New insights towards disinfecting viruses – short notes

Djamel Ghernaout, Noureddine Elboughdiri and Saleh Al Arni

ABSTRACT

Water treatment specialists need more and more to understand how viruses behave in potable water pipes and wastewater setups. This work discusses the late advances in dealing with viruses present in water treatment processes. Activated carbon adsorption (ACA) remains one of the most efficient and credible physicochemical methods. Nanoparticles have been utilized to turn activated carbon into a more efficient sorbent. Membrane filtration could lead to total elimination of viruses and ensure the safety of drinking water plants. As a feasible utilization for disinfecting potable water, solar disinfection (SODIS) remains a green and cost-efficient technology with its optical and thermal pathways and deserves more interest in its large and industrial implementation. Identically, solar distillation remains a viable solution for disinfecting and treating water. The water treatment techniques that are currently utilized for surface water treatment are appropriate for eliminating viruses like influenza A viruses, as proved by the literature. More strict precautions have to be taken to secure viruses' total elimination from water and wastewater as for influenza A and H5N1 in terms of advanced oxidation processes, ACA, and membrane processes application. Before reaching surface water, pathogens have to be removed efficiently from hospital and municipal wastewaters.

Key words | activated carbon adsorption (ACA), disinfecting viruses, membrane filtration, nanoparticles, solar disinfection (SODIS)

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HIGHLIGHTS

- Waterborne pathogenic viruses constitute a grave menace to human health and life.
- Coronaviruses' behavior in water and wastewater processes has to be well examined.
- Nanoparticles have been utilized to adjust activated carbon into more efficient sorbent.
- Water treatment plants combining UV irradiation and membrane UF would allow excellent coronaviruses removal to be attained.
- Advanced oxidation processes, solar disinfection, activated carbon adsorption, and membrane processes are promising towards viruses' removal.

INTRODUCTION

With diameters from 20 to 300 nm, viruses are a menace to potable water safety (Zhang & Zhang 2015; Shimabuku *et al.* 2018; Ghernaout 2019a). Both underground water and surface water may begin to be polluted with viruses from diverse fecal sources (Gerba 2015). A massive quantity of resistant bacteria has been found in treated sewage (Huang *et al.* 2012a, 2012b; Ghernaout & Elboughdiri 2020a). To make matters worse, viruses and bacteriophages are known to remain longer than bacteria following disinfection applications (Allue-Guardia *et al.*

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2012; Ortega-Gómez *et al.* 2015; Ghernaout & Elboughdiri 2020b).

The ability to eliminate pathogenic viruses, like adenovirus, norovirus, rotavirus, poliovirus, and hepatitis A, as well as virus indicators, is considered when assessing the quality of water treatment methods (Gerba *et al.* 1975; Abad *et al.* 1994; Xagoraraki *et al.* 2004; Page *et al.* 2009; Kuo *et al.* 2010; Costa *et al.* 2012; Park *et al.* 2014). Owing to their specificity and resistance when juxtaposed with bacterial indicators, bacteriophages have been selected as indicators of microbiologic pollution in water (Brehant *et al.* 2010). The bacteriophage is found in medium polluted with *Escherichia coli* (Ghernaout *et al.* 2008, 2019a; Ghernaout 2017), like residual waters and raw sewage. Furthermore, it has been proved that its existence is proportional to the degree of fecal pollution (Shimabuku *et al.* 2018). When investigating virus elimination methods, bacteriophages are frequently employed as substitutes for animal viruses as they are not infectious to human beings and are easier to manipulate (Schijven & Hassanizadeh 2000; Grabow 2001; Ghernaout & Ghernaout 2010; Ghernaout 2018).

Bacteriophages have been used as typical infectious agents, working as viral indicators to estimate diverse elimination techniques (Cookson & North 1967; Schijven *et al.* 2002, 2013; Mamane *et al.* 2007; Sadeghi *et al.* 2013). As one of the biggest double-chain deoxyribonucleic acid (DNA) bacterial viruses, bacteriophage T4 has been utilized as a typical virus in numerous investigations (Lv *et al.* 2006; Mamane *et al.* 2007; Shimabuku *et al.* 2018). To obtain low-cost potable water, it is vital to re-evaluate traditional disinfection technologies and introduce new procedures (Biswas & Bandyopadhyaya 2016; Ghernaout 2019b, 2019c; Ghernaout *et al.* 2019b, 2019c; Ghernaout & Elboughdiri 2019).

Activated carbon adsorption (ACA) remains one of the most effective and credible physicochemical methods (Babu & Gupta 2008; Gentscheva *et al.* 2008). ACA merits comprise its easy implementation and low cost when contrasted with different separation techniques (Bhattacharyya & Gupta 2008; Sahmoune & Ouazene 2012); these features are attributed to its porosity, internal surface, and high adsorption potential (Pezoti *et al.* 2014). Nevertheless, to ensure that the activated carbon filters do not retain microorganisms (such as bacteria and viruses) (Acevedo *et al.* 2014), an improvement is needed. The activated carbon structure and its chemical properties are linked to the selected precursor, and elevated rates of adsorption affect its surface functionalization, which improves both adsorbent–adsorbate interactions and pore structure, authorizing local adsorption access (Schijven *et al.* 2002; Shimabuku *et al.* 2018).

Lately, nanoparticles have been utilized to adjust activated carbon into favorable and efficient sorbents (Nekouei *et al.* 2016). Nanotechnology remains one of the quickest expanding techniques (Ghernaout *et al.* 2018a), with outcomes in numerous domains, thanks to the inverse correlation between size (10^{-9} m) and surface area (White *et al.* 2006; Shimabuku *et al.* 2018). There are multiple levels of adverse biological impacts provoked by nanoparticles on cells, including subcellular and molecular scales alike (Fortner *et al.* 2005; Brunner *et al.* 2006).

Investigation of the interactions between nanoparticles and viruses in water is needed to enhance the present water treatment methods and develop new nanomaterials designed for disinfecting water (Zhang & Zhang 2015; Shimabuku *et al.* 2018). Nanoparticles and silver and copper oxide components have been utilized in a set of viral elimination treatment technologies (Zodrow *et al.* 2009; Vincent *et al.* 2016).

This work discusses removing viruses using nanotechnological processes, drinking water treatment techniques. Further, it presents a simple functionalized sand filter as a promising method. Special attention is accorded to the solar disinfection (SODIS) and electrochemical engineering applied in killing viruses. Merging processes such as coagulation–membrane filtration for ultraviolet (UV) disinfection is also an attractive approach. Finally, dealing with viruses in the water cycle is suggested.

APPLIED TECHNIQUES FOR REMOVING VIRUSES

Removing viruses using nanoparticles' processes

Shimabuku *et al.* (2018) investigated the impact of silver nanoparticles (NP-Ag), copper oxide (NP-CuO), and silver and copper oxide (NP-Ag-CuO) levels, when impregnated in granular activated carbon (GAC), on viral elimination.

They employed bacteriophage T4 as a virus indicator model and performed their tests in batch mode below the governed circumstances of 25 °C and pH 7. Their findings illustrated a considerable elevation in both virus elimination and the rate constant following the incorporation of nanoparticles on the GAC surface (Figure 1). Virus elimination and rate constants were greater for the samples in which the synergistic effect of silver and copper oxide nanoparticles (NP-Ag-CuO) had occurred. GAC, changed with NP-Ag-CuO (GAC/NP6), seems to be a promising adsorbent for virus elimination through brief residence periods. Formulating nanomaterials may be implemented to water treatment technologies as a substitutional disinfection process.

Similarly, Zhang *et al.* (2019) presented a novel category of metal-free heterojunction photocatalysts that combine oxygen-doped graphitic carbon nitride microspheres (O-g-C_3N_4) with hydrothermal carbonation carbon (HTCC). This material was used in an easy low-temperature solvothermal–hydrothermal procedure to eliminate human adenovirus type 2 (HAdV-2). The sample of O-g-C_3N_4/HTCC-2 with a uniform coverage of HTCC, strong visible light absorption, and a narrow band gap depicted the high virucidal activity versus highly resistant HAdV-2 under visible light irradiation, juxtaposed to HTCC, bulk g-C_3N_4, and O-g-C_3N_4 (Figure 2). A titer of 10^5 MPN/mL viruses was eliminated during 120 min of photocatalysis, and the viral elimination efficiency was improved with the elevation of water temperature from 4 °C to 37 °C, the diminution of pH from 8 to 5, salinity (NaCl), and hardness (Ca^{2+}). Moreover, its performance in HAdV-2 elimination in actual potable water and the excellent photocatalyst stability of O-g-C_3N_4/HTCC-2 were encouraging results that suggest this material could be used for disinfecting water. The ameliorated virucidal effectiveness of O-g-C_3N_4/HTCC has been attributed to improved charge separation via the generation of heterojunction in the photocatalyst. Furthermore, Z-scheme heterojunction was suggested to allow the formation of •OH as a powerful antiviral agent in photocatalysis, in opposition to type II heterojunction. Most importantly, •OH rather than $•O_2^-$ dominated HAdV-2 elimination, and it conducted to holes in the viral capsid that distorted and ruptured it. In addition to the good photocatalytic efficiency of O-g-C_3N_4/HTCC for HAdV-2 elimination, the photocatalyst showed negligible toxicity to a human cell line, further confirming that the material is secure for treating drinking water. Such an investigation not only shows the promising future of an emerging metal-free visible-light-responsive heterostructure for killing viruses and an efficient, sustainable, and secure water treatment method, but it also illustrates the fundamental photocatalyst features and pathways that enhance the photocatalytic effectiveness.

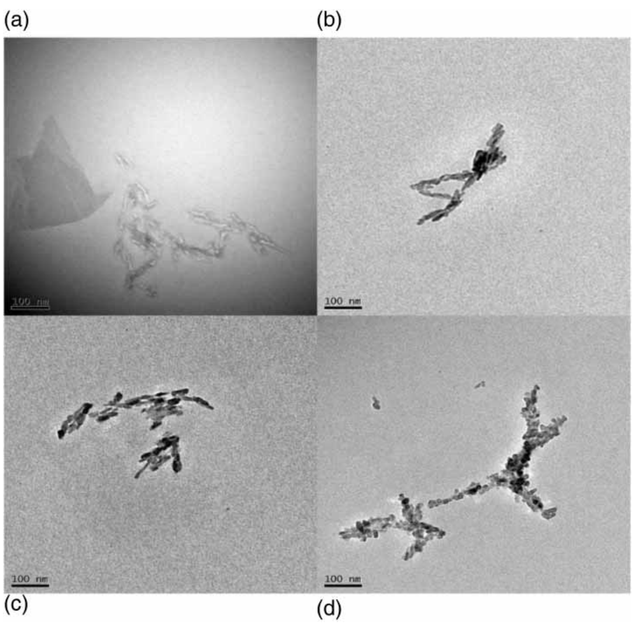

Figure 1 | Transmission electron microscopy (TEM) micrograph: (a) activated carbon (GAC), (b) modified activated carbon – (GAC/NP1), (c) modified activated carbon – (GAC/NP4), and (d) modified activated carbon – (GAC/NP6) (Shimabuku *et al.* 2018).

Zinc oxide is a significant chemical in the rubber and pharmaceutical industries that has attracted attention as an antimicrobial agent. In nanoscale, zinc oxide has proved to have antimicrobial characteristics that make it potentially useful in numerous applications. Dimapilis *et al.* (2018) reviewed the fabrication of zinc oxide with a focus on precipitation method, its antimicrobial property, the factors affecting it, the disinfection mechanisms (Figure 3), and its potential application to water disinfection. Ortega-Gómez *et al.* (2015) estimated the demobilization of the coliphage MS2 via solar photo-Fenton at pH ~7 in carbonate buffer solution. They focused on the impacts of reactant injection (H_2O_2, Fe^{2+}, Fe^{3+}) and solar irradiance on the photo-Fenton reaction. The solar exposure/Fe^{3+} treatment illustrated a strong dependence on the iron level and solar

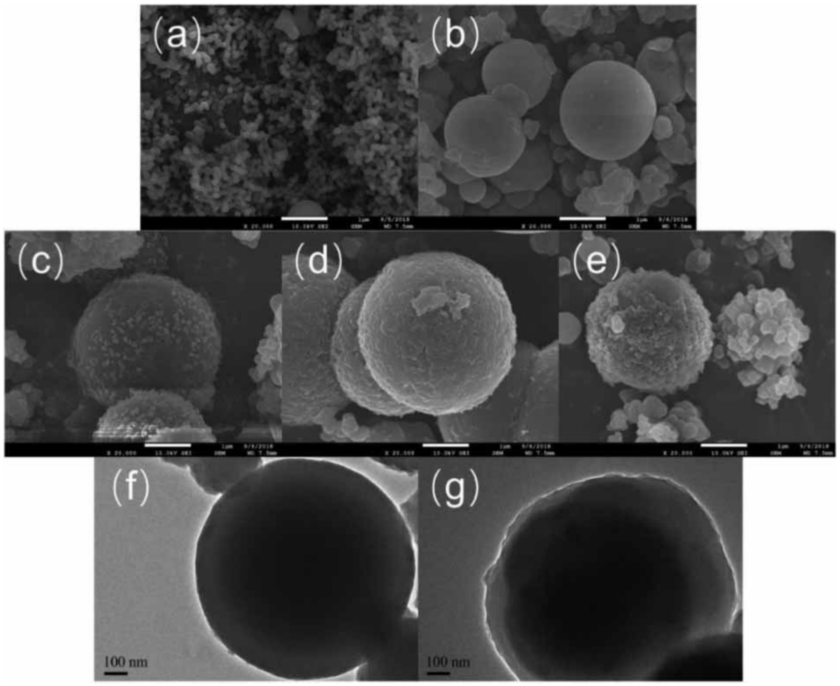

Figure 2 | Scanning electron microscopy (SEM) images: (a) HTCC, (b) O-g-C_3N_4, (c) O-g-C_3N_4/HTCC-1, (d) O-g-C_3N_4/HTCC-2, and (e) O-g-C_3N_4/HTCC-3, and TEM images: (f) O-g-C_3N_4 and (g) O-g-C_3N_4/HTCC-2 (Zhang *et al.* 2019).

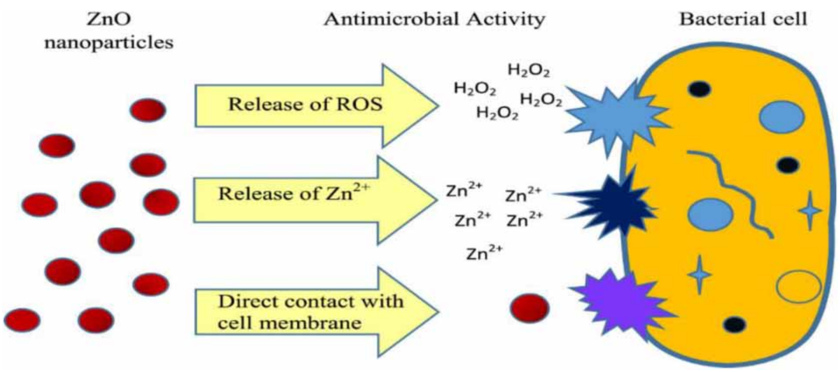

Figure 3 | ZnO disinfection mechanisms (Dimapilis *et al.* 2018).

irradiance intensity leading to total demobilization with 1 mg/L of Fe^{3+} and 60 min of solar irradiance (45 W/m^2). The MS2 demobilization noted with the photo-Fenton process (solar exposure/H_2O_2/$Fe^{2+/3+}$) performed with Fe^{3+}, was faster than with Fe^{2+}. Further, virus demobilization via photo-Fenton below numerous solar irradiance degrees (15, 30, and 45 W/m^2), H_2O_2 and Fe^{3+} injections (0.1, 0.5, and 1 mg/L) and diverse pH levels (6, 7, and 8) were estimated. A conceptual mechanistic explanation was suggested concerning how solar photo-Fenton acts on viruses in water, involving the key species Fe^{2+}, Fe^{3+}, H_2O_2, solar irradiance, OM, and their probable reactions (Figure 4).

Removing bacteriophages through potable water treatment

Boudaud *et al.* (2012) studied the elimination of MS2, Qβ, and GA, F-specific RNA bacteriophages, possible surrogates

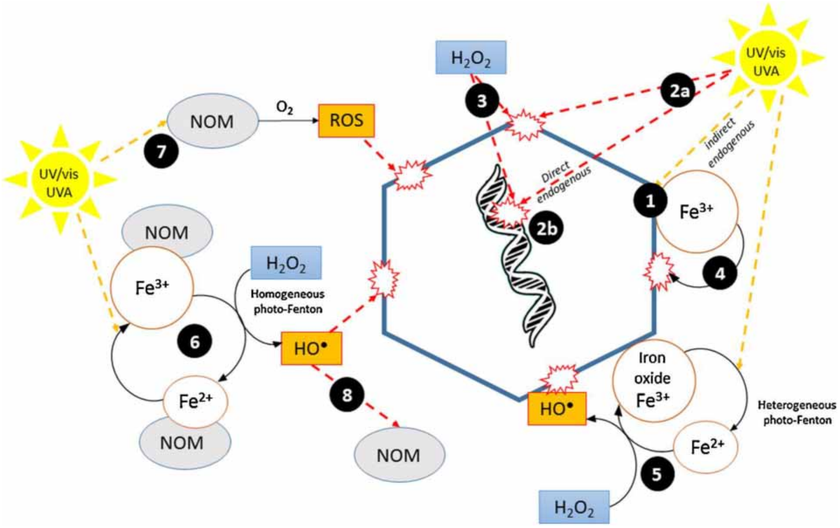

Figure 4 | Mechanistic representation of possible pathways involved in the photo-inactivation of bacteriophage MS2 (Ortega-Gómez *et al.* 2015).

for pathogenic waterborne viruses, using a traditional potable water treatment at a pilot-scale by employing river water artificially and independently spiked with these bacteriophages. They aimed to present a standard procedure for evaluating the performance of potable water plants in eliminating MS2, Qβ, and GA bacteriophages via a traditional pretreatment method (coagulation-flocculation–settling-sand filtration) pursued or not by an ultrafiltration (UF) membrane (complete treatment method). They estimated the specific performances of three UF membranes alone using: (i) pre-treated water, and (ii) a 0.1 mM sterile phosphate buffer solution (PBS) spiked with bacteriophages. Initially, they hypothesized that the interfacial characteristics for such bacteriophages, in terms of electrostatic charge and the degree of hydrophobicity, may cause changes in the elimination efficiencies obtained via potable water treatments.

Their findings revealed an identical behavior for both MS2 and Qβ surrogates; however, the GA surrogate was especially atypical. The infectious character of MS2 and Qβ bacteriophages was mainly eliminated following clarification by sand filtration techniques (more than a 4.8-log reduction). At the same time, genomic copies were reduced more than 4.0-log following the full treatment process. In contrast, the GA bacteriophage was only slightly reduced via clarification pursued by sand filtration, with less than a 1.7-log and 1.2-log removal, respectively. Following attainment of the full treatment process, GA bacteriophage was reduced with less than 2.2-log and 1.6-log reduction, respectively (Boudaud *et al.* 2012).

The performance of the three UF membranes tried in terms of bacteriophage reduction showed considerable differences, particularly for GA bacteriophage. Such findings provide recommendations for potable water suppliers in terms of selection criteria for membranes (Boudaud *et al.* 2012).

MS2 bacteriophage remains largely utilized as a surrogate for pathogenic waterborne viruses in many countries. It was proved that GA bacteriophage is a considerably better surrogate case than MS2. Taking into account that GA bacteriophage was the best surrogate in their investigation, Boudaud *et al.* (2012) affirmed that a chlorine disinfection stage could guarantee total elimination of this model and ensure the safety of drinking water plants.

Removing viruses in a simple functionalized sand filter

Samineni *et al.* (2019) focused on a molecular pathway for unprecedented elevated virus elimination from a practical sand filter. Sand filters functionalized employing a water extract of *Moringa oleifera* (MO) seeds, functionalized sand (f-sand) filters, and achieved a ~7 $\log_{10}$ virus reduction. Such trials were realized with the MS2 bacteriophage, a known surrogate for pathogenic norovirus and rotavirus. They investigated the molecular pathway of such increased elimination because it can have considerable consequences for sand filtration, the most usual water treatment technique in the world. They depicted that the virus reduction potential of f-sand is attributed to the existence of a chitin-binding protein, the *M. oleifera* chitin-binding protein (MoCBP). They also demonstrated that MoCBP binds preferentially to MS2 capsid proteins, establishing that specific molecular interactions underlie the improved virus elimination. Furthermore, they suggested a simplified procedure for making f-sand and showed how it could be regenerated employing saline water. F-sand filters may be viewed as a highly efficient, energy-efficacious, and practical technology for virus reduction that both poor and rich nations can use.

Solar disinfection (SODIS): An underestimated water treatment technology

Sunlight remains one of the oldest registered techniques of water treatment (Reed 2004). Nevertheless, it is only in more recent times that the scientific basis of this process has been elucidated. The first methodical investigation into the repressing impacts of solar radiation on bacteria was that of Downes & Blunt (1888). They mentioned that the growth of bacteria in nutrient broth and urine could be stopped via exposure to the sun and that such solutions 'may be absolutely and perfectly sterilized by sunlight.' Moreover, they proved that the spores of mycelial fungi are more resistant than bacterial cells to the repressive effect of sunlight, and they also illustrated that short-wavelength solar radiation possesses the most significant antimicrobial impact (Reed 2004). Acra *et al.* (1980) suggested the feasible utilization of sunlight for disinfecting oral rehydration solutions and potable water in a method commonly named solar disinfection (SODIS) (Acra *et al.* 1984, 1989; Reed 2004).

Photo elimination

Even if sunlight could induce direct deterioration to biomolecules, like that observed if UVB radiation is absorbed by DNA (Jaegger 1985), it is more frequent for solar UV and visible light to engender indirect deterioration, being absorbed via photosensitizer molecules, which are then raised to an excited state (Reed 2004). Such photosensitizers may be found either within microbial cells (e.g., porphyrins, flavins, and photosynthetic pigments) (Curtis *et al.* 1992) or in the surrounding water (e.g., humic substances in natural waters (Curtis *et al.* 1992; Voelker *et al.* 1997; Porras *et al.* 2018). Consequently, an excited photosensitizer could react directly with cellular biomolecules (type I reaction), or more frequently, with molecular oxygen (type II reaction). Molecular oxygen leads to the generation of varied reactive oxygen species (ROSs), including singlet oxygen, superoxide, hydroxyl radicals, and hydrogen peroxide (Reed 2004). Subsequently, ROS produced by solar irradiation will react with cellular constituents, involving DNA, proteins, and cell membrane components, particularly membrane lipids (Gourmelon *et al.* 1994), leading to the elimination of the cell (as an example, due to augmented permeability and/or the disruption of transmembrane ion gradients) (Bose & Chatterjee 1995; Futsaether *et al.* 1995). Oxygen-dependent type II photoreactions are likely to generate the main component of the optical component of solar elimination as a consequence of ROS-induced membrane lipid peroxidation (Bose & Chatterjee 1994; Davies-Colley *et al.* 2000) and DNA deterioration (Jeffrey *et al.* 1996). During the time that cellular antioxidant systems exist to counter the formation of ROSs, involving superoxide dismutase (Rao & Sureshkumar 2000) and catalase (Hillar *et al.* 1999), these antioxidant defense systems are as well recognized to be light-sensitive (Kapuscinski & Mitchell 1981).

Optical influences usually explain the principal component of SODIS, particularly in non-turbid waters; therefore, Acra *et al.* (1984) accounted 70% of sunlight to the optical features of solar UV radiation. Not surprisingly, optical elimination is affected significantly by the concentration of dissolved oxygen in the treated water (Reed 2004), being optimum under oxygen-saturated conditions (Reed 2004).

Thermal elimination

The absorption of sunlight, particularly solar infrared radiation, lifts the temperature of the water to a level where microorganisms are eliminated, in an approach usually called solar pasteurization, by similarity with commercial pasteurization (Wegelin & Sommer 1998). Therefore, easy batch-process solar pasteurization has been performed by employing a solar box cooker and black-painted container, showing that those fecal coliforms are eliminated at water temperatures of 60 °C or greater (Ciochetti & Metcalfe 1984). Small-scale solar pasteurizers are available in the market (Reed 2004). These devices are based entirely on thermal elimination, which is improved by non-transparent black containers that increase the absorbance of infra-red radiation.

Solar water distillation setups depend on the heating impacts of infra-red radiation to evaporate water, with the resulting condensate being free of microbial and chemical pollution from the initial source (Cappelletti 2002). Solar distillation needs much more energy input than solar pasteurization, as the running temperature of the water is higher in the former case (Reed 2004). Nevertheless, a solar still as well gives a means of eliminating chemical pollution, comprising the desalination of seawater to output drinking water (Garcia-Rodriguez & Gomez-Camacho 2001; Ghernaout *et al.* 2011; Ghernaout 2013a, 2019d). More pieces of information of commercial setups are presented elsewhere (Rolla 1998).

Reciprocal influence among optical and thermal impacts

Many investigations have mentioned the synergy among optical and thermal elimination. On that account, Tyrell (1976) illustrated a synergistic impact of UV radiation and heat in eliminating *Escherichia coli*, and Wegelin *et al.* (1994) thereafter established that temperatures above 50 °C lead to a three-fold lowering in the UVA radiation injection required to eliminate *E. coli*, with even more amazing impacts for bacteriophages and enteroviruses. Researchers (McGuigan *et al.* 1998) depicted synergy at temperatures above 45 °C, where the integrated influences of simulated sunlight and heat led to a higher rate of elimination of *E. coli* than that anticipated from the rates reached via employing each factor in isolation (Reed 2004).

Moreover, Lawand *et al.* (1997) observed a synergistic impact of solar radiation and heat on fecal coliforms in polluted water at temperatures above 40 °C, proposing that clear containers have to be put on a dark surface to elevate such impact. Following identical thinking, scientists (Sommer *et al.* 1997) have advised that the backs of SODIS containers have to be painted black, to improve the thermal influence. In addition, researchers (Reed 2004) have shown that eliminating *E. coli* could be improved via a factor of nearly two-fold through adding an aluminum foil backing to the containers to reflect UV and visible light, that way improving the optical component of the technology. Comparative tests of foil-backed and black-backed containers have yet to be performed (Reed 2004). It will be crucial to assess both kinds of containers under diverse weather circumstances. This is due to the fact that absorptive, black-backed containers might be expected to give the best impact in full-strength sunlight, where thermal influences are likely to elevate the water temperature to 45 °C and above. However, reflective, foil-backed containers might be more effective in suboptimal sunlight and cloudy circumstances, where thermal impacts will be considerably diminished, and the optical (UV-mediated) elimination gains relevance (Reed 2004).

Electrochemical technology for viruses' removal

Treating water electrochemically remains an encouraging option for small-scale and distant water setups that need working capability or appropriate access to chemicals for classical coagulation and disinfection (Ghernaout 2013b; Ghernaout & Elboughdiri 2020c, 2020d, 2020e, 2020f). Heffron *et al.* (2019) studied the reduction of viruses employing electrocoagulation (EC) as a pretreatment before electrooxidation (EO) treatment utilizing boron-doped diamond electrodes. They used bench-scale and batch devices to estimate the alleviation of viruses in changing water quality by EO and a consecutive EC–EO treatment train. The EO of two bacteriophages, MS2 and FX174, was hindered by natural organic matter (NOM) and turbidity, showing the likely necessity for pretreatment. Nevertheless, the EC–EO treatment train was useful only in the model surface waters used. In model groundwater, the single EC was as good as or better than the integrated EC–EO treatment train. The decrease of human echovirus was considerably lower than one or both bacteriophages in all model waters, even though bacteriophage FX174 was a more representative surrogate than MS2 in the occurrence of NOM and turbidity. Juxtaposed to traditional treatment via ferric salt coagulant and free chlorine disinfection, the EC–EO setup was less efficient in model surface waters but performed better in model groundwater. Consecutive

EC–EO was helpful for many usages, even if functional reflections may presently outbalance the advantages.

Combining coagulation–membrane filtration for UV disinfection

Numerous research works have proved the effectiveness of membrane filtration and UV disinfection in potable water treatment (Ghernaout *et al.* 2018b, 2018c; Ghernaout 2019e; Ghernaout & Elboughdiri 2020 g, 2020 h). Guo & Hu (2012) focused on virus reduction, taking into account two significant viewpoints: (i) decreased virus rejection following hydraulic backwash, and (ii) UV disinfection can be negatively compromised by the upstream treatment efficiency. The impact of upstream coagulation–membrane filtration on UV disinfection has not been well explained. Thus, Guo & Hu (2012) examined this issue by employing a batch and a continuous-mode system (Ghernaout *et al.* 2009). For microfiltration (MF) filtration, low MS2 rejections were detected initially, which was followed by a gradual elevation in rejections as the filtration time augmented. This badly affected the UV injection needs downstream when a particular log removal was to be achieved by this hybrid membrane–UV disinfection setup. In general, the UV disinfection performance of MS2-associated flocs was greater than in the unassociated MS2. Elimination (positive impact) by coagulants was more dominant than the negative effects of turbidity. Even if it was predicted that MS2 rejection might be compromised immediately following the backwashing of MF, the findings did not support this view. MS2 rejections initially fluctuated in the range of 86–100% and augmented gradually to 100% as the filtration time increased. Following hydraulic backwash, MS2 rejection was still maintained consistently at 100%.

CHALLENGES AND FUTURE TRENDS

Water treatment experts have to understand how viruses behave in potable water and wastewater setups (Lénès *et al.* 2010). In other words, are the water treatment filtration and disinfection techniques enough for eliminating viruses? Viruses remain the main danger to wastewater and water industries because of their small levels in urban wastewater and the high decomposition capabilities of aqueous ecosystems (Lénès *et al.* 2010).

As a rule, McLellan *et al.* (2020) affirmed that viruses could be eliminated readily when water treatment specialists take suitable safeguards and attention to hazards (Ghernaout & Elboughdiri 2020i, 2020j).

Antiseptics

Wastewater from hospitals must be thoroughly disinfected. Wastewater treatment plants receiving sewage from hospitals and isolation centers treating virus patients – and urban sewage from zones of known pollution – could have increased levels of viruses. Highly polluted water from these sources has to be purified through a collection of processes to reduce the infection effects on the adjacent receiving ecosystems (Lénès *et al.* 2010).

Usage of chemicals

Following McLellan *et al.* (2020), secondary wastewater treatment is believed to reduce 90% of viruses, even if large investigations mention the degree of virus reduction is considerably variable, ranging from little to more than 99%. Due to such variability, the most important method for neutralizing viruses in wastewater treatment is chemical disinfection. As a conventional disinfection technique, chlorination remains largely employed (McLellan *et al.* 2020).

Updating water treatment industry

With upstream wastewater influences, surface water treatment plants remain the most subject to receiving viruses infection in the raw water supply during, and after, an outbreak. Viruses remain generally unprotected to many potentially eliminating stresses in surface waters, comprising sunlight, oxidative chemicals, and predation by microorganisms. Enveloped viruses are more liable to usual drinking water disinfectants than non-enveloped viruses; consequently, potable water treatment should be efficient (Lénès *et al.* 2010).

Since 2003, there has been considerable worry concerning the probability of an outbreak of avian influenza virus subtype H5N1. Furthermore, around 2010, the A(H1N1) pandemic of swine origin caused hundreds of thousands of human cases of illness and thousands of deaths. Because such viruses could likely pollute water resources via wild birds' excreta or sewage, Lénès *et al.* (2010) focused on finding out whether the treatment processes in usage in the potable water industry are sufficient for exterminating them. They evaluated the performance of physical treatments (coagulation-flocculation–settling, membrane UF, and UV) on H5N1. They proved that disinfectants (monochloramine, chlorine dioxide, chlorine, and ozone) work for both the H5N1 and H1N1 viruses (Lénès *et al.* 2010).

The influence of coagulation settling on the H5N1 subtype was relatively small and variable. In contrast, UF attained more than a 3-log reduction (and more than a 4-log reduction in most circumstances), and UV treatment was effective (more than a 5-log elimination with a UV dose of 25 mJ/cm^2). Concerning the chemical disinfection treatments, ozone, chlorine, and chlorine dioxide were all very efficient in eliminating H5N1 and H1N1; however, monochloramine treatment needed bigger injections and more extended residence periods to achieve significant removals (Lénès *et al.* 2010).

Ten years ago, Lénès *et al.* (2010) concluded that the water treatment techniques that are currently utilized for surface water treatment are appropriate for eliminating influenza A viruses. Suitable preventive actions can be described for single disinfection treatment plants.

Figure 5 presents an overview of disinfection requirements for 99% demobilization of microorganisms using various disinfectants (Gerba 2015).

CONCLUSIONS

Here, we review and discuss recent improvements in applied processes for removing viruses from water. Water treatment specialists need to understand how viruses behave in potable water pipes and wastewater setups. From this work, the following conclusions can be drawn.

1. GAC adjusted with Ag and CuO nanoparticles led to an important amelioration in eliminating viruses. NP-Ag gave better results than NP-CuO. The combination of nanoparticles with GAC/NP-Ag-CuO proved to be synergistic. The rapid elimination kinetics of the virus using

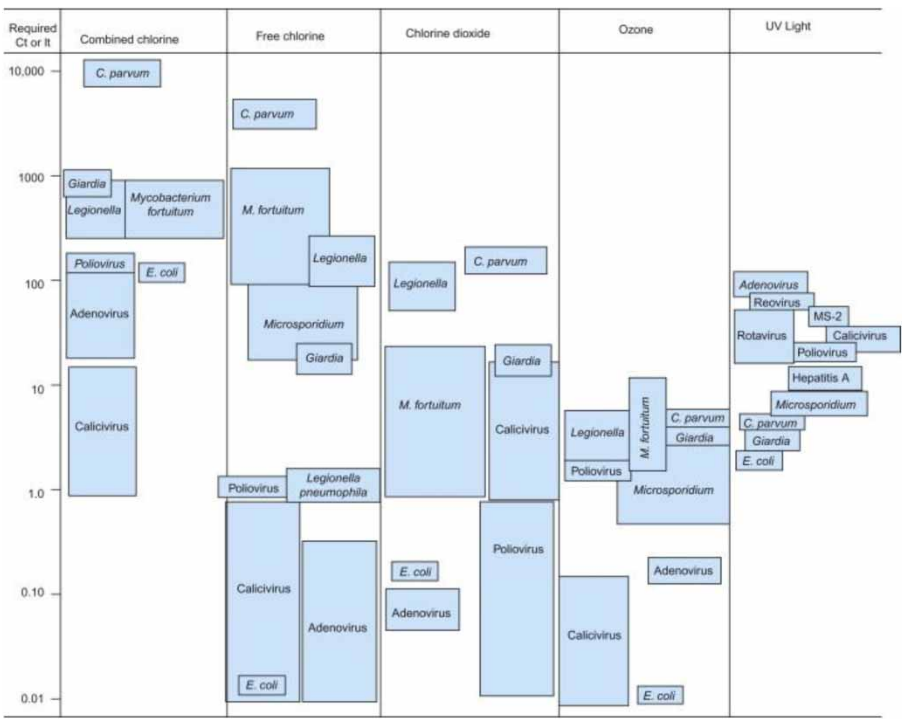

Figure 5 | Overview of disinfection requirements for 99% demobilization of microorganisms. *Ct* = concentration of disinfectant × time. *It* = ($\mu W \cdot s/cm^2$) (time) (Gerba 2015).

GAC/NP6 showed that this material is a viable and encouraging option to treat potable water (Shimabuku *et al.* 2018).

2. Wastewater and drinking water treatment plants will be under intense scrutiny in the event of a large virus pandemic (Lénès *et al.* 2010). Utilities would be required to react quickly to reduce occupational and public health dangers and make decisions founded on experimental evidence. Wastewater effluents would likely touch recreation, irrigation, and potable water streams. Wastewater treatment reduces virus concentrations; however, pathogenic human viruses frequently remain in the wastewater treatment plant effluent (Lénès *et al.* 2010).
3. The efficient use of SODIS in decreasing the occurrence of cholera in several countries proves the relevance of such a technique. The finding that traditional batch-process SODIS may be adjusted to benefit from TiO_2-improved photocatalysis, this way decreasing the irradiation dose and/or expanding the domain of pathogens versus which it is efficient, encourages more investigation in this area (Reed 2004).
4. Even if the EC–EO treatment device suggested by Heffron *et al.* (2019) was not useful in all of the water matrices, the ameliorated virus reduction attained by EC–EO in model surface waters is encouraging. The advantage of EC–EO was possibly not attributed to iron-improved oxidation. Instead, bigger virus removal detected in the EC–EO treatment train was probably obtained through the additive impacts of physical removal by coagulation/filtration, ferrous iron-based disinfection, and EO disinfection.
5. Even if the clarification process (coagulation-flocculation settling) does not significantly decrease H5N1 levels in the water, integrating ozonation and final disinfection techniques (chlorine, chlorine dioxide, or monochloramine) could lead to at least a 7-log elimination, as long as the requested oxidant residuals and residence periods are respected (Lénès *et al.* 2010). In high-performance treatment plants that utilize membrane UF and/or UV irradiation, the elimination will be much improved since such technologies allow further 4-log removal of H5N1 to be attained.
6. The more we study the composition of viruses and their behavior in nature and water and wastewater treatment industry, and the more we try the engineering methods for their disposal in water treatment plants, the more we realize that it is difficult to get rid of them using a single treatment method. Employing advanced water treatment trains (such as chemical clarification, reverse osmosis, UF, advanced oxidation) was proposed to guarantee removal of viruses to differing degrees of regulatory control following the degrees of human subjection and related health hazards. Further, before reaching surface water, pathogens have to be removed efficiently from hospital and municipal wastewater through adopting a multi-barrier techniques' strategy, i.e., advanced oxidation processes, ACA, membranes processes, etc. (Ghernaout & Elboughdiri 2020g, 2020h, 2020i, 2020j, 2020 k, 2020l).

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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