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REVIEW ARTICLE

Disinfection of corona and myriad viruses in water by non-thermal plasma: a review

Ahlem Guesmi[1] · **Mohamed Majdi Cherif**[2] · **Oussama Baaloudj**[3] · **Hamza Kenfoud**[3] · **Ahmad K. Badawi**[4] · **Walid Elfalleh**[2] · **Naoufel Ben Hamadi**[1] · **Lotfi Khezami**[1] · **Aymen Amine Assadi**[5]

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Abstract

Nowadays, in parallel to the appearance of the COVID-19 virus, the risk of viruses in water increases leading to the necessity of developing novel disinfection methods. This review focuses on the route of virus contamination in water and introduces non-thermal plasma technology as a promising method for the inactivation of viruses. Effects of essential parameters affecting the non-thermal discharge for viral inactivation have been exposed. The review has also illustrated a critical discussion of this technology with other advanced oxidation processes. Additionally, the inactivation mechanisms have also been detailed based on reactive oxygen and nitrogen species.

Keywords COVID-19 · Disinfection · Non-thermal plasma · Inactivation · Reactive species

Introduction

In the last 100 years, pandemics have been defined as disease outbreaks that have swept across an entire region or the globe, resulting in significant death tolls. There have been four global pandemics, the worst of which was the 1918 influenza pandemic, which killed between 50 and 100 million people worldwide (Capelli et al. 2021). These days, the world faces a new disease, coronavirus disease-2019 (COVID-19); the first time it appeared was at the end of December 2019 (Zhang et al. 2020b). It is an infection caused by the coronavirus-2 that generates acute respiratory syndrome SARS-CoV-2. SARS-CoV-2 is a beta coronavirus that belongs to the Sarbecovirus subgenus. It is a massive number of mono ribonucleic acid viruses of the subgroup Orthocoronavirinae and group Coronaviridae order Nidovirales. Coronaviruses are now classified into alpha, beta, delta, and gamma coronaviruses, linked with human symptoms (Chen et al. 2020). This disease began to spread throughout the world and became an international epidemic. COVID-19 was declared as a Public Health Emergency of International Concern (PHEIC) by the World Health Organization (WHO) as it caused thousands of deaths (Debata et al. 2020). COVID-19 has not only affected people, but it has also caused a halt in trade, business, and economic activity, where the world has paid a heavy price in terms of human lives lost, economic consequences, and increased poverty (Zakaria Abouleish 2020). Companies and researchers worldwide seek solutions to combat the disease, solve the virus's hurdles, and curb its spread with this expanding dilemma. Science and technology are crucial in this perplexing conflict (Khoo and Lantos 2020). For example, there were studies done on the treatment of viruses in the air using non-thermal plasma, and they have shown promising results (El Zowalaty et al. 2020). How about aquatic environments,

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Responsible Editor: Philippe Garrigues

✉ Lotfi Khezami
lhmkhezami@imamu.edu.sa

✉ Aymen Amine Assadi
Aymen.assadi@ensc-rennes.fr

[1] Department of Chemistry, Imam Mohammad Ibn Saud Islamic University (IMSIU), P.O. Box 5701, Riyadh 11432, Saudi Arabia

[2] Energy, Water, Environment and Process Laboratory, (LR18ES35), National Engineering School of Gabes, University of Gabes, 6072 Gabes, Tunisia

[3] Laboratory of Reaction Engineering, USTHB, BP 32, 16111 Algiers, Algeria

[4] Civil Engineering Department, El-Madina Higher Institute for Engineering and Technology, Giza 12588, Egypt

[5] Univ Rennes, ENSCR, 11 Allée de Beaulieu, 35708 Rennes, France

such as water? Aquatic environments are essential for human growth and health outcomes, particularly during the COVID-19 pandemic.

Water is essential for life, but there is evidence that coronavirus can survive in it for days (Braga et al. 2020; Sivakumar 2021; Baaloudj et al. 2022); it is a typical vehicle for virus transmission (Li et al. 1998). Viruses can survive in water through mutation, recombination, and reassortment, allowing them to adapt to new environments, from air to aquatic life (Badawi et al. 2022). Human pathogenic viruses are frequently found in water settings and are thought to be responsible for a significant proportion of waterborne illnesses (La Rosa et al. 2020). Virus contamination affects almost all types of water, especially surface freshwater, including lakes and rivers, groundwater, estuary, marine waters, and even ice (Ikner et al. 2012; Pinon and Vialette 2018). Viral water contamination can occur through various causes, the majority of which are related to human activities, such as the discharge of untreated sewage, the reuse of partially treated effluent, and the use of animal waste as manure (Pinon and Vialette 2018; Islam et al. 2021). Faeces and masks of patients with virus disease are also principal routes of virus transmission into water and wastewater (Tran et al. 2021). Another source of viral water pollution is bats and birds requiring aquatic habitats for living. Bats and birds are known to be significant reservoirs for numerous viruses. It has been demonstrated that these species can shed virus RNA through faeces (Wartecki and Rzymski 2020). Viruses with a necessary aquatic transmission are mostly enteric viruses, a varied collection of non-enveloped viruses that can proliferate in the human gastrointestinal tract (La Rosa et al. 2020). Coronavirus is a respiratory virus transmitted primarily via airborne pathways; however, even the transmission of SARS-CoV-2 via water appears to be epidemiologically significant (Lahrich et al. 2021). In addition to the respiratory tract, coronavirus can infect the digestive system and then be defecated. It could occur via the faecal-oral route, and their RNA can be present in the stool, which means it can infect sewages from urinals, and toilets (Wartecki and Rzymski 2020). For instance, through toilet flushing, the coronavirus will be diluted by wastewater and enter sewer systems (Buonerba et al. 2021). In the absence of disinfection, the coronavirus can survive in wastewater for hours to days (Farkas et al. 2020). A recent study found that all coronaviruses, including the recently discovered SARS-CoV-2, have time to survive in wastewater, around 2 to 6 days (Buonerba et al. 2021). Another study has demonstrated that the survival time of coronavirus in water is seven days at 23 °C (Tran et al. 2021). To be precise, coronavirus survival in water and wastewater depends on temperature, wastewater type, suspended particles, organic matter concentrations, solution pH, and disinfectant dose (Tran et al. 2021). The coronavirus can be eliminated in wastewater by chlorine dosing (as it is sensitive to disinfectants such as chlorine); however, it is insufficient to control and eliminate the virus in wastewater (Karam et al. 2021; Lahrich et al. 2021).

This technique can only eliminate roughly 20–80% of viruses, leaving a considerable viral load in effluent discharge and spreading in the environment (Rosa et al. 2011). Improving water security is critical for preventing and combating future pandemics (Giné-Garriga et al. 2021). Therefore, the world should focus on new approaches to treat viruses in water and wastewater under different conditions (Tortajada and Biswas 2020; Tran et al. 2021). Conventional water treatment methods are composed of a series of filters, followed by a disinfection step that involves ozone and chlorine injection. Those methods, on the whole, have significant disadvantages (Badawi et al. 2021a). One of these disadvantages is the contamination with disinfection by-products with carcinogenic consequences and environmental pollution (Su et al. 2018; Badawi et al. 2021b). Chlorine, for example, interacts with organic chemicals to produce reactive chlorinated organic compounds that are toxic to people, and their treatment using UV irradiation takes a long time to be removed (El-Kalliny et al. 2021).

In contrast to those chemical approaches, non-thermal plasma (NTP), also known as cold plasma (CP), joined the decontamination processes as an innovative, effective, costless, clean, and eco-friendly alternative for inactivating viruses (Lacombe et al. 2017; Filipić et al. 2020; Ghernaout and Elboughdiri 2020). It has the potential to replace conventional water treatment procedures as a new hope in the field of viral inactivation. This prospect is because of the synergy of factors such as ultraviolet (UV), ozone, active species, and strong electric fields in the cold plasma, which have a vital role in water treatment (Yadav et al. 2019; Nguyen et al. 2020). Non-thermal-plasma, especially dielectric barrier discharge (DBD), has been extensively used for water and air treatment (Brinkmann et al. 2015; Palau et al. 2015; Assadi et al. 2016), because of its highly effective and non-selective generation of active species. This process has the ability to produce large concentrations of reactive oxygen and nitrogen species (ROS and RNS) at room temperature and without the need for costly equipment (Aman Mohammadi et al. 2021).

Plasma is the fourth fundamental state of matter, and it is an ionized state of a gas that consists of a cloud of free-flowing ions or electrically charged atoms (Filipić et al. 2019). It was given that name because the charged species that constitute plasma behave similarly to the biological components of blood that swim in blood plasma (Chen et al. 2020). The plasma that is not in thermodynamic equilibrium is known as non-thermal plasma (NTP), where the temperature of electrons is substantially higher than the temperature of massive species such as atoms and neutrons (Bourke et al.

2017). It is widely utilized because it may inactivate harmful microorganisms at room temperature without wasting energy in heating the background gas (Assadi et al. 2021). It has been proven to remediate contaminated surfaces safely and efficiently at atmospheric pressure and room temperature (Gururani et al. 2021). A variety of techniques can be used to create cold plasma, such as DBD and corona discharges (CD) (Van Nguyen et al. 2019; Domonkos et al. 2021). However, DBD devices are the most studied and industrialized non-thermal plasma generators among these approaches, as they showed their effectiveness in treating water (Berardinelli et al. 2021).

Based on various studies, the plasma equipment generally included the disinfection lei, the DBD reactor with a high voltage power supply. The DBD plasma reactor consisted of two electrodes (Costa et al. 2017; Assadi et al. 2015). To generate the DBD plasma, an internal electrode (high voltage electrode), placed in a glass tube, is immersed in the reactor at a distance of a few tens of millimetre from the surface of the infected solution to be treated. The outer electrode (ground electrode) is placed close to the reactor wall. The thickness of the dielectric medium, the reactor wall, was a few millimetre. The high electrical voltage applied is a few tens of kilovolt in different forms, such as sine waves or else in pulse form through a high voltage generator applied to the terminals of the two electrodes.

Plasma is then generated in the gas phase using both plasma electrons and excited species energies, called indirect discharges. An electric arc is formed between the two electrodes, bringing a voltage difference.

Non-thermal plasma is an effective method for water disinfection, where it can be injected into the water. Thus, NTP interacts with the water and produces ultraviolet ozone light and active species (Guo et al. 2018a). Those active species are reactive oxidative species and nitrogen species (ROS and RNS), including hydroxyl radical ($^{\cdot}OH$), oxygen ($O_2^{\cdot -}$), ozone (O_3), hydrogen peroxide (H_2O_2), and nitric oxide ($^{\cdot}NO$) (Wang et al. 2016; Li et al. 2020). These radicals play a significant role in the inactivation of viruses by oxidizing the viral capsid protein and altering the lipoproteins and DNA of the virus (Huang et al. 2018; El-Kalliny et al. 2021).

The radicals have an essential role in cold plasma water treatment. The NTP's high efficiency could also play a significant role, owing to the synergistic effect of energetic free electrons, UV light, active species, and the strong electric field (Van Nguyen et al. 2019). NTP has been reported as an approach for viral inactivation in water only in a few articles; however, it has shown great potential and has been proven to inactivate various viruses in water. For instance, NTP has successfully inactivated all SARS-CoV-2 (Chen and Wirz 2020; Ghernaout and Elboughdiri 2020; Capelli et al. 2021; Gururani et al. 2021), Rotavirus CP ((El-Kalliny et al. 2021), bacteriophages T4, 174, and MS2 (Guo et al. 2018a), Potato Virus Y (Filipić et al. 2019), and Tulane virus (Min et al. 2016).

Although NTP has exhibited efficient inactivation for numerous viruses, initiatives to enhance NTP-based technologies to combat viruses for humanity's long-term benefit should continue to be developed. Previous research has shown that when NTP is combined with other advanced oxidation processes like photocatalysis, the combined process is more efficient than the two processes working separately (Taranto et al. 2007; Berardinelli et al. 2021). NTP can also be combined with ozonation technology (Niveditha et al. 2021). Many works have investigated the combination of photocatalytic and plasma processes in air, showing a fascinating efficiency (Assadi et al. 2017, 2021; Khezami et al. 2021). Nevertheless, limited investigations have been conducted on the mechanism of virus inactivation by NTPs in water.

This review highlights the recent literature and articles that dealt with the inactivation of viruses using non-thermal plasma. Furthermore, it identifies and discusses research gaps and offers ideas for implementing such technologies and approaches. This work recapitulates data from the most current published studies in the exciting field of viral inactivation in water, highlighting applications and inactivation processes. It is divided into five sections apart from the introduction. The first section discussed viruses' water pollution and their impact on health and the environment. The following section deals with routes of virus transmission in water. The subsequent section proposed non-thermal plasma as a promising method for the inactivation of viruses in water. It also gives the effect of some essential parameters controlling the non-thermal discharge for viral inactivation, such as virus concentration, Input power, pH, reactor design, salinity, and temperature. The fourth section detailed a critical discussion of this technology with other advanced oxidation processes. Finally, the mechanism of viral inactivation by the non-thermal plasma combined in water was illustrated, accompanied by the conclusions and outlooks.

Viruses in water and health impact

Water is a primary key to the survival of human beings as they are of paramount importance in maintaining and regulating the body's functions. However, the concern of clean water consumption is critical. Due to the poor hygiene and the inadequate sewage system, waterborne pathogens act as water pollutants presenting an unending threat to human health. In this regard, the US Environmental Protection Agency (USEPA) has considered waterborne enteric viruses as a significant water pollutant (Chen et al. 2021b). Water contains a plethora of pathogens like viruses, bacteria, fungi, and protozoans. Among them, viruses are imperative intracellular pathogens available in water, and water also acts as a common vehicle in the transmission of most viruses. Generally, virus transmission occurs through several environmental routes, including air and liquid transmission. In this case, the fluid transmission of viruses is of grave concern, which passes through different water entries like oral and faecal routes of the body. In the current era, viral disease is of primary concern that poses a severe health hazard to human health, resulting in the death of millions of people worldwide. According to WHO, an average of 829,000 people die from diarrhoea that emerges from contaminated drinking water (Gibson 2014; Gall et al. 2015).

The viruses are primarily transmitted by consuming contaminated water/food and through the discharge of biological wastes of the infected hosts into several water streams. For instance, polyomaviruses are excreted through biological waste and viruses such as Influenza and coronaviruses are transmitted through water. The elimination of water viruses includes the physical removal of pathogens by conventional methods and the inactivation of viruses by ultraviolet or chemical oxidants like chlorine and chloramines (Kılıç 2020). Nonetheless, the waterborne viruses can only be 50–90% removed after wastewater treatment through chlorination, ozonation, lime coagulation, oxidation, etc. This drawback causes high amounts of the virus to be discharged, leading to water contaminants resulting from an inadequate water treatment process. Reports have shown that most viruses have a longer life span and remain stable for an extended period. For example, 90% of adenoviruses were reduced after 60 days. This result leads to water pollution with waterborne viruses and leads to profound health impacts on humans (Bofill-Mas and Rusiñol 2020).

There are more than two hundred different waterborne viruses present in contaminated water. Several waterborne viruses contain similar properties but differ based on their genome content and capsid protein. Some of the commonly encountered waterborne viruses include Enteroviruses (*Picornaviridae*), noroviruses (*Caliciviridae*), adenoviruses (*Adenoviridae*), rotaviruses (*Rotaviridae*), sapoviruses (*Caliciviridae*), astroviruses (*Astroviridae*), polyomaviruses (*Polyomaviridae*), Influenza viruses, hepatitis viruses (*Picornavirida*e), and SARS-CoV-2 (*coronaviruses*). These pathogens can be identified from the wastewater, and most viruses are involved in gastroenteritis disease (Kılıç 2020). The size of the virion varies from 20 to 125 nm in diameter, and they are icosahedral with enveloped/non-enveloped in structure. Noroviruses are one of the major causes of waterborne viral disease, leading to diarrhoea. Such active viruses in the body include vomiting, fever, and abdominal cramping. The severe illness caused by the waterborne viruses encloses cancer by polyomaviruses, brain inflammation (encephalitis), brain and spinal cord inflammation (meningitis), inflammation in the middle of the heart (myocarditis) by enteroviruses, and hepatitis by hepatitis viruses. Rotavirus is another severe acute virus that leads to gastroenteritis disease in children. Some of the short-term diseases of the waterborne virus include respiratory disease, skin disease (dermatitis), eye disease (conjunctivitis), cholera, typhoid fever, and leptospirosis (Pinon and Vialette 2018; Ibrahim et al. 2021).

The inactivation of the virus depends on the structure and the genome properties of the virus. In general, the structure of a virus contains a genome that consists of single or double-stranded RNA/ DNA, protein capsid, and an envelope. The virion capsid is a complex structure that protects the nucleic acid. A reliable agent must interfere with the capsid to destroy the virus. Hence, virus inactivation is accomplished by altering one of these components by a foreign specimen. The outer part of the virus, which consists of proteins and lipids present in the envelope, can be more easily attacked than the other parts of the virus (Prevost et al. 2015; Masciopinto et al. 2019). The main factor which affects the survival of the virus is the due rise in temperature, thereby leading to damage to nucleic acid, protein denaturation, and capsid dissociation. It is conveyed that UV light is more reactive with nucleotides and damages the viral protein. Also, pH plays a significant role in the surface charges of the virus, where at low pH, several viruses are effectively inactivated (Kotsiri et al. 2022).

Since water is one of the most versatile and possible origins of infection, virologically clear water is essential. Viruses are not the only pathogens present in water that causes disease in human. These pathogens in the water environment will continue to impact public health adversely. For this reason, ensuring safe drinking water without harmful bacteria/viruses is detrimental to avoiding potentially critical health threats. Given the rising human population needing water, water pollution increases due to the rise of untreated water. Referring to that, it is indispensable to protect the environment for sustainable living. In addition to the conscious consummation of water, simple measures could be taken to improve and monitor the water treatment without impairing our quality of life. A multi-disciplinary approach is required to treat waterborne viruses to control the public health impact of viruses.

Routes of virus transmission in water

Viruses may persist in water, which is a typical vehicle for their transmission. Viruses can contaminate almost any type of water, including surface freshwaters like lakes and rivers, groundwater, estuarine and marine waters, and even ice (Shoham et al. 2012). Contamination occurs due to various factors, most of which are related to human activity, such as the discharge of untreated sewage and the reuse of incompletely treated effluent. Many viruses from multiple families and over 100 species may be detected in contaminated water, usually by human faeces, and they are all pathogenic to humans (Zhang et al. 2020a). Waterborne enteric viruses are classified into the families: Caliciviridae (Norovirus), Picornaviridae (Enterovirus and Hepatitis A virus), and Adenoviridae (Adenovirus) (Farkas et al. 2020). They have also been detected in almost all forms of water, including wastewater, sea, freshwater, groundwater, and drinking water (Fig. 1).

Viruses in water may affect humans through the mouth, eyes, nose, ears, scratches, and breaks on the skin's surface, which is obviously a significant concern when someone swims or bathe in virus-contaminated water. Virus transmission can also ensue when contaminated water is reused for irrigation of vegetable crops, aquaculture, or food washing.

Because viral transmission from water to humans is so familiar, there are several possible virus transmission pathways. Nowadays, there is a growing awareness that human populations all over the world are being exposed to viruses via a variety of routes, including shellfish grown in contaminated ocean or estuary water, food crops grown on land irrigated with wastewater or fertilized and conditioned with sludge, recreational waters, and drinking water that has been contaminated with viruses (Pinon and Vialette 2018).

Combined sewage overflows in large cities following heavy rain periods can transfer untreated wastewater into surface water bodies. People in disadvantaged communities frequently release untreated wastewater into surface water bodies used for drinking water. Even treated wastewater effluent, which is often discharged into surface water, can contain detectable levels of human viruses (Simmons and Xagoraraki 2017).

Viruses are transmitted as smaller organisms than bacteria, unable to multiply outside the host but frequently coupled with bigger particles in the aqueous environment. However, they have a proven track record of transmission by water and other environmental pathways, and they appear to be highly effective as waterborne pathogens. Viruses transmitted by water are excreted with faeces and infect through the oral route. Each has a unique set of host cells that may infiltrate to begin an infection. Usually, the initial vulnerable host cells are found in the intestinal tract; nevertheless, some viruses that infect the mouth are transferred to other organs (e.g., the liver), producing more severe sickness than normal gastroenteritis (La Rosa et al. 2020).

Parameters controlling the viruses' inactivation using non-thermal plasma in water

The NTP technique, like many other approaches, requires improvement. As a result, understanding the parameters that influence NTP's antiviral efficacy is critical. Numerous studies have found that several parameters substantially impact the effectiveness of NTP (Bermudez-Aguirre 2019; Gururani et al. 2021). These parameters are essential in the inactivation of viruses. They can influence the inactivation impact of NTP, such as virus concentration, input power water thickness, pH and conductivity, salinity and temperature, feed gas type and composition, and reactor design. Parameters were organized based not only on their effect

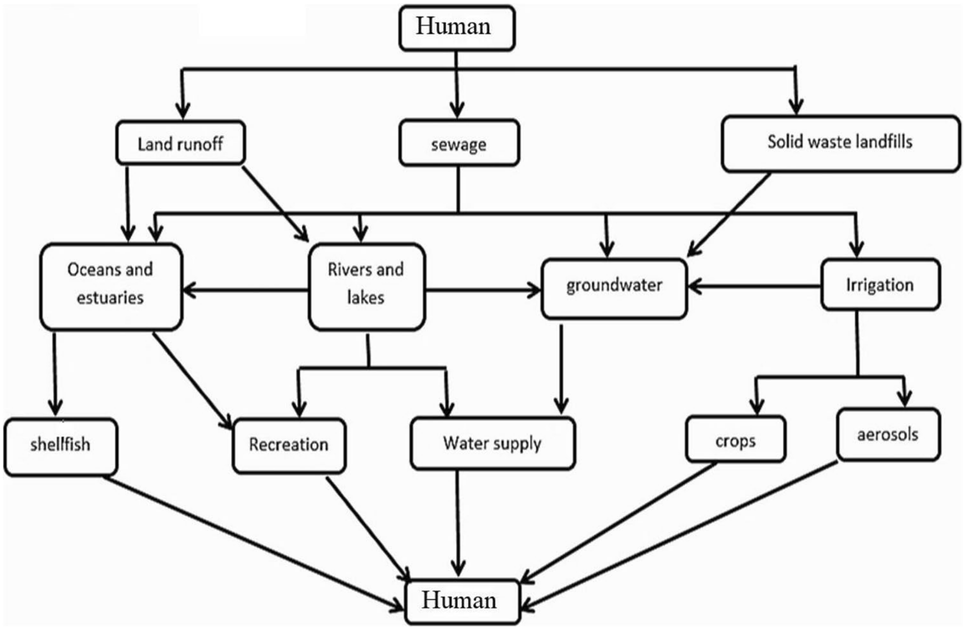


Fig. 1 Potential routes of virus transmission in water (Ramia 1985)

on plasma but also on their effect on each other. Figure 2 displays a list of factors that influence non-thermal plasma process efficiency for viruses' inactivation (Aman Mohammadi et al. 2021).

Effect of the viruses' concentration

Initial viral concentration is considered one of the most factors influencing the inactivation rate of viruses. Several researchers have reported that the viral concentration impacts the inactivation of non-thermal discharge viruses (Chen et al. 2010). High initial viral concentration could result in early virus inactivation using NTP until the generation of reactive species or viruses is a limiting step (Lee et al. 2021). Moreover, a less marked effect of viral inactivation was reached at lower virus concentrations when viruses were diluted before applying NTP treatment (Zimmermann et al. 2011; Aman Mohammadi et al. 2021). On the other hand, the inactivation efficiency of NTP can also differ depending on the viral kind and type, and that is because of viral characteristics like protein, lipid composition as well as the relative relevance of the viral matrix (Aman Mohammadi et al. 2021).

Effect of input power and water thickness

The water thickness is the distance measured from the top of the textural asperities on the pavement (in terms of mean texture depth or mean profile depth). There is an interaction effect between the water thickness and the input voltage on the NTP efficiency in virus inactivation (El-Kalliny et al. 2021). The efficiency of NTP is significantly affected by changes in water thickness. The increase in water thickness can cause an increase in the NTP efficiency, and low water thickness levels cause a low efficiency. In NTP reactors, input power has a significant impact on virus inactivation. Virus inactivation rates of NTP are related to input power, where the rate of inactivation increases following the increase in input power (Bermudez-Aguirre 2019). This behaviour is because increasing input power favours an increase in electric current in the virus area, allowing the virus to establish direct contact with plasma and be exposed

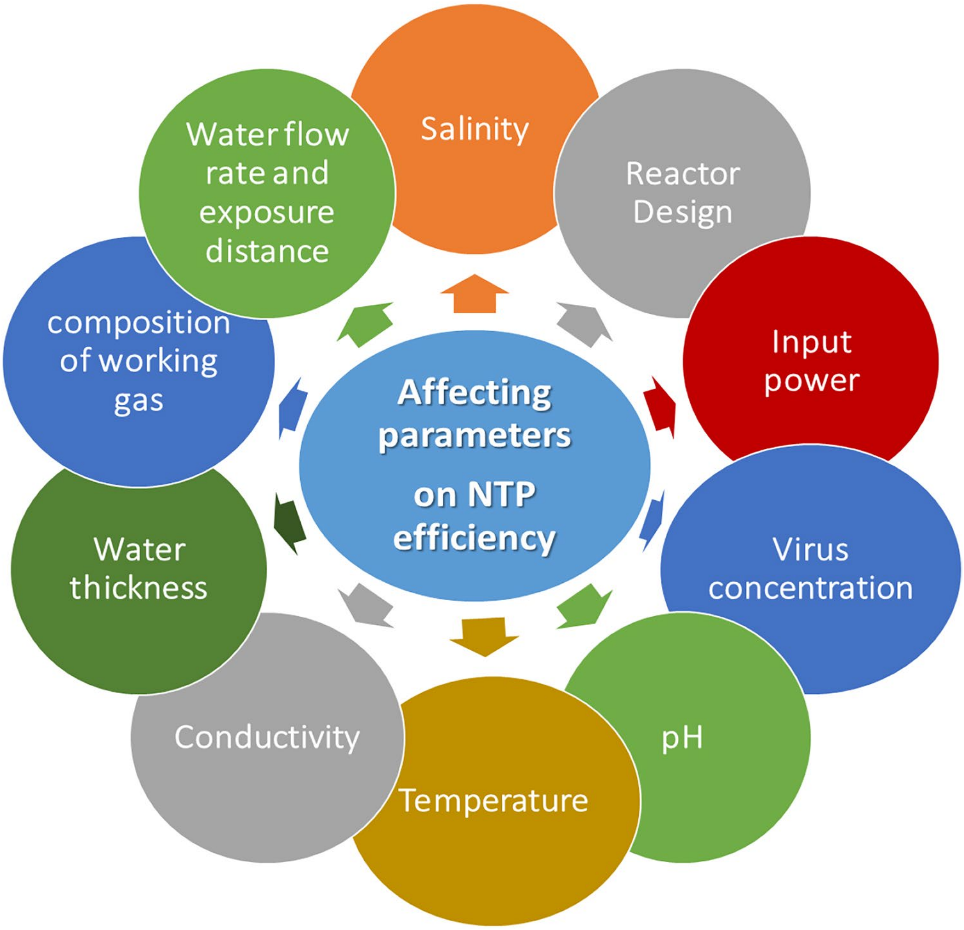


Fig. 2 Process factors influencing non-thermal plasma efficiency in water disinfection

to species produced by plasma (Van Nguyen et al. 2019; Mohamed et al. 2021).

Effects of pH and conductivity

The pH and conductivity of the reaction media are also crucial in determining the NTP potential, as they are directly related to ion production in the aqueous medium, and hence the reactor's effectiveness in producing active species in water. There is a proportional relationship between pH, conductivity, and viral inactivation efficacy. The application of NTP results in the formation of nitrite species in the water, which lowers the pH of the medium and increases the conductivity due to the interaction of the ionic species generated (Wang et al. 2016). Viral inactivation is favourable at acidic pH because virus cells are sensitive to the acidic environment, affecting intracellular contents, including enzymes and proteins (Wang et al. 2016). The Haber–Weiss reactions at acidic pH converted O_2^- into OH radicals to be transformed by protonation into hydroperoxyl (HOO) radicals (Ghernaout and Elboughdiri 2020; Purification et al. 2021). The point of zero charges (pzc) is defined as the pH at which the net charge of the total particle surface is equal to zero. Pzc of viruses is found in pH values ranging from 1.9 to 8.4. However, it appears to be scattered widely within single virus species (Michen and Graule 2010). Therefore, The pH of the solution likewise has a role in changing the surface charges of viruses (Pinon and Vialette 2018).

Effects of salinity and temperature

Temperature and salinity also have significant influences when it comes to viral inactivation. Salinity is related to temperature since salinity has a more substantial effect at lower temperatures (cold-salty) (Brown et al. 2007). The temperature has been demonstrated to considerably reduce viral persistence in water, with an impact more significant than salinity alone (Martin et al. 2018). High salinity can increase viral persistence at low temperatures (Martin et al. 2018). On the other hand, slight temperature variations have nonlinear effects on viral persistence. Viral persistence means less NTP inactivation efficiency. Several studies have shown that viruses inactivate more quickly at higher temperatures (Charles et al. 2009; De Roda Husman et al. 2009; Bertrand et al. 2012; Pinon and Vialette 2018). That is because of the effects of temperature on enzyme activation, catalytic rates, and enzyme kinetics, which significantly impact numerous physiologic processes (Brown et al. 2007).

Effects of reactor design and NTP devices

NTP reactors and devices must be designed to achieve maximum energy utilization through a given energy input. NTP reactors are typically constructed of glass or Perspex in rectangular containers or reaction column type reactors used in batch, continuous, or circulating-flow modes (Aman Mohammadi et al. 2021). The most important factors to consider for plasma devices are high electrode compatibility with the reactor and the electrical discharge zone (Wang et al. 2016). So, there is a strong link between reactor design and used plasma devices. Generally, two asymmetric conductive media with a high curvature are utilized as electrodes for plasma devices. Recently, different types of plasma and reactor designs have been investigated for water treatment, and there are 27 different types of plasma devices. Those devices are all simple, effective, and do not require chemical agents to inactivate microorganisms (Wang et al. 2016; Aman Mohammadi et al. 2021). Figure 3 illustrates the primary non-thermal plasma devices used for water disinfection (Fig. 3 A, B, C, and D), emphasizing COVID-19 virus inactivation in water (Fig. 3E). Among the plasma devices, the pulsed plasma produced in a gaseous medium has proven to be the most effective method, in which a gas-phase discharge is in contact with liquid water (Wang et al. 2008; Ajo et al. 2018). This process is preferable to breaking the discharge with electrodes immersed in water (Wang et al. 2016). High-flow reactors that expose thin layers of liquid to the plasma are the most valuable reactors utilized for water treatment applications (Purification et al. 2021). This result is because the treatable water flow rate affects the plasma-liquid interface (Purification et al. 2021).

Water flow rate and exposure distance

The interaction time is the significant parameter that controls this phenomenon. The duration of the exposure process can be affected by various operating parameters such as water flow rate, water thickness, and exposure distance. NTP viral inactivation efficiency is directly related to the time of the procedure and inversely related to the distance between the plasma source and water (Aboubakr et al. 2015). The time required for viral inactivation varies depending on the virus type and the process parameters; full virus inactivation can take a few seconds to 1 h. The NTP efficiency decreases by increasing the thickness of the water or exposure distance because of the contact interface between plasma and water (Aman Mohammadi et al. 2021). Water flow rate significantly affects the NTP viral inactivation efficiency; as the water flow rate increases, the contact time between plasma and the water surface decreases, which leads to a linear reduction in ozone and concentrations of active species in the water (Van Nguyen et al. 2019). Furthermore, increasing the water flow rate causes a thicker water layer, which decreases the interface between plasma and water, as mentioned previously (Nguyen et al. 2020).

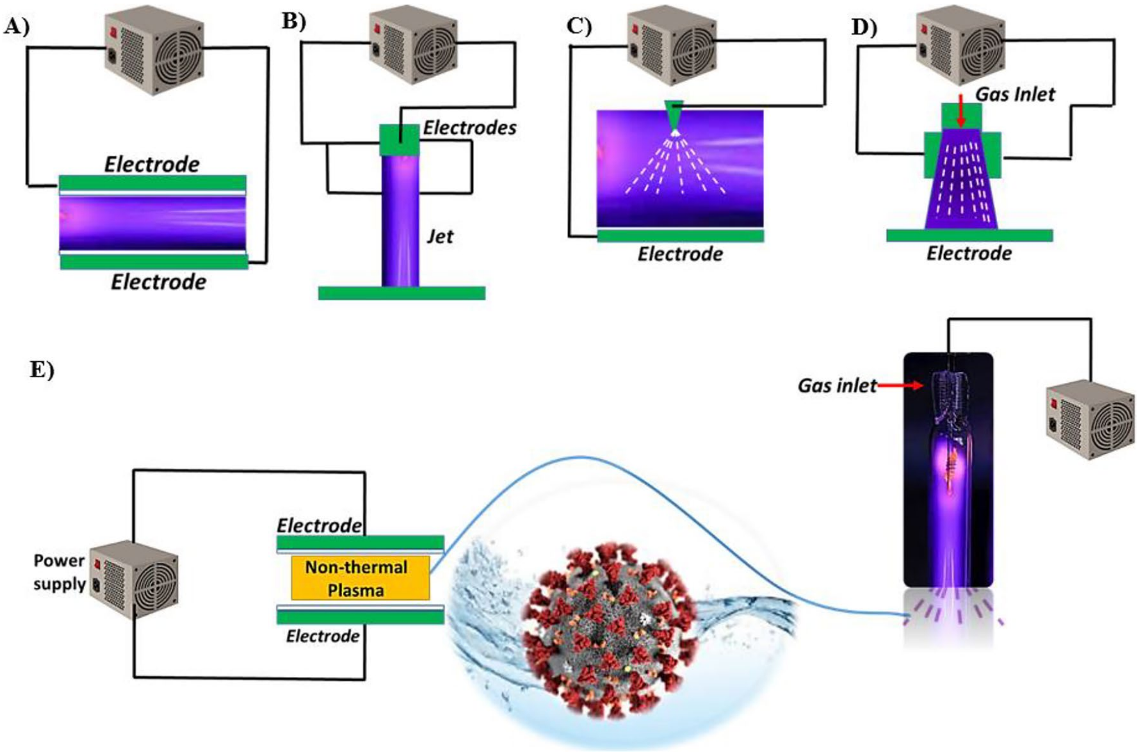


Fig. 3 Various non-thermal plasma devices: **A** dielectric barrier discharge, **B** plasma jet, **C** corona discharge, **D** gliding arc discharge, and **E** COVID-19 virus inactivation in water by non-thermal plasma

Effect of the composition of working gas

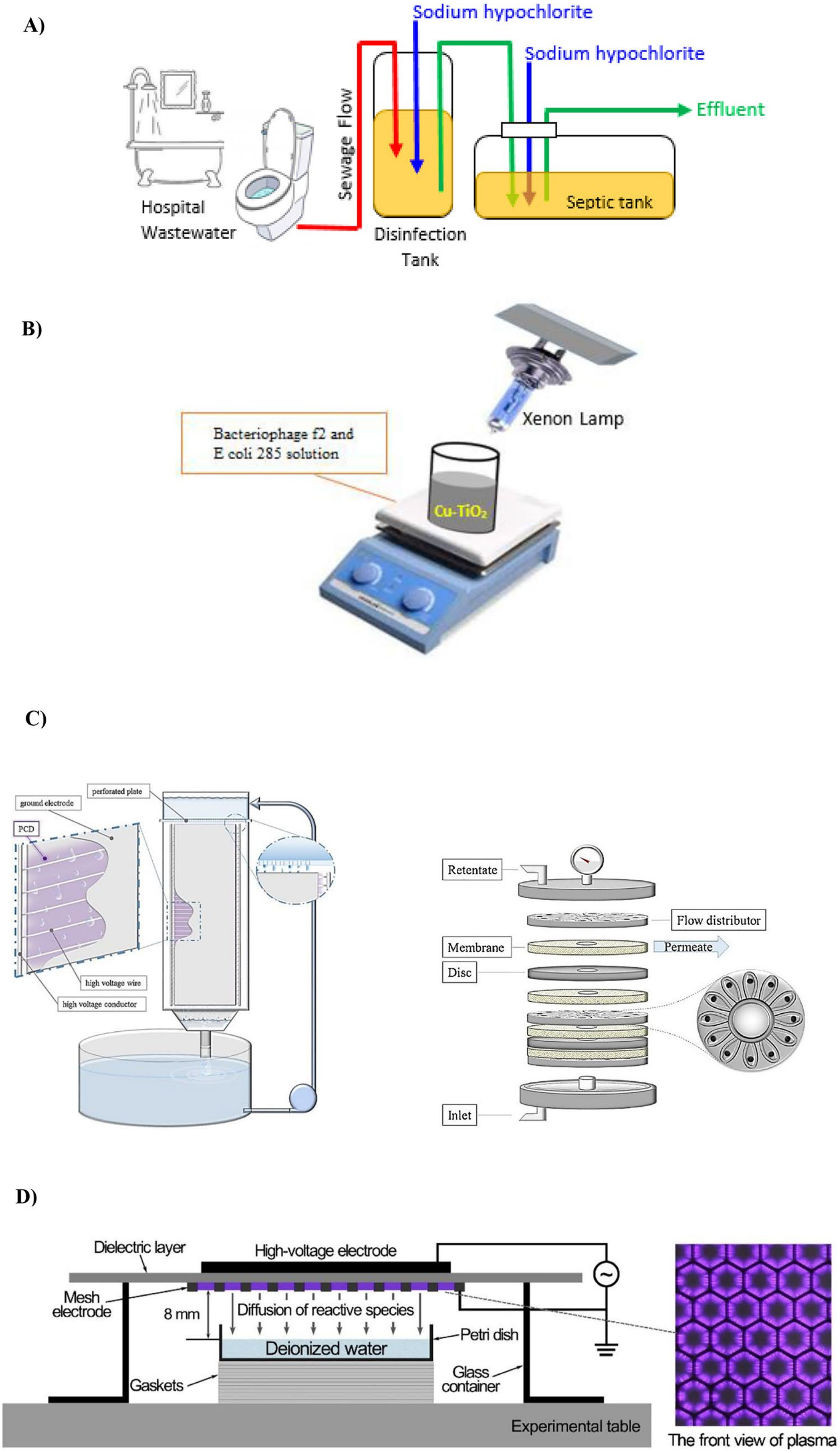
The feed gas type and composition employed in NTP discharge substantially impact process efficiency. They are primarily responsible for determining the kind and quantity of reactive species generated in the water (Bermudez-Aguirre 2019). Several scientists have looked at the influence of gas composition on viral inactivation in NTP tests. The findings support that oxygen has a substantial oxidizing effect on organisms exposed to NTP. The inactivation efficiency is greatly improved when oxygen is present in greater concentrations (Aboubakr et al. 2016). This phenomenon is because oxygen in gas composition can increase the concentration of reactive oxygen species (ROS), which are essential in the inactivation process. Atmospheric air and nitrogen also have a significant oxidizing effect on living organisms (Sakudo et al. 2017) because they can increase the concentration of reactive nitrogen species (RNS) participating in the inactivation of viruses (Sakudo et al. 2014, 2016).

Combined systems for virus disinfection

Viruses are thought to be more resistant to traditional water disinfection than bacteria, emphasizing the importance of developing new, cost-effective methods for viral inactivation in water. In general, various WWTP disinfection processes, such as ozonation, chlorination, ultraviolet light, adsorption, and membranes, are ascertained to be efficient in inactivating diverse viruses. However, more research on the effectiveness of such technologies in inactivating SARS-CoV-2 is required. A range of combined treatment systems might be utilized to lessen the dangers of hospital wastewater. Figure 3 depicts various hospital wastewater disinfection systems. Zhang et al. (2020a) investigated the incidence of SARS-CoV-2 in septic tanks of medical wastewater disposed at Wuchang Cabin Hospital-China. A stunningly elevated level of $(0.5\text{–}18.7) \times 10^3$ copies/L of SARS-CoV-2 viral RNA was found in the discharged daily wastewater. A disinfection process was applied using sodium hypochlorite to inactivate the SARS-CoV-2 virus. The wastewater was piped from the toilets and showers into disinfection tanks before being dumped into septic tanks outside the hospital and into the sewage system. The sequence of the disinfection procedure is depicted in Fig. 4A.

To ensure total deactivation of SARS-CoV-2, 800 to 6700 g/m^3 sodium hypochlorite was added for 1.5 h contact. The treated effluents showed negative results for SARS-CoV-2 viral RNA when overdosed with sodium hypochlorite. It did, however, have a high amount of disinfection by-product residuals, which posed considerable ecological problems (Zhang et al. 2020a). The disinfection efficiency

Fig. 4 Diverse treatment/disinfection systems for virus inactivation in water: **A** chemical disinfection; **B** photocatalytic disinfection; **C** plasma pilot system associated with ultrafiltration unit, adapted with permission from Ref. (Ajo et al. 2018), Copyright, Elsevier, 2018; and **D** plasma-based system, adapted with permission from Ref. (Guo et al. 2021), Copyright, Elsevier, 2021



of synthesized Cu-TiO_2 nanofibres under visible light was reported by (Zheng et al. 2018) for the inactivation of bacteriophage f2 and its host *E. coli* 285 in water (Fig. 4B). According to the results, the synthesized Cu-TiO_2 nanofibres had a superior capacity to remove bacteriophage f2 and *E. coli* 285 under visible light. The efficacy of bacteriophage f2 elimination improved as catalyst dose, light intensity, and temperature rose but declined when the initial virus concentration increased. In a virus/bacteria mixed system, bacteriophage f2 was more resistant to photocatalytic oxidation than *E. coli* 285. The removal of bacteriophage f2 was influenced by being combined with E. coil 285, while the removal of E. coil 285 remained nearly unaffected (Zheng et al. 2018).

Plasma-based systems (PBS) were efficiently reported for bacteria and virus inactivation by causing damage to biological macromolecules in water. Moreover, various researchers recommended PBS as a potent disinfection strategy to combat the epidemic caused by SARS-CoV-2 (Ekanayake et al. 2021; Guo et al. 2021). Ajo et al. (2018) evaluated a plasma pilot-scale system associated with an ultrafiltration treatment unit (Fig. 4C) for the oxidation of micro-concentrations of pharmaceuticals in wastewater collected from stationary sources. The system achieved superior removal rates reaching 100% for most pharmaceuticals like Bisoprolol, Carbamazepine, Trimethoprim, and Doxycycline. On the other side, noticeable low energy consumption was reported by using such a promising combined system. In another study, a plasma disinfection system was conducted to inactivate pseudoviruses with the SARS-CoV-2 S protein (Fig. 4D). The receptor-binding domain (RBD) was employed to investigate the molecular features, and the RBD binding activity was inhibited by plasma-activated water via RBD change. The results demonstrated the triviality of the plasma system efficiency for inhabiting pseudovirus infection via S protein inactivation (Guo et al. 2021).

Moreover, Chen et al. (2020) investigated the NTP system fed by argon gas for SARS-CoV-2 inactivation on leather, plastic, and metal surfaces. The findings show that the NTP system has great potential as a safe and effective way to inhibit virus transmission and illnesses on a broad range of surfaces with several human interactions (Chen et al. 2021a). Table 1 summarizes the advantages and limitations of using the commonly used technologies in virus inactivation. A common gap is detected for all the listed techniques, indicating that all approaches require more research for COVID-19 viral inactivation in water.

Our previous review on the inactivation of viruses in the air using combined systems with non-thermal plasma technologies has shown that it is more efficient than each technique alone (Baaloudj et al. 2022). Various approaches have been

Table 1 Advantages and limitations of the most common approaches used for virus inactivation in water

Approach	Advantages	Limitations	Ref
Chemical disinfection	– Simple operation and low energy consumption – Fast and consistent performance	– Not sufficient to control and eliminate viruses in water – Risky and hazardous for human health – Could be costly in case of use of Ozone disinfectant – Fast volatilization and requires special storage tanks	Wang et al. (2020); Zhang et al. (2020a)
Heat inactivation	– Effective approach with a high rate of inactivation	– Energy-intensive and high operating cost when more heat is required – Unsustainable technology and perilous for human health	Kampf et al. (2020)
Photocatalytic disinfection	– Reliable and efficient for viral disinfection	– High Capex for large effluent disinfection	Habibi-Yangjeh et al. (2020); Baaloudj et al. (2021)
Membranes	– Partially operational against viruses – Automatization is possible	– High probability to be clogged – Expensive consumables – Vastly turbid samples need compound filtration units	Castro-Muñoz (2020)
Adsorption	– Effective for viral inactivation in a short period of time – Ease operation	– A filtration unit is essential – pH adjustments are required – Vessels must be periodically washed	Badawi and Zaher (2021); Sellaoui et al. (2021)
Non-thermal plasma (NTP)	– Wide sterilization range – Lower toxic risk – An efficient approach for bacterial and viral inactivation	– Not available on a commercial scale – The mechanisms of viral inactivation in water are not completely understood	Khanikar; Guo et al. (2018b, 2021); Ekanayake et al. (2021)

combined with different forms of non-thermal plasma or other decontamination procedures to boost inactivation efficiency to deal with diverse pathogenic microorganisms' high levels of contamination in the air (Baaloudj et al. 2022). So, it is exciting to test combined systems in treating water from viruses. Several studies on the non-thermal plasma approach for virus and bacterial inactivation treatment in water have been published. However, there is a lack of using combined systems for water disinfection. It would be great to do more tests with non-thermal plasmas and other technologies such as photocatalysis to show how efficient this process is (Table 2) .

Mechanism of viral inactivation by the non-thermal plasma combined with catalysis

The reactive species generated inside the plasma or as a result of plasma interactions with the surrounding media are considered the most important components responsible for biological plasma effects. The plasma effluent is exposed to atmospheric air containing predominantly oxygen, nitrogen, and water. Traces of these, especially the water, are contained in the working gas in low ppm-amounts, too. These atmospheric air compounds are the precursors for secondarily generated non-radical and radical reactive oxygen and nitrogen species (ROS, RNS), and some species migrate from the gas phase to the liquid phase. Previous works (Ajo et al. 2018) have revealed that the long-lived species H_2O_2, NO_2^-, and NO_3^-, as well as the short-lived species $^{\cdot}OH$, $^1O_2$, $^{\cdot}NO$, $O_2^{\cdot -}$, NO_2, and $ONOO^-$, are present in water with concentrations of the order of 200 M. These reactive species will be widely very involved to play an essential role in plasma-induced microbial effects. There is some evidence that the ROS-RNS composition resulting from plasma generation under atmospheric air conditions is more toxic for microorganisms because both oxygen and nitrogen-containing reactive species are required for antimicrobial effects.

The acids formed in the air are an outcome of a series of reactions beginning with the plasma discharge as indicated in the following reactions (Burlica et al. 2010; Reddy and Subrahmanyam 2012):

$$N_2 + e^- \rightarrow 2N^\circ + e^- \tag{R1}$$

$$O_2 + e^- \rightarrow 2O^\circ + e^- \tag{R2}$$

$$N^\circ + O^\circ \rightarrow NO \tag{R3}$$

$$NO + O^\circ \rightarrow NO_2 \tag{R4}$$

$$NO_2 + {}^\circ OH \rightarrow HNO_3 \tag{R5}$$

$$2NO_2 + H_2O \rightarrow HNO_2 + HNO_3 \tag{R6}$$

During the plasma degradation process, H^+ ions are formed in the aqueous phase, as demonstrated by the following general reactions (Verheust et al. 2017):

$$NO^\circ{}_2 + NO^\circ{}_2 + H_2O \rightarrow NO_2^- + NO_3^- + 2H^+ \tag{R7}$$

$$NO^\circ + NO^\circ{}_2 + H_2O \rightarrow 2NO_2^- + 2H^+ \tag{R8}$$

In addition, the reaction between ozone and water generates superoxide radicals. The acid formed by the reactions between superoxide O_2 and H^+ radical was named plasma acid. These species can interact aggressively with viruses which can then inactivate them in the water.

Conclusions and outlook

In recent years, interest in applying non-thermal plasma technology for virus inactivation in water has gained more interest with the release of different variants of COVID 19. Non-thermal plasma technology is a promising approach for resolving water treatment problems. However, it requires more development and research due to the numerous challenges that remain to overcome. As a result, there is a need to analyse further and discuss the shortcomings of this particular process to commercialize its use. This review focused on the route of virus contamination in water and the critical parameter effects of non-thermal plasma deactivation. In addition, the inactivation mechanisms have been detailed based on reactive oxygen and nitrogen species. It appears that the treated water only contains viruses. It is probably loaded with micropollution. It would be wise to review the performance of plasma for virus deactivation in different water matrices and to validate the performance also in real

Table 2 Combined plasma with photocatalysis for inactivation treatment in water viruses

Virus	Reactive species responsible for the inactivation	NTP reactor configuration	Mode of inactivation	References
SARS-CoV-2	RONS	Cylindrical cold atmospheric plasma reactor (CCAPR)	DNA/RNA degradation	Chen et al. (2020)

waste loaded with organic and particular pollution. An exciting idea from this review is that combining processes based on plasma with other processes such as photocatalysis can create a hybrid process with more advantages and fewer limitations than both processes alone. However, there is a lack of studies in the literature, especially in the field of virus disinfection in water. It is highly recommended to conduct investigations in this field by using combined plasma processes for water disinfection.

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Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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