-covalent organic framework into MoS2	1	2.31	91.8	-	High temperatures operations damage cells structure	244
Bacteria	*E. coli*	Graphene + natural wood	1	1.6	110	-	Direct contact by nanomaterial results in break pathogens' cell membrane integrity ascribe to the sharp edges and superior oxidation rate of graphene	245
Bacteria + Algae	*E. coli, staphylococcus aureus and and Navicula parva*	Polyurethane@CNT fabric and polystyrene foam on zwitterionic hydrogel	1	2.2	93.5	-	The zwitterionic hydrogel immobilized on polyurethane fabrics lead to formation of hydration layer through ionic solvation and intrinsic anti-biofouling	228
Bacteria +	*Staphylococcus*	MXene-graphene	0.5	10.5	92.5	10	Formation of hydration layer	246

Algae	*aureus, Candida albicans Nitzschia*	oxide+ commercial PVDF membrane					between structure and microorganism Electrostatic repulsion between the negatively charged membrane surface and the negatively charges on the surface of microorganism	
Bacteria	*E. coli, staphylococcus aureus*	Graphene oxide with Chitosan/ZnO	10	13.5	89.4-89.7	10 (for 3 days)	Direct contact with nanomaterial	247
Bacteria	*staphylococcus aureus*	polypyrrole + crosslinked ethyl cellulose microspheres based aerogels and sprayed poly ionic liquid	1	1.6	90.86	10	poly ionic liquid with positively charged imidazole rings impacted the negatively part of the phospholipid bilayer through electrostatic interaction, leading to rupture of pathogen membrane and leakage of pathogen cytoplasm.	248
Bacteria	*E. coli*	vanadium oxide-based thin film	1	1.25	85.3	15	High acidic environment through generation of hypobromous (HBrO)	249
Bacteria	-	Candle soot coating on surface of cotton	1	0.95	80	10	Separating microorganism through evaporation process	250
Virus	*Pseudovirus SC2-P (expressing as the SARS-CoV-2 S protein)*	Amorphous tantalum pentoxide + carbon	1	4.02	-	24 hours (for 30 days)	Separation process during interfacial evaporation	258
Bacteria + AMR	*E. coli, Staphylococcus epidermidis, Staphylococcus aureus and Methicillin-resistant Staphylococcus aureus*	aggregation-induced emission luminogens materials	1	3.6	-	24 hours	Photodynamically elimination of pathogen through ROS generation	259
AMR	*Methicillin-resistant Staphylococcus aureus*	rGO + Ag Nanoparticle coated on the surface of natural wood	3	5.99	92.91	11	Direct contact with rGO/Ag nanostructure results in to damage pathogen's cell membrane	260
Fungi	*Yesst*	Poly(N-isopropylacrylamide) hydrogel, polydopamine layer and sodium alginate network	1	7.18	-	10	Sodium alginate layer act as filter against various organic/inorganic fouling including biofouling	261
Fungi	*Mildew*	Au decorated on rGO layer on a wood-	1	1.39	90.1	24 hours (for 5	Removing starch and monosaccharides as nutrient for	262

		based aerogel				days)	mold	
Fungi	*Mildew*	Ag microparticle doped bamboo shoot porous-carbon	1	1.51	86.8	20	Direct contact with Ag nanoparticle inhibited the growth of mildew	263
Fungi	*Mildew*	Wood-based aerogel	1 and 3	1.17	85.9	20	Removing starch and monosaccharides as nutrient for mold	264

7.2.6 High-temperature steam for sterilization

Recently, researchers shed light on the feasibility of using SISGs as high-temperature steam sterilizers. A vacuum double-wall solar tube combined with a copper heat exchanger for high-temperature sterilization under natural sunlight was proposed by Chang et al. [265]. Indoor experiments show that by modifying the SISG structure under 1 sun the temperature of produced steam can increase from 102 to 165°C while outdoor investigation revealed under natural sunlight with low intensity, the steam temperature exceeds 121°C, which is effective enough to eliminate bacteria [266]. Findings revealed that the produced steam readily eliminated both *Geobacillus stearothermophilus* and *E.coli* bacteria. Zhao et al. [267] presented a SISG prototype by combining a compound parabolic concentrator and silica aerogels and reported appropriate conditions for pathogen elimination at temperature and pressure of 128°C and 205 kPa respectively. Wang et al. [268] fabricated a cooper-based SISG prototype to generate high-temperature steam of 259°C under 10 Sun. The sterilization tests by a biological indicator showed the SISGs produce steam at 132°C, eliminating most pathogens. Lie et al. [269] experimented the effectiveness of SISG made by biochar-based materials against three bacteria of E. coli, S. aureus and Bacillus and reported more than 6 log reduction for all pathogens. Neumann et al. [270] developed two compact Au nanoparticle-based structures SISGs with the parabolic dish to sterilize dentistry equipment and human waste. Their results indicated that the proposed system could generate steam from 115°C (30 min) to 132°C (5min) and eradicate

Geobacillus stearothermophilus bacteria. Importantly, this study mentioned an interesting point about the type of water for steam generation. They stated that the nanoparticles are not consumed during the process and the only consumable material is water to produce steam, hence, the feed water does not need to be sterile (or free of any microorganism) before use in the chamber of the SISG which means the system can use biologically-contaminated water for sterilization.

7.3 Post-treatment of distillated water in small-scale solar evaporators

Although, plenty of mechanisms by utilizing nanomaterial in small-scale solar evaporators could be implemented to eliminate the biological species during the desalination process, it is logical to consider there is still a possibility in presence of pathogens in generated water by solar still and interfacial steam generation systems. In this regard, post-treatment can be considered as an important strategy to deliver high quality hygiene water. Generally, post-treatment methods such as chlorination, filtration at any capacity (ultra/micro/nano), and advanced oxidation processes are employed for large-scale desalination and water treatment plants[11] while for small-scale systems the post-treatment process has not outshined as an important parameter. Hence, solar water disinfection (SODIS) could be considered as an appropriate low-cost method for post-treatment of generated water. In an attempt to produce high quality hygiene water by solar still which used antibacterial silver nanofluid, Parsa et al.[4] proposed to employ SODIS as post-treatment method to generate pathogen-free water during solar desalination process. They collected the produced water by solar still in a plastic bottle and maintain it under sunlight during the experiments for eight hours to simultaneously take the advantage of water disinfection. The other method which can be combined with solar evaporators is thermal treatment. In this approach, temperature of produce water could be increase until a certain temperature (normally up to 80°C which is critical temperature for most of pathogens) by any source of energy (fire, electricity, gas, etc.) to take the advantage heat treatment. However, this method could be an energy-consuming process with greenhouse gas emission.

7.4 A general comparison between solar stills and SISGs

A short comparison between solar stills and SISGs in terms of combatting against pathogenic-contaminate water seems necessary. From technical viewpoint the difference between solar stills and SISGs is evident. Briefly, the photothermal efficiency in solar still is generally less than 50% but for SISGs it usually higher than 80% and can be raise as high as 700% [271]. Subsequently, the productivity of SISGs compared to solar stills is in accordance with photothermal efficiency. On the other side of the coin, SISGs are still in their infancy stage and commercialization in order to vastly utilize in every corner of the world needs further development. Conversely, solar stills ascribe to their longtime operation during last decades are used in many remote regions and poor communities [191]. In the context of systems' effectiveness against biologically-contaminated water, SISGs have great advantages because eliminating pathogens through variety of aforementioned mechanisms were employed while for solar stills -so far- only two possible mechanisms were used. Furthermore, numerous studies on SISGs considering various types of pathogens have been conducted while for solar stills there is no study on practicality of nanomaterial against pathogens. Therefore, from real-world-application point of view SISGs would be considered at the forefront of providing safe drinking water from biologically-contaminated water. It is necessary to point out that the reason for SISGs divers mechanisms for killing pathogens is that precise synthesizing/designing of nanostructure materials is the cornerstone of SISGs and various analytical characteristics measurement performed to ensure reaching the intended architecture that leading to design a desirable antibacterial platform. On the contrary, utilizing nanomaterials in solar stills is based on nanofluids or absorbers' nano-coating. Although, the two methods could be effective against pathogens in water, many prerequisite analysis would not performed in this context. For example, measuring absolute zeta potential of nanofluids is critically important to ensure about the stability of nanofluids and their effectiveness, but this important parameters in most studies has not examined.

8. A new horizon toward realizing the Sustainable Development Goals (SDGs)

Generally, when speaking about small-scale solar desalination systems the most important part usually highlighted by researchers is the technical aspect and the ways leading to improve and modify the systems. However, another side of this technology that has not been outshined is their impact on realizing the Sustainable Development Goals. The United Nations (UN) in 2015 announced an international action plan named the Sustainable Development Goals (SDGs); consisting 17 goals and 169 targets which is a global plan of action for people, planet and prosperity and calls all governments to address those goals and targets by making practical efforts [272].

The Goal 6 of SDG (i.e., SDG6) entitled "***Clean Water and Sanitation***" explicitly focuses on the problem of providing safe drinking water and sanitation. Accordingly, solar stills and SISGs could play a vital role to meet targets of this goal in which the target 6.1 of SDG6 stated that "*By 2030, global and equal access to safe and affordable drinking water for all*" should be achieved [273]. In target 6.1 the words "*safe*" and "*affordable*" are of great importance which indicates that the produced water should be free of any organic/inorganic pollutants while the capital cost and cost-per-liter of drinking water should not be expensive in order to be payable even for people with the lowest income in developing countries. From an economic standpoint, solar stills in the recent decades proved to be a cost-effective method with a capital cost for passive and active types as much as low of 33$ and

80$ and the cost-per-liter at the lowest price by around 0.0014 $/L and 0.006 $/L respectively [274]. A comprehensive economic analysis considering the real world applications is limited for solar interfacial evaporators since it is in the infancy stage. However, Zhang and co-workers [275] discussed on economic feasibility of solar interfacial evaporator considering three important parameters of capital cost, production rate and lifespan of the system and compared the results with price of bottle and tap water for real world application. The findings indicated that, to realize a commercially competitive solar interfacial evaporator device, a water yield rate greater than 5 $L/m^2.h^1$, capital cost less than \$100 m^{-2} and lifespan longer than a few years are desired (Figure 17 a-b). This is a very important parameter of solar evaporators which should be consider in the conceptual stage, because a solar evaporator could be highly powerful against a broad range of pathogens but the high cost of structure or limited lifetime would be inhibited its widespread use especially in low-income countries and poor communities.

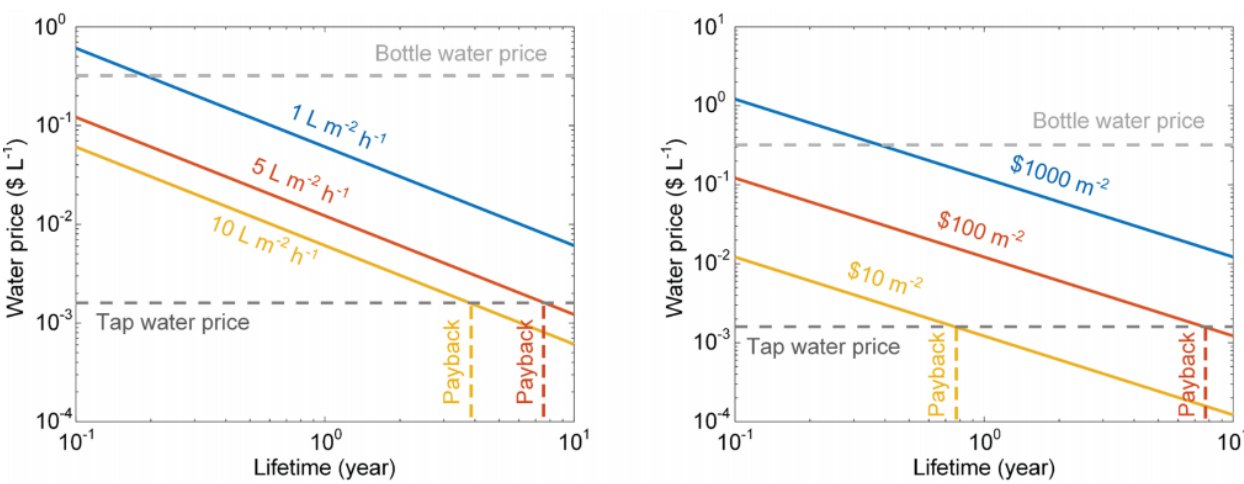

Figure 17. Economic analysis for solar steam generators. (a) Price of produced water as a function of unit lifespan when the productivity rate is 1 L/m^2h^1, 5 L/m^2h^1 and 10 L/m^2h^1 (The calculation is based on a device cost of \$100 m^{-2}) (b) Price of produced water as a function of system's lifespan when the cost of structure is \$1000 m^{-2}, \$100 m^{-2} and \$10 m^{-2}. (The calculation is based on a water productivity rate of 5 L/m^2h^1). Reproduce from reference [275] with permission from Royal Society of Chemistry, copyright 2020.

On the other side of the coin, clean water as the cornerstone of human health would be directly or indirectly related to other SDGs. A good example for direct relation of solar desalination systems is their impact on SDG3. Obviously, providing safe drinking water by solar desalination systems reduces water-related disease, which is part of target 3.3 of SDG3, focusing on "***Good Health and Well-being***". Moreover, interdependency of clean water and SDG11 is a good instance for indirect relation. As the SDG11 focused on "***Make cities inclusive, safe, resilient and sustainable***", numerous parameters have contribution to realize this goal from financial, technical and cultural aspects. From technical viewpoint, the target 11.1 stated to "*ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums*". In this phrase, the term "basic services" designate to all services that is essential for a healthy life, accordingly, access to safe drinking water would be as one the first parameters in this context. Furthermore, upgrading slum communities is a broad term which would be included many items. Although the target has not explicitly mentioned the importance of drinking water to upgrade slums, one of the main critical problem that repeatedly reported in last decades by global organizations and researchers is the problem of safe drinking water in developing world and poor communities [276–278]. Last but not least, utilizing solar energy as the energy source to provide safe drinking water would be steps toward realizing SDG7 "***Affordable and Clean Energy***" and its targets, particularly targets 7.2 and 7.B which focused on *increasing the share of renewable energy in global energy mix* and *providing sustainable energy services for all* in developing countries respectively.

9. Outlooks, research gaps and future directions

This critical review focused on the performance of nanostructured materials in solar-driven interfacial evaporation and solar stills against biologically contaminated water, highlighting recent advances and contributions in this field. A conceptual framework was developed, addressing particular pathogen characteristics, parameters impacting the performance of both solar desalination systems, and the mechanisms for eliminating pathogens. Rather than selecting a specific nanostructure as the most efficient option against pathogens in solar desalination units, this review aimed to spotlight various mechanisms employed thus far and identify research gaps for future real-world applications.

Since the discussion here is on the possible mechanisms against biological species and their transfer in produced water of solar stills and SISGs considering the pathogens' characteristics, it is important to realize how these two parameters are related concurrently. Particle size for most of pathogens that placed in the category of GCBRs, particularly viruses (particle size: 27-1000 nm) and AMR (particle size: 0.2-3 μm) is small enough to transmit via droplets through all types of solar stills in which transmission of the some bacteria such as E. coli, K. pneumoniae, and E. faecalis (particle size: 0.5-3 μm) in solar still units are reported before. For SISGs, no studies were reported on pathogens transfer through the steam; however, the number of studies on viruses is limited to examine the SISGs not only from pathogens' elimination viewpoint but for elucidating particle transfer through the vapor. It is important to note that we have not highlighted the particle size of other pathogens (Tables 3, 4 and 5 of protozoa, bacteria and AMRs respectively) since viruses have the smallest particle size among pathogens. Additionally, microbes could severely affect by increasing temperature (see section 6.3) as it is one of the well-established methods for killing pathogens. As it can be observe, most dangerous viruses are sensitive at high temperature 50-90°C while the exposure time also plays an important role. For example, *Influenza A* H_1N_1 inactivated at 90°C in 1 minute, but such high temperature would not achieved in solar stills and only in some rare cases of SISGs were observed. For lower temperatures like 60°C a pathogen like Ebola virus at least need 60 minutes to completely inactivate.

Moreover, two important protozoa (i.e., *Giardia* and *Cryptosporidium parvum*) inactivated at temperature range of 60-72°C while this temperature is consider moderate-to-high for both systems. The same is true for bacteria that most of those aforementioned in Table 4 have an inactivation temperature above >65°C. Importantly, the critical temperature for AMRs is quite high and critical temperature for most of them such as *MRSA, drug-resistant mycobacterium tuberculosis, drug-resistant candida auris*, to name a few is high (>80°C), hence, thermal inactivation of pathogens for both systems which generally have working temperature operation below these numbers is not trustable and effective option. Accordingly, the possible elimination mechanism for those pathogens with temperature-resist (i.e., those which have higher inactivation temperature) characteristics would by other methods through ROS, surface engineering or direct contact with nanomaterials. However, it is important to note that, the temperature effect would define as synergic effect alongside other inactivation mechanisms simultaneously.

For solar stills, extensive efforts on the use of nanostructured materials have been done, however, the main concern in all of previous studies was to further improve the performance of systems from thermodynamic point of view rather than focusing on their effectiveness against pathogens. Although some studies claimed that the use of antimicrobial nanoparticles lead to simultaneous water desalination and disinfection, in actual experiments, the feed water in none of those studies was biologically contaminated. Hence, one important thing that should be addressed is to evaluate the effectiveness of solar stills in the presence of real pathogens in different scenarios for utilizing nanomaterial whether in the form of nanofluid in water or nanocoated in the absorber of solar stills. Moreover, a limited number of pathogens in solar stills have experimented and the reliability of solar stills against other pathogens –particularly those in the category of GCBR- was not realized. Thus, addressing this vital gap could open a broad interesting multi-disciplinary research direction in front of researchers. It is important to point out that the nanofluids as one of the main nanostructures utilized in solar stills has another issue regarding the agglomeration phenomenon. Indeed, one of the main challenges of using nanofluids in solar stills is the long-term stability of nanofluids after operating for several cycles. Since the stability of nanofluids would (particularly in saline environment [156]) decreases, their practical application in solar desalination systems for real world application would be questionable. Obviously, agglomeration of nanoparticle could lead to generate particles at greater sizes in micro or higher that results in losing their unique characteristics to kill pathogens through different mechanisms. Therefore, addressing the stability of nanofluids in solar stills is a prerequisite aspect of utilizing this from of nanostructure to be effective against pathogens for long-term operation. Moreover, comparing the antibacterial efficiency of both applied methods (nanofluid and absorber's nanocoating) under the same conditions with different pathogens is another interesting approach which has not realized yet.

Plenty of researches on different types of pathogens with different antimicrobial strategies have been conducted for solar interfacial evaporation. Among all of the aforementioned pathogens, bacteria is the most frequent microorganism group that used to evaluate the effectiveness of solar interfacial evaporation against biological contamination water, ascribed to their facile cells culture procedure, low-cost pathogen detection (compared to protozoa and viruses). In this regard, viruses are significantly underutilized (only in a single study) in systems for evaluation of the biofouling performance of SISGs; however, they are the most possible candidates for starting epidemic and pandemic. Hence, one important research gap which could be consider as the future direction is to use different types of viruses – particularly those with potential of starting any epidemic/pandemic such as H_1N_1 and SARS-CoVs – in SISGs to realize their effectiveness against this type of pathogen.

Moreover, the lack of any study for protozoa makes it necessary for further research on deactivation performance of SISGs since this type of pathogen is well-known for resistance against temperature, environmental conditions and conventional wastewater treatment plants disinfection strategies.

Although fungi are less important in the category of GCBR pathogens, several studies highlighted applying SISGs against them and utilizing contaminated water by *yeast* and mildew-resistant structures. Considering the common occurrence of mildew formation in biomass-based SISGs structures and emerging this type of solar evaporator as a low-cost method in recent years, developing mildew-resistant structures should be considered as one of the cornerstones of this types of SISGs. Indeed, mildew-formation tests for biomass-driven SISGs should be mandatory for practical real-world applications.

Preeminently, the AMR pathogens are at the foremost importance of biologically contaminated water as the multifaceted global phenomenon since they have multiple routes to water matrices while consider as the most possible agent for starting the next pandemic which can kill more than 10 million people annually by 2050. So far, two studies have conducted AMR pathogen which was on MRSA removal by SISGs that seems insufficient regarding their importance for future public health. Thus, it is vital to conduct further researches on other AMRs – particularly *Drug-resistant Neisseria gonorrhoeae*, *Drug-resistant Candida auris*, *Carbapenem-resistant Acinetobacter baumannii*, *Drug-resistant Clostridium* *difficile* and *Carbapenem-resistant Enterobacterales* as they are considered urgent threats by CDC- in solar interfacial evaporation. Among various antimicrobial mechanisms of SISGs, ROS generation and direct effect of antimicrobial nanoparticles (e.g., gold, silver, cooper, iron etc.) are of great importance mechanisms against biological contamination, while, it seems that in polymer-based SISGs, surface engineering by anti-adhesion surfaces plays an important role against pathogens.

Moreover, the potential of SISGs with photocatalytic activity such as integrating by photo-Fenton process was not in the spotlight. Regarding the fact that photocatalytic disinfection is one of the most prominent well-established methods for pathogens removal [279,280], for this context, developing SISGs with this capability would be a promising approach toward highly microbicidal SISG structures.

Importantly, the direct effect of solar UV on microbial activity in SISGs has not been realized yet. Its role is mainly considered as an indirect effect by promoting photocatalytic activity or ROS generation. Since solar absorbers are capable to absorb broadband of whole spectrum (including solar UV) [281,282], the direct effect of UVA and UVB wavelengths and their synergies on pathogens in SISGs have not examined yet, thus one of the interesting future researches is to elucidate the direct effect of UV on pathogens elimination. It should be point out that for conducting such study; the structure should be fabricated and designed in a way that none of the other antimicrobial mechanisms involved, in order to explicitly evaluate the solar UV effect on pathogens removal.

Last but not least, the matter of real world application of SISGs is not only related to cost analysis [275] but the long-term stability of structure in term of biofouling is of great importance. Most of studies in the literature evaluate the antimicrobial efficacy of structure no more than one week (and in many cases just for one day); therefore, conducting long-term experiments for more than one month (up to one year) would be a great approach to realize the real world application of SISG in this context.

10. Conclusion

The effects of clean water on human health make it one of the crucial matters of our world. Water and human health are closely interconnected and highly interdependent. Choices made and actions taken in one major can greatly affect the other, positively or negatively. Trade-offs need to be managed to limit negatives. As the clean water resources become scarce in past decades, developing water purification systems by use of affordable renewal energy resources, particularly solar energy is of great interest by scientific community. The exponential ever-rapid growth progress of aforementioned small-scale water evaporation and purification systems in recent years put them as one of the exceptional alternatives for a sustainable solution of providing safe drinking water not only for individuals in poor communities and developing world but for people all around the world even in the industrialized countries. However, most scientists and researchers are focused on technological advancements of these systems by proposing innovative configurations and utilizing/synthesizing novel and advance materials for high-yield and efficient systems. Though these advancements are imperative for practical applications, little attention and effort have been made to evaluate their effectiveness against biological contaminations; accordingly, realizing their feasibility against various viruses, bacteria, fungi, protozoa, and AMR pathogens has become more vital. Thus, it is highly recommended to evaluate the performance of these systems against microorganisms, particularly those emerging

AMR pathogens that have not yet brought into the spotlight in this context. Indeed, the rational way to face potential threats is to prepare before it happens, specifically when it relates to human life. Although the worth of human life is priceless, experts estimate that each human life is worth nearly $10 million [283]. Regardless of such numbers, as human beings, it is a global responsibility on the shoulder of all people to save each life, particularly children and vulnerable people in developing countries, because we must leaving no one left behind.

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