



Advanced Oxidation Processes for Water and Wastewater Viral Disinfection. A Systematic Review

Petros Kokkinos¹ · Danae Venieri² · Dionissios Mantzavinos¹

Received: 26 January 2021 / Accepted: 6 June 2021 / Published online: 14 June 2021

© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2021

Abstract

Water and wastewater virological quality is a significant public health issue. Viral agents include emerging and re-emerging pathogens characterized by extremely small size, and high environmental stability. Since the mainly used conventional disinfection methods are usually not able to achieve complete disinfection of viral and other microbial targets, in real water and wastewater matrices, effective strategies for the treatment, use and reuse of water and the development of next-generation water supply systems are required. The scope of the present systematic review was to summarize research data on the application of advanced oxidation processes (AOPs) for viral disinfection of water and wastewater. A literature survey was conducted using the electronic databases PubMed, Scopus, and Web of Science. This comprehensive research yielded 23 records which met the criteria and were included and discussed in this review. Most of the studies (14/23) used only MS2 bacteriophage as an index virus, while the remaining studies (9/23) used two or more viral targets, including phages (MS2, T4, T7, phiX174, PRD-1, S2, φB124-14, φcrAssphage) and/or Adenovirus, Aichivirus, Norovirus (I, II, IV), Polyomavirus (JC and BK), Sapovirus, Enterovirus, Coxsackievirus B3, Echovirus, and Pepper mild mottle virus. The vast majority of the studies applied a combination of two or more treatments and the most frequently used process was ultraviolet light-hydrogen peroxide (UV/H₂O₂) advanced oxidation. The review is expected to highlight the potential of the AOPs for public health protection from the waterborne viral exposure.

Keywords Advanced oxidation processes · Water · Wastewater · Treatment · Disinfection · Virus

Introduction

General Issues

The contamination of water resources is an issue of global concern and the need for provisions of clean water is increasingly becoming demanding (Kokkinos et al., 2020). Moreover, water scarcity has been identified as a major problem of this century (Schmitz et al., 2016). Limited and

frequently deteriorated freshwater resources, along with an increasing water consumption, combined with the climate change has led to water reclamation concepts, which support the reuse of treated wastewater worldwide for different purposes (e.g. agricultural, industrial, potable, etc.) (Giannakis et al., 2017a; Gomes et al., 2019; Schmitz et al., 2016). Water microbiological quality issues have been extensively investigated, since waterborne outbreaks have been recorded in both developing and developed countries, and contaminated water may seriously affect economic activities (primary production, tourism, etc.) (Kokkinos et al., 2011, 2020). Bacteria, viruses and protozoa are the cause of many emerging and new waterborne infectious diseases, and the most common cause is fecal pollution of human and/or animal origin (Kokkinos et al., 2020). More stringent water quality regulations are adopted and, nowadays, it is well recognized that chlorination and other conventional disinfection methods are often not able to achieve complete disinfection of bacterial, viral and protozoa microbial targets, in real water and wastewater matrices (Galeano

✉ Petros Kokkinos
pkokkin@upatras.gr

Danae Venieri
danae.venieri@enveng.tuc.gr

Dionissios Mantzavinos
mantzavinos@chemeng.upatras.gr

¹ Department of Chemical Engineering, University of Patras, University Campus, Caratheodory I, 26504 Patras, Greece

² School of Environmental Engineering, Technical University of Crete, 73100 Chania, Greece

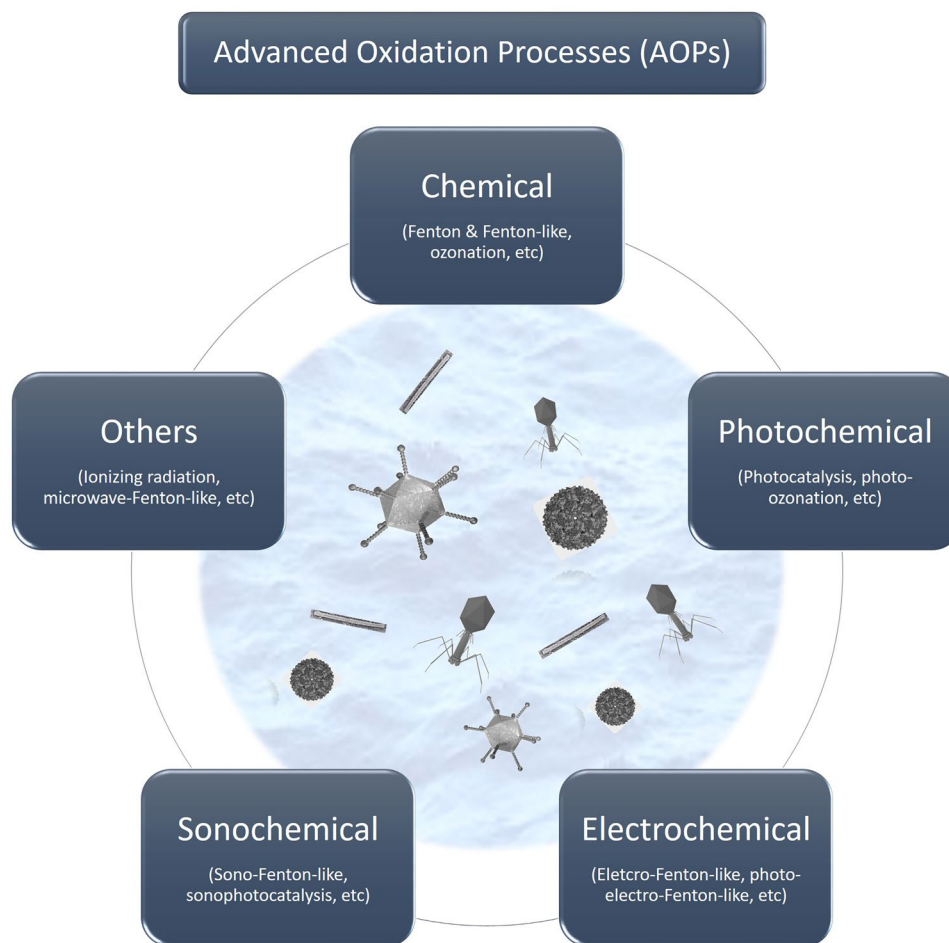
et al., 2019; Giannakis et al., 2017a; Nieto-Juarez & Kohn, 2013). The prevalence of human enteric viruses in water and wastewater may pose a serious threat to public health, and new and more efficient treatment methods are required to ensure the microbiological quality of water and specifically the abatement of enteric viruses to levels that pose no significant risk to human health (Gerba et al., 2018; Nieto-Juarez & Kohn, 2013). Interestingly, the vast majority of the viral agents, which are transmitted via the fecal–oral route are non-enveloped, highly stable under environmental conditions, characterized by extremely small size, and include emerging and re-emerging pathogens with the most relevant of them belonging to the families of Adenoviridae, Caliciviridae, Hepeviridae, Picornaviridae and Reoviridae (Rodríguez-Lázaro, et al., 2012). The enteric viruses of human stool and urine belong to more than 140 types (Kokkinos et al., 2011). Surprisingly, untreated wastewater has been identified as the most diverse viral metagenome examined so far, with most sequence reads having little or no sequence relation to known viruses, indicating that most of the viruses have not yet been characterized (Cantalupo et al., 2011). The current global outbreak of SARS-CoV-2, the virus that causes COVID-19, has highlighted the urgent need to investigate the fate and transport of coronavirus and other enveloped viruses in urban sewage and drinking water, and also to develop rapid, sensitive, specific and inexpensive methods for water virological analysis (Foladori et al., 2020; La Rosa et al., 2020).

Advanced Oxidation Processes

Nowadays, it is well recognized that the existing biological and physicochemical treatment methods are unable to deal with the complete abatement of viral agents in hydric resources. In spite of its inherent weaknesses such as the production of disinfection by-products (e.g. trihalomethanes), chlorination is still the most common disinfection technique (Giannakis et al., 2017a). However, the adoption of advanced treatment technologies such as advanced oxidation processes (AOPs) are a promising approach for the improvement of water and wastewater treatment (Feitz, 2005). AOPs have emerged as promising, environmentally friendly and efficient alternative disinfection methods to conventional ones, to control water microbiological quality. They rely on the in situ formation of chemical oxidants to disinfect water and degrade diverse harmful organic contaminants (Giannakis et al., 2017a; Marjanovic et al., 2018; Nieto-Juarez & Kohn, 2013; Shabat-Hadas et al., 2017). AOPs are, in practice, redox technologies including different processes such as ozonation, ozonation coupled with H₂O₂ and/or ultraviolet (UV) radiation, Fenton and alike reactions, photocatalysis activated by semiconductors such as TiO₂, sonolysis, electrochemical oxidation, and various combinations of them

(Fig. 1). They are based on the production of highly reactive oxygen species (ROS), characterized by the non-selectivity on the target and can be used as pre- or post-treatment to a biological process (Galeano et al., 2019; Kokkinos et al., 2020; Monteiro et al., 2015). The principal oxidizing agent is the hydroxyl radical, being the second most powerful oxidant after fluorine. However, other ROS may also be produced (e.g. hydroperoxyl radicals, superoxide radical anions, etc.) (Giannakis et al., 2017a, 2017b, 2017c). Hydroxyl radicals are frequently produced by the homolytic cleavage of the O–O bond of hydrogen peroxide with UV light (Bounty et al., 2012; Shabat-Hadas et al., 2017). A well-studied AOP is the photo-Fenton process, in which hydroxyl radicals are produced by light, iron and hydrogen peroxide (Nieto-Juarez et al., 2010, Marjanovic et al., 2018). It is an environmentally friendly, simple, low-cost process which has been shown to be effective in the abatement of structurally simple, complex or resistant microbes (Giannakis et al., 2017a). Indeed, AOPs have shown a high disinfection potential against a wide range of microorganisms like virus, protozoa, spore-forming bacteria, fungus, and yeasts, mainly through the action of ROS such as singlet and triplet oxygen, anion-radical superoxide, hydroxyl and hydroperoxyl radical, and hydrogen peroxide. ROS are known oxidants of different types of molecules, such as proteins, lipids, and also nucleic acids. Specifically for nucleic acids, ROS may exert their action at different levels (e.g. change the nucleotides, break the phosphodiester bond, enhance the formation of pyrimidine dimers, change the tridimensional structure, and affect DNA replication) (Galeano et al., 2019). Different factors, such as the use of sunlight (a renewable source of energy), the minimal needs of hydrogen peroxide and consequently reduced costs, and the application of a low-cost catalyst such as Fe³⁺, which is frequently present in natural waters, render photo-Fenton a process of great potential for viral abatement in water matrices (Ortega-Gomez et al., 2015). Sulfate radicals, which are characterized by a redox potential close to that of hydroxyl radicals (2.6 V), may be used as an alternative to hydroxyl ones, since they are more selective against various target contaminants and pollutants. Different activating factors (light, heat, transition metals, etc.) may promote the production of sulfate radicals from chemicals such as peroxydisulfate and peroxydisulfate (PDS) (Marjanovic et al., 2018). Although during the last years, the photo-Fenton and alike processes have been used as a green alternative to chemical disinfection of waters and wastewaters, they have still to be completely clarified (Giannakis et al., 2017b, Giannakis, 2018). Different studies have revealed the order of microbial resistance to solar photo-Fenton process as follows, bacteria < viruses < spores (fungi or bacteria) (Giannakis et al., 2016). The assessment of the disinfection using light-driven AOPs is based on the use of different approaches such as computational fluid dynamics,

Fig. 1 Categorization of AOPs for environmental applications with a potential for viral disinfection in water and wastewater matrices



chemical actinometry or biosimetry (Shabat-Hadas et al., 2017). The concurrent abatement of pathogens and chemical pollutants by solar-enhanced AOPs has been reviewed by Tsydenova et al. (2015)

To face the limitations of the homogeneous Fenton processes, which are associated with the pH-dependent solubility and stability of ferrous and ferric species, the use of an alternative iron source, i.e. iron (hydr)-oxide particles, has been assessed in a process called heterogeneous Fenton-like. The effectiveness of such a process for viral inactivation catalyzed by colloidal iron around neutral pH under sunlight has been proved (Nieto-Juarez & Kohn, 2013; Nieto-Juarez et al., 2010). Interestingly, iron-bearing particles may support viral disinfection by different ways, i.e. physical removal by adsorption onto particles, by Fenton-like processes, photocatalysis or disintegration upon adsorption (Nieto-Juarez & Kohn, 2013). More research is needed though on viral inactivation by photo-Fenton process (Gianakis et al., 2017b, 2017c).

Nanoparticle-mediated photocatalysis is another interesting approach for water disinfection, and TiO_2 has been found to be effective against different pathogens such as viruses, bacteria, and fungi (Prasse & Ternes, 2010) Zhu et al. (2020)

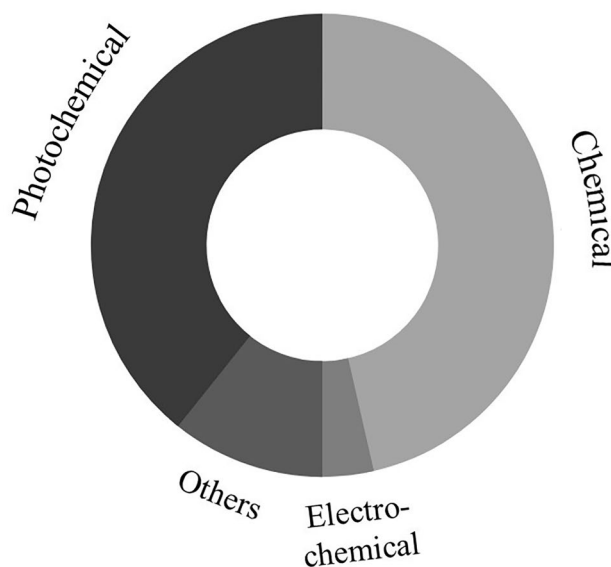


Fig. 2 Donut chart visualization of the grouping of the reviewed studies into the main categories of Advanced Oxidation Processes. The vast majority of the studies applied chemical and photochemical processes, while limited cases on the application of electrochemical and other AOPs were also found

reviewed the formation of nanostructured manganese oxides and their application in wastewater remediation; these oxides can catalyze peroxides to produce ROS in aqueous phase, thus initiating in situ chemical oxidation and AOPs. Duan, (2019) performed a proof-of-concept study to unravel the principles in developing fine-tuned and high-performance transition metal (TM)@carbon composites for advanced catalytic oxidation for water decontamination.

During the last decades, the UV technology is upgraded through its application in AOPs (Timchak & Gitis, 2012). The use of UV irradiation for water disinfection of enteric pathogens is an emerging technique characterized by high efficiency and the absence of the formation of disinfection by-products (Chu et al., 2012). Microbial disinfection by UV irradiation is mainly exerted by UV-induced photochemical reactions of the genetic material. Direct (or endogenous) inactivation involves the absorbance of UVB light by the viral genome, which causes its degradation. Although viral proteins may also absorb UVB radiation to a lesser extent, the contribution to viral inactivation has still to be clarified (Mattle et al., 2015). While UVC/UVB are strongly absorbed by DNA and have additive disinfection effects, UVA cannot induce DNA damage and has no direct photochemical reactions on DNA. However, it may produce reactive intermediates such as ROS (e.g. hydroxyl and superoxide radicals, hydrogen peroxide, etc.), which in turn may damage microbial targets (e.g. proteins, DNA, etc.) (Mamane et al., 2007; Song et al., 2019). Compared to DNA, RNA is known to be more susceptible to oxidative damage by exposure to UV (Galeano et al., 2019). In indirect (or exogenous) inactivation, UVB/UVA and visible light are known to be absorbed by different water sensitizers (e.g. organic matter, nitrate, iron-containing complexes, etc.), which produce reactive species with viral inactivation potential. The type of virus, as well as the solution conditions, are both critical factors, which dictate the relative contribution of direct and indirect inactivation (Mattle et al., 2015). The UV treatment disinfection efficacy may be impeded by absorbing particles and microorganisms that are captured in aggregates of particulate matter (Kosel et al., 2017). One of the most widely used AOP is the UV/H₂O₂. Such a process has been shown to be highly efficient for the treatment of burdened wastewater like that of meat processing industry. (Yapıcıoğlu, 2018).

Another new advanced technique is hydrodynamic cavitation, which exerts its disinfective action through chemical (production of hydroxyl radicals) and physical mechanisms (pressure gradients, shock waves, shear forces, very high local temperatures). Although the exact mechanisms of viral disinfection have not yet been clarified, it may be hypothesized that hydrodynamic cavitation may cause structural damages at different components of a viral particle (coat, host recognition receptors, capsid, genome) (Kosel et al., 2017).

We have recently reviewed the main categories of nano-materials used in catalytic processes (carbon nanotubes/graphitic carbon nitride (CNT/g-C₃N₄), composites/graphene-based composites, metal oxides and composites, metal–organic framework and commercially available nano-materials) and discussed their application in the removal of different classes of pollutants, as well as for the elimination of bacterial, viral and protozoan microbial targets, from water and wastewater matrices (Kokkinos et al., 2020).

Since AOPs are typically energy-intensive processes, the so-called electrical energy per order (i.e. the energy needed to reduce the concentration of contaminant by an order of magnitude in a unit volume of water, EEO) is a useful measure to classify them in three groups as follows: < 1 kWh m⁻³ (e.g. O₃/H₂O₂, O₃/UV, UV/H₂O₂, etc.), 1–100 kWh m⁻³ (e.g. photo-Fenton) and > 100 kWh m⁻³ (e.g. UV-based photocatalysis) (Miklos et al., 2018). The energy efficiency and treatment cost associated with the use of AOPs are important parameters for the practical assessment of their disinfection efficiency (Chen, 2021).

The wide application of AOPs is expected to enhance the removal of emerging contaminants and pathogens from water and wastewater (Sherchan et al., 2014). According to Gerba et al. (2018), although advanced water treatment trains have been applied for the reduction of viral loads, it is of pivotal importance to understand viral inactivation processes by different treatments, improve current estimates and identify new research tasks (Gerba et al., 2018). A donut chart of the grouping of the reviewed studies into the main categories of AOPs is shown in Fig. 2.

Use of Indexes and Applicability

Viruses with diameters from 20 to 300 nm are an important threat to water safety and a significant microbial target, which should be taken into consideration in water treatment processes. Their diversity and polymorphic nature have been recognized and are continuously unraveled (Cantalupe et al., 2011; Giannakis et al., 2017b; Marjanovic et al., 2018). Enteric viruses are listed as emerging biological contaminants on the United States Environmental Protection Agency (USEPA) Contaminant Candidate List (Gomes et al., 2019). Water treatment technologies are required to achieve a 99.99% (4-log) reduction in sample viral concentrations after treatment, to be considered efficient by USEPA and Health Canada (Monteiro et al., 2015).

Bacteriophages have been used as indicators of water microbiological quality due to their specificity and resistance, compared to the traditional bacterial indicators, and they are valuable viral indicators for the assessment of different treatment techniques (Table 1) (Gheraout, 2020; Ortega-Gomez et al., 2015). The USEPA has recommended the use of coliphages as surrogates of human enteric viruses

Table 1 Summary of studies dealing with MS2 bacteriophage as the sole index virus

Method	Results	Reference
Solar disinfection enhanced by moderate addition of iron and sodium peroxydisulfate	1) Solar/heat CP with natural Fe < solar/PDS Solar/ Fe < CP in presence of NOM < CP 2) The abatement was achieved at minute-range residence times	Marjanovic et al., 2018
Heterogeneous Fenton-like processes catalyzed by iron (hydr)oxide particles	1) Adsorption onto α -FeOOH, Fe ₃ O ₄ , Fe(OH) ₃ particles caused virus inactivation of 7%, 22%, and 14%, respectively, while first-order inactivation rate constants were 6.6×10^{-2} , 8.7×10^{-2} , 0.55 and 1.5 min ⁻¹ , respectively 2) Additional inactivation of viruses which were adsorbed on particles was shown by the action of sunlight and H ₂ O ₂ , while the inactivation for suspended viruses was insignificant. In the absence of sunlight or H ₂ O ₂ , no inactivation was recorded apart that resulted by the adsorption, with the exception of Fe ₃ O ₄ , which inactivated viruses via a dark Fenton-like process	Nieto-Juarez, Kohn 2013
Ultraviolet reactor in combination with hydrogen peroxide	1) Ultraviolet radiation caused a decrease of 5.3–5.8 log ₁₀ of MS2, and a 1.7–2.8 log ₁₀ decrease in viral RNA copy number 2) MS2 abatement was increased by the addition of H ₂ O ₂ (at 2.5 or 5 ppm with UV at different flow rates), with a reduction of more than 7 log ₁₀ , while qPCR showed only a 3–4-log ₁₀ reduction in viral RNA copy number	Sherchan et al., 2014
Ozone treatment of reverse osmosis concentrates	Ozonation caused a 5-log abatement in concentrate samples at 1.18 mg O ₃ /mg DOC	King et al., 2020
Ozone, ozone/H ₂ O ₂	Dissolved ozone concentration integrated over time values of 1 mg-min/L caused inactivations higher than 6-log	Gamage et al., 2013
Ultraviolet light-emitting diodes	UVA pretreatment followed by UVC inactivation was found to cause no amelioration of MS2 inactivation, in comparison to <i>E. coli</i>	Song et al., 2019
UV/H ₂ O ₂ followed by free chlorine	No synergy was recorded for the treatment by UV irradiation followed by free chlorine, while increased inactivation was found when H ₂ O ₂ was added in the primary UV disinfection step	Cho et al., 2011
Hydrodynamic cavitation	Reductions of viral infectivity higher than 4-logs were recorded	Kosel et al., 2017
UV/H ₂ O ₂ flow through system followed by free chlorine	A 5.78 log abatement was achieved with a flow rate at 50 L/h, while a 4.49 log removal was achieved with a flow rate of 100 L/h	Chu et al., 2012
N-doped TiO ₂ -coated Al ₂ O ₃ photocatalytic membrane reactors (PMRs)	1) In natural surface water the viral abatement under irradiation was found to be 4.9 ± 0.1 log 2) Complex virus–PMR interactions were found even before the exposure to light 3) Electrostatic forces in addition to photocatalytic inactivation dictate the viral abatement in a complex water matrix by PMR. While alkaline water pH causes a limited interaction and a reduced viral abatement by PMR, the addition of Ca ²⁺ results to higher MS2 abatement	Horovitz et al., 2018

Table 1 (continued)

Method	Results	Reference
Iron- and copper catalyzed Fenton systems (H ₂ O ₂ , metal concentrations, HO• production, and sunlight)	<ol style="list-style-type: none"> 1) Viral reduction was first-order in relation to H₂O₂ 2) The inactivation rate constant k_{obs} in the Cu/H₂O₂ system, increased with added Cu up to 2.5 μM, and then was stabilized 3) The inactivation in the Fe/H₂O₂ system was dictated by colloidal iron 4) Sunlight irradiation influenced only the Fe/H₂O₂ system, causing a 5.5-fold increase in k_{obs} (up to 3.1 min⁻¹), 4) HO• generation could not account for the recorded abatement in the Fe/H₂O₂ system 	Nieto-Juarez et al., 2010
Photo-Fenton process (Fe species and concentration, solar irradiance, pH and microbial competition)	<ol style="list-style-type: none"> 1) In comparison to their Fe(III) counterparts, Fe(II) salts, resulted in a faster abatement, in any combination of H₂O₂ concentration, sunlight irradiance or starting pH (6–8) 2) Starting with Fe(II) resulted to more iron in solution longer than Fe(III), which is responsible for higher inactivation kinetics 3) Exposure to 600 W/m² (30 min) in presence of Fe(III) and H₂O₂ (1:1 ratio) resulted in a 4-log MS2 reduction. 4) MS2 reduction was moderately reduced in presence of the bacterial host, indicating a limited competition for the oxidants in the bulk 	Giannakis et al., 2017a, 2017b, 2017c
Advanced oxidation processes (AOPs), UVC, UVC/H ₂ O ₂ , and UV/Fenton based	<ol style="list-style-type: none"> 1) A reduction of the viral load by approximately 4-log was recorded for UVC and UVC/H₂O₂ treatment, after 2 or 1.5 min of exposure, respectively 2) Iohexol delayed kinetics of abatement to approximately 80% for MS2, in all studied matrices, while a value of 60% was recorded by the addition of H₂O₂ 3) MS2 bacteriophage was found to cause an average 45% reduction of the bacterial inactivation in all studied matrices, and similarly, <i>E.coli</i> was shown to delay the inactivation of MS2, except in synthetic wastewater matrices 	Giannakis et al., 2018
Heterogeneous photo-Fenton process	<ol style="list-style-type: none"> 1) Low concentrations of iron oxides in wastewater without H₂O₂ (wüstite, maghemite, magnetite) was found to cause restricted semiconductor-mediated MS2 inactivation 2) The isoelectric point of the iron oxides and the active surface area are important parameters of the process, as was demonstrated by the working pH and the size of the oxide particles 3) A significant enhancement of the abatement process was shown after the addition of low amounts of Fe-oxides (1 mg L⁻¹) and H₂O₂ (1, 5 and 10 mg L⁻¹), leading to heterogeneous photo-Fenton processes on the surface of the oxides 4) Photo-dissolution of iron in the bulk, lead to homogeneous photo-Fenton, which was supported by the complexation by the dissolved organic matter in the solution 	Giannakis S et al., 2017b

due to their interesting characteristics (similarity of structural, morphological, and inactivation resistance characteristics) (Schmitz et al., 2016). It is well recognized that the

assessment of disinfection processes cannot be based on classic faecal bacterial indicators, since they are too sensitive

to disinfectants compared to viral and protozoan pathogens (Sommer et al., 2004).

MS2 bacteriophage is an F+ specific, single-stranded RNA phage, with similarities in size (27.5 nm) and structural complexity to some human enteric viruses. It is small, spherical (icosahedron), non-enveloped, and characterized by high resistance to chemical disinfectants and/or environmental stressed conditions (e.g. temperature, osmotic pressure, and desiccation). Interestingly, it seems to be more resistant to inactivation compared to many waterborne viruses of public health concern with similar basic features, such as size, morphology, structure and overall behaviour (Jolis, 2002). Due to its resistibility characteristics and its high numbers in sewage, it is frequently used as an index of wastewater contamination and a quantitative marker for the assessment of the function of water treatment plants and filtration devices as well as for the effectiveness of antiviral/antiseptic agents (Table 1) (Kosel et al., 2017). It is characterized by a negative charge under a wide pH range (isoelectric point ~ 3.9) and it is relatively hydrophobic (Horovitz, 2018). It is also non-pathogenic and easily propagated and purified in laboratory, up to elevated viral titers, which are frequently required for inactivation experiments. (Kosel et al., 2017, Giannakis et al., 2017a, 2017b, 2017c, Giannakis, 2018, Horovitz et al., 2018) A 5-log reduction of MS2 is used in California for the assessment of disinfection systems for non-potable reuse applications (King et al., 2020). It has been extensively used as a surrogate for human enteric viruses in studies of assessment of the AOPs potential for viral abatement. Its inactivation requires a high oxidation power because is mainly based on the denaturation of capsid proteins, whose structure is simple and rigid (Horovitz et al., 2018; Mamane et al., 2007). MS2 has been proposed as a reference virus for the assessment of solar disinfection (SODIS) processes, since it is expected to support the standardization and interpretation of diverse experimental setups, focusing on different water matrices and using different light sources and reactor setups (Cho et al., 2011; Gamage et al., 2013; Giannakis et al., 2017a; Marjanovic et al., 2018; Mattle et al., 2015; Sherchan et al., 2014).

Like MS2, PRD-1 (a coated, double-stranded DNA bacteriophage with an approximate diameter of 65 nm), PMMoV (a rod-shaped, 18 × 312 nm RNA virus used as a non-pathogenic fecal indicator), bacteriophages related to non-pathogenic human gut microbiota (e.g. ϕ crAssphage and ϕ B124-14, spherical, double-stranded DNA viruses with diameters of approximately 50 nm and 75 nm, respectively), as well as adenoviruses and polyomaviruses have been proposed as indicators for contamination and microbial-source tracking and have been used for the evaluation of viral disinfection in advanced water treatment systems (Table 2). (Papp et al., 2020; Schmitz et al., 2016; Sommer et al., 2004; Vaidya et al., 2019).

Adenovirus has been recorded to be the most resistant known pathogen to disinfection by UV light, a finding which affected the regulations on the application of UV disinfection for virus inactivation in surface and groundwater by USEPA (Bounty et al., 2012). Direct or indirect inactivation processes are responsible for the solar disinfection of viruses. Similarly to MS2, adenovirus is sensitive to ROS but relatively resistant to direct inactivation, while phiX174 (single-stranded DNA) was found to display the contrary behaviour (Mattle et al., 2015) Gerba et al. (2018) stressed out the need to use the appropriate viruses for the assessment of individual treatment processes. For example, they suggested the use of adenoviruses for the evaluation of UV light disinfection, while reoviruses have been proposed for the assessment of chlorination. (Gerba et al., 2018).

It should be taken in consideration that, although viral inactivation may be reached by targeting the viral capsid through direct reaction of disinfectants with its constituents, the diffusion of disinfectants inside other microorganisms through an outer membrane may be required. In such case, disinfectants with a short lifetime such as those produced by photo-Fenton processes, may not be efficient. (Nieto-Juarez et al., 2010) Some studies focused on the MS2 inactivation by the photo-Fenton process, but complete viral abatement was not succeeded (Ortega-Gomez et al., 2015). The main MS2 inactivation pathway during photo-Fenton treatment has to do with the generation of oxidants in the bulk, while bacterial inactivation is principally attributed to oxidative-stress inside the cell and, to a lesser extent, to that from the bulk concentration of hydroxyl radicals. (Giannakis, 2018) Moreover, due to the absence of repair enzymes and molecular processes for the repair of nucleic acids damages, MS2 is not able to repair UV-induced RNA damages through photoreactivation, in the contrary to bacteria such as *E. coli*. (Song et al., 2019).

Phage T4 is one of the biggest double-stranded DNA bacterial viruses, and it has also been used as a viral indicator in numerous studies (Gheraout et al., 2020). Similarly, T7 is a double-stranded DNA bacteriophage with many applications, especially in studies of solar UV disinfection assessment (Mamane et al., 2007). Endogenous inactivation by UVC/UVB irradiation has been found to depend on the type and size of the viral genome (Nelson et al., 2018). Hence, MS2 which is an RNA virus, shows a different UV inactivation behaviour compared to the T series viruses, which are DNA viruses (Mamane et al., 2007).

Compared to lab-made strains, naturally occurring pathogens are characterized by elevated resistance to oxidative processes (Giannakis et al., 2016). It must be pointed out that wild strains should also be considered to successfully assess the performance of engineered treatment processes; moreover, field scale systems should also be used for the confirmation of laboratory and pilot plant experimental data.

Table 2 Summary of studies dealing with more than one viruses

MS2 and T4 bacteriophages	Degradation of free and nano-bound RhB by direct UV photolysis, UV/H ₂ O ₂ AOP and solar light-induced photocatalysis	<p>1) Minor Rhodamine B degradation was shown by direct UV and solar light</p> <p>2) A nearly linear Rhodamine B degradation was found in the presence of a solid catalyst by UV/H₂O₂ and photocatalysis/photosensitization</p> <p>3) A significant adsorption of soluble (free) Rhodamine B was recorded on bismuth-based catalyst vs. no adsorption of virus-bound (nano-bound) Rhodamine B on this catalyst or of any form of the dye on titanium dioxide</p> <p>4) Virus-bound Rhodamine B showed high potential as an indicator of advanced oxidation process</p>	Shabat-Hadas et al., 2017
MS2 bacteriophage, and phages T4, and T7	UV/H ₂ O ₂ advanced oxidation	<p>1) Bacteriophages T4 in phosphate buffered saline (PBS) were sensitive to > 295 nm filtered UV irradiation (without H₂O₂), while MS2 was very resistant</p> <p>2) addition of H₂O₂ at 25 mg/l in the presence of filtered UV irradiation over a 15 min reaction time did not result in any additional disinfection of virus T4</p> <p>3) an additional one log inactivation for T7 and 2.5-logs for MS2 were obtained</p>	Mamane et al., 2007
MS2 bacteriophage, and phages phi X 174 and T4	Advanced UV/H ₂ O ₂ oxidation process	<p>1) The viral abatement was not affected by the presence of dyes but the addition of hydrogen peroxide improved it.</p> <p>2) The addition of 0.2 M H₂O₂ at 70 ml/cm² enhanced the MS2 abatement by two logs, while was found to have no effect on phi X 174 and T4 phages.</p> <p>3) The presence of viruses caused the reduction of the bleaching of fluorescent dyes due to restricted availability of hydroxyl radicals and their preferential involvement in virus inactivation</p>	Timchak & Gitis, 2012
MS2 bacteriophage, and phages φX174, and PRD-1	Ozone and hydrogen peroxide	The ozone/hydrogen peroxide process was found to have a significant microbicidal effect. MS2 bacteriophage, and phages φX174, and PRD-1 showed a reduction of approximately 6-log	Sommer et al., 2004
MS2 bacteriophage and Pepper mild mottle virus (PMMoV)	Two pilot-scale advanced water treatment plants were compared. The two treatment approaches included a carbon-based treatment process (flocculation/sedimentation, ozone-biofiltration, granular activated carbon (GAC) adsorption, ultraviolet (UV) disinfection; 20,000 L/day) and a membrane-based treatment process (ultrafiltration, reverse osmosis, UV-hydrogen peroxide advanced oxidation; 160,000 L/day)	In both advanced water treatment processes a > 8-log removal of MS2 and > 6-log removal of Pepper mild mottle virus was achieved	Vaidya et al., 2019

Table 2 (continued)

Adenovirus, and somatic and male-specific coliphage	Advanced oxidation-based Net-zero water (NZW) pilot system (septic tank, membrane bioreactor (MBR), aluminum electrocoagulation (EC), flocculation, vacuum ultrafiltration, peroxone or UV-hydrogen peroxide advanced oxidation, chlorine disinfection, and point of use granular activated carbon (GAC) filtration)	No viruses were found in the treated water, although adenovirus genetic material was detected probably due to the presence of inactive viral particles in hydraulic dead zones	Gassie et al., 2016
Adenovirus	Low-dose UV/H2O2 advanced oxidation	1) A UV dose of approximately 200 mJ/cm ² from a low-pressure source (emitting at 253.7 nm) was needed for a 4-log reduction of adenovirus 2) Addition of H2O2 (10 mg/L) caused a 4-log viral abatement at a dose of 120 mJ/cm ²	Bounty et al., 2012
Adenovirus (human adenovirus type 5)	Photo-electro-oxidation process	1) A 60 min treatment by the photo-electro-oxidation process caused an adenovirus reduction of 7 log10. 2) Exposure of 75 min was required for the complete abatement of DNase-treated samples, while completely non-viable adenoviruses were obtained after 30 min	Monteiro et al., 2015
Norovirus genotype I and II, and JC virus	Single and catalytic ozonation (by a volcanic rock)	Catalytic ozonation caused the complete abatement of all target viruses (Norovirus genotype I and II and JC virus), while JC virus could not be eliminated even after 150 min of treatment by single ozonation	Gomes et al., 2019
Eleven (11) different virus types (pepper mild mottle virus, atchi virus, noroviruses genogroup I, II, and IV, enterovirus, sapovirus, rotavirus group-A, adenovirus, and JC and BK polyomaviruses)	Advanced Bardenpho technology	1) Advanced Bardenpho wastewater treatment was proved to be more efficient compared to conventional treatments, 2) Atchi virus was found to be a conservative index virus for the assessment of viral removal in wastewater treatment 3) Bardenpho processes were the major sources of virus removal probably because of virus sorption to solids	Schmitz et al., 2016
Enterovirus	Treatment train consisting of ozone, biological activated carbon, microfiltration, reverse osmosis, and ultraviolet light with an advanced oxidation process	1) Performance distribution functions (PDFs) evidenced treatment that consistently surpassed the 12-log thresholds for virus, (as required for potable reuse in California) 2) Application of free chlorine disinfection during the treatment, achieved a median annual infection risk by enterovirus of 1.5×10^{-14} (no failures) and a maximum annual value of 2.1×10^{-5} (assuming one 24-h failure per year)	Pecson et al., 2017

Table 2 (continued)
Coxsackievirus B3

Two different peracetic acid formulations (15 and 22%) and low-pressure ultraviolet irradiation	Kibbee & Ormeci, 2020
<p>1) Coxsackievirus B3 was found to be highly sensitive to low-pressure ultraviolet irradiation at 20 mJ/cm², while it was very resistant to peracetic acid with ≤ 1 Log₁₀ tissue culture infectious dose 50% assay (TCID₅₀) reduction to concentrations ≤ 50 mg/L at a contact time of 15 min</p> <p>2) Simultaneous application of 3 mg/L peracetic acid with 20 mJ/cm² low-pressure ultraviolet irradiation caused a TCID₅₀ decrease of approximately ~ 4 Log₁₀</p>	

(Giannakis, 2018, Gerba et al., 2018) Numerous confounding factors affect the correct comparison of different treatment processes (e.g. season, wastewater origin, sampling and analysis methods, etc.) (Schmitz et al., 2016). Moreover, the biological diversity within families and genera of viruses and specific virus types (e.g. serotypes or genotypes) is a significant source of uncertainty (Gerba et al., 2018). More research is needed for the elucidation of the viral behaviour in natural surface waters and engineered systems in an attempt to enhance the disinfection of hydric resources (Ghernaout et al., 2020; Nelson et al., 2018).

Miklos et al. (2018) evaluated in their critical review the application of AOPs for water and wastewater treatment. They reviewed the major reaction mechanisms and formation of by-products, and also performed a critical comparison of different AOPs based on electrical energy per order (EEO) values. Chen et al. (2021) have recently reviewed AOPs for water disinfection. However, authors focused almost exclusively on bacterial inactivation and very limited data on viral abatement were reported. The current literature survey was performed with the view to summarize research data on the application of AOPs for viral disinfection of water and wastewater matrices and to identify the most frequently applied processes as a single or combined treatment(s). Overall, we aimed to highlight the potential of the AOPs for viral abatement and public health protection.

Materials and Methods

Data Sources and Search Strategy

Scopus, PubMed, and Web of Science were the selected databases used to find peer-reviewed articles dealing with the application of AOPs for viral disinfection of water and wastewater. Database searches were conducted between April and July 2020. However, a continuous reviewing of the databases has been performed during the whole time period of the preparation of the manuscript. The searches were conducted by using the following search terms and their variations in combination: “advanced oxidation processes AND water AND virus”, “AOPs AND water AND virus”, “advanced oxidation processes AND wastewater AND virus”, “AOPs AND wastewater AND virus”. The titles, abstracts and key words of articles included in the online databases were searched for these search terms.

Data Selection Criteria

This systematic review included both experimental and non-experimental studies from 2000 onward. All study design types were included, while non-English language studies, conference abstracts, editorials and letters to the editor were

excluded. The selection criteria developed a priori were as follows: i) The type of water/wastewater matrix; ii) The type of target virus (indicator and/or pathogenic); iii) The type of AOP. Eventually, twenty three articles fulfilled the inclusion criteria and were analyzed in the systematic review. The outcome variables were extracted independently by two investigators into a spreadsheet (Excel, Microsoft) with a standardized approach and any disagreement was resolved by discussion.

Disinfection Studies

Photo-Fenton and Related Processes

For the photo-Fenton process, irradiation with sunlight or an artificial light source is required to enhance the treatment efficiency of the respective dark reaction by the photoreduction of Fe^{3+} to Fe^{2+} and the additional production of hydroxyl radicals. A drawback of this process is the additional cost for artificial irradiation (Brienza & Katsoyianis, 2017). To overcome the limitations associated with homogeneous Fenton processes (Table 3), including the need to operate at highly acidic conditions, production of large amounts of iron-containing sludge, need to re-adjust the treated effluent to near-neutral conditions, heterogeneous Fenton processes are used based on transition metal catalysts (e.g. zero valent iron, iron minerals, metal oxides, etc.). (Chen et al., 2021).

Marjanovic et al. (2018) studied the enhancement of solar disinfection by the simultaneous addition of iron and PDS. They evaluated PDS activation by three individual factors (i.e. iron, heat and solar light), as well as their possible combinations. Authors reported that the abatement of MS2 bacteriophage was achieved in few minutes, when triple activation was applied (Marjanovic et al., 2018). In another study, the fate of MS2 coliphage in heterogeneous solar Fenton-like processes catalyzed by different iron (hydr)oxide particles was studied. Adsorption to goethite ($\alpha\text{-FeOOH}$), magnetite (Fe_3O_4) and amorphous iron(III) hydroxide ($\text{Fe}(\text{OH})_3$) was found to cause virus inactivation of 7%, 22%, and 14%, respectively. No inactivation was recorded in the absence of sunlight or H_2O_2 with the exception of magnetite, where partial MS2 inactivation occurred through a dark Fenton-like process. The findings of that study proved that heterogeneous Fenton-like processes can support viral abatement from water by physical removal, and inactivation by adsorption and a particle-mediated (photo-)Fenton-like process. (Nieto-Juarez & Kohn, 2013) Ortega-Gomez et al. (2015) also studied the inactivation of MS2 by solar photo-Fenton process, and assessed the effects of reactant concentrations (H_2O_2 , Fe^{2+} , Fe^{3+}) and solar irradiance on the process. Complete MS2 inactivation (from 10^6 PFU/mL to the detection limit)

was achieved with 1 mg/L Fe^{3+} after 60 min of solar irradiance at 45 W/m^2 , in the absence of H_2O_2 . After the addition of 1 mg/L H_2O_2 , complete inactivation was achieved after 20 min at 30 W/m^2 . Additionally, it was observed that the process with Fe^{3+} was faster than with Fe^{2+} , showing that the source of iron may be a significant inactivation parameter. MS2 and echovirus inactivation by the photo-Fenton process was also tested in natural water samples. Echovirus was more resistant than MS2 and, in either case, inactivation rates were reduced presumably due to the competition between the natural organic matter and the virus for oxidative species. (Ortega-Gomez et al., 2015).

In another study of Nieto-Juarez et al. (2010) regarding MS2 inactivation by iron- and copper catalyzed Fenton-like systems, it was found that viral reduction followed a first-order rate in relation to H_2O_2 . For the $\text{Cu}/\text{H}_2\text{O}_2$ system, the rate constant increased with increasing copper concentration up to $2.5 \mu\text{M}$, above which it reached a plateau, thus implying that only soluble copper was responsible for viral inactivation. On the other hand, inactivation in the $\text{Fe}/\text{H}_2\text{O}_2$ system was dictated by colloidal iron. Moreover, solar irradiation influenced only the $\text{Fe}/\text{H}_2\text{O}_2$ system; oxidants such as ferryl species could have also been implicated, complementing the action of hydroxyl radicals (Nieto-Juarez et al., 2010).

Giannakis et al. (2017b) investigated the application of heterogeneous photo-Fenton process for MS2 disinfection in wastewater matrices. They reported that low concentrations of iron oxides (wüstite, magnetite, maghemite) in wastewater without H_2O_2 resulted in restricted semiconductor-mediated MS2 inactivation. The dissolved organic matter was proved to be a catalyst poison since it competes with MS2 for the active sites and oxidants. A significant enhancement of the abatement process was shown after the addition of low amounts of H_2O_2 , leading to heterogeneous photo-Fenton processes on the surface of the oxides. The use of nano-sized iron oxides caused an increase of the active sites of the catalyst which in turn increased the active photo-Fenton sites positively affecting viral abatement. Moreover, partial photo-dissolution of iron in the bulk led to homogeneous photo-Fenton, which was supported by the complexation by the dissolved organic matter in the solution. According to the authors, the financial feasibility of such systems based on magnetically separable and reusable catalysts will affect the implementation of photo-Fenton treatment processes in combination with UVA, medium pressure UV lamps or solar light. In another study of photo-Fenton process assessment Giannakis et al. (2017c), evaluated the effect of principal parameters, such as Fe species and concentration, solar irradiance, pH and microbial competition on MS2 disinfection in wastewater. They found that ferrous materials were more effective than their ferric counterparts, resulting in faster abatement at any combination of H_2O_2 concentration,

Table 3 The main advantages and disadvantages of different advanced oxidation processes (AOPs)

AOP	Advantages	Disadvantages
Homogeneous photo-Fenton	Efficient and rapid oxidation and mineralization Production of reduced quantities of iron sludge compared to the dark Fenton reaction Low operating costs Effective at ambient temperatures Suitability for batch treatment	Need to operate at highly acidic conditions Potential effects on downstream processes due to the use of iron and acidic conditions Production of iron-containing sludge
UV/H ₂ O ₂	Efficient against most organic pollutants and for the disinfection of water matrices Fast treatment due to the production of hydroxyl radicals Proved functionality in existing full-scale treatment systems	Potential interference of compounds (e.g. nitrate) to the UV light absorbance Colour and turbidity may impede UV light penetration and decrease its effectiveness Deterioration of lamp performance at high temperatures Hydrogen peroxide is a costly chemical
Ozone-based processes	High efficiency against a variety of pollutants No sludge production Possible combination with various catalysts Use of ozone as a gas and thus no increase of treated water volume	High turbidity, particulate matter and heavy metals may negatively affect effectiveness Need for protection measures due to the use of ozone which is a highly toxic gas Potential generation of toxic by-products High capital and operating costs
Hydrodynamic cavitation	Potential for incorporation into a continuous flow process Potential scale-up that allows for a cost-effective treatment system High potential if applied in combination with other processes (UV, ozone treatment) reaching a synergistic effect	Immature technology The combination with other processes (UV, ozone, etc.) may result in an increase of the operating costs
Semiconductor photocatalysis	Titania is the single most suitable and low-cost material Environmentally friendly process Functionality with light of different wavelengths, including solar irradiation Possible recycle/reuse of the catalysts	Need for detailed preliminary studies on optimum catalyst type and concentration Requirement for catalyst separation if added as a slurry (this limitation may be faced by the hybrid photocatalytic membrane reactor, in which photocatalysis is combined with filtration in a single step) Potential generation of harmful by-products
Photo-electro oxidation	No requirements for extra chemicals Operation at ambient conditions	Low selectivity High operating cost due to electricity consumption

sunlight irradiance or starting pH (6–8). Initial treatment with Fe(II) caused the presence of more free iron ions in solution compared to Fe(III), which led to higher inactivation kinetics. Even so, exposure for 30 min at 600 W/m² in the presence of Fe(III):H₂O₂ at 1:1 ratio resulted in a 4-log MS2 reduction. Finally, it was shown that MS2 inactivation was moderately reduced in the presence of the bacterial host, indicating a limited competition for the oxidants in the bulk. Although ROS scavengers were present, an effective inactivation of MS2 was recorded (Giannakis et al., 2017c).

In another study, Giannakis et al. (2018) assessed the application of UVC, UVC/H₂O₂ and photo-Fenton methods against *E. coli* and MS2 in ultrapure water, wastewater and urine. Disinfection kinetics were investigated in the presence and absence of iohexol (an iodinated contrast medium). A reduction of the viral load by approximately 4-logs was recorded for UVC and UVC/H₂O₂ treatment after 2 and 1.5 min of exposure, respectively. MS2 bacteriophage was found to cause an average 45% reduction of the bacterial inactivation in all studied matrices, and similarly, *E. coli* was

shown to delay the inactivation of MS2, except in synthetic wastewater matrices. Interestingly, the study showed that a rapid bacterial and viral inactivation was achieved even in the presence of significant quantities of iohexol, as found in hospital effluents. (Giannakis et al., 2018).

Solar Disinfection

Sunlight is known to be effective for waterborne viral abatement via both direct and indirect processes. The sunlight is absorbed by virus, but it is also absorbed by external chromophores, which subsequently generate reactive species finally attacking viral targets (Mattle et al., 2015). Photocatalysis is an attractive “green” disinfection strategy since solar energy is used and there is no need of additional oxidants. It is mainly based on semiconductors that are sensitive to the UVA and/or visible regions of the solar spectrum and, thus, the disinfection processes are based on the photoinduced electron–hole pairs on the excited semiconductor to produce different ROS (Chen et al., 2021).

Numerous semiconductors have been applied but titanium dioxide (either as such or in various modified forms) has been extensively used due to its interesting characteristics (chemical inertness, high photoactivity, non-toxicity, low cost) (Brienza & Katsoyiannis, 2017).

In the study of Mattle et al. (2015) focusing on solar viral disinfection, three viral targets were used (MS2, phiX174, adenovirus) to study quantum yields of direct inactivation. Moreover, the second-order rate constants of four reactive species ($\text{OH}\cdot$, $^1\text{O}_2$, $\text{CO}_3^{\bullet-}$, triplet states) implicated in indirect inactivation process were estimated. ϕX174 was more sensitive to direct inactivation, with the highest quantum yield, than the other studied viruses. Second-order rate constants took values from 1.7×10^7 to $7.0 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$ in the order: MS2 > adenovirus > phiX174. A predictive model was used to assess the solar disinfection of MS2 and ϕX174 in a natural water sample. Viral abatement was mainly performed by direct processes, although indirect inactivation by $^1\text{O}_2$ also participated in the disinfection of adenovirus and MS2 (Mattle et al., 2015).

In the study of Venieri et al. (2015) Mn-, Co- and binary Mn/Co-doped TiO₂ catalysts were evaluated for the abatement of MS2 in real wastewater samples under simulated and natural solar irradiation (dopant concentration: 0.02–1 mol wt%, wavelength: > 420 nm, photon flux: $4.93\text{--}5.8 \times 10^{-7} \text{ E}/(\text{L s})$). Disinfection was found to follow a pseudo-first-order kinetic rate. Metal-doped catalysts caused a 60% MS2 abatement in 60 min under simulated solar irradiation (for an initial MS2 concentration of $10^5 \text{ PFU}/\text{mL}$). Interestingly, binary Mn/Co-doped TiO₂ catalysts showed the highest photocatalytic activity resulting in almost 99% MS2 disinfection in less than 20 min of irradiation, a finding which underlined the synergistic effect of composite dopants. (Venieri et al., 2015).

UV-Based AOP

Ultraviolet (UV) irradiation has been characterized by high efficiency towards microbial disinfection including viral inactivation. The most common UV sources are mercury lamps, such as low-pressure (LP) and medium pressure (MP) lamps for monochromatic UV at 254 nm, and polychromatic UV with a broad spectrum, respectively (Song et al., 2019).

The study of Song et al. (2019) focused on MS2 and *E. coli* inactivation by sequential UVA and UVC irradiation using light-emitting diodes (UV-LED). UVA pre-treatment followed by UVC treatment did not enhance MS2 inactivation, in comparison to *E. coli*, a finding which was attributed to the limited viral metabolic activities (Song et al., 2019).

Coxsackievirus B3 was found to be highly sensitive to low-pressure UV irradiation at $20 \text{ mJ}/\text{cm}^2$, while it was very resistant to peracetic acid with less than 1 log₁₀ tissue culture infectious dose 50% assay (TCID₅₀) reduction

at acid concentrations up to 50 mg/L and a contact time of 15 min. However, the simultaneous application of 3 mg/L peracetic acid with $20 \text{ mJ}/\text{cm}^2$ irradiation caused a TCID₅₀ decrease of approximately $\sim 4\text{--}10$. Secondary wastewater effluent samples were used for that study (Kibbee & Ormeci, 2020).

UV/H₂O₂ AOP

UV/H₂O₂ AOP based on the production of hydroxyl radicals due to the photolysis of H₂O₂ has been proved to be an efficient approach for the degradation of organic pollutants and microbial agents in water matrices. However, this AOP is less effective when the wastewater is characterized by high absorbance, while its application is restricted by high operational cost (Table 3) (Rasalingam et al., 2014).

Sherchan et al. (2014) studied the MS2 inactivation in deionized water using a small community ultraviolet light reactor (with energy-efficient, high-output amalgam lamps) combined with hydrogen peroxide. Ultraviolet radiation caused an MS2 decrease of 5.3–5.8 log₁₀ (as assessed by plaque counts) and a 1.7–2.8 log₁₀ decrease in viral RNA copy number (as assessed by quantitative polymerase chain reaction). MS2 abatement was increased by the addition of 2.5–5 mg/L H₂O₂ with a reduction of more than 7 log₁₀, while qPCR showed only a 3–4-log₁₀ reduction in viral RNA copy number, an indication that this technique overestimates the infective viruses (Sherchan et al., 2014). It is well recognized that compared to the traditional culture-based methods, sequence-specific DNA amplification strategies can significantly decrease the required time of microbiological/virological analyses of environmental samples, especially for non- or slow-culturable organisms/virus types. However it is also known that a positive PCR result does not discriminate between infective and inactivated viruses since viral nucleic acid can also be amplified even when no infective virus is present. Thus the interpretation of PCR/qPCR data regarding virus survival should be carefully performed.

A sequential UV treatment, with and without the addition of H₂O₂, followed by free chlorine MS2 disinfection was studied by Cho et al. (2011) in organic-free water. No synergy was recorded for the treatment by UV irradiation followed by free chlorine, while increased inactivation was found when H₂O₂ was added in the primary UV disinfection step. In this case, a significant synergy was recorded since an additional 1.5-log inactivation was added to the 2 logs occurring by UV treatment and free chlorine. The synergistic effect was based on the additional inactivation achieved during the primary UV disinfection step due to the generation of hydroxyl radicals during H₂O₂ photolysis, and also on the microbial injury during the primary step which facilitated the subsequent secondary chlorine disinfection. Overall the addition of H₂O₂ in the primary step, and thus

the conversion of the UV process to an AOP, could significantly enhance the efficiency of UV/free chlorine sequential disinfection processes (Cho et al., 2011). Similarly, a UV/H₂O₂-Cl₂ integrated flow through system was assessed by Chu et al. (2012) for MS2 disinfection. A 5.78 log abatement was achieved at a flow rate at 50 L/h (corresponding to a hydraulic retention time HRT = 7 s), while a 4.49 log removal was achieved at a flow rate of 100 L/h (HRT = 36 s) (Chu et al., 2012). Mamane et al. (2007) studied the virucidal efficiency of a UV/H₂O₂ system on MS2, T4 and T7 phages, filtering out UV radiation between 200 and 295 nm in order to i) limit the effect of direct UV photolysis, and ii) isolate the effect of hydroxyl radicals. Authors reported that bacteriophages T4 in phosphate buffered saline were sensitive to irradiation > 295 nm in the absence of H₂O₂, nonetheless, MS2 was very resistant. Overall, sensitivity decreased in the order: T4 > T7 > MS2, with MS2 suffering no inactivation at wavelengths > 295 nm. Interestingly, the addition of 25 mg/L H₂O₂ under UV irradiation for 15 min resulted in 2.5-logs of MS2 inactivation, had a small additional effect on T7 inactivation (of 1 log), but it did not result in any additional T4 disinfection (Mamane et al., 2007). To investigate dye-virus interactions, Timchak and Gitis (2012) used various combinations of phages (MS2, φX174 and T4) and fluorescent dyes (rhodamine B and fluorescein) to study inactivation and degradation processes. Authors found that viral abatement was not affected by the presence of dyes but the addition of 0.2 M H₂O₂ at 70 mJ/cm² UV dose enhanced MS2 abatement by two logs; however, peroxide addition was found to have no effect on φX174 and T4 phages. The presence of viruses caused the reduction of the bleaching of fluorescent dyes presumably due to restricted availability of hydroxyl radicals and their preferential involvement in virus inactivation (Timchak & Gitis, 2012). In another study, Bounty et al. (2012) focused on the improvement of UV adenovirus abatement with the addition of hydrogen peroxide. A UV dose of approximately 200 mJ/cm² from a low-pressure source emitting at 253.7 nm was needed for a 4-log reduction of adenovirus without peroxide. The addition of 10 mg/L H₂O₂ was capable of achieving a 4-log viral abatement at a reduced dose of 120 mJ/cm² (Bounty et al., 2012). Virus-bound rhodamine B was employed as an indicator of advanced disinfection in the study of Shabat-Hadas et al. (2017), who evaluated direct UV photolysis, UV/H₂O₂ and solar light-induced photocatalysis using fluorescence-labelled MS2 and T4 phages (Shabat-Hadas et al., 2017).

A schematic representation of the UV/H₂O₂ AOP effects on viral targets is shown in Fig. 3.

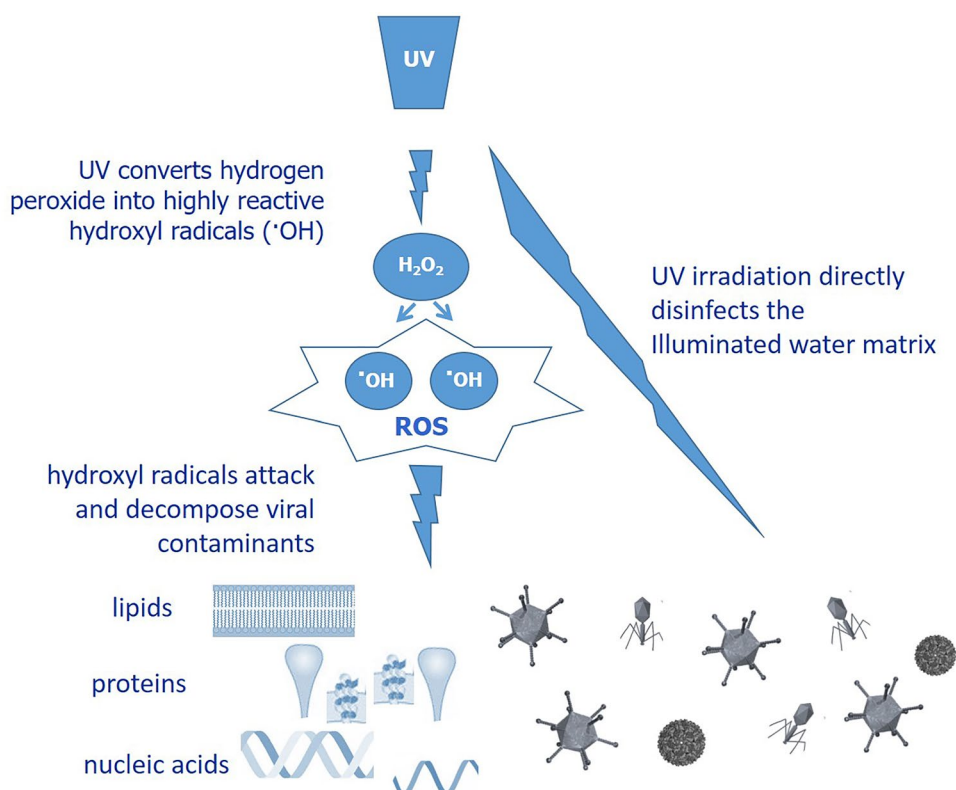
Ozone-Based AOP

Ozone is a powerful oxidizing agent that can effectively degrade different organic pollutants, as well as disinfect

microorganisms, either by direct electrophilic attack or indirectly through its reaction with water and the subsequent formation of hydroxyl radicals (Rasalingam et al., 2014). Different parameters may affect treatment efficiency (e.g. O₃ concentration, treatment duration, water temperature, pH, scavengers, etc.). Homogeneous and heterogeneous catalytic ozonation processes are applied for disinfection purposes, employing transition metal ions or solid catalysts (activated carbon, metal oxides, etc.), respectively. (Chen et al., 2021). Ozone-based AOPs are characterized by elevated capital and operating costs, and high electric power consumption besides other drawbacks, such as low water solubility of ozone and formation of hazardous by-products (Table 3) (Brienza & Katsoyiannis, 2017; Rasalingam et al., 2014).

King et al. (2020) assessed ozone treatment of pathogens and pollutants in reverse osmosis (RO) concentrates produced during the potable reuse of municipal wastewaters. Approximately 5-log removal was observed at 0.30 mg O₃/mg of dissolved organic carbon (DOC) when 10⁶–10⁷ PFU/mL of MS2 were spiked into RO concentrate samples from facilities where nitrite was not measurable. Samples from facilities, which contained nitrite, required higher O₃ doses to achieve 5-log inactivation of MS2. However, ozonation led to a 5-log abatement of MS2 in all concentrate samples at 1.18 mg O₃/mg of DOC. Due to its higher selectivity, ozone may be a more effective oxidant for controlling pathogens in RO concentrates compared to other AOPs which are based only on hydroxyl radicals, given that the contact time is sufficient before its rapid degradation and partial conversion to hydroxyl radicals (King et al., 2020). Gamage et al. (2013) assessed ozone and ozone/H₂O₂ for MS2 inactivation in secondary wastewater effluents. Time-integrated dissolved ozone concentrations of 1 mg·L⁻¹·min caused MS2 inactivation higher than 6 logs. Various process control indicators, i.e. ozone to DOC ratio, differential UV₂₅₄ absorbance and differential total fluorescence were also assessed in the context of this study and they were found useful for predicting the inactivation of MS2 (Gamage et al., 2013). To assess the disinfection efficiency of ozone and hydrogen peroxide treatment at a pilot plant, different phages (MS2, φX174, and PRD-1) were used in the study of Sommer et al. (2004). The ozone/hydrogen peroxide process was found to have a significant microbicidal effect. MS2 bacteriophage and phages φX174 and PRD-1 showed a reduction of approximately 6 logs. These findings corresponded to ozone disinfection in controlled batch experiments (residual 0.4 mg/L after 4 min contact time, 20°C) (Sommer et al., 2004). In another study, catalytic ozonation with a volcanic rock led to complete abatement of all target viruses (norovirus genotype I, II, and JC virus) from secondary municipal wastewater, while JC polyomavirus could not be eliminated even after 150 min of treatment by non-catalytic ozonation (Gomes et al., 2019).

Fig. 3 Schematic representation of the ultraviolet light-hydrogen peroxide (UV/H₂O₂) Advanced Oxidation Process effects on viral targets



Hydrodynamic Cavitation

Sun et al. (2020) have summarized the fundamental principles of hydrodynamic cavitation (HC) and the recent progress achieved in HC disinfection. HC is a promising emerging technology for large-scale disinfection without the need of using chemicals. Interestingly, it may generate extreme conditions (pressures of ~1000 bar, local hotspots of ~5000 K, high oxidation—hydroxyl radicals) which in turn can be highly destructive for microorganisms in water matrices. Kosel et al. (2017) studied the effect of hydrodynamic cavitation on MS2 infectivity. Reductions of viral infectivity higher than 4-logs were recorded using small scale reactors. Authors underlined the viral disinfection efficiency of wastewater and discussed the potential of using cavitation generators for large-scale applications (Kosel et al., 2017).

Photocatalytic Membrane Reactor

When an AOP such as photocatalysis is combined with membrane filtration, high quality water may be produced by the combination of filtration/photocatalytic inactivation, in a single step treatment Horovitz et al. (2018) assessed MS2 inactivation by a hybrid photocatalytic membrane reactor (PMR), which included a photocatalyst immobilized onto a membrane substrate. Authors used water of different quality

to investigate the viral removal efficiency of a N-doped TiO₂-coated Al₂O₃ PMR and they recorded a viral abatement of 4.9 ± 0.1 log (> 99.99%) in natural surface water under irradiation. Complex virus–PMR interactions were found to occur even before the exposure to light. Electrostatic forces, in addition to photocatalytic inactivation, were also responsible for viral abatement in complex matrices. Although alkaline water pH reduced interactions and, consequently, the extent of viral abatement, the addition of Ca²⁺ had a beneficial effect (Horovitz et al., 2018).

Photo-Electro-Oxidation

The main advantage of photo-electro-oxidation processes is that they do not require the use of additional chemicals and/or disinfectants, while they operate at ambient conditions of pressure and temperature (Table 3). On the other hand, they are frequently characterized by low selectivity and reaction rates. Their application may be restricted by high operational costs associated with the use of UV irradiation and electric power (Monteiro et al., 2015; Rasalingam et al., 2014).

A 60-min treatment by the photo-electro oxidation process was capable of decreasing human adenovirus type 5 (HAdV-5) by 7 log₁₀ in no DNase-treated samples. Exposure for 75 min was required for the complete abatement of DNase-treated samples used to study intact viruses only. Completely non-viable adenoviruses were obtained after

30 min, as was evidenced by integrated cell culture quantitative polymerase chain reaction (ICC/qPCR) analysis (Monteiro et al., 2015).

Commercial Installations

Different commercial installations involving 1) the use of a membrane bioreactor and a full advanced treatment (FAT) train, 2) an advanced Bardenpho process, 3) an advanced oxidation-based Net-zero water (NZW) pilot system, and 4) a full-scale direct potable reuse demonstration facility are summarized below.

Papp et al. (2020) studied water reuse facilities using different microbial surrogates such as bacteriophage ϕ B124-14 and ϕ crAssphage, as well as the pepper mild mottle virus (PMMoV). PMMoV, ϕ B124-14 and ϕ crAssphage were detected in membrane bioreactor (MBR) feeds at concentrations of approximately 10^3 , 10^5 and 10^6 gene copies/mL, respectively. Only PMMoV was detected above the limit of quantification in the MBR filtrate (25 ± 8 gene copies/mL). Viral log removal values were found to be 1.4 ± 0.5 for PMMoV, $> 3.9 \pm 0.3$ for ϕ B124-14 and $> 6.2 \pm 0.3$ for ϕ crAssphage (Papp et al., 2020). The study of Schmitz et al. (2016) compared the advanced Bardenpho to conventional treatment processes by assessing the abatement of eleven different types of viruses. The Bardenpho process is a multiple stage biological nutrient removal process without any addition of chemicals and in the study of Schmitz et al. (2016) was composed of serial compartments (anaerobic, anoxic, oxic, anoxic, and oxic). Interestingly, the advanced Bardenpho wastewater treatment was proved to be more efficient than conventional treatments in reducing pathogenic viruses. The highest mean reduction values were recorded for nine target virus types, and also the highest rate of removal to concentrations below the detection limit was achieved. Mean reduction of viruses as calculated by the mean difference between influent and effluent sample sets were $> 2.7 \pm 1.6$, $> 2.7 \pm 0.9$, $> 1.7 \pm 1.4$, $> 2.6 \pm 0.6$, $> 3.6 \pm 0.4$, $> 3.0 \pm 0.6$, $> 2.5 \pm 0.5$, $> 1.7 \pm 1.1$, $> 3.3 \pm 1.2$, $> 3.1 \pm 0.5$, $> 3.4 \pm 1.1$ for pepper mild mottle virus (PMMoV), Aichi virus (AiV), genogroup I, II, and IV noroviruses (GI NoV, GII NoV, GIV NoV), enterovirus (EV), sapovirus (SaV), group-A rotavirus (ARV), adenovirus (AdV), JC and BK polyomaviruses (JCPyV and BKPyV), respectively. Following the advanced Bardenpho treatment all viruses except PMMoV were found at concentrations of $< 4.0 \log_{10}$ copies/L. Aichi virus was found to be a conservative index virus for the assessment of viral removal in wastewater treatment. Bardenpho processes were the major sources of virus removal probably because of virus sorption to solids (Schmitz et al., 2016).

Vaidya et al. (2019) compared the performance of two pilot-scale, advanced water treatment plants with different

treatment processes, a carbon-based and a membrane-based. The carbon-based treatment process involved flocculation/sedimentation, ozone-biofiltration, granular activated carbon (GAC) adsorption, and ultraviolet (UV) disinfection. The membrane-based treatment process was composed of ultrafiltration, reverse osmosis, and UV-hydrogen peroxide advanced oxidation steps. In both water treatment processes, a > 8 -log removal of MS2 and > 6 -log removal of Pepper mild mottle virus was achieved (Vaidya et al., 2019). An advanced oxidation-based net-zero water (NZW) pilot system was evaluated in the study of Gassie et al. (2016). The system consisted of a septic tank, membrane bioreactor (MBR), aluminum electrocoagulation (EC), flocculation, vacuum ultrafiltration, peroxone or UV-hydrogen peroxide advanced oxidation, chlorine disinfection, and point-of use granular activated carbon (GAC) filtration. No viruses (somatic, male-specific coliphage and adenovirus) were found in the treated water, although adenovirus genetic material was detected probably due to the presence of inactive viral particles in hydraulic dead zones (Gassie et al., 2016). Pecson et al. (2017) assessed the efficiency of a full-scale, direct potable reuse demonstration facility. The treatment train included ozonation, biological activated carbon, micro- or ultrafiltration, reverse osmosis, and a UV-based advanced oxidation process. Performance distribution functions evidenced treatment that consistently surpassed the 12-log thresholds for virus, as required for potable reuse in California (Pecson et al., 2017).

Table 1 summarizes the studies which have used only MS2 bacteriophage as the index virus, while Table 2 summarizes the studies which have assessed more than one viruses.

Future Aspects

Although constructed wetlands, stabilization ponds and membrane filtration have traditionally been employed for microbial abatement, the use of AOPs as tertiary or disinfection processes capable of dealing with resistant microbial targets, including viruses, has received less attention (Meric & Fatta Kassinos, 2009). The increasing application of AOPs has been recognized as one of the most promising technological strategies for efficient water treatment, as well as the safe discharge or potential reuse of wastewater effluents. Specifically, photo-Fenton processes have been proven to be effective for the treatment of secondary effluents and potable water and are also efficient against micropollutants and different microbial targets (Galeano et al., 2019; Giannakis et al., 2016, 2017a; Gogate & Pandit, 2004). Of course, AOPs suffer from certain limitations, including the production of significant quantities of ferrous sludge associated with Fenton and alike processes, costly chemicals such as

hydrogen peroxide and ozone, elevated installation and operating costs for UV/ozone processes, etc. (Srivastav et al., 2020). Interestingly, such limitations can partly be counterbalanced through process integration, involving the coupling of various AOPs either together or to other physical and/or biological processes. For instance, the synergy recorded when two or more AOPs are combined is mainly due to the enhancement of free radicals production, which in turn is responsible for increased oxidation rates, but also to the modification of the reactor conditions and/or configuration (Gogate & Pandit, 2004). Although viral abatement in water and wastewater matrices is a tricky task, the application of advanced water treatment trains is expected to support the efficient disinfection goals. The adoption of a multi-barrier techniques' approach is expected to reduce the risks due to the prevalence of viruses for both the environment and public health (Gheraout et al., 2020).

To promote the application of AOPs in real world scenarios, issues such as i) the investigation of metabolites generated during the process, ii) the examination of biological safety linked to cytotoxic and/or genotoxic effects, and iii) the execution of scaling-up and economic feasibility studies, have to be taken into account (Galeano et al., 2019). AOPs are expected to find broader full-scale applications, according to the trend which is recorded during the last decade. Most probably, diverse technological solutions will be applied locally, according to the specific prevailing conditions (e.g. solar driven processes will be adopted in areas with high solar irradiation levels) (Kokkinos et al., 2020). Omics tools (high throughput sequencing, metagenomics, proteomics, transcriptomics, etc.), are expected to further support the exploitation of the viral diversity in water matrices and also to elucidate the mechanisms of disinfection achieved by treatment methods such as AOPs. They will also expand the research from culturable pathogens and indicators to whole microbial communities (Nelson et al., 2018).

To compare fairly the disinfection potential of various AOPs with particular focus on the virological quality of water matrices, energy consumption and treatment cost, it would be interesting to link the EEO values with the viral load. This could provide a useful tool for the selection of the most effective processes for viral abatement with the higher potential for full-scale applications according to energy and operational cost.

The current Coronavirus Disease 2019 (COVID-19) pandemic has stressed out, among others, the need to better understand wastewater as potential source of epidemiological data, environmental and human health risks, and to effectively disinfect wastewater to reduce the risks to the public and the environment (Carraturo, 2020; Kitajima et al., 2020; Wang, 2020). Limited research data are available on endogenous and exogenous reaction rates of enveloped viruses (Nelson et al., 2018). The implications of SARS-CoV-2

prevalence in water and wastewater matrices have to be clarified, along with its fate during different treatment processes. According to Gheraout et al. (2020), the combination of UV irradiation with membrane ultrafiltration will successfully remove coronaviruses from water matrices (Gheraout et al., 2020). The role of AOPs, alone or in combination with other processes in wastewater and drinking water treatment plants in the event of future pandemics may be crucial towards safeguarding public and environmental health.

References

- Bounty, S., Rodriguez, R. A., & Linden, K. G. (2012). Inactivation of adenovirus using low-dose UV/H₂O₂ advanced oxidation. *Water Research*, 46(19), 6273–6278. <https://doi.org/10.1016/j.watres.2012.08.036>
- Brienza, M., & Katsoyiannis, I. (2017). Sulfate radical technologies as tertiary treatment for the removal of emerging contaminants from wastewater. *Sustainability*, 9, 1604. <https://doi.org/10.3390/su9091604>
- Cantalupo, P. G., Calgua, B., Zhao, G., Hundesa, A., Wier, A. D., Katz, J. P., Grabe, M., Hendrix, R. G., Girones, R., Wang, D., & Pipas, J. M. (2011). Raw sewage harbors diverse viral populations. *mBio*. <https://doi.org/10.1128/mBio.00180-11>
- Carraturo, F., Del Giudice, C., Morelli, M., Cerullo, V., Libralato, G., Galdiero, E., & Guida, M. (2020). Persistence of SARS-CoV-2 in the environment and COVID-19 transmission risk from environmental matrices and surfaces. *Environmental Pollution*, 265(Pt B), 115010. <https://doi.org/10.1016/j.envpol.2020.115010>
- Chen, Y., Duan, X., Zhou, X., Wang, R., Wang, S., Ren, N. Q., & Ho, S. H. (2021). Advanced oxidation processes for water disinfection: Features, mechanisms and prospects. *Chemical Engineering Journal*. <https://doi.org/10.1016/j.ccej.2020.128207>
- Cho, M., Gandhi, V., Hwang, T.-M., Lee, S., & Kim, J.-H. (2011). Investigating synergism during sequential inactivation of MS-2 phage and *Bacillus subtilis* spores with UV/H₂O₂ followed by free chlorine. *Water Research*, 45(3), 1063–1070. <https://doi.org/10.1016/j.watres.2010.10.014>
- Chu, X., Hu, J., & Xu, Y. (2012). Investigating the performance of a UV/H₂O₂ integrated flow-through system followed by free chlorine. *Water Science and Technology: Water Supply*, 12(6), 715–719. <https://doi.org/10.2166/ws.2012.046>
- Duan, X., Kang, J., Tian, W., Zhang, H., Ho, S. H., Zhu, Y. A., Ao, Z., Sun, H., & Wang, S. (2019). *Interfacial-engineered cobalt at carbon hybrids for synergistically boosted evolution of sulfate radicals toward green oxidation*. *Applied Catalysis B: Environmental*. <https://doi.org/10.1016/j.apcatb.2019.11779>
- Feitz, A. (2005). Advanced oxidation processes and industrial wastewater treatment. *Water*, 32, 59–65.
- Foladori, P., Cutrupi, F., Segata, N., Manara, S., Pinto, F., Malpei, F., Bruni, L., & La Rosa, G. (2020). SARS-CoV-2 from faeces to wastewater treatment: What do we know? *Science of the Total Environment*, 743, 140444. <https://doi.org/10.1016/j.scitotenv.2020.140444>
- Galeano, L. A., Guerrero-Flórez, M., Sánchez, C. A., Gil, A., & Vicente, M. Á. (2019). Disinfection by chemical oxidation methods. In *Applications of Advanced Oxidation Processes (AOPs) in Drinking Water Treatment. The Handbook of Environmental Chemistry*, Springer, Cham, 67, 257–295.
- Gamage, S., Gerrity, D., Pisarenko, A. N., Wert, E. C., & Snyder, S. A. (2013). Evaluation of process control alternatives for the inactivation of *Escherichia coli* MS2 Bacteriophage, and *Bacillus*

- subtilis* spores during wastewater ozonation. *Ozone Science and Engineering*, 35(6), 501–513. <https://doi.org/10.1080/01919512.2013.833852>
- Gassie, L. W., Englehardt, J. D., Wang, J., Brinkman, N., Garland, J., Gardinali, P., & Guo, T. (2016). Mineralizing urban net-zero water treatment: Phase II field results and design recommendations. *Water Research*, 105, 496–506. <https://doi.org/10.1016/j.watres.2016.09.005>
- Gerba, C. P., Betancourt, W. Q., Kitajima, M., & Rock, C. M. (2018). Reducing uncertainty in estimating virus reduction by advanced water treatment processes. *Water Research*, 133, 282–288. <https://doi.org/10.1016/j.watres.2018.01.044>
- Ghernaout, D., Elboughdiri, N., & Arni, S. A. (2020). New insights towards disinfecting viruses – short notes. *Journal of Water Reuse and Desalination*, 10(3), 173–186. <https://doi.org/10.2166/wrd.2020.050>
- Giannakis, S. (2018). Analogies and differences among bacterial and viral disinfection by the photo-Fenton process at neutral pH: A mini review. *Environmental Science and Pollution Research*, 25(28), 27676–27692. <https://doi.org/10.1007/s11356-017-0926-x>
- Giannakis, S., Androulaki, B., Comminellis, C., & Pulgarin, C. (2018). Wastewater and urine treatment by UVC-based advanced oxidation processes: Implications from the interactions of bacteria, viruses, and chemical contaminants. *Chemical Engineering Journal*, 343, 270–282. <https://doi.org/10.1016/j.cej.2018.03.019>
- Giannakis, S., Liu, S., Carratala, A., Rtimi, S., Bensimon, M., & Pulgarin, C. (2017a). Effect of Fe(II)/Fe(III) species, pH, irradiance and bacterial presence on viral inactivation in wastewater by the photo-Fenton process: Kinetic modeling and mechanistic interpretation. *Applied Catalysis B: Environmental*, 204, 156–166. <https://doi.org/10.1016/j.apcatb.2016.11.034>
- Giannakis, S., Liu, S., Carratalà, A., Rtimi, S., Talebi Amiri, M., Bensimon, M., & Pulgarin, C. (2017b). Iron oxide-mediated semiconductor photocatalysis vs. heterogeneous photo-Fenton treatment of viruses in wastewater. Impact of the oxide particle size. *Journal of Hazardous Materials*, 339, 223–231. <https://doi.org/10.1016/j.jhazmat.2017.06.037>
- Giannakis, S., Lopez, M. I. P., Spuhler, D., Sanchez Pérez, J. A., Fernandez Ibáñez, P., & Pulgarin, C. (2016). Solar disinfection is an augmentable, in situ-generated photo-Fenton reaction Part 2: A review of the applications for drinking water and wastewater disinfection. *Applied Catalysis B: Environmental*, 198, 431–446. <https://doi.org/10.1016/j.apcatb.2016.06.007>
- Giannakis, S., Rtimi, S., & Pulgarin, C. (2017c). Light-assisted advanced oxidation processes for the elimination of chemical and microbiological pollution of wastewaters in developed and developing countries. *Molecules*, 22(7), 1070. <https://doi.org/10.3390/molecules22071070>
- Gogate, P. R., & Pandit, A. B. (2004). A review of imperative technologies for wastewater treatment II: Hybrid methods. *Advances in Environmental Research*, 8(3–4), 553–597. [https://doi.org/10.1016/S1093-0191\(03\)00031-5](https://doi.org/10.1016/S1093-0191(03)00031-5)
- Gomes, J., Frasson, D., Quinta-Ferreira, R. M., Matos, A., & Martins, R. C. (2019). Removal of enteric pathogens from real wastewater using single and catalytic ozonation. *Water*, 11(1), 127. <https://doi.org/10.3390/w11010127>
- Horovitz, I., Avisar, D., Luster, E., Lozzi, L., Luxbacher, T., & Mamane, H. (2018). MS2 bacteriophage inactivation using a N-doped TiO₂-coated photocatalytic membrane reactor: Influence of water-quality parameters. *Chemical Engineering Journal*, 354, 995–1006. <https://doi.org/10.1016/j.cej.2018.08.083>
- Jolis, D. (2002). The effect of storage and Lag time on MS2 bacteriophage susceptibility to ultraviolet radiation. *Water Environment Research*, 74(6), 516–520. <https://doi.org/10.2175/106143002x140305>
- Kibbee, R., & Ormecí, B. (2020). Peracetic acid (PAA) and low-pressure ultraviolet (LP-UV) inactivation of Coxsackievirus B3 (CVB3) in municipal wastewater individually and concurrently. *Water Research*, 183, 116048. <https://doi.org/10.1016/j.watres.2020.116048>
- King, J. F., Szczuka, A., Zhang, Z., & Mitch, W. A. (2020). Efficacy of ozone for removal of pesticides, metals and indicator virus from reverse osmosis concentrates generated during potable reuse of municipal wastewaters. *Water Research*, 176, 115744. <https://doi.org/10.1016/j.watres.2020.115744>
- Kitajima, M., Ahmed, W., Bibby, K., Carducci, A., Gerba, C. P., Hamilton, K. A., Haramoto, E., & Rose, J. B. (2020). SARS-CoV-2 in wastewater: State of the knowledge and research needs. *Science of the Total Environment*, 739, 139076. <https://doi.org/10.1016/j.scitotenv.2020.139076>
- Kokkinos, P., Mantzavinos, D., & Venieri, D. (2020). Current trends in the application of nanomaterials for the removal of emerging micropollutants and pathogens from water. *Molecules*. <https://doi.org/10.3390/molecules25092016>
- Kokkinos, P. A., Ziros, P. G., Mpalasopoulou, G., Galanis, A., & Vantarakis, A. (2011). Molecular detection of multiple viral targets in untreated urban sewage from Greece. *Virology Journal*, 8, 195. <https://doi.org/10.1186/1743-422X-8-195>
- Kosel, J., Gutierrez-Aguirre, I., Rački, N., Dreó, T., Ravnikar, M., & Dular, M. (2017). Efficient inactivation of MS-2 virus in water by hydrodynamic cavitation. *Water Research*, 124, 465–471. <https://doi.org/10.1016/j.watres.2017.07.077>
- La Rosa, G., Bonadonna, L., Lucentini, L., Kenmoe, S., & Suffredini, E. (2020). Coronavirus in water environments: Occurrence, persistence and concentration methods - A scoping review. *Water Research*, 179, 115899. <https://doi.org/10.1016/j.watres.2020.115899>
- Mamane, H., Shemer, H., & Linden, K. G. (2007). Inactivation of *E. coli*, *B. subtilis* spores and MS2 T4 and T7 phage using UV/H₂O₂ advanced oxidation. *Journal of Hazardous Materials*, 146(3), 479–486. <https://doi.org/10.1016/j.jhazmat.2007.04.050>
- Marjanovic, M., Giannakis, S., Grandjean, D., de Alencastro, L. F., & Pulgarin, C. (2018). Effect of μM Fe addition, mild heat and solar UV on sulfate radical-mediated inactivation of bacteria, viruses, and micropollutant degradation in water. *Water Research*, 140, 220–231. <https://doi.org/10.1016/j.watres.2018.04.054>
- Mattle, M. J., Vione, D., & Kohn, T. (2015). Conceptual model and experimental framework to determine the contributions of direct and indirect photoreactions to the solar disinfection of MS2, phiX174, and adenovirus. *Environmental Science & Technology*, 49(1), 334–342. <https://doi.org/10.1021/es504764u>
- Meric, S., & Fatta Kassinos, D. (2009). Water Treatment. *Municipal in Encyclopedia of Microbiology Third Edition, Elsevier*. <https://doi.org/10.1016/B978-012373944-5.00164-4>
- Miklos, D. B., Remy, C., Jekel, M., Linden, K. G., Drewes, J. E., & Hübner, U. (2018). Evaluation of advanced oxidation processes for water and wastewater treatment - A critical review. *Water Research*, 139, 118–131. <https://doi.org/10.1016/j.watres.2018.03.042>
- Monteiro, G. S., Staggemeier, R., Klauk, C. R., Bernardes, A. M., Rodrigues, M. A. S., & Spilki, F. R. (2015). Degradation and inactivation of adenovirus in water by photo-electro-oxidation. *Brazilian Journal of Biology*, 75(4), S37–S42. <https://doi.org/10.1590/1519-6984.00813suppl>
- Nelson, K. L., Boehm, A. B., Davies-Colley, R. J., Dodd, M. C., Kohn, T., Linden, K. G., Liu, Y., Maraccini, P. A., McNeill, K., Mitch, W. A., Nguyen, T. H., Parker, K. M., Rodriguez, R. A., Sasso, L. M., Silverman, A. I., Wigginton, K. R., & Zepp, R. G. (2018). Sunlight-mediated inactivation of health-relevant microorganisms in water: A review of mechanisms and modeling

- approaches. *Environmental Science: Processes and Impacts*, 20(8), 1089–1122. <https://doi.org/10.1039/c8em00047f>
- Nieto-Juarez, J. I., & Kohn, T. (2013). Virus removal and inactivation by iron (hydr)oxide-mediated Fenton-like processes under sunlight and in the dark. *Photochemical & Photobiological Sciences*, 12(9), 1596–1605. <https://doi.org/10.1039/C3PP25314G>
- Nieto-Juarez, J. I., Pierzchła, K., Sienkiewicz, A., & Kohn, T. (2010). Inactivation of MS2 coliphage in Fenton and Fenton-like systems: Role of transition metals, hydrogen peroxide and sunlight. *Environmental Science and Technology*, 44(9), 3351–3356. <https://doi.org/10.1021/es903739f>
- Ortega-Gomez, E., Ballesteros, M. M. M., Carratala, A., Fernandez Ibanez, P., Perez, J. A., & Pulgarin, C. (2015). Principal parameters affecting virus inactivation by the solar photo-Fenton process at neutral pH and μM concentrations of H_2O_2 and $\text{Fe}^{2+/(3+)}$. *Applied Catalysis B: Environmental*, 174–175, 395–402. <https://doi.org/10.1016/j.apcatb.2015.03.016>
- Papp, K., Moser, D., & Gerrity, D. (2020). Viral surrogates in potable reuse applications: Evaluation of a membrane bioreactor and full advanced treatment. *Journal of Environmental Engineering*, 146(2), 04019103. [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0001617](https://doi.org/10.1061/(ASCE)EE.1943-7870.0001617)
- Pecson, B. M., Triolo, S. C., Olivieri, S., Chen, E. C., Pisarenko, A. N., Yang, C.-C., Olivieri, A., Haas, C. N., Trussell, R. S., & Trussell, R. R. (2017). Reliability of pathogen control in direct potable reuse: Performance evaluation and QMRA of a full-scale 1 MGD advanced treatment train. *Water Research*, 122, 258–268. <https://doi.org/10.1016/j.watres.2017.06.014>
- Prasse, C., & Ternes, T. (2010). Removal of organic and inorganic pollutants and pathogens from wastewater and drinking water using nanoparticles - A review (Book Chapter) *Nanoparticles in the Water Cycle: Properties, Analysis and Environmental Relevance*. <https://doi.org/10.1007/978-3-642-10318-6>
- Rasalingam, S., Peng, R., & Koodali, R. T. (2014). Removal of hazardous pollutants from wastewaters: Applications of TiO_2 - SiO_2 mixed oxide materials. *Journal of Nanomaterials*. <https://doi.org/10.1155/2014/617405>
- Rodríguez-Lázaro, D., Cook, N., Ruggeri, F. M., Sellwood, J., Nasser, A., Nascimento, M. S. J., D'Agostino, M., Santos, R., Saiz, J. C., Rzeutka, A., Gironés, R., Carducci, A., Muscillo, M., Kovač, K., Diez-Valcarce, M., Vantarakis, A., von Bonsdorff, C.-H., de Roda Husman, A. M., Hernández, M., & van der Poel, W. H. M. (2012). Virus hazards from food, water and other contaminated environments. *FEMS Microbiology Reviews*, 36, 786–814. <https://doi.org/10.1111/j.1574-6976.2011.00306.x>
- Schmitz, B. W., Kitajima, M., Campillo, M. E., Gerba, C. P., & C.P., Pepper, I.L. (2016). Virus reduction during advanced Bardenpho and conventional wastewater treatment processes. *Environmental Science and Technology*, 50(17), 9524–9532. <https://doi.org/10.1021/acs.est.6b01384>
- Shabat-Hadas, E., Mamane, H., & Gitis, V. (2017). Rhodamine B in dissolved and nano-bound forms: Indicators for light-based advanced oxidation processes. *Chemosphere*, 184, 1020–1027. <https://doi.org/10.1016/j.chemosphere.2017.06.076>
- Sherchan, S. P., Snyder, S. A., Gerba, C. P., & Pepper, I. L. (2014). Inactivation of MS2 coliphage by UV and hydrogen peroxide: Comparison by cultural and molecular methodologies. *Journal of Environmental Science and Health, Part A: Toxic/hazardous Substances and Environmental Engineering*, 49(4), 397–403. <https://doi.org/10.1080/10934529.2014.854607>
- Sommer, R., Pribil, W., Pflieger, S., Haider, T., Werderitsch, M., & Gehringer, P. (2004). Microbicidal efficacy of an advanced oxidation process using ozone/hydrogen peroxide in water treatment. *Water Science and Technology*, 50(1), 159–164. <https://doi.org/10.2166/wst.2004.0047>
- Song, K., Mohseni, M., & Taghipour, F. (2019). Mechanisms investigation on bacterial inactivation through combinations of UV wavelengths. *Water Research*, 163, 114875. <https://doi.org/10.1016/j.watres.2019.114875>
- Srivastav, A. L., Patel, N., & Chaudhary, V. K. (2020). Disinfection by-products in drinking water: Occurrence, toxicity and abatement. *Environmental Pollution*, 267, 115474. <https://doi.org/10.1016/j.envpol.2020.115474>
- Timchak, E., & Gitis, V. (2012). A combined degradation of dyes and inactivation of viruses by UV and $\text{UV}/\text{H}_2\text{O}_2$. *Chemical Engineering Journal*, 192, 164–170. <https://doi.org/10.1016/j.cej.2012.03.054>
- Tsydenova, O., Batoev, V., & Batoeva, A. (2015). Solar-enhanced advanced oxidation processes for water treatment: Simultaneous removal of pathogens and chemical pollutants. *International Journal of Environmental Research and Public Health*, 12, 9542–9561. <https://doi.org/10.3390/ijerph120809542>
- Vaidya, R., Buehlmann, P. H., Salazar-Benites, G., Schimmoller, L., Nading, T., Wilson, C. A., Bott, C., Gonzalez, R., & Novak, J. T. (2019). Pilot plant performance comparing carbon-based and membrane-based potable reuse schemes. *Environmental Engineering Science*, 36(11), 1369–1378. <https://doi.org/10.1089/ees.2018.0559>
- Venieri, D., Gounaki, I., Binas, V., Zachopoulos, A., Kiriakidis, G., & Mantzavinos, D. (2015). Inactivation of MS2 coliphage in sewage by solar photocatalysis using metal-doped TiO_2 . *Applied Catalysis B: Environmental*, 178, 54–64. <https://doi.org/10.1016/j.apcatb.2014.10.052>
- Wang, J., Shen, J., Ye, D., Yan, X., Zhang, Y., Yang, W., Li, X., Wang, J., Zhang, L., & Pan, L. (2020). Disinfection technology of hospital wastes and wastewater: Suggestions for disinfection strategy during coronavirus Disease 2019 (COVID-19) pandemic in China. *Environmental Pollution*, 262, 114665. <https://doi.org/10.1016/j.envpol.2020.114665>
- Yapıcıoğlu, P. S. (2018). Environmental impact assessment for a meat processing industry in Turkey: Wastewater treatment plant. *Water Practice and Technology*, 13(3), 692–704. <https://doi.org/10.2166/wpt.2018.051>
- Zhu, S., Ho, S.-H., Jin, C., Duan, X., & Wang, S. (2020). Nanostructured manganese oxides: Natural/artificial formation and their induced catalysis for wastewater remediation. *Environmental Science: Nano*, 7, 368–396. <https://doi.org/10.1039/C9EN01250H>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.