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A critical review on the existing wastewater treatment methods in the COVID-19 era: What is the potential of advanced oxidation processes in combatting viral especially SARS-CoV-2?

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ABSTRACT

The COVID-19 epidemic has put the risk of virus contamination in water bodies on the horizon of health authorities. Hence, finding effective ways to remove the virus, especially SARS-CoV-2, from wastewater treatment plants (WWTPs) has emerged as a hot issue in the last few years. Herein, this study first deals with the fate of SARS-CoV-2 genetic material in WWTPs, then critically reviews and compares different wastewater treatment methods for combatting COVID-19 as well as to increase the water quality. This critical review sheds light the efficiency of advanced oxidation processes (AOPs) to inactivate virus, specially SARS-CoV-2 RNA. Although several physicochemical treatment processes (e.g. activated sludge) are commonly used to eliminate pathogens, AOPs are the most versatile and effective virus inactivation methods. For instance, TiO_2 is the most known and widely studied photo-catalyst innocuously utilized to degrade pollutants as well as to photo-induce bacterial and virus disinfection due to its high chemical resistance and efficient photo-activity. When ozone is dissolved in water and wastewater, it generates a wide spectrum of the reactive oxygen species (ROS), which are responsible to degrade materials in virus membranes resulting in destroying the cell wall. Furthermore, electrochemical advanced oxidation processes act through direct oxidation when pathogens react at the anode surface or by indirect oxidation through oxidizing species produced in the bulk solution. Consequently, they represent a feasible choice for the inactivation of a wide range of pathogens. Nonetheless, there are some challenges with AOPs which should be addressed for application at industrial-scale.

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1. Introduction

Water and wastewater virological quality is of great importance due to its probabilistic public and environmental risks. Different kinds of viruses excreted by infected people enter to water bodies [1–3]. Coronaviruses (CoVs) are responsible for three zoonotic epidemics in the last 20 years including severe acute respiratory syndrome (SARS) identified in China 2002–2003, Middle East Respiratory Syndrome (MERS) started in 2012 in the Middle East, and the current COVID-19 pandemic caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). As of December 2019, the first detection of COVID-19 was found in Wuhan, Hubei Province, China [4–6]. Then as of January 30, 2020, World Health Organization (WHO) declared the COVID-19 outbreak as a public health emergency of international concern [5].

Findings indicated that both symptomatic and asymptomatic COVID-19 patients excreted SARS-CoV-2 virus through feces and other body secretions that disposed in wastewater. In the same vein, virus introduces into the wastewater treatment plants (WWTPs) by sewer systems [2,4,6]. Coronaviruses can survive for several days in wastewater under different situations and the plumbing systems are described as the possible transmission route for this kind of viruses in 2003 [2,4,5,7]. However, the main transmission route of SARS-CoV-2 virus is known as human to human transmission by small respiratory droplets [4,8], live SARS-CoV-2 detection in some patient feces highlighted the possibility of fecal transmission route of the viruses [6,9]. The presence of SARS-CoV-2 RNA (genetic material of the virus) in influent and effluent of WWTPs as well as in sludge has been reported in different countries. This last raised the question of the efficiency of treatment methods in eliminating the virus [4,6]. Although, such data do not imply infectivity of the virus, the route of possible spread of the viral through the wastewater cannot be neglected [2,6,9].

WWTPs play a crucial role in protecting public health due to the use of effluents for irrigation, recreational purposes, or discharge in rivers [2]. The emergence of COVID-19 influences the quality of the wastewater in different ways. Besides the prevalence of SARS-CoV-2 in untreated water, an increase in the use of hand sanitizers, disinfectants, and different kinds of pharmaceuticals raised the organic load of wastewater. If there is not a proper and effective treatment, effluents may pose many environmental and public health risks in the receiving environments [4,5]. Different treatment processes have their own merits and drawbacks, and they are not equally effective in the virus inactivation owing to the involvement from several physical and chemical parameters in the water matrix [3,4,9]. Physical disinfection can be compromised by the small size and unique properties of virus, while chemical disinfection processes may result in carcinogenic by-products [3,5]. Advanced oxidation processes (AOPs) are promising newly developed methods to sanitize polluted wastewater. Such methods are based on the generation of oxidant species to degrade organic pollutants and disinfect wastewater. They can be an effective alternative for conventional treatment methods [3,5].

In battling such pandemics, exploring, and developing an integrated multi-treatment strategy for contaminated wastewater is essential [5,9,10]. In this era, majority of studies are focused on the concentration, extraction, detection, and quantification methods of the viruses [11–13]. However, it is of great importance to critically compare different conventional and advanced wastewater treatment approaches to achieve the highest reclaimed water quality [5]. Even though, there are some studies that were conducted on this hot topic, they mainly focused on conventional disinfection methods such as UV irradiation, ozonation, and chlorination [4,7] or common specific treatment technologies (e.g. membrane bioreactors and activated sludge) [8]. In some other studies, more recent treatment technologies have been reviewed specifically without any comparative point of view [5,14–16]. As aforementioned, this pandemic affects wastewater quality in different aspects and conventional WWTPs are not specifically designed to overcome this kind of situation. Herein, this study aimed to critically review and compare different wastewater treatment methods in combatting COVID-19 and its consequences on wastewater quality with an emphasis on AOPs. COVID-19 is not the first and would not be the last epidemic of this kind and the scientific studies on the effectiveness of wastewater treatment techniques in viral inactivation would be an insight into managing probable future epidemics.

2. Fate of SARS-CoV-2 genetic material in the wastewater treatment plants

As aforementioned, main sources of SARS-CoV-2 in the domestic wastewaters are considered as faeces and other bodily secretions (sputum, saliva, urine) excreted by symptomatic and asymptomatic COVID 19 patients. These excretions are released via the toilet and bathroom systems [17,18] as well as by laundry discharges originated from washing of contaminated clothes and personal protective equipment [18]. The other sources can be listed as hospitals, health care centres, funeral homes, and ghusl rooms. After discharging to sewage systems, SARS-CoV-2 infectivity may decay owing to existence of (i) free active enzyme activities, (ii) predators such as protozoan or metazoan, (iii) solvents, (iv) detergents in such wastewaters, or (v) by the adsorption onto the solid fraction [19–22]. Nevertheless, SARS-CoV-2 may be potentially still infectious. If SARS-CoV-2 is capable of surviving during the collection and transportation by sewage pipe network, it will be reach to the inlet of wastewater treatment plants (WWTPs). Then, WWTPs work as the latest barriers to foreclose the dissemination of SARS-CoV-2 RNA into the environment matrix [23].

WWTPs comprise a combination of preliminary, primary, secondary, and tertiary treatment stages depending on the treatment degree needed to meet permissible standard. Preliminary treatment, also called as a mechanical treatment, involves physically separation of coarse solids, grit, and oil/greases by screens, grit chambers, and dissolved air flotation tanks. In primary treatment stage, high density solids are settled by gravity and deposited on the bottom of the primary settlers or clarifiers referred to primary sludge. Secondary treatment serves for decomposition of biodegradable organic matter and suspended solids by microorganisms into simple compounds such as carbon dioxide, water, mineral salts, and methane. Activated sludge process (ASP), membrane bioreactors (MBR), trickling filter beds and moving bed biofilm reactors (MBBR), sequencing batch reactors (SBR), and up-flow anaerobic sludge blankets (UASB) are typically biological treatment techniques employed in WWTPs. Excess generated sludge from such processes, which consists of dead microorganisms and organic residues transformed into sludge, is called as secondary sludge. Finally, tertiary treatment can be applied as an additional step aimed at improving the quality of the secondary treated effluents, removing nutrients and inert organic matters or disinfecting pathogens microorganisms depending on the intended use of effluent.

Based on studies conducted at the early COVID-19 era, most of them have been devoted to proving the presence of SARS-CoV-2 genetic material in wastewaters. Hence, the detection and quantification assays were mostly performed on influents gathered from WWTPs situated in several cities all over the world [24–30]. Within this context, the role of WWTPs in the decay of SARS-CoV-2 has been generally discussed considering the treated effluents. Consequently, research efforts focused on the fate of SARS-CoV-2 along water and sludge lines of WWTPs are quite limited.

Fig. 1 displays the sampling points selected along water and sludge lines of WWTPs in the relevant literature. Following the given order in the figure, the role of each treatment stage, except disinfection, in reduction of SARS-CoV-2 RNA in untreated water will be summarized herein. The studies dealt with the tertiary treatment, particularly disinfection, will be explicated and discussed in the forthcoming sections since intention of this paper is to provide more detailed information about inactivation SARS-CoV-2 by several methods.

The liquid-solid partition of SARS-CoV-2 virus in water matrices

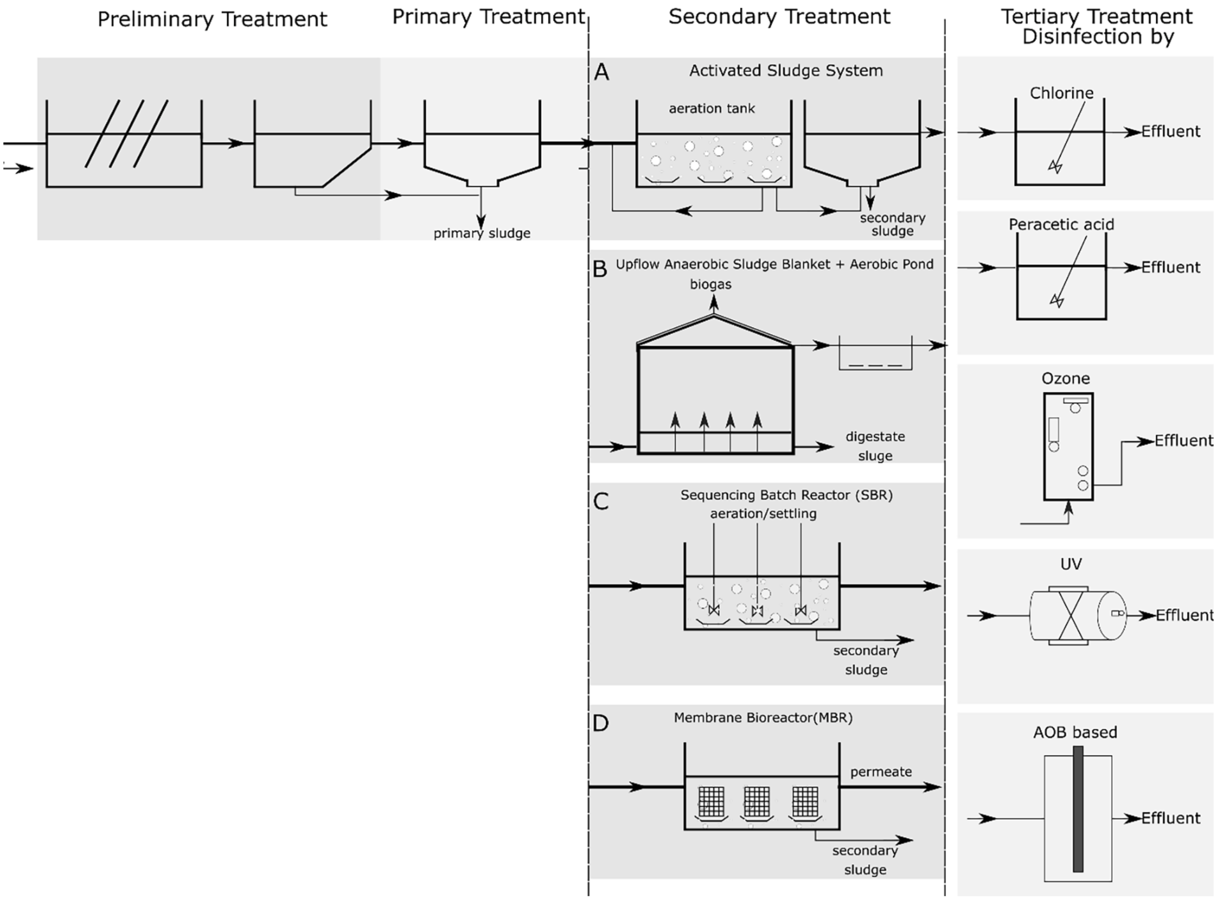

Fig. 1. The sampling points selected along water and sludge lines of WWTPs. Modified after Foladori et al. [2].

because of the hydrophobic nature of this kind of viruses has been confirmed by recent scientific data [31–33]. Based on this partition, the adsorption of SARS-CoV-2 into large solids due to the lipid bilayer surrounding the SARS-CoV-2 protein capsid was shown as a responsible SARS-CoV-2 virus elimination mechanism occurring in gravitational settling tanks [21,24]. Indeed, current data have proved this removal mechanism [33–35]. Peccia et al. [34] reported that SARS-CoV-2 RNA N1 and N2 genes loads varied in a range of 1.7×10^3 and 4.6×10^5 virus RNA copies per millilitre in primary sludge produced by the primary stage. Another study compared SARS-CoV-2 RNA gene signals in solids withdrawn from two post-grit chambers and two primary clarifiers. Then, the incidence of SARS-CoV-2 RNA in both solids was established [33]. For this purpose, the solid samples were collected from WWTPs operated as conventional activated sludge processes in Canada. In the study, the primary clarified sludge found to be more solids-rich sample than the post-grit solids based on the SARS-CoV-2 viral RNA N1 and N2 detections during declining and low incidence of viral load in communities. Kocamemi et al. [36] stored two primary sludge and seven waste-activated sludge samples from several WWTPs in Turkey to prove the presence of the SARS-CoV-2 RNA. Secondary treatment was accomplished by activated sludge processes with either nitrogen and/or phosphorous removal modification in WWTPs. In the primary sludge samples, SARS-CoV-2 genetic material loads were detected as 6.88×10^3 and 1.12×10^4 virus titer per litre. Similar SARS-CoV-2 virus loads (7.35×10^2–1.13×10^4 virus titer per litre), but in general lower than those of primary sludge samples, were quantified for waste activated sludge samples. In a study conducted by Balboa et al. [35], the fate of SARS-CoV-2 RNA was determined in water and sludge lines of WWTP employing SBR for carbon and nitrogen removal. Sampling points for water line selected as outflows of grit chamber, primary settler, and secondary settler. Sludge samples were withdrawn from primary and secondary settlers, sludge thickeners, and digesters. Primary and secondary sludge were concentrated in thickeners for further sludge treatment. Up to 9 copies per millilitre SARS-CoV-2 RNA was quantified in their influent samples. Only in one occasion (4.2 Copies/mL), SARS-CoV-2 RNA fragment was detected after primary treatment stage in the water line. Similarly, no genetic material was present in the secondary sludge except only one sample (1.9 Copies/mL). According to the data, SARS-CoV-2 RNA (i) was mostly retained at the primary settler (up to 24 Copies/mL), (ii) was concentrated in thickeners with a long retention time (24 h) and extremely high solid content, and (iii) was completely abated after thermal treatment and anaerobic digestion. Serra-Compte et al. [37] conducted a similar research to that of Balboa et al. [35] but with a more detailed sampling program covering eight WWTPs in both Spain and France to clarify the role of wastewater treatment approaches for removing SARS-CoV-2 RNA. Although their sludge data were consistent with those of Balboa et al. [35], the occurrence of SARS-CoV-2 RNA along the water treatment lines was slightly different. SARS-CoV-2 RNA was present in 36.4 % of the samples after ASP followed by clarification, and 18.2 % of the ASP plus nutrient removal effluents. MBR followed by chlorination yielded complete elimination of SARS-CoV-2 RNA.

In summary, Biosolids, also called sludge, are those residues which are produced as by-products of wastewater treatment processes [2,38–40]. This sludge is often classified as primary (produced from primary processes such as chemical coagulation) and secondary (the activated waste biomass generated from biological techniques). Primary and secondary sludge removed from the wastewater treatment line are sent to the so-called sludge line, aimed at reducing water content and degrading organic matter.

Because of the potential infectious disease risks of SARS-CoV-2 virus present in wastewater and sludge, its sampling and required treatment either on-site or off-site should be mandatory. Typical treatment processes are effective for enveloped viruses. Operating parameters such as retention time, dilution, oxidation, sunlight, elevated pH, and biological activity result in further diminution of pathogens into sludge [2]. For instance, lessening of viruses is caused under unfavorable conditions namely, a high temperature (thermophilic digestion or thermal treatment) during relatively long hydraulic retention time [38]. However, biosolids need to be safely contained to avoid environmental pollution (e.g., groundwater).

In this context, the disposal of sewage sludge is one of the major challenges when design and operation of WWTPs are performed. The diminishing of volume as well as the stabilization of organic material are main factors to be considered. Several treatment technologies including thickening, digestion, composting, thermal drying, liming, and dewatering have been studied [39–41]. In the case of digestion, it lessens the total mass of solids, destroys pathogens, and makes it easier to dewater or dry the sludge. Moreover, the dissolved matter can be transformed by other bacteria into biogas, which may serve as a fuel generate electricity and heat. This last reduces operation costs of the WWTPs. Additionally, treated (and disinfected) sludge (classified as Class A by US-EPA) can be used for gardening, building material, as well as agricultural and soil filler purposes [39,40].

Regarding sludge produced during the COVID-19 epidemic and undergoing disinfection treatment, it is believed that farther pollution is minimal given the effectiveness of all applied treatments. However, monitoring and controlling to confirm a correct implementation of mentioned treatment processes as well as manual cleaning must be adopted.

SARS-CoV-2 RNA fragments were absent or not detected in some SBR, MBBR, UASB, and ASP treated effluents [42–45]. In general, the negative results were explained by the capability of such biological processes in the elimination of SARS-CoV-2 virus to an undetectable limit of the molecular assay [42,45] or operational conditions, for example, a long retention time. A thorough sampling program covering 14 WWTPs in Northern India was carried out to compare SARS-CoV-2 RNA removal rates of SBR, MBBR, and ASP. For this purpose, samples taken from inlet, primary, secondary, and tertiary (chlorination and UV disinfection if applied) treatment stages were tested for SARS-CoV-2 genetic material. The intact SARS-CoV-2 RNA was present in 33.3 % of influent samples and primary treatment effluent, while all post-primary treated effluents found to be null during all sampling period indicating a complete reduction/degradation of SARS-CoV-2 RNA in all three processes. Comparison of the changes in the threshold cycle (Ct) values of the SARS-CoV-2 E gene, RdRp gene, and N gene indicated SARS-CoV-2 RNA degradation/reduction efficiency of MBBR was better than those of SBR and ASP [46].

Conflicting results were also available for the virus removal in ASP. Some studies reported a limited or poor reduction of SARS-CoV-2 genetic material in ASP [31,46,47]. Randazzo et al. [48] quantified SARS-CoV-2 RNA targeting N2 gene as 5.4 $\log_{10}$ gc/L in secondary effluent. This value was almost the same that of influent quantified targeting N1, N2 and N3 as 5.1 ± 0.3, 5.5 ± 0.2 and 5.5 ± 0.3 $\log_{10}$ gc/L, respectively. In another study [47], SARS-CoV-2 RNA content in a secondary (ASP) treated effluent was measured as 2.4×10^3 copies/L indicating a partial reduction of the virus in the process.

Kumar et al. [43] monitored a conventional treatment plant utilized UASB coupled with aeration process to evaluate its efficacy to remove SARS-CoV-2. Grab samples were taken from inflows of WWTP and UASB as well as outflows of UASB, aeration tank, and final effluent of WWTP. SARS-CoV-2 genome concentrations were quantified as 1810 and 3520 copies/L for raw wastewater and UASB inlet, respectively. On the other hand, the virus concentration reduced under the limit of quantification (LOQ) of the overall method (1.7×10^2 copies/L) during both UASB and aeration processes corresponding to a reduction >1.3 $\log_{10}$.

The inactivation/removal of SARS-CoV-2 from wastewater is depending on treatment technologies employed in wastewater treatment plant. However, still under investigation and until now, limited data about this issue have been published. Although convincing data on role of primary treatment stage, particularly primary settler in concentrating effect of SARS-CoV-2 from wastewater, conflicting data on the efficacy of biological processes in reduction of SARS-CoV-2 in aquatic environment take place in literature. For instance, some studies confirmed the absence of SARS-CoV-2 in the treated water, but some others reported its reduction to some extent in ASP.

Considering discrepancies existing on the reported performance of biological processes, the role of wastewater treatment units in elimination of SARS-CoV-2 in wastewater is an urgent issue to be deeply investigated for the assessment of potential risks of SARS-CoV-2 posed on human health as well as environment. In the same vein, scarcely any data the viability and infectivity of SARS-CoV-2 in drinking/waste water are available in the literature. According to the literature, only one study has reported the infectivity of SARS-CoV-2 in influent and effluent samples collected from WWTPs as null [19].

There is a general agreement that sludge line, particularly primary settler, contributes as a concentrator of SARS-CoV-2 genome and the primary sludge seems to be a potential tool to track trends in the SARS-CoV-2 outbreak within the WBE surveillance context [33–35,37].

3. Existing treatment methods to inactive viral (particularly SARS-CoV-2) in wastewater

The severity of human health concerns varies depending on how viruses, including SARS-CoV-2, are inactivated in aquatic settings. The understanding of how SARS-CoV-2 and its RNA are inactivated would help to enhance control measures and wastewater treatment needs, but little is known about SARS-CoV-2 survival in water and wastewater matrices. Moreover, untreated wastewaters coming out of hospitals or other patient care wastewater treatment settings pose a greater barrier in the remediation processes. Recent findings showed that the SARS-CoV-2 can persist in an untreated virus from few hours to days. In such an incident, SARS-CoV-2 RNA concentration was found between 1.2×10^1 and 1.8×10^3 copies of RNA per mL in natural water bodies (rivers) near WWTPs located in Italy [49] and in sewage from distinct locations in the Netherlands [50]. It requires urgent measures and careful considerations of treatment strategies for disinfecting the wastewater before introducing to the water bodies.

As mentioned in Section 2, conventional wastewater treatment processes, followed by chlorine disinfection, anaerobic digestion, UV radiation, membrane bioreactors, up-flow anaerobic sludge blanket processes as well as the activated sludge, have recently been proved to be effective in removing SARS-CoV-2 RNA from wastewater [48,51–55]. Also, according to a World Health Organization (WHO) technical brief, it has been stated that there is no indication that SARS-CoV-2 may survive in treated wastewater or drinking water [56]. It might be due to the enveloped nature of CoVs, which makes it more susceptible to chlorine disinfectants, high pH, and temperature as well as lesser stability in the environment than non-enveloped viruses. Therefore, it emphasized on the use of conventional wastewater treatment processes in wastewater treatment plants and multiple filters used in drinking water treatment plants, as this should easily thwart the progression of SARS-CoV-2 to non-detected levels ($<10^{-4}$ annual risk). However, some previous studies comprising of surrogate CoVs suggest that depending on several physicochemical parameters. These CoVs can persist in infectious forms into aquatic bodies from days to weeks [57]. The presence of significant levels of SARS-CoV-2 viral load in treated wastewater raises concerns about the efficiency of current procedures [58]. Therefore, considering the ever-changing viral genetics which help in their resistance to disinfectants and other measures, it is important to determine and eliminate the persistence of viruses in the wastewaters.

Various disinfectant technologies such as UV, chlorination, and filtration, which are recommended by the WHO for the removal of pathogens, are commonly used in wastewater treatment plants. While all these technologies are relatively common, the algae-based methods are new and could be effective against the removal of pathogens like SARS-CoV-2. The following sections describe the applicability and efficiency of these technologies for remediation of wastewater containing SARS-CoV-2.

3.1. Chlorination

The approaches consisting of chemical agents liberating free chlorine such as hypochlorous acid (HOCl) and hypochlorite ion (OCl^{-}) remain the most efficient strategy to address pathogenic contamination especially viral [59]. Most common sources of free chlorine are sodium hypochlorite, calcium hypochlorite, chlorine dioxide, elemental chlorine in the gas form, and chloramines. Although, it produces several disinfection byproducts (DBPs) including trihalomethanes (THMs) and haloacetic acids (HAAs) when chlorine reacts with dissolved organic matter, it is the most widely used chemical agent recommended by the WHO as it is efficient at low concentrations and is reasonable compared to other sanitizers to eliminate SARS-CoV-2 from polluted wastewater [60]. Wang et al. [61] studied the effect of high concentrations of chlorine and chlorine dioxide (5, 10, 20, and 40 mg L^{-1}) on the survival of pathogens including SARS-CoV, *Escherichia coli*, and the *f2 phage* in municipal wastewater, hospital and domestic wastewater, urine, and feces during the 2005 SARS outbreak. In the same study, the effect of residence time on SARS-CoV deactivation in wastewater with low (10 mg L^{-1}) and high (20 and 40 mg L^{-1}) Cl_2/ClO_2 concentrations was explored. The comparison of the data obtained for all tested pathogens revealed that SARS-CoV was more susceptible to disinfectants. Furthermore, free chlorine proved more efficient than chlorine dioxide in neutralizing SARS-CoV. The optimum concentration for free residual chlorine (>0.5 mg L^{-1}) and for chlorine dioxide (2.19 mg L^{-1}) in wastewater were adequate for the removal of SARS-CoV.

Sodium hypochlorite (NaOCl) can be treated with a maximum of 6 mg L^{-1} of free Cl2, as published by the German Water Directive [62]. However, in hospital wastewater treatment plant, Zhang et al. [63] investigated the removal of SARS-CoV-2 using NaOCl. It was observed that sodium hypochlorite was more effective in disinfecting medical wastewater containing SARS-CoV-2 after injecting free chlorine >0.5 mg L^{-1} for 90 min of residence time and 6700 g/m^3 dose of sodium hypochlorite into the septic tank [63].

3.2. Membrane processes

Membranes have been extensively used in chemical technology and have a wide range of applications. The removal of pathogens, especially viruses, is one of the vital applications of membrane technologies as wastewater in many settings is recycled and reused. Currently, pressure-driven membranes are extensively employed among wastewater treatment processes in many effluent treatment facilities. The effect of membrane materials such as adsorption or electrostatic repulsion is essential for removing viruses, chemical species, and other pathogens. Adsorption removes the viruses by directly interacting with them by exploiting electrostatic and hydrophobic interactions between viruses and membrane surfaces, whereas, through electrostatic repulsion, the viruses and material have the same charge [64]. As shown in Fig. 2, the water filtration membranes are classified according to their pore size such as microfiltration, nanofiltration, ultrafiltration, and reverse osmosis. Since the average pore size of a microfiltration membrane is >100 nm, they are more effective for the removal of bacteria and protozoa than the viruses [65]. On the other hand, the pore size used in the nanofiltration membranes is 10 nm, which is much lower than the size of any virus but still there is a paucity of data on its potential of actively removing viral particles in a wastewater setting. Considering the size of SARS-CoV-2, which is around 100 μm, and the extensive studies conducted in wastewater settings, reverse osmosis and ultrafiltration have the capability to efficiently remove the virus and other pathogens. The potential of these membrane technologies in viral removal from wastewater has been discussed below.

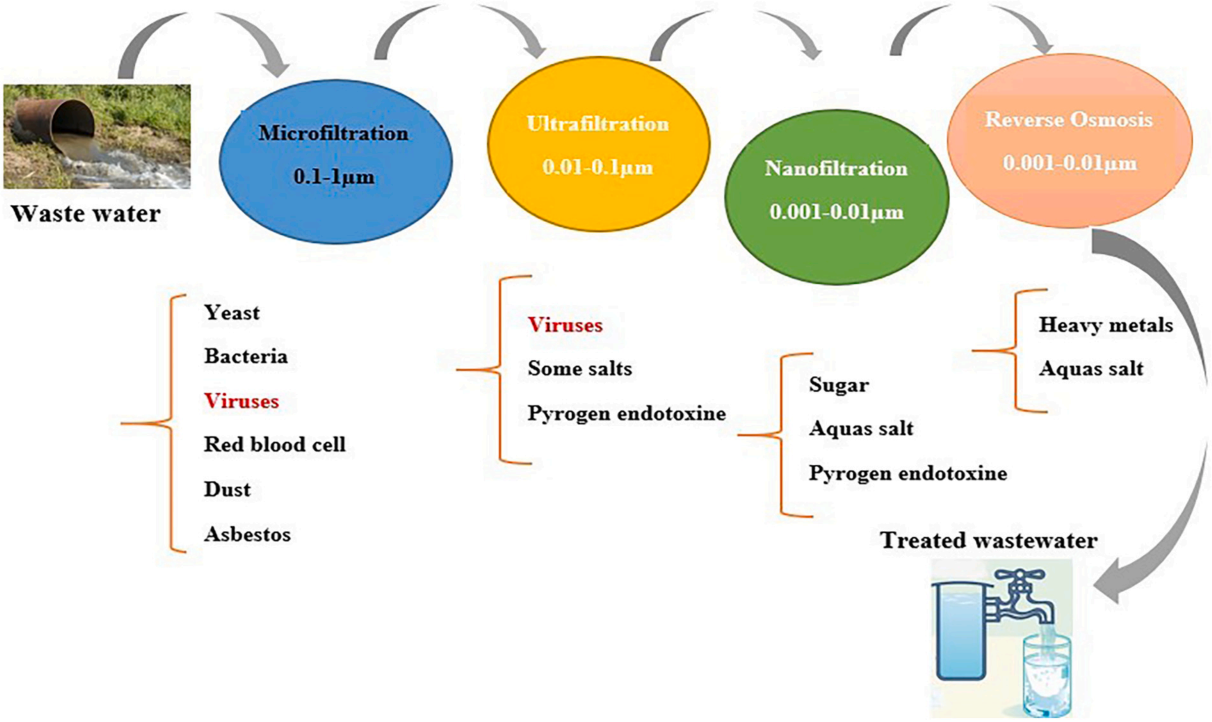

Fig. 2. Classification of water/wastewater filtration membranes based on pore size and pollutant removal criteria.
Modified after Eloffy et al. [66].

3.2.1. *Reverse osmosis*

Because of its high removal efficiency, the reverse osmosis (RO) method is widely used to produce high quality water for potable purposes. In tertiary treatment for water reuse applications, RO membranes are commonly utilized due to their high potential to remove pathogens [67]. In laboratory systems, RO membranes have shown to achieve higher than 5-log removal values (LRV) of viruses [68,69]. Also, this kind of research has been performed in pilot-scale systems [70,71]. LRV measures the efficiency with which a target, such as a particle, organism, or surrogate, is eliminated or inactivated. Irrespective of the advantages of RO including most energy-efficient desalination technology, high quality water production with low fouling potential, some drawbacks such as organic fouling caused by dissolved organic matter and scaling due to the abundance of marginally soluble salts can be mentioned [72].

Recently, Wlodarczyk and Kozlowska [54] reviewed the treatment strategies for the removal of waterborne pathogens by RO. In another study using RO system, Vickers et al. [71] achieved the overall LRV reduction from 5 to 4.16. Considering the size of MS2 to be 27 μm, which is roughly 60–70 times smaller than SARS-CoV-2, RO has the potential to remove SARS-CoV-2 from the influent [71]. They also reported the removal of noroviruses from raw sewage using sand-anthracite filters and a membrane bioreactor/reverse osmosis approach. However, an industrial-scale membrane installation results tedious due to its intricate design and continuous monitoring because the barriers often get leaky from time to time. Further, there is not a globally accepted validation protocol for RO to date.

3.2.2. *Ultrafiltration*

Ultrafiltration (UF), more than any other membrane-based technology, is widely regarded as the most effective way for removing viruses from wastewater. Ultrafiltration, which is frequently utilized as a pretreatment stage prior to RO treatment, improves virus removal efficacy. In a study, Lee et al. [73] employed a synergic process, i.e., coagulation and UF for wastewater treatment on a pilot-scale system. By adjusting pH value in the secondary effluent, a virus removal factor of 6.8–7.5 log10 was achieved. In another study, a polyethersulfone UF membrane with average membrane pore size of 67 nm was used to remove the bacteriophage PP7 [74]. Further, in a study by Lu et al., the ultrafiltration membrane efficiently removed the MS2 and HAdV-2 human viruses [75]. These findings showed that ultrafiltration membranes can be used in wastewater treatment facilities to remove SARS-CoV-2.

3.2.3. *Membrane bioreactor (MBR)*

Membrane bioreactor (MBR), which combine a membrane-based filtering approach with a suspended growth biological reactor, are considered to be effective for removing pathogens, particularly viruses, from aquatic wastes [76]. The MBR technology is capable of generating high quality effluent at lower environmental footprint [77]. Fig. 3 illustrates four main mechanisms involved in a full scale MBR for viral removal: i) attachment of virus to mixed liquor solids; ii) virus retention by a clean membrane; iii) virus retention by the membrane cake layer; and iv) virus inactivation due to predation [78]. In a study on use of membrane along with biofilm as an adsorption approach in a bench-scale aerobic membrane bioreactor, 0.8 log MS-2 phage elimination efficiency was achieved, whereas 0.4 log removal efficiency was achieved by using membrane only filter [79]. Another study reported a 1.5 log removal of norovirus GI in 60 min after mixing the viral particles with the MLSS [80]. In a study consisting of viral removal by MBR, 6.3 LRV of adenoviruses, 4.8 LRV of noroviruses, and 6.8 LRV of enteroviruses were obtained [81]. Finally, a research showed that under optimum conditions, the MBR is capable of 7-$\log_{10}$ reduction in virus concentration [82].

However, to achieve maximal removal efficiency, the MBR system needs periodic membrane maintenance. Due to its drawbacks such as higher operating cost, an energy-intensive procedure, and inadequate virus-containing sludge disposal management, it has led to the application of hybrid processes [83].

3.3. *Nanomaterials*

The usage of nanomaterials in removal and neutralization of viruses in wastewater is an important approach. It consists of the membrane containing nanomaterials, such as carbon nanotubes (CNTs), titanium dioxide (TiO_2), and zerovalent ions (ZVIs) [84–86]. In a study by Kim et al. [87], it was reported that silver multiwall nanotubes (Ag-MWCNT) were highly effective in removing several different viruses. In another study, Domaga et al. [88] investigated Cu_2O/MWCNTs filters for removing MS2 virus from water. By optimizing pH value at 5, three samples achieved a 7 $\log_{10}$ decrease in MS2. Similarly, Nemeth et al.

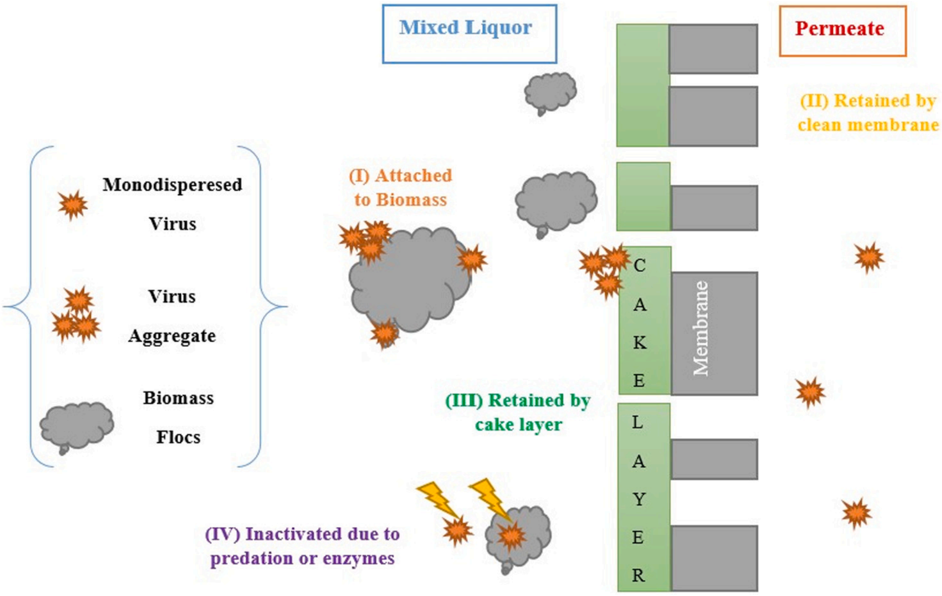

Fig. 3. Main mechanisms of viral removal in a full-scale MBR.
Modified after Chaudhry et al. [78].

[89] attained a 4 $\log_{10}$ MS2 reduction in a pH interval of 5–9 by employing the Cu_2O-coated MWCNT membrane. Also, using smectic liquid-crystalline ionic membranes, Kuo et al. [90] achieved a 7 $\log_{10}$ reduction on MS2 bacteriophage, Q bacteriophage, and Aichi virus. Additionally, nanoparticle adsorbents with a small particle size, high specific surface area, and low internal diffusion resistance have been employed to improve the adsorption capacity of membrane filters for virus removal. Magnetic nanoparticles modified with bio-protein had showed superior adsorption efficiency with bacteria or viruses. In a recent study using these nanoparticles, Park et al. [91] found that magnetic hybrid colloid complexes containing a 30 nm Ag nanoparticle (Ag30@MHC) had the highest antiviral effectiveness against the bacteriophage MS2 (2–3 log decrease).

Additionally, graphene has received great attention from the researcher community due to its stable mechanical, thermal, electrical, and other properties. In a recent study [92], reduced graphene oxide (rGO)-Fe3O4 nanoparticles complexed with cetyltrimethylammonium bromide (CTAB) were employed to retain SARS-CoV-2 spike pseudovirus and three human enteric viruses (HuNoV, HAdV, and HRV). Maximal adsorption capacities of 3.55×10^7, 2.21×10^7, 7.01×10^7, and 6.92×10^6 genome copies mg^{-1} were obtained, respectively. Moreover, from coastal, tap, and river water, the complex was able to adsorb and so capture the four types of viral particles. The findings indicated that viruses were caught on the CTAB functionalized rGO-Fe3O4 complexes surface via electrostatic interactions and rGO's inherent adsorption capabilities. Therefore, these nano-complexes have the potential for effective adsorption and SARS-CoV-2 removal from aqueous environments.

3.4. Conventional coagulation and electrocoagulation

Conventional coagulation (CC) and electrocoagulation (EC) have been extensively studied in the removal of heavy metals, organic matter, pathogens, and other contaminants from wastewater [93–98]. The EC process requires less coagulant and, consequently, produces less sludge than the CC. In addition, it does not require chemical storage, dilution, or rapid mixing. However, very limited studies have been associated with the efficiency of CC and EC in the elimination of virus from wastewater. EC followed by microfiltration (MF) was investigated to eliminate MS2 bacteriophage from wastewater [99]. The results indicated that using MF approach alone to abate MS2 virus resulted in <0.5-log reduction in viral removal. However, the synergic treatment, using iron as coagulant, a virus removal efficiency of 4-log reduction value (LVR) was achieved with 6–9 mg L^{-1}. Another study [100] was performed using CC with $FeCl_3$ and, Fe(0)-EC to remove surrogate (φ6 *bacteriophage*) from wastewater. In such techniques, the adhesion of φ6 *bacteriophage* to the coagulant (precipitated iron hydroxide) resulted in virus inactivation. This study showed that both techniques, CC and EC, were highly efficient in removing the virus from wastewater (LVR of ~5 within 20 min.). Similar approaches can be used in the removal management of SARS-CoV-2. Fig. 4 shows the simplest EC cell used to remove pathogens from wastewater. Once the electrodes are connected to an external power supply, the oxidation process commences with the anode, generating metallic cations. Concurrently, water is reduced to form hydrogen gas bubbles and hydroxide ions at the cathode [101]. A charge neutralization of pollutants and disinfection of wastewater is induced when an isoelectric point is reached by the coagulating agents (M(*OH*)n) (Eq. (1))

$$M_{(s)} + nH_2O \rightarrow M(OH)_n + \frac{n}{2}H_2 \tag{1}$$

3.5. Algae-based treatment systems

Algal-based treatment systems are highly capable for inactivating high levels of pathogens as well as carbon/nutrient removal from wastewater [102,103]. In the 1950s, wastewater treatment methods co-driven by heterotrophic bacteria and photoautotrophic algae were established to lessen energy consumption of the activated sludge (AS)

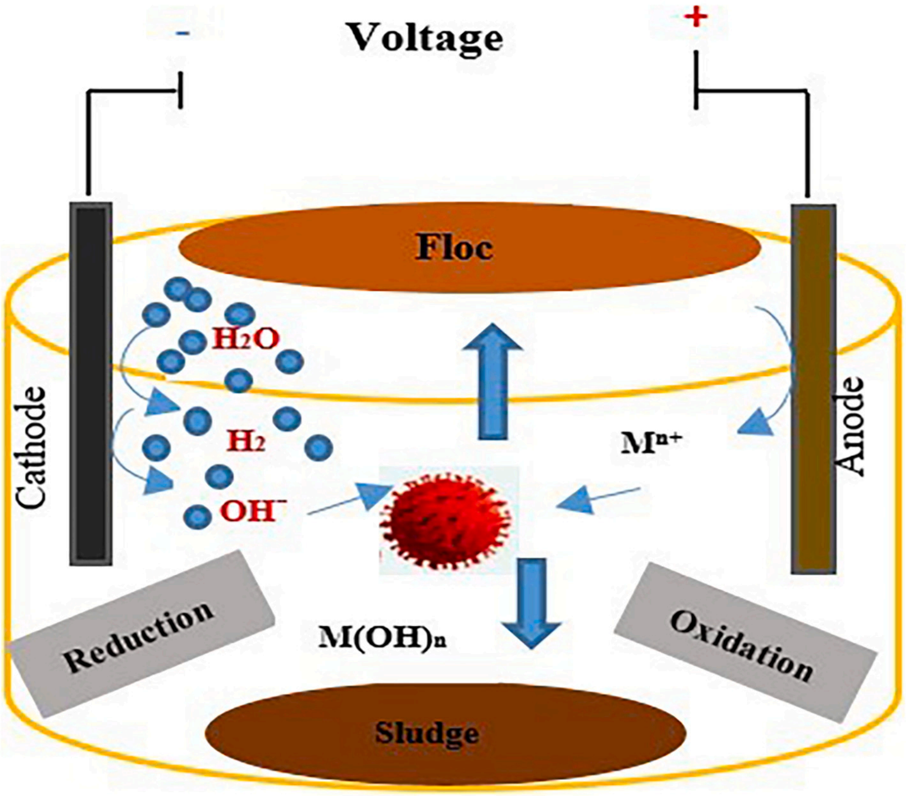

Fig. 4. Basic electrocoagulation reactor for removing pathogens from polluted water.

process and/or enhance secondary effluent to meet nutrient discharge regulations. Algal-based wastewater treatment systems have emerged since then as energy-efficient and cost-effective alternative to traditional wastewater treatment systems [104]. Although several studies have shown that algal systems can meet carbon/nutrient discharge standards, only a few have suggested their role in pathogen inactivation. Extreme culture conditions such as elevated dissolved oxygen (DO) concentrations, pH value, solar irradiation, and algal toxins have been reported as important factors which contribute to pathogen inactivation [105,106]. Photolysis, denaturation of proteins and nucleic acids, predation, and virus attachment to biomass are some of removal mechanisms [107]. A new algae-based wastewater treatment system based on mixotrophic metabolism has recently been proposed, with significant benefits over traditional heterotrophic/photoautotrophic systems [108]. Previous studies on algae-based wastewater treatment systems have been limited to basic coliform and coliphage enumerations [109]. In a recent study [110], high removal rates were reported in wastewater treatment of noroviruses (1.49 ± 0.16 LRV) and enteroviruses (1.05 ± 0.32 LRV) by using *Galdieria sulphuraria algae*. Interestingly, *Chroococcus* sp.1 was found to be efficient in removing pathogens from livestock wastewater [111]. The microalgae culture was shown to be optimum for biomass production under controlled indoor ($2.13\ g\ L^{-1}$) and outdoor conditions ($4.44\ g\ L^{-1}$) with >80 % of nutrients removal.

Recently, Zhang et al. [112] performed a microrobotic strategy to eliminate SARS-CoV-2 using angiotensin-converting enzyme 2 (ACE2) receptor functionalized algae microrobot (denoted “ACE2-algae-robot”) as depicted in Fig. 5. The ACE2-algae-robot was created via a click chemistry reaction that incorporated the ACE2 receptor on the surface of *Chlamydomonas reinhardtii* algae, as the ACE2 receptor was an active partner of the SARS-CoV-2 spike protein. This study demonstrated that, using SARS-CoV-2 spike protein (S protein) and pseudovirus as model contaminants, by moving the ACE2 receptor on the algae surface produced high removal efficiencies above 90 % of such contaminants. These findings demonstrated the potential of bio-hybrid microrobot for industrial-scale process to eliminate coronavirus and other pathogens that pose a harm to the environment in wastewater [112].

3.6. Activated sludge process

As discussed above, most studies dealt with pathogens (including SARS-CoV-2) in wastewater have focused on the fate of these pathogens in water lines and very little emphasize has been put on the sludge line. Data indicated that many species of pathogenic origin like members of *Picornaviridae*, *Caliciviridae*, and *Reoviridae* could be adsorbed onto the activated sludge particles [113,114]. Furthermore, activated sludge system has found a highly effectivity against fecal indicator organisms (FIOs) such as F-specific RNA bacteriophages and coliforms [115]. There is still a paucity of data of their use in the removal of SARS-CoV-2 from wastewater.

Recently, some studies have shown that the activated sludge section can act as a potent barrier for genetic material of SARS-CoV-2. In such a study [116] a two-month comparative analysis of the removal effectiveness of activated sludge (AS) and root zone treatments (RZT) was conducted using 44 samples. The results showed that AS treatment gave better SARS-CoV-2 RNA removal efficacy ($p = 0.014$) than RZT ($p = 0.032$). In a similar study [117] on SARS-CoV-2 removal by AS, the viral RNAs were reduced in the effluent as compared to the influent when passed through the activated sludge. The viral RNAs with concentrations ranging from 1.8×10^4 to 22.4×10^4 gene copies L^{-1} were decreased up to 0.3×10^3–2.1×10^3 gene copies L^{-1} in an activated sludge-oriented

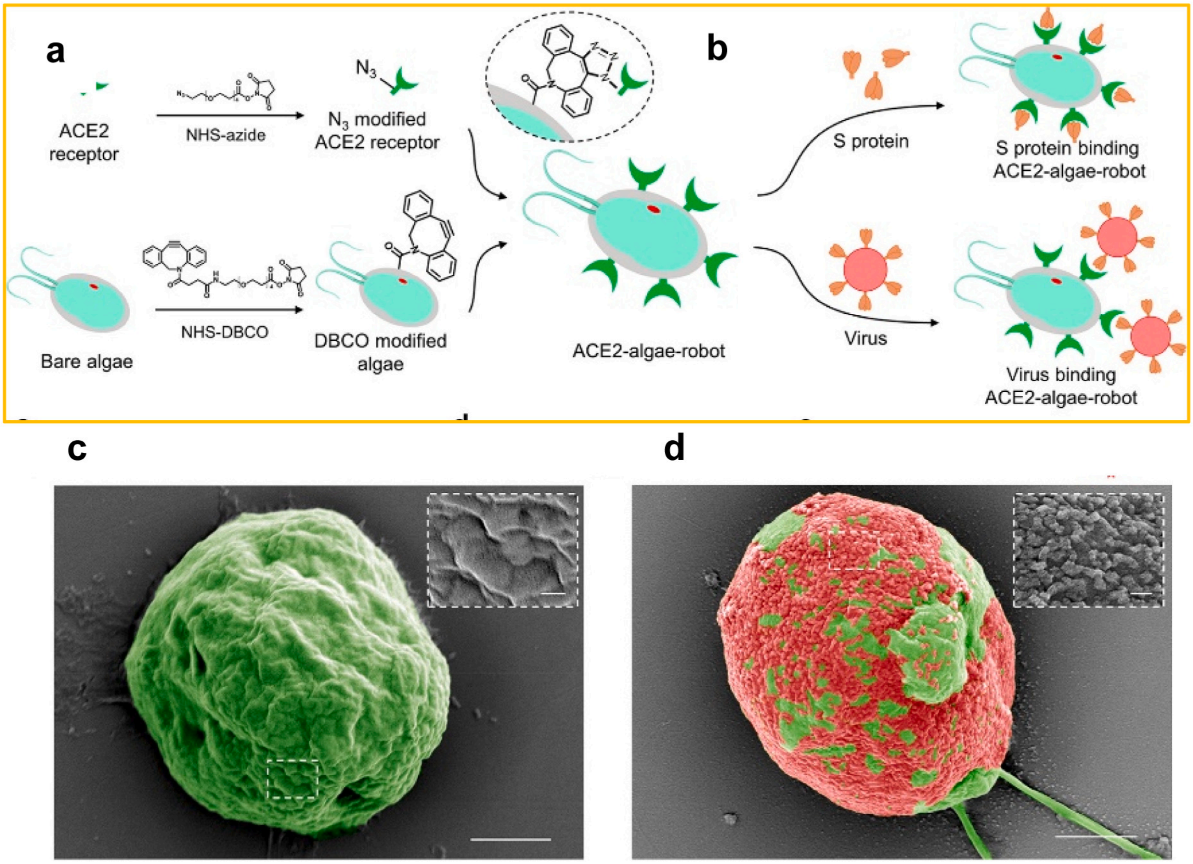

Fig. 5. (a) The functionalization of microalgae with ACE2 receptor, (b) the use of the ACE2-algae-robot for the binding and removal of spike protein and SARS-CoV-2 virus, and the surface morphology of the ACE2-algae-robot (c) before and (d) after contact with the virus.
Modified after Zhang et al. [112].

treatment approach. Beyond that, activated sludge process was found as a feasible technology to SARS-CoV-2 RNA reduction from WWTPs in Thailand, France, and Spain [6,118].

4. Advanced oxidation processes to inactive viral (particularly SARS-CoV-2) in wastewater

In this section, the efficiency of advanced oxidation processes (AOPs) to inactivate SARS-CoV-2 RNA is analysed. AOPs are a lately technology to deactivate pathogens in the contaminated water by generating reactive oxygen species (ROS) such as hydroxyl radicals (•OH). The production of radicals may be electro-generated by primary oxidants namely hydrogen peroxide (H_2O_2) and ozone (O_3), or catalysts such as titania. The produced radicals degrade organic compounds present at the virus cell wall and, thus, the virus is disturbed. An effective wastewater treatment approach is crucial to release treated water into environmental water bodies to avoid waterborne diseases. Commonly, the tertiary stage into wastewater treatment train improves the water quality before discharge. In this step, disinfection methods or AOPs can be introduced to inactivate or remove pathogens [119]. Fig. 6 summarizes typical radical reactions occurred during disinfection utilized AOPs.

4.1. UV/H_2O_2 and photo-Fenton

The mostly employed disinfection procedures include ultraviolet (UV) radiation and chlorination. However, the dichlorination process after disinfection is the main disadvantage. The preventive effect of ultraviolet radiation against SARS-CoVs is proven [10]. UV light hinders the spread of viruses by destroying their reproductive ability. 1–2 min irradiation of UV on a culture medium containing SARS-CoVs destroys viral infectivity [2]. In another study by Duan et al. after exposure to UV light for one hour a strain of SARS-CoV virus decreased to an undetectable amount [120].

Recently different doses of UVC radiation have been studied to prevent the spread of the SARS-CoV and sometimes specifically the SARS-CoV-2 virus as a non-contact technology. Based on the results, in low virus concentrations, a small dose of UVC is sufficient to inactivate the virus entirely and in higher viral concentrations complete inactivation can be achieved by increasing the radiation doses [4]. Hydroxyl radicals have shown promising effects in reducing the concentrations of coronaviruses including SARS-CoV-2 in wastewater [10].

UV/H_2O_2 process appears as a potential technology as well as a common and desirable option to chlorination for domestic water decontamination [121]. The non-selective hydroxyl radicals produced from H_2O_2 in UV/H_2O_2 method (Eq. (2)) seems to be one of the most utilized AOP to disinfect wastewater. To increase the in-situ production of hydroxyl radicals, carbon-based materials are preferably used owing to its worldwide abundance, large surface area, good electrical conductivity, corrosion resistance, and minimal price [122].

$$H_2O_2 + h\nu \rightarrow 2(^{\bullet}OH) \tag{2}$$

UV disinfection has several advantages such as short contact time and no adding chemical products like chlorine gas. However, some organic contaminants can be incompletely degraded generating by-products that, in some cases, they are even more toxic than their initial compounds [123]. Furthermore, the disinfection effectiveness may be influenced by the quantity of suspended particles or dispersed microbial. Also, some virus species and antibiotic resistant bacteria might stay alive after UV disinfection process. Moreover, bacteria may recover in the darkness such oxidation process [124–126]. It should be also mentioned that, in comparison with other viruses, coronaviruses are generally more resistant to UV so using this type of treatments in combination with other disinfection methods would be more effective than using UV alone [4,7].

UV/H_2O_2 process is faster and possesses higher power of microorganisms inactivation compared with other technologies [14]. Fenton's reagent consists of a solution of hydrogen peroxide (H_2O_2) with ferrous iron ($FeSO_4$) as a catalyst that is used to oxidize pollutants. Ferrous iron is oxidized to ferric stated in presence of hydrogen peroxide. In addition, hydroxyl radical and hydroxide are generated according to Eq. (3). Then, ferric iron is reduced to Fe^{2+} producing a hydroperoxyl radical and a proton (Eq. (4)). Further, the disproportionation of hydrogen peroxide generates two distinct oxygen-radical species (Eq. (5)). These free radicals cause the degradation/mineralization of pollutants [127].

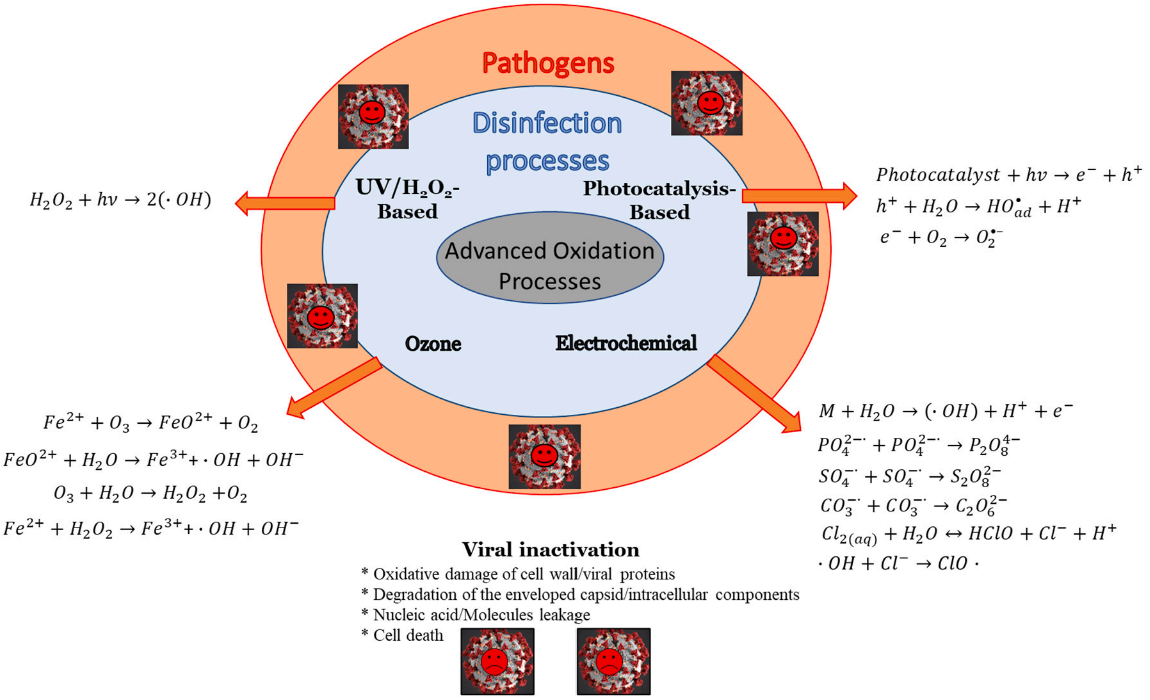

Fig. 6. Advanced oxidation processes used to disinfect wastewater.

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + \bullet OH + OH^- \tag{3}$$

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + \bullet OOH + H^+ \tag{4}$$

$$2H_2O_2 \rightarrow \bullet OH + \bullet OOH + H_2O \tag{5}$$

However, the chemical consumption of oxygen peroxide and the acid media to preserve ionic iron concentrations comprise the major disadvantages for real scale systems [128].

Recently, the solar photo-Fenton process at roughly neutral pH and extremely low doses of H_2O_2 and Fe^{3+} (in μM) proved to be an effective AOP for virus (MS2 coliphage) inactivation in natural water [129]. Before that using an iron hydroxide mediated Fenton-like process to in activate MS2 virus under the sunlight and in the dark was investigated by Nieto-Juarez et al. in 2010 [130]. Findings pointed out that i) virus adsorption onto iron particle significantly affected inactivation efficiency by the process performed at nearly neutral pH; ii) ROS produced near to the virus in the existence of Fe^{3+}damaged to the virus; iii) the virus-Fe^{3+} complex caused indirect-endogenous damage in the virus due to its photo-sensitivity; and iv) inactivation rates decreased in the case of natural water indicating competition between natural organic matter (NOM) oxidation and virus inactivation. In the study, possible pathways involved in the activation of bacteriophage MS2 by photo-Fenton were proposed [129] as depicted in Fig. 7.

4.2. Photocatalysis

Photocatalysts are semiconductors with higher energy compared with its band gap, raising an electron from the valence band to the conduction band. This last generates an electron-hole pair. Several photocatalyst nanomaterials have been used as antibacterial/or antiviral materials. They attack living or non-living microstructures stored on any surface [131]. TiO_2 is the most known and studied photo-catalyst used to degrade pollutants as well as photo induced bacterial and virus disinfection owing to its effective photo-activity, high chemical stability, and non-toxicity [132,133].

Viral disinfection of water by means of photocatalysis was used for the first time in 1994 (Fig. 8) when Sierka and Sjogren [134] inactivated MS2 by TiO2 photocatalyst under UV irradiation. Since then different kinds of metal, non-metal and carbon-based catalysts have been developed and investigated for virus disinfection [5].

TiO_2 photocatalyst has demonstrated good potential for treating sewage wastewater. TiO_2-based photocatalysts yield extremely oxidizing free radicals ($O^{2\bullet\,-}$, HOO•, and HO•) that are famous to have bactericidal and antiviral performance against numerous microbes and viruses [135]. Accordingly, many studies have shown successful deactivation of viruses like phage MS2, bacteriophage Qβ, phage f2, murine norovirus, and human adenovirus using TiO2 photocatalysts [5].

As can be seen in Fig. 8, the photocatalytic method involves: i) generation of photo-induced charge carrier, ii) separation of charge carrier and movement to the photocatalyst surface, and iii) oxidation/reduction reactions at photocatalyst surface [131]. TiO_2 particles destroy the protein shell/capsid of viruses. ROS attack the cell membrane and, consequently, genetic materials, minerals, and proteins are released initiating the deactivation of respiration, to finally cause the cell death [5].

Several advantages are listed for photocatalysis as i) the formation of harmless compounds, ii) in some cases the photocatalytic process may eliminate some toxic substances, iii) no chemicals products are added, iv) it completes with in short reaction time, and v) some value-added products like hydrogen may be generated. However, degradation happens mainly on the surface of TiO_2, therefore, mass transfer restrictions must be diminished. Another important drawback is the slow photocatalytic degradation rates owing to the poorly attraction of TiO_2 with hydrophobic organic pollutants [136]. Moreover, the TiO2 nanoparticles can be accumulated resulting in the impediment of light incidence on the active zones, reducing the catalytic activity [137]. To enhance the photocatalytic performance and improve degradation strengthened, the design of new photocatalyst is mandatory [138–140].

Disinfection of viruses by photocatalysis or photo- electrocatalysis could cope with disadvantages of the conventional disinfection procedures. Coupling TiO2 photocatalyst with another metals to produce heterojunction photocatalyst could extend the photocatalytic action on virus degradation through UV–Vis light irradiation [137].

4.3. Ozone-based advanced oxidation processes

Ozonation is a traditional method in pathogen sterilization from wastewater [142–144]. Ozone (O_3) is one of the most powerful oxidizing

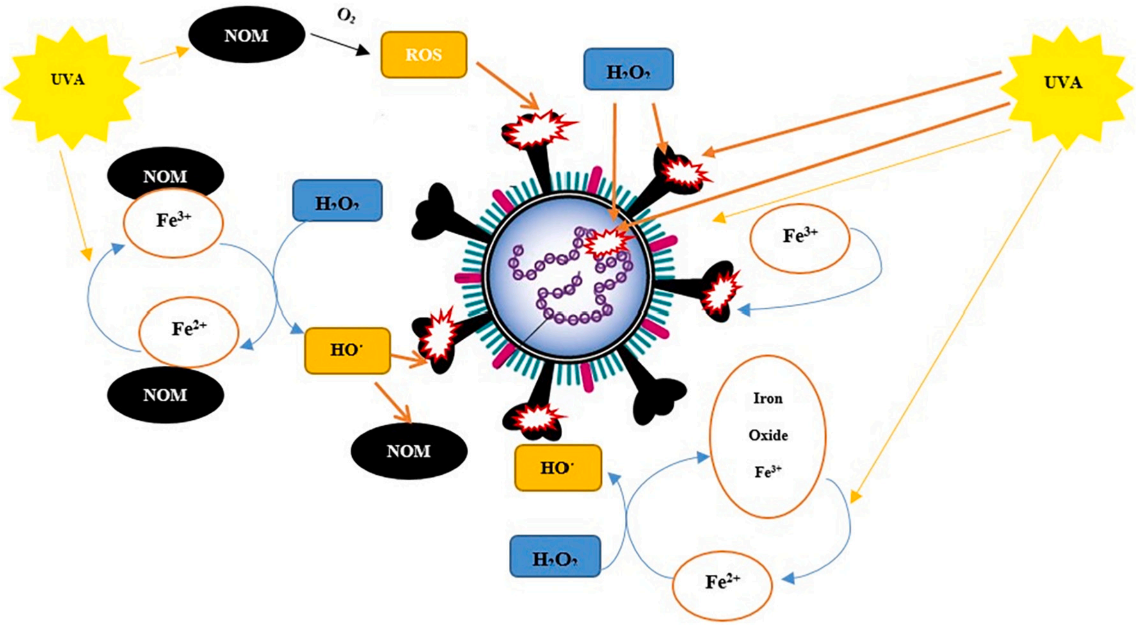

Fig. 7. Possible pathways for the inactivation of bacteriophage MS2 by photo-Fenton. Modified after Ortega-Gómez et al. [129].

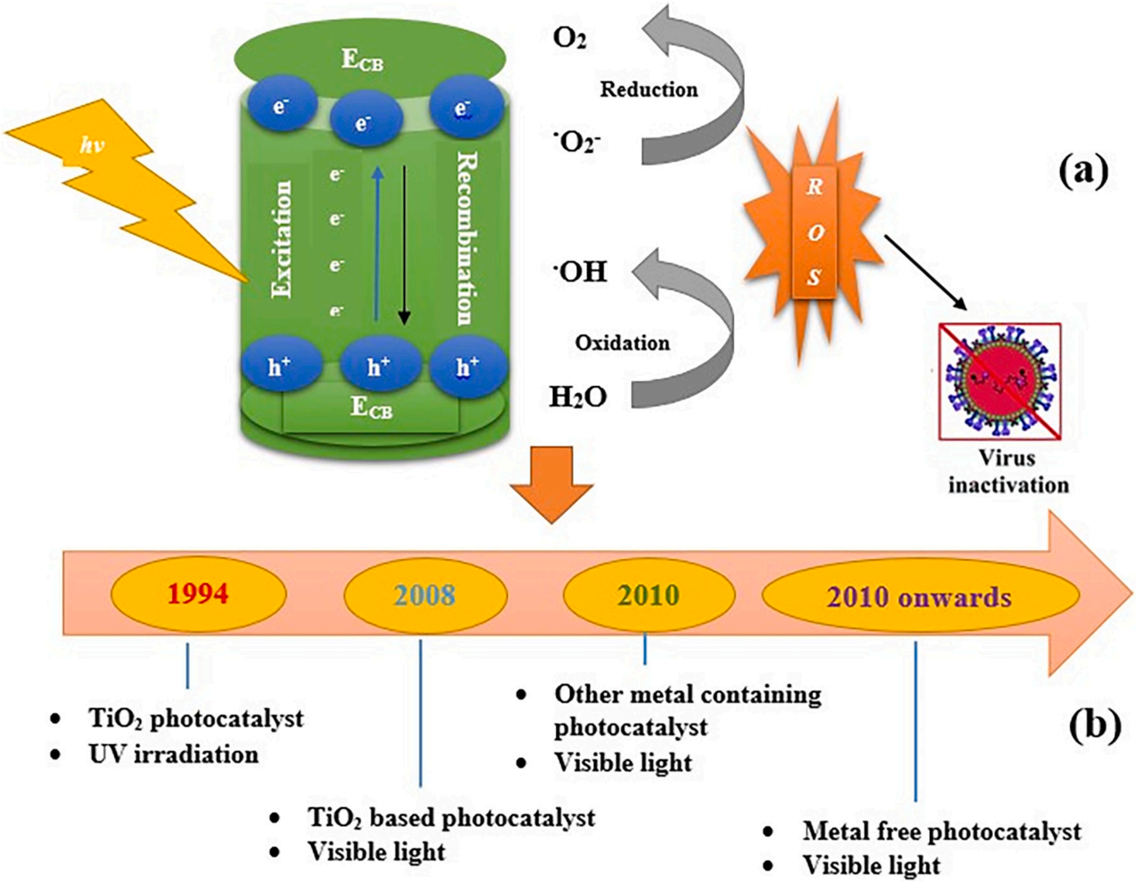

Fig. 8. Schematics illustrating (a) reactive oxidative species (ROS) involved in virus inactivation through photocatalysis and (b) a chronological overview of development of photocatalysis in viral removal from the water system.
Modified after Kumar et al. [141] and Mohd Nasir [5] et al.

species. A wide spectrum of ROS is generated when O_3 is dissolved in water. However, ozone molecules play the major role in disinfection, which are responsible to degrade materials present in virus membranes, damaging the cell wall. Lastly, it leads to cell bursting.

Since ozonation has shown positive results against enveloped viruses and SARS-CoV-1 which are morphologically like SARS-CoV-2, it is believed that it can be a promising approach in the inactivation of SARS-CoV-2 [2,4,10]. Based on a study by Zucker et al. [145] corona pseudoviruses as a viral model decreased by 99 % after the 30 min treatment by 1000 ppmv ozone. So, it can be assumed that ozonation can be an alternative method for liquid inactivation of SARS-CoV-2.

In general, disinfection processes for wastewaters is usually carried out in a synergic treatment with H_2O_2 or UV irradiation [146]. This last is a consequence of the higher operation costs and by the presence of competitive reactions with organic matter affecting pH, alkalinity, and temperature, which may modify the oxidant efficiency [7,147]. Moreover, ozone is highly reactive and difficult to store [148]. In addition, its occurrence into wastewater could produce toxic by-products such as aldehydes, carboxylic acids, and bromate [149].

The increase in temperature decreases the solubility of O_3 which causes ozone decomposition augmenting the disinfection efficiency [150]. On the same vein, at higher pH values more radicals are produced because of the indirect action of ozone (formation of radicals species) that attack microbes [151].

4.4. Electrochemical technologies

Taking into consideration the limitations of the AOPs previously mentioned electrochemical advanced oxidation processes (EAOPs) are considered as environmentally friendly methods owing to the high production of ROS using electrical current. As stated, they represent an effective alternative for inactivating a widespread type of pathogens including virus, bacteria, and parasites [128,152]. The pathogens inactivation is carried out by direct oxidation of pathogen at the anode surface or by indirect oxidation through physic/chemisorbed hydroxyl radicals in the surrounding area of the anode surface [101,153,154]. Quasi-direct oxidation also includes the electrochemical production of oxidizing species which can decontaminate effluents in the bulk solution [14,127,155,156]. Moreover, improvements of EAOP disinfection can be accomplished by coupling an external source of UV–Vis energy named as photo assisted EAOPs, e.g., photo-electrocoagulation process [101].

Electrochemical oxidation is the most popular EAOP owing to its simplicity, low cost, easily operated, and high effectiveness to treat different wastewaters [127]. Tu et al., [157] studied an electrochemical disinfection method to inactivate the SARS-CoV-2 virus in aqueous solution. They employed Ni-foam electrodes in a Na_2CO_3 aqueous solution. High inactivation efficiency (95 %) was achieved at an applied voltage of 5 V during 30 s. Moreover, a complete deactivation was observed after 5 min. Such method provided an environmental-friendly route to disinfect SARS-CoV-2 viruliferous effluents [157]. Photo-assisted electrocoagulation is also a disinfection technology that has augmenting attention. Electrocoagulation process consists in use an electrical current through for the electro-dissolution of the anode to form coagulants agents that catch pollutants from the solution [101].

Electro-Fenton process involves in-situ formation H_2O_2 during EC utilized iron electrode in aerobic conditions. Recently, this EAOP was effectively employed by Kim et al. [158] to inactivate a non-enveloped virus surrogate (MS2 bacteriophage) under slightly acidic conditions. As seen in Fig. 9, reactive oxygen species i.e. •OH and high valent oxoFe (IV) were generated during electro-Fenton reactions excited by electrochemically produced H2O2 and Fe(II). In their study, an EC operation performed at a solution pH of 6.4 and an iron dose of 20 mg Fe L^{-1} provided high virus removal efficiency corresponding to 5-logs and 6-log for electrolysis time of 30 and 60 min respectively.

Above mentioned data pointed out that EAOPs can be potentially well-suited to inactivate a wide range of viruses. Together with their success in virus inactivation, some process engineering and water chemistry issues require to be resolved before field implementation of EAOPs.

5. Major challenges, recommendations, and conclusions

It is evident that SARS-CoV-2 cannot survive in treated waste/drinking water. It may be due to the enveloped nature as CoVs are less stable in natural environment. Also, they are highly sensitive to disinfectants such as chlorine as well as to higher pH and temperature values compared to most of non-enveloped viruses. Therefore, it is essential to use proper treatment procedures before introducing treated water to the water bodies. In the same vein, wastewater treatment strategies play a significant role to SARS-CoV-2 reduction. Although membrane filtration (e.g., RO), nanomaterials (e.g., TiO2), electrochemical (e.g., EC), and biological (e.g., AS) processes have traditionally been employed for pathogens abatement, they suffer from certain limitations such as formation of high by-products pollution, high operating cost, need to chemical additives, and production of waste stream. In this manner, it is necessary to embrace wastewater treatment processes which cost effective and most importantly enjoy no secondary pollution. Some following recommendations and future directions can be concluded:

- Chemical agents such as sodium hypochlorite, chlorine dioxide, and chloramines have potentially shown antiviral effects, especially for SARS-CoV-2.
- Secondary and tertiary treatments have shown efficient in reducing the risk of SARS-CoV-2 transmission from WWTPs.
- The raw wastewater of hotspot places contaminated with SARS-CoV-2, including medical and quarantine centres as well as isolation wards, should be treated correctly before being released into WWTPs.
- Implementation of combined disinfection and membrane with molecular imprinting technology such as a hybrid MF-UV process with a photocatalytic membrane would be an innovative and enhanced degradation process.
- AOPs suffer from the production of hydroxide radicals and disinfectant by-products as well. As a result, hybrid AOPs with membrane processes should be considered as safe barriers against such defects.
- The application of AOPs as tertiary or disinfection processes capable of dealing with viruses including SARS-CoV-2 has received less attention. Therefore, more studies are needed to evaluate the effectiveness of state-of-the-art treatment techniques like integrated UV/O_3 with AOPs.
- Installation and development of smart decentralized wastewater treatment systems with solar energy in impoverished nations as a techno-economic strategy to efficiently inactivate SARS-CoV-2.

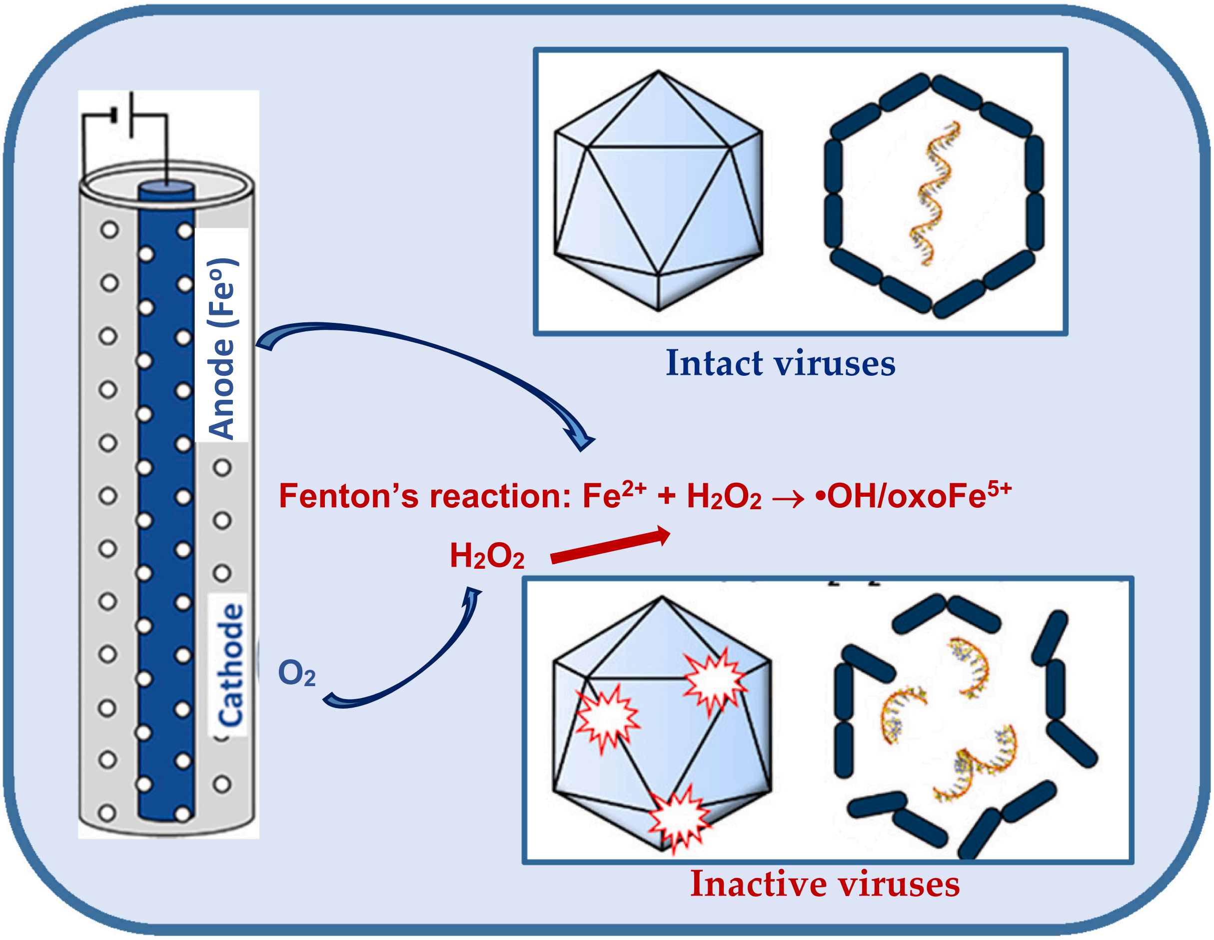

Fig. 9. Virus inactivation by electro-Fenton process.
Modified after Kim et al. [158].

- Indicators as virus detectors can be associated with novel wastewater treatment processes in a joint effort.
- In underdeveloped nations, where wetlands are abundant, some wastewater processes approach including wetlands, ponds, or lagoons could be a superior option for viral inactivation.
- In countries where hospital wastewater is not well managed due to lack of economic resources and inefficient environmental management, upgrading of hospital WWTPs to eliminate emerging pollutants and develop more strict discharge standards is expected.
- Further efforts are needed to understand in depth the sludge management and disposal from WWTPs contaminated with SARS-CoV-2.
- Fundamental studies should be developed to explore the mechanisms of SARS-CoV-2 degradation by AOPs processes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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