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Towards hybridizing and intensifying electrochemical disinfection techniques

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ABSTRACT

Halting the transmission of waterborne diseases relies heavily on disinfection, a crucial barrier against pathogenic microorganisms. Electrochemical disinfection (ED) has emerged as a widely studied and implemented approach for effectively neutralizing these harmful microorganisms in water and wastewater. This is primarily due to ED's simplicity, efficiency, and environmentally friendly nature. This review provides a concise overview of ED's fundamental mechanisms and systematically examines the targeted species. Furthermore, we comprehensively explore the explore the actual employment of ED in dealing with water and wastewater. Lastly, we discuss the potential for combining ED with other technologies and synergies, laying the groundwork for future engineering advancements. The literature primarily focuses on various ED methods for eliminating pathogens. Still, there is limited understanding of how process variables and reactor design impact the effectiveness of pathogen kills. The microbial killing mechanisms of ED, including the role of free radicals and the electric field (EF), are inherently harmful to microorganisms. Additionally, other mechanisms have been proposed to explain the timeframes for implementing ED in different applications. The processes involved in ED can be categorized into four pathways. The first pathway involves oxidative stress and cell death caused by the production of oxidants. The second pathway is the cell membranes' irreparable permeabilization due to the used EF. The third pathway is the electrooxidation of critical cellular components when exposed to electric current or induced EFs. Lastly, the fourth pathway is the electrosorption of negatively charged bacteria onto the anode, pursued by a direct electron transfer reaction. The coming exploration must concentrate on comprehending the impact of EF on ED and implementing safe multi-hurdle methods such as distillation, plasma discharge, nanotechnologies, and membrane processes in industrial settings. Granular activated carbon is recommended as a post-treatment method to reduce the concentrations of disinfection by-products (DBPs). Adsorptive techniques and membrane processes remain promising research areas due to their comparatively small prices and simplicity of application. Further investigations into improving electrochemical reactors and optimizing electrolysis conditions are necessary. Integrating the ED process with different treatment methods guarantees improved disinfection effectiveness, reduced power use, and minimized DBPs. This review encourages combining more than two processes simultaneously or consecutively for better efficiency.

Keywords: Disinfection by-products; Antibiotic-resistant bacteria; Electrocoagulation (EC); Electrolytic water splitting; Antibiotic-resistant genes; Reactive oxygen species.

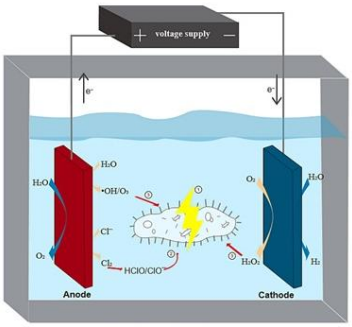
Highlights

- Discussing the routes behind electrochemical disinfection (ED).
- Reviewing pathogens encountered in water.
- Analyzing the valuable implementations of integrating ED with additional methods.
- Do not settle for only two integrated processes for ED.
- Adopting intensified processes (solar disinfection through distillation, plasma discharge, ultrasound, membrane processes, etc.).

Abbreviation

AOP	Advanced oxidation process
ARB	Antibiotic-resistant bacteria
ARGs	Antibiotic-resistant genes
BP	Bias potential
BDD	Boron-doped diamond
BES	Bioelectrochemical system
CB	Conduction band
CC	Chemical coagulation
CD	Current density
DBPs	Disinfection by-products
DNA	Deoxyribonucleic acid
DEO	Direct electrooxidation
DO	Direct oxidation
EC	Electrocoagulation
EO	Electrooxidation
ED	Electrochemical disinfection
EF	Electric field
EFT	Electric field treatment
EMs	Electrified membranes
EMR	Electrode material
EP	Electroporation
ES	Electrocatalytic sterilization
EWS	Electrolytic water splitting
FES	Flow-through electrode system
GAC	Granular activated carbon
GNB	Gram-negative bacteria
GPB	Gram-positive bacteria
HGT	Horizontal gene transfer
HRT	Hydraulic retention time
IEO	Indirect electrooxidation (IEO)
IEP	Isoelectric point
IO	Indirect oxidation
LEEFT	Locally enhanced electric field treatment
MF	Membrane fouling
NOM	Natural organic matter
NW	Nanowire
PC	Photocatalysis
PEC	Photoelectrocatalytic
PEF	Pulsed electric field
RCSs	Reactive chlorine species
RNA	Ribonucleic acid
ROSs	Reactive oxygen species
UC	Ultrasonic cavitation
US	Ultrasound
UV	Ultraviolet
VB	Valence band
WC	Water column
WTP	Wastewater treatment plant

Graphical abstract



Electrochemical disinfection (ED) routes (① Electric field (EF) self-action; ② Chlorination; ③ Oxidation)

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1. Introduction

Ingesting polluted water can lead to waterborne diseases provoked by various infectious agents such as bacteria, viruses, protozoa, and helminths [1]. The burden on public health and socio-economic progress posed by the global challenge is significant. If current trends persist, billions of individuals across the globe will continue to be deprived of safe and properly maintained household potable water, purification, and cleanliness facilities by 2030 [2]. Water treatment practitioners continuously search for more effective processes for killing pathogens to pursue a more secure water reservoir and purification. Their ultimate goal is to protect persons from harmful bacteria during the time that minimizing the ecological impact [2].

The perfect killing pathogens technology encompasses several key factors: high efficiency, minimal energy consumption, affordability, wide-ranging cleaning, and the loss of disinfection by-products (DBPs) [2]. Chlorination is the primary procedure used for disinfecting drinking water. Nevertheless, its progress has been hindered by the appearance of chlorine-resistant microorganisms and DBP production [3]. With its higher redox potential (2.07 V) than chlorine oxidizers, ozone can successfully eliminate organic matter and pathogens from water. However, ozone utilization encounters its defiance, including its temporary effectiveness, security worries throughout carriage, increased functional costs, and the DBPs creation [4]. Peroxide hydrogen (H_2O_2) killing agents offer the merit of producing more hygienic secondary products. However, their generation heavily depends on the energy-intensive anthraquinone method, which is not secure and poses hazards during carriage and storage [5]. Ultraviolet (UV) irradiation is highly regarded as a disinfection method thanks to its potential to effectively eradicate several types of germs without chemical additives, thereby avoiding the production of DBPs. However, UV disinfection has certain limitations, such as a restricted capacity to kill germs, an inability to provide long-lasting killing pathogens impacts, and the potential for photoreactivation and dark repair processes that can revive deactivated cells, thereby increasing the risk of waterborne transmission [6, 7].

To address the issues above, electrochemical techniques have lately received significant interest as a robust and adaptable option for water sterilization. Electrochemical disinfection (ED) is essentially composed of two main processes: the direct oxidation (DO) of electrodes that results in the temporary inactivation of microbial cells and the generation of reactive oxygen species (ROSs) that are electrocatalyzed (e.g., H_2O_2, O_3, or $^{\bullet}OH$) or reactive chlorine species (RCSs) (e.g., Cl_2, HClO, ClO^-, etc.) to help with neutralizing pathogens [8]. ED is distinguished by its ecological sustainability, employment of solar-powered energy, functioning clarity, and high automation capacity [2]. As a result, this method inactivates various harmful microorganisms, including viruses and bacteria [9].

As a result, various reviews have been produced, examining this research field in depth [2]. Researchers [10] discussed the principles and utilizations of electrocoagulation (EC), direct electrooxidation (DEO), and indirect electrooxidation (IEO) in removing microbes from various water and wastewater sources. Conversely, scientists [11] discussed the effects of the treatment environment, choice of oxidants, and functioning exercises on the needs of ED devices in terms of dose generation and energy consumption, and they provided specific analyses of the connection between these two quantities. Researcher [12] discussed the typical production of disinfectants via electrochemistry, considered the risk of by-products to enhance the design of cells and methods for disinfection, and discussed the hybrid technology and future ED trends. Scientists [13] categorized electrochemical decontamination techniques into high-voltage pulsed electric field (PEF) sterilization and electrocatalytic sterilization (ES), suggesting pathways for PEF and ES and summarizing the distinguishing electrode types used in high-pressure PEF sterilization and ES.

This article discusses the subject of ED in detail, focusing on practical uses and a systematic approach. The first part explores the mechanisms of ED, starting from DO and indirect oxidation (IO) to electric field (EF) self-acting, which is discussed in more detail further. Based on that, we investigate the potential of integrating treatment processes and ED technologies by employing novel techniques like electroporation (EP), EC, adsorption, ultrasound (US), photocatalysis (PC), and electrified membranes (EMs). Lastly, we also suggest contributing to more studies on this issue, theoretically and practically, to promote its further usage.

2. Electrochemical disinfection (ED) routes

The ED process involves using an electrochemical device powered by an external source to inactivate microorganisms in water, resulting in water purification [2]. ED is primarily characterized by DO, IO, and the influence of self-generated EFs (Table 1, Fig. 1) [14].

Table 1

Main suggested actions elucidating the lethal nature of electrochemical disinfection (ED) [15].

Oxidants	**Electric Field (EF)**
The occurrence of oxidative stress can lead to cellular damage and eventual cell death.	1) The cell membranes undergo a permanent loss of permeability. 2) The essential components within the cells undergo oxidation through electrochemical processes. 3) Bacteria with a negative charge (such as *Escherichia coli* cells) bond to the anode surface and directly move electrons through electrosorption.

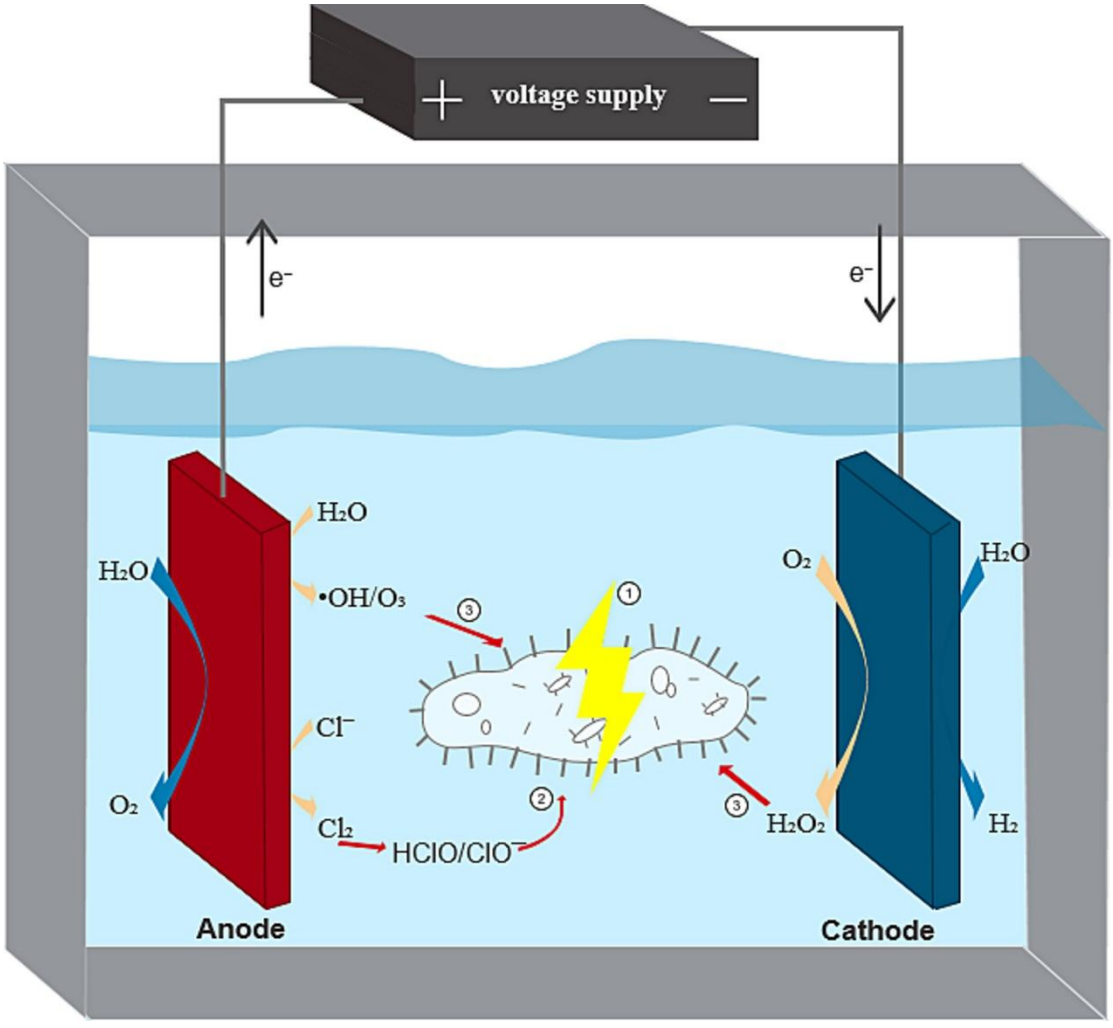

Fig. 1. Electrochemical disinfection (ED) routes (① Electric field (EF) self-action; ② Chlorination; ③ Oxidation) [2].

2.1. Direct oxidation (DO)

The bacterial electrostrictive mechanism relies heavily on oxidation, which can occur through two main modes: DO and IO [16]. In the case of DO, bacteria directly interact with the surface of the anode, leading to a multi-electron response within the proteins or functional groups of the cell membrane [2]. This response creates sites for free radicals and limited electrolytic oxidation on the membrane, disturbing particular regions [17]. Research has shown that lower voltages result in mild cellular depression and dehydration, preserving the overall structure of the cell. However, higher voltages exacerbate lipid peroxidation, triggering a chain reaction of free radicals that ultimately compromise cellular integrity and lead to cell death [18, 19].

2.2. Indirect oxidation (IO)

Similarly, IO is the destruction of pathogens by interacting the anode with mediators present in the solution and forming intermediates based on highly oxidizing substances [2]. The nature of the mediating substances in the solution determines what oxidizing agents are electrochemically generated, including ROSs and RCSs, which are extensively used in this field.

2.2.1. Active chlorine

The standard oxidation potential for Cl_2 is -1.40 V relative to SHE, while those for $SO_4^{\bullet-}$ and $^{\bullet}OH$ are -2.44 and -2.73 V *vs.* SHE, respectively [2]. In this sense, using a disinfectant system based on chlorine leads to a lower operating voltage and correspondingly less energy consumption by about 50% compared to a setup based on $SO_4^{\bullet-}$ and $^{\bullet}OH$ [11].

In solutions that contain chlorine salts such as NaCl or KCl, oxidizing Cl^- at the anode causes the formation of Cl_2 (Eq. (1)), which spreads out and endures rapid hydrolysis, resulting in the production of HClO and Cl^- (Eq. (2)). Some HClO transforms into ClO-, thereby setting up an acid-base equilibrium with ClO^- via Eq. (3) (pKa = 7.55) [20]. In practical manufacturing wastewater situations, the Cl^- occurrence is regular, indicating that chloride ions' IO in the ED system has a relevant role to play in these wastewater treatments [2]:

$$2Cl^- \rightarrow Cl_2 + 2e^- \quad (1)$$

$$Cl_2 + H_2O \rightarrow HClO + Cl^- + H^+ \quad (2)$$

$$HClO \rightarrow H^+ + ClO^- \quad (3)$$

The potential of chlorine is a function of pH, and the standard reduction potential of HClO ($E°$ = 1.49 V/SHE) is much higher than that of ClO^- ($E°$ = 0.89 V/SHE), showing that the electrically produced chlorine's oxidizing capacity depends on pH [21]. Under acidic conditions, HClO dominates, being highly oxidizing, hence accelerating bactericidal action by Cl^- mediated ED [22, 23]. This ability is attributed to its smaller size and electrical neutrality, making it easier to penetrate cellular membranes [24]. It disrupts the cell membrane, leading to cytoplasmic leakage, causing protein denaturation, deoxyribonucleic acid (DNA) damage, and lipid peroxidation, as well as the initiation of cell death via apoptosis and necrosis [2].

Nevertheless, operation of long duration is bound to result in DBPs, which are inorganic chlorine by-products ClO_2^-, ClO_3^-, and ClO_4^- when the chlorine ion concentration is high and organic matter is not present. Free chlorine will also react with organic substances in their existence, forming organochlorine secondary products such as trihalomethanes, haloacetic acids, haloacetonitriles, and more [2]. However, DBPs can have reproductive toxicity or even carcinogenicity and make the reliable use of electrochemical water treatment impossible. Adjusting chlorine levels, electrode types, and electrochemical parameters to control more significant bacterial elimination and lower damaging DBPs is a complex problem in electrochemical chlorination disinfection technology [25]:

$$OCl^- \rightarrow OCl^{\bullet} + e^- \quad (4)$$

$$OCl^{\bullet} + OH^{\bullet} \rightarrow ClO_2^- + H^+ \quad (5)$$

$$ClO_2^- \rightarrow ClO_2^{\bullet} + e^- \quad (6)$$

$$ClO_2^- + OH^{\bullet} \rightarrow ClO_3^- + H^+ \quad (7)$$

$$ClO_3^- \rightarrow ClO_3^{\bullet} + e^- \quad (8)$$

$$ClO_3^- + OH^{\bullet} \rightarrow ClO_4^- + H^+ \quad (9)$$

2.2.2. Active oxygen

Recognizing the dangers associated with DBPs from chlorine and discovering that microbial demobilization in ED can be achieved through various oxidizing agents has attracted increasing attention to utilizing ROSs (•OH) as a possible killing agent [2, 26]. With an impressive redox potential ($E°$ = 2.80 V), •OH plays a crucial role in oxidizing ROSs, as shown in Eqs. (10)-(14) [27, 28]. Also, •OH exhibits several times greater disinfection efficiency than chlorine, even in small quantities [2]. Microorganism inactivation is observed at varying concentrations. The primary target of •OH is the cell surface, initiating oxidative responses with structural constituents on the cell membrane.

Consequently, the cell wall construction is disrupted, and the microbial cytoplasm (comprising peptidoglycan, lipopolysaccharide, and phospholipid bilayer) is attacked, leading to a compromise in the structural integrity of the cell membrane and causing the liberation of cellular constituents for sterilization purposes [29, 30]:

$$M + H_2O \rightarrow M(HO^{\bullet}) + H^+ + e^- \quad (10)$$

$$HO^{\bullet} \rightarrow O^{\bullet} + H^+ + e^- \quad (11)$$

$$2O^{\bullet} \rightarrow O_2 \quad (12)$$

$$2HO^{\bullet} \rightarrow H_2O_2 \quad (13)$$

$$O^{\bullet} + O_2 \rightarrow O_3 \quad (14)$$

ROSs and RCSs are produced simultaneously in the solution using a chlorine-based electrolyte for ED, leading to synergistic and competitive interactions between these substances. As powerful oxidizing agents, both ROSs and RCSs can eliminate microorganisms. Additionally, they may also participate in other processes. Various factors, including electrolysis circumstances and water quality, can affect the production of ROSs and RCSs during electrochemical processes. The quantities of these species generated can vary depending on the specific exploratory factors, electrode types, water quality parameters, and treatment goals. If conditions are not conducive to the production of one species, the other may become more dominant. Investigators [31] have shown that ED exhibits a more substantial disinfection effect than electrochemical chlorination in saline or non-chlorinated water. Recently, there has been an increasing focus on the expansion of electrochemical systems that rely on the generation of ROSs [32]. Investigators [9] utilized Sb-doped $Sn_{80\%}$-$W_{20\%}$-oxide anodes in a 0.1 M NaCl solution, applying a current density (CD) of 60 A/m^2 for 60 s. Scientists [29] revealed that the principal factor in charge of the deactivation of *E. coli* in chlorine-free ED was the •OH species. This deactivation action was particularly enhanced at further down temperatures due to the augmented formation of ozone. This procedure wholly deactivated *E. coli*, with RCSs and ROSs (such as •OH) identified as the underlying agents carrying out the bacterial demobilization process. Likewise, scientists [33] successfully achieved a chlorine-free, thorough inactivation of *E. coli* (5 log) using graphene sponge electrodes. This remarkable feat was accomplished at a CD of 115 A/m^2 and a contact period of 3.5 min. The process resulted in ozone and hydroxyl radical production in a weak-conductivity solution. Notably, this investigation demonstrated further down power expending than previously reported ED setups, comprising those relying on chlorine generation.

2.3. Electric field (EF)

The potential, shape, and behavior of bacterial cell membranes can be influenced by EFs, resulting in structural damage and the deactivation of bacteria (**Fig. 2**) [34]. The demise of microorganisms caused by EFs depends on the membrane's impairment and the induction of oxidative stress through direct exposure to the EF [35]. When EFs are applied, they provoke chemical changes in bacteria lipids and the role of membrane proteins, augmenting membrane permeability and interaction with oxidative activators, ultimately causing microbial deactivation. The time and intensity of the EF pulse contribute to the enlargement of the pores in the cell membrane [2]. Pores with smaller diameters can reseal after the EF is discontinued, resulting in minimal impact on the viability of microorganisms. This phenomenon is known as reversible EP [36]. However, if the electric field treatment (EFT) is sufficient, irreparable pores can be generated, resulting in the depletion of bacterial vitality until the pores are closed. The production of substances that can cause cell death has been documented [37]. Researchers have determined that a critical EF strength of 3 to 6 kV/cm is necessary to induce bacterial EP.

In contrast, irreversible EP typically requires an EF strength more significant than 10 kV/cm [38, 39]. Additionally, if microbes are exposed to an outer EF, the balance of oxidation inside and outside the microbe membrane is disturbed, leading to an oxidative stress response and high levels of intracellular ROS. While moderate levels of ROS help maintain cellular redox balance and regulate normal cellular activities, an immoderate stream of ROS resulting from oxidative stress can damage biomolecules and disrupt redox signaling [2]. This oxidative damage affects constituents and ultimately leads to cell death.

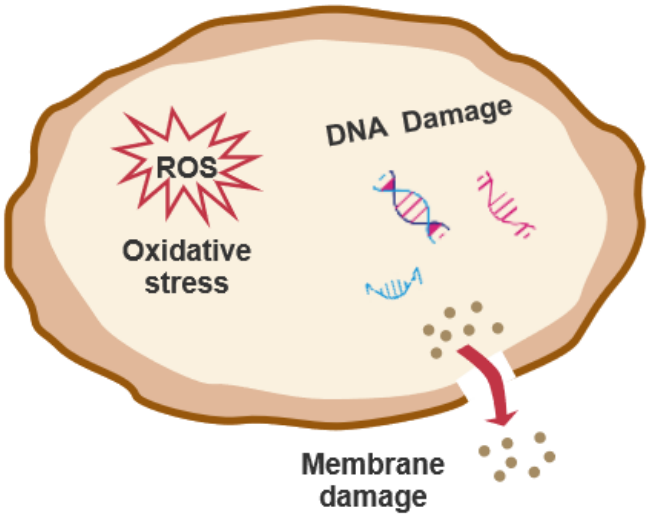

Fig. 2. Bacterial eradication by applying an electric field (EF) during disinfection [2]. (ROS: reactive oxygen species).

When an EF is applied, the rate at which *E. coli* is eliminated increases as the initial concentration of bacterial cells decreases. Microbes can be eradicated more rapidly if their density is small rather than elevated. This phenomenon can be attributed to the reality that the bug *E. coli* is more resistant to the EF when it exists in high-density populations than in low-density populations. As a result, ED has a targeted lethal impact on individual microorganisms rather than a collective one [40].

EF is poisonous to microbial cells by nature. Also, it functions as a destabilization agent and assists in separating pollutants from water. Future investigations must be more devoted to the impact of EF on EC-killing pathogens, as it is central to the mechanisms involved [41, 42].

3. Target pathogens

3.1. Bacteria

3.1.1. Gram-negative bacteria (GNB) and Gram-positive bacteria (GPB)

The primary classification system for bacteria, Gram staining, categorizes them into Gram-positive bacteria (GPB) and Gram-negative bacteria (GNB) groups [2]. This division is essential for identifying bacteria and is closely linked to their physiological, metabolic, and biochemical traits. Extensive research in the scientific literature highlights the significant differences in disinfection effectiveness among these groups.

When disinfectants are applied, there is a notable contrast in the response of GPB and GNB [43]. GPB, in particular, display a higher resistance level, making them less susceptible to disinfection [44, 45]. Such differences in susceptibility could be related to variations in the structure of their cell walls [46]. GNB possess an external membrane that contains membrane proteins, lipoproteins, and lipopolysaccharides. Their cell walls comprise a thin peptidoglycan layer, constituting less than 10% of the total cell wall composition.

Moreover, GPB have a thicker peptidoglycan layer, accounting for 30% to 70% of their cell wall structure [47, 48]. Peptidoglycan is a multiplex network of disaccharides connected by tiny peptides consisting of four to five amino acids. Its chemical composition and elasticity make it less vulnerable to the effects of oxidizing agents [2].

As a result, GPB generally depict more outstanding durability to ED [49]. Ni et al. [46] investigated the performance of a flow-through electrode system (FES) based on carbon fiber in disinfecting GNB (*E. coli* and fecal coliform) and GPB (*Enterococcus faecalis* and *Bacillus subtilis*) in typical salty. They explored a wide range of applied voltages (1 - 5 V) and hydraulic retention times (HRTs) (1 - 10 s). The findings revealed that the FES system was particularly effective against GNB due to their thinner cell walls. At an applied voltage of 2 V and an HRT of 2 s, an impressive 6.5 log reduction was achieved, resulting in the complete eradication of live bacteria. However, higher voltages (3 V, 2 s) or longer HRTs (2 V, 5 s) were needed for GPB to neutralize them effectively.

3.1.2. Resistant bacteria

The global antibiotic resistance crisis poses significant health risks and environmental integrity risks [50]. This issue has been exacerbated by the general misuse of antibiotics in healthcare, beast cultivation, and various industries [51]. Additionally, the persistent admission of antibiotic-resistant bacteria (ARB) and antibiotic-resistant genes (ARGs) into water media has further contributed to such problem [52]. It has been observed that bacteria carrying ARGs exhibit more excellent resistance to disinfection methods than bacteria susceptible to antibiotics [2]. In a study by researchers [53], the demobilization of tetracycline-resistant *E. coli* and antibiotic-sensitive *E. coli* by chlorination was compared. The findings revealed that the tetracycline-resistant *E. coli* showed a significantly lower rate of inactivation when exposed to elevated dosages of chlorination, in contrast to the antibiotic-susceptible *E. coli*. This resistance to chlorination in tetracycline-resistant *E. coli* may be related to hydrophobic tet(A) efflux proteins [53, 54]. The increased hydrophobicity of the bacterial cellular surface likely hinders its interplay with oxidizing agents, reducing the probability of demobilization.

It is worth mentioning that specific strains of bacteria resistant to antibiotics have developed efflux pumps, which are specialized mechanisms that aid in removing antibiotics [55]. Efflux pumps enhanced bacteria's ability to withstand multiple antibiotics, granting them multidrug resistance. Extensive research has revealed that these pumps serve various functions beyond removing antibiotics from the cell [2]. For example, studies have indicated that tetracycline efflux proteins share similarities with transporter proteins associated with multidrug resistance, suggesting their potential involvement in expelling chloride ions from cellular compartments [53].

The transmission of ARGs poses a more significant concern than nonresistant genes regarding ARB. These genes' ability to spread durability through bacteria of identical types and divergent genera relies on pathways like horizontal gene transfer (HGT). Such transfer is more effortless through essential mechanisms like transformation and conjugation transfer [56]. As shown in **Fig. 3(a)**, purification methods can liberate intracellular ARGs into nature, generating ecological DNA. Other bacteria can then uptake this environmental DNA through transformation, leading to the dissemination of ARGs [57]. Therefore, effectively removing released ARGs from water is crucial for disinfecting ARB and has significant implications for waterborne risks.

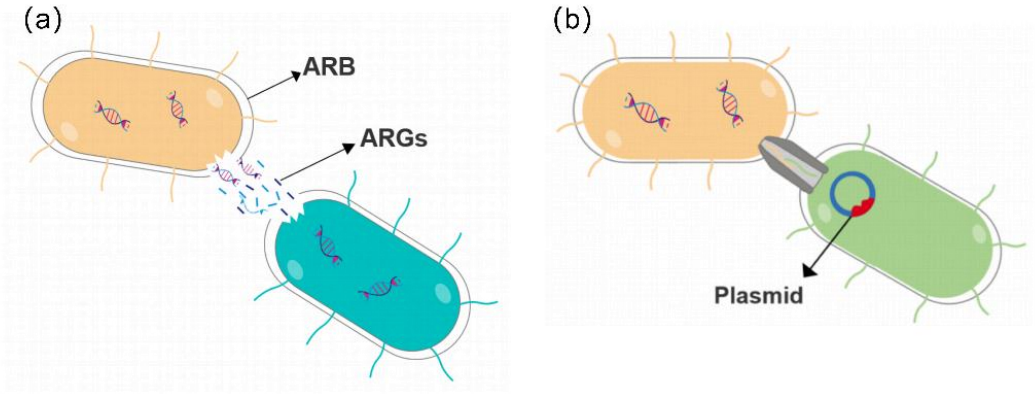

Fig. 3. Horizontal gene transfer (HGT) in resistant bacteria. (a) transformation; (b) conjugation [2]. (ARB: antibiotic-resistant bacteria; ARGs: antibiotic-resistant genes).

The reduction of ARB and ARGS levels is effectively achieved through the traditional sterilization methods of chlorination and ozonation.

However, these techniques liberate and concentrate ARGs in solution, thereby increasing the danger of antibiotic resistance transmission [2]. Fortunately, there is a promising alternative in the form of ED, which has appeared as a viable procedure for eliminating ARB and ARGs from used water [58, 59]. In a study conducted by scientists [60], twenty-three classes of ARGs that were immune to eight different antibiotics were examined in the secondary effluent of a wastewater treatment plant (WTP). The results proved that ED effectively weakened bacteria antibiotic resistance and significantly decreased ARGs' relative abundance.

In addition, the transfer of genes between bacteria, known as the conjugation effect, increases the chances of transmitting antibiotic resistance (**Fig. 3(b)**). Researchers [61] conducted a study using six *E. coli* strains resistant to antibiotics, which carried three ARGs (NDM-1, mcr-1, and tetX), to assess the ED effectiveness in eliminating these genes. The results showed that nearly all ARGs could be destroyed after 120 minutes of handling at 3 V, and the electrochemical application considerably reduced the occurrence of microbial conjugation, reducing the danger of transmission. ED has

excellent potential for removing ARBs and ARGs from used water, providing an encouraging approach to control the spread of antibiotic resistance [2].

EC technology, specifically bioelectrochemical system (BES), has proven to be highly efficient and energy-saving in reducing various antibiotics in wastewater. BES offers the advantage of minimizing the spread of ARGs by producing less sludge than traditional WTPs. However, it is crucial to consider that the electrical stimulation involved in BES may impact the permeability and potential of bacterial membranes, potentially leading to increased ARB and ARGs within the BES. We explored the application of EC method, particularly BES, for eliminating antibiotic and investigated the behavior of ARB and ARGs within these devices [51]. BES has shown promising results in the effective removal of antibiotics.

Low electric current facilitates the vertical and horizontal transfer of ARGs in BES. In contrast, a higher electric current can inhibit ARB and ARGs. This raises inquiries about the contribution of BES in removing antibiotics and the subsequent destiny of ARGs and ARB in used water. To understand the benefits of BES, it is imperative to conduct additional research and uncover the primary mechanism behind ARGs' transfer [51].

3.2. Viruses

The focus of research and practical applications in ED has predominantly revolved around eliminating and eradicating microbes. Such predilection stems from the common comprehension that microbes are the first culprits of bacterial pollution in dealing with water [2]. At the same time, viruses tend to exist in lower concentrations in these environments. Additionally, electrochemical processes are more effective in deactivating bacteria than viruses. However, the increasing danger of virus diffusion in water treatment has led to increased examinations supporting ED's efficacy in neutralizing viruses [62].

When comparing viruses to bacteria, it becomes evident that viruses possess distinct characteristics that set them apart. These characteristics include nucleic acids, which house genetic information, and capsids, which serve as protective shields for the nucleic acids. Disinfection methods aim to render viruses inactive by damaging their proteins or impairing their genetic material [2, 63]. Notably, researchers [64] conducted a study demonstrating the rapid demobilization of the SARS-CoV-2 virus by ED at 5 V. In just 95 s, the sterilization performance attained 30%, and during 99 min, it escalated to 99.5%, confirming the effectiveness of ED in deactivating the virus.

In just 5 min, exposure to various disinfectants such as sodium hypochlorite (1%), ethanol (70%), iodine (7.5%), soap solution, and additional frequent killing agents led to a significant reduction of SARS-CoV-2 titer by 7-8 logs [65]. The efficacy of thermal treatment in deactivating SARS-CoV-2 was also demonstrated, with either 30 min at 56˚C or 5 min at 70˚C enough to eliminate infectivity. Additionally, sunlight and UV radiation proved effective in quickly demobilizing SARS-CoV-2. Using UV-C at 254 nm and an intensity of 2.2 mW/cm^2, a 3-log reduction in SARS-CoV-2 titer was achieved in less than 3 s [65].

Additionally, scientists [66] compared the ED of *E. coli* and model viruses MS2 and PRD1. Their findings revealed that exposing bacteria to a small current (5 mA) for a prolonged time resulted in an inactivation rate 2.1 to 4.3 times higher than that of the phages, highlighting the greater resilience of viruses compared to bacteria. In a recent study [67], a laser-induced graphene electrode infused with titanium suboxide at 2.5 V successfully eradicated MS2 with a 6-log reduction. When operated at 10 V, the same electrode eliminated T4 and Phi6. The proposed mechanism behind virus inactivation involves the combination of nanofiber-enhanced EF-induced EP and generating reactive substances through electrochemical means. Another group of researchers [68] examined the morphological and constructional changes of MS2 throughout ED. They revealed that the transit of MS2 across the SnO2-Sb reactive membrane electrode caused significant harm to the capsid and inner compositions, including proteins and ribonucleic acid (RNA). Such enduring damage inflicted upon the virus confirms that ED leads to viral demobilization by impairing viral proteins and the genome.

Heffron et al.'s [69] research focused on reducing viruses. To enhance the effectiveness of electrooxidation (EO) treatment using boron-doped diamond (BDD) electrodes, Heffron et al. [69] implemented EC as a pretreatment. They conducted experiments using bench-scale and batch devices to evaluate the depletion of viruses in varying water conditions through EO and a sequential EC-EO process. Natural organic matter (NOM) and turbidity hindered the EO of bacteriophages MS2 and FX174, indicating the need for pretreatment. However, the EC-EO process was solely effective in typical surface waters. In typical groundwater, the sole EC treatment was as effective as, if not superior, the combined EC-EO treatment. In all cases, reducing human echovirus was significantly further down than one or both bacteriophages. Although bacteriophage FX174 was a more accurate substitute than MS2 in terms of NOM and turbidity, the EC-EO device was less successful in treating typical surface waters than conventional methods using $FeCl_3$ and Cl_2. However, the EC-EO system showed improved performance in treating typical groundwater. The consecutive application of EC-EO proved beneficial for various purposes despite the possibility that functional considerations currently outweigh the benefits [69].

In our previous publication [15], we explored the current research on virus mitigation through coagulation in its various forms: chemical coagulation (CC), enhanced coagulation, and EC. We delved into the latest findings on virus immobilization. The intricate nature of viruses as biological particles and the process of virus immobilization must be considered, although the function of permeability in virus adsorption and aggregation requires further clarification. Empirical electrophoretic mobility has been used to assess virion permeability, as no practical measures are available. However, a definitive connection between permeability, virion composition, and morphology has not yet been established. The straight impact of internal virion constructions on surface charge or adsorption has yet to be decisively proven. CC systems employing zero-valent or ferrous iron may be susceptible to iron oxidation, which could be addressed by employing EC and EO techniques. Developing oxidants in the Fe oxidation process has shown encouraging results in immobilizing bacteriophage MS2. However, further investigations employing an elution procedure are necessary to confirm that bacteriophage elimination results from immobilization rather than adsorption.

In this context, understanding and predicting the end of a virus relies on the interplay of electrostatic forces in both natural environments and physicochemical treatments [70]. A method that accurately predicts virions' isoelectric point (IEP) would greatly aid in this endeavor. A straightforward approach to predicting the IEP is to determine the pH at which the charges from the ionizable amino acids in the capsid proteins balance to nil. However, these predicted IEPs based on capsid charges often differ by a few pH units from experimentally measured IEPs. This discrepancy can be attributed to neutralizing the expected polynucleotide-binding zones inside the capsid. We discussed models that consider either the influence of viral polynucleotides on surface charge or the participation of solely outer remainders to the surface charge [70]. It should be noted that these models apply only to non-enveloped viruses, and developing an equivalent model for enveloped viruses poses challenges due to the limited information available on enveloped virus IEPs and doubts surrounding the impact of the phospholipid envelope on charge and ion gradients. The assessment of the required EF application in the EC process could potentially benefit from virus modeling in IEPs. Factors like pH and aqueous matrix play a significant role in influencing both IEPs and EC.

As we delve deeper into examining viruses' composition and their interactions within ecosystems, and as we experiment with various methods for eliminating them in water treatment facilities, we understand the challenge of completely eradicating viruses using a singular treatment approach (**Fig. 4**). To ensure the comprehensive removal of viruses, it has been suggested that advanced water treatment systems be implemented, incorporating techniques like coagulation, reverse osmosis, ultrafiltration, and advanced oxidation process (AOP). The effectiveness of these methods would vary based on the level of regulatory oversight and associated health risks posed to humans [71].

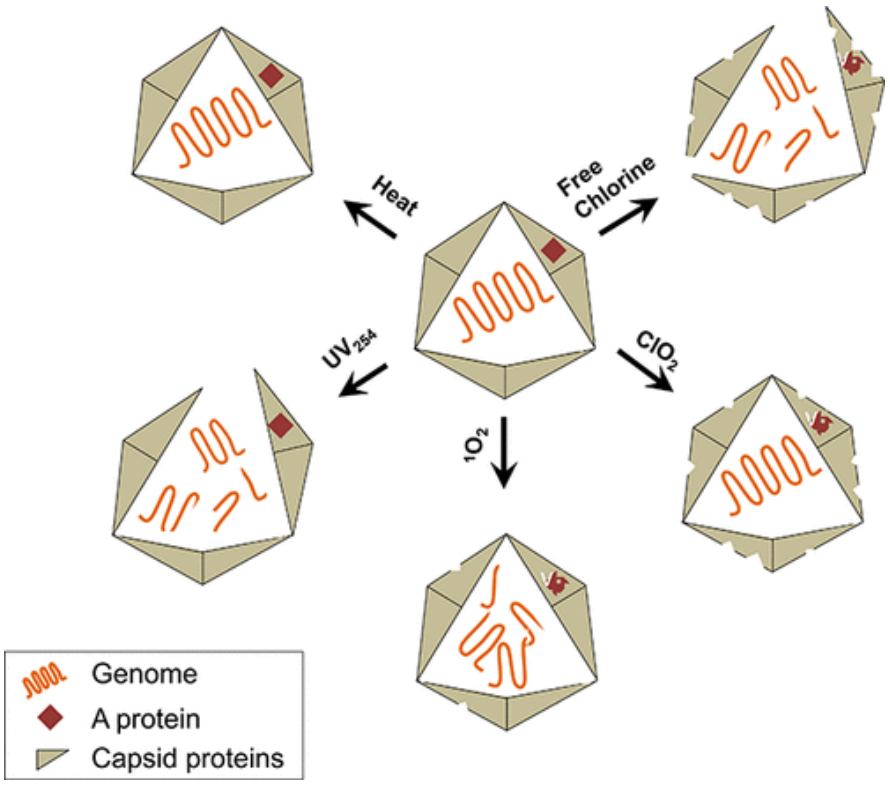

Fig. 4. Mechanism of MS2 virus deactivation by disinfectants [72].

4. Combining Electrochemical disinfection (ED) technology

By integrating ED with other methods, the effectiveness and cost-efficiency of this process can be improved. Crossbreeding or integration techniques involve the simultaneous or consecutive use of two separate methods. This can be achieved by combining various water treatment processes in a one-reaction container or system or utilizing a two-step treatment procedure to obtain a synergistic sterilization effect [73].

4.1. Electrochemical disinfection-locally enhanced electric field treatment (ED-LEEFT)

The EFT has been developed to deactivate bacteria using EP. When an EF is applied, **Fig. 5(a)** illustrates establishing a transmembrane potential through the cell's phospholipid bilayer. This potential causes water molecules at the interface between the membrane and water to align themselves with the localized EF, creating a water column (WC) that spans the lipid bilayer. Consequently, the lipids and their hydrophilic heads reorient themselves towards the WC, generating openings in the cell membrane. This phenomenon is called EP [2]. However, it is essential to note that generating a stable EF requires the application of high voltages, which can raise security worries, cause unwanted secondary responses, and increase power expending [74].

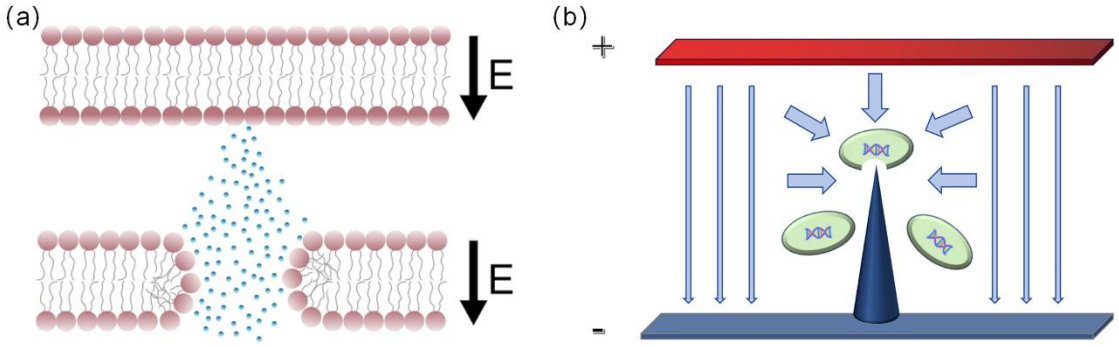

Fig. 5. Locally enhanced electric field treatment (LEEFT) for bacteria demobilization. (a) Concept of electroporation (EP) in cell membranes under electric field (EF) (: phospholipid molecule; : water molecule); (b) Schematic of LEEFT [2].

The EF surrounding extremities with high aspect ratios, characterized by nanometer diameter and micrometer length, could exhibit a phenomenon known as the "lightning rod effect." This effect significantly amplifies the EF strength near the extremity, reaching some orders of higher magnitude. This locally enhanced electric field treatment (LEEFT), as depicted in **Fig. 5(b)**, enables the achievement of lethal EP using low external voltages [75]. Nanowire (NW)-assisted EP sterilization has been developed as a choice to conventional disinfection techniques. Nanomaterials accompanied by distinct nanoscale extremity or edge constructions, such as carbon nanotubes and graphene nanosheets, have effectively eradicated microorganisms like microalgae and bacteria at low applied voltages [2]. Remarkably, total microbial demobilization could be attained with a mere 1 V voltage and an elevated flux (2 m^3 h^{-1} m^{-2}) by employing stable Cu3PNW-Cu electrodes and harnessing the nanotip's enhanced EF impact [2]. Scientists [76] successfully explained the mechanistic details of the LEFFT method at the individual cell level and proved that the amplified EF leads to irreversible EP, resulting in bacterial inactivation.

However, the LEEFT is not sufficient for continuous sterilization without the presence of reactive substances. When the EP threshold is not exceeded, it only causes partial damage to the cell membrane [2]. Emerging EP and electrochemical methods can create infiltration passages through reversible EP-caused cellular pores to overcome this limitation. These channels allow reactive oxidants to enter the cells, significantly enhancing bacterial inactivation [77]. In a study by [78], Co_3O_4 NW arrays adjusted on graphene foam electrodes were used for coexistent disinfection employing EP and chlorination. This procedure proved effective against many microbes, including chlorine-resistant/sensitive and GPB/Gram-negative races. Its integrated disinfection potency surpassed that of each process.

Enhanced disinfection outcomes can be achieved through the consecutive conjugation of EP and electrochlorination. Researchers [79] proposed a novel method using a copper mesh cathode adjusted with copper phosphide NWs to enhance the localized EF during EP. An adapted mixed metal oxide anode for Cl_2 formation followed this. Implementing this original procedure resulted in excellent treatment circumstances and an additional, comprehensive enhancement of disinfection effectiveness. Another study [80] focused on targeting multidrug-resistant *E. coli* cells using a combined EP and EO approach. This study's findings proved that the EP-caused cellular pores were widened more via the active species'

oxidation. As a result, ARGs were effectively removed at lower applied voltages, significantly reducing power expenditures compared to traditional EO techniques that utilized Co3O4 membrane-altered electrodes. This procedure dramatically mitigates the risk of ARG transmission in drinking water systems. By utilizing a nano-needle, the EF at its tip can be enhanced, resulting in a solid and non-uniform EF that influences the movement of cells through electrophoresis and dielectrophoresis. Numerous indicators, like electric pulse parameters and the medium's physicochemical properties, affect the behavior of cells in the system [2]. The EF strength near the NW tip could be considerably boosted, intensifying charge density, allowing for adequate cells' transit inside the setup, and optimizing the intensification of EP and EO via localized boosted EFs. It is essential to highlight that such original integration of processes requires further study and adjusting to ensure expanded thoroughness and performance.

4.2. Electrochemical disinfection-electrocoagulation (ED-EC)

The primary EC method uses sacrificial anodes, such as aluminum and iron, which generate metal cations by applying an electric current. Such coagulating species are subject to hydrolysis close to the anode, producing metal hydroxide. This process leads to the aggregation of suspended particles, allowing for their precipitation or the adsorption of dissolved pollutants [81]. The effectiveness of EC technology lies in its ability to neutralize pathogens using EFs and Al^{3+} or $Fe^{2+/3+}$ ions [82]. This leads to their separation through flotation with the help of $H_{2(g)}$ and $O_{2(g)}$ bubbles or through flocculation/decantation with the assistance of $Al(OH)_{3(s)}$ or $Fe(OH)_{2(s)}$/$Fe(OH)_{3(s)}$ flocs [83]. EC offers numerous benefits, including minimal use of chemicals, rapid precipitation of flocculants, small mud production, straightforward apparatus, and facile running [10]. However, there are challenges specific to EC disinfection. It has been observed that this process struggles to eliminate microorganisms, making their complete removal difficult effectively.

Additionally, the flocs formed during EC carry elevated levels of metal ions, making direct discharge into the environment problematic [84]. Furthermore, a significant amount of sludge may be generated, which has been found to contain substantial quantities of metal ions, such as Fe and Al, and other persistent pollutants [2]. Dealing with the sludge afterward will present a significant hurdle that needs to be overcome.

One possible solution to overcome the EC process's limitations is to combine it with ED. This combination promotes microbial aggregation and removal in a shorter period, thereby improving the effectiveness of EO disinfection and reducing energy usage [81]. The sequential use of EC and ED bears similarities to traditional multi-hurdle water treatment setups, as it effectively eliminates a significant amount of organic matter. The effectiveness of ED in reducing the oxidant demand and eliminating *E. coli* has been highlighted by Lynn et al. [85]. Researchers [30] focused on dealing with restaurant wastewater utilizing a successive EC-ED approach, which yielded impressive outcomes. The concentration of *E. coli* in the treated effluent was reduced to concentrations under the measurement limit, with EC proving to be more influential than the ED method. A setup could be suggested to implement concurrent ED-EC remediation via embodying pierced Al/Fe plates as bipolar electrodes in the middle of the cathode and anode for ED, as illustrated in **Fig. 6** [86]. Scientists [87] also experimented with positioning pierced Fe plates in the middle of a BDD anode and a stainless-steel cathode, producing a coagulant by disintegrating one side of a cathode-facing iron foil. Such coagulants effectively deactivated microorganisms, attaining total killing at CDs of 6.70 A/m² or more. Al, as a bipolar electrode, can impede colloid elimination and killing effectiveness by forming a passivation film. However, disinfection efficiency can be enhanced by avoiding this passivation layer compared to using Al.

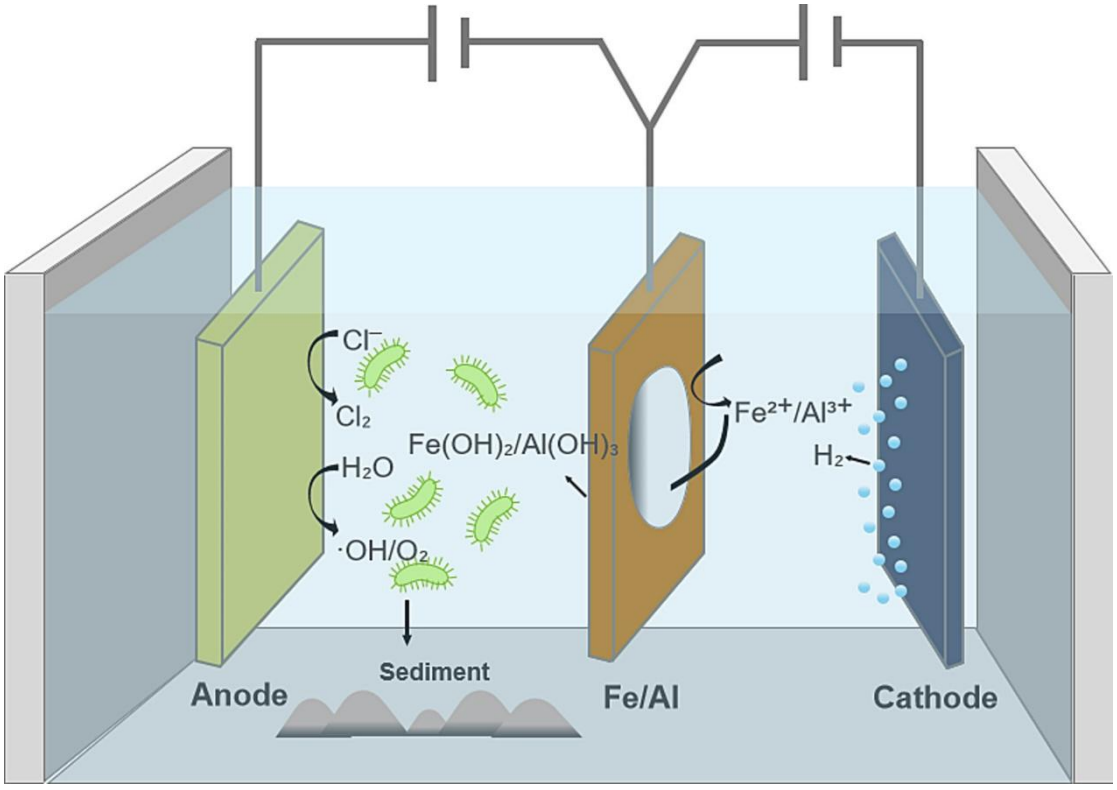

Fig. 6. Electrochemical disinfection-electrocoagulation (ED-EC) synergistic disinfection mechanism [2].

Nevertheless, further investigation and adjusting are necessary to dictate the optimal working factors for simultaneous ED and EC treatment. High CDs are generally beneficial for EO as they increase the generation rate of reactive oxides and the oxidation rate of pathogens. High CDs benefit EO by augmenting the average of reactive oxides' generation and microbes' oxidation. Still, using elevated CDs can lead to a fast ending of the EC anode, resulting in frequent electrode replacement and increased operating costs. Additionally, electrode passivation can impede electron flow during EC, potentially requiring more energy and a residence period to kill microbes effectively [2].

The year 2020 served as additional evidence that municipally treated wastewater has the potential to be completely recycled, eliminating the production of dangerous chlorates and perchlorates [88]. This was achieved through pilot-scale experiments utilizing ED-EC, resulting in lower energy consumption. Such results establish a solid theoretical basis for applying ED-EC. Therefore, it is crucial to carefully consider various parameters and operating conditions to maximize this technology's benefits while minimizing operational costs and potential environmental risks.

4.3. Electrochemical disinfection (ED)-adsorption

A new and innovative approach to combining adsorption and ED processes is achieved by integrating three-dimensional (3D) electrodes. This involves embodying particles, particulate electrode materials (EMRs), or materials with adsorption features, like granular activated carbon (GAC) and metal particles, inside the traditional two-dimensional (2D) electrode electrochemical reactors. By embodying these particles and materials with adsorption capabilities, like GAC, metal particles, carbon fiber mats, and other adsorbent substances, into the electrochemical reactor, 3D electrodes can be created inside the existing 2D electrode framework. Such a combination of 3D electrodes enables the effective integration of ED and adsorption processes [46, 89, 90]. When subjected to suitable voltages, those particles become polarized and generate numerous charged microelectrodes, which ease physicochemical and electrical adsorption and electro-oxidative reactions on their surfaces and surrounding areas [2, 91]. According to Ma et al. [92], using charged microelectrodes substantially enhances both the effective electrode area and the number of catalytically active sites. Additionally, the distance for mass transfer is considerably reduced, resulting in a considerable improvement in disinfection efficiency.

GAC functional groups enhance the system's oxidation capabilities, catalyzing the H_2O_2 electrochemical formation and easing the $^{\bullet}OH$ production. Researchers [93] demonstrated the effectiveness of ED-adsorption using a FES that utilized carbon fiber mats. Impressive results were achieved, with a depletion of 6.5 log in *E. coli* concentrations at a flow rate of 1500 $L \cdot m^2 \cdot h^{-1}$ and a voltage of 3.0 V. Researchers [94] employed graphite materials with electrochemical regeneration

inside a consecutive sporadic reactor and demonstrated their ability to kill diverse microbes. In a study [46], *in-situ* sampling trials were performed to uncover the critical pathway beyond FES remediation. The results revealed that microbial demobilization mainly happens via successive adsorption on the porous 3D anode of the FES, with DO being the primary process rather than IO via chemical oxidants. Investigators [95] juxtaposed the efficacy of a 3D flow-through electrochemical reactor using filled GAC for greywater remediation with that of a traditional 2D flow-through electrochemical reactor. Electrosorption significantly killed *E. coli*, and the 3D electrochemical reactor exhibited greater power efficiency, highlighting the synergistic interaction among EO and GAC adsorption. Investigators [96] employed a lamellar graphite-inserted composite adsorbent to remove *E. coli* with electrochemical treatment in a consecutive batch reactor. This strategy achieved an elimination rate higher than 99.98% in 5 min. Furthermore, the adsorbed *E. coli* remained stable after five treatment cycles, highlighting the capability for reusing the adsorbent and confirming the practicality and cost-effectiveness of such a method. A study by Li et al. [97] also demonstrated that the electrodes of the GAC successfully adsorbed and isolated DBPs. Investigators [98] incorporated GAC adsorption after water chlorination, resulting in a significant 45% reduction in aromatic halogenated DBPs in the remedied used water. In addition, the control sample's overall harmfulness is significantly lower. The presence of adsorbed tap water samples was significantly reduced, leading to the conclusion that incorporating an adsorption setup following disinfection could effectually mitigate the formation of DBPs throughout the disinfection method, thereby improving the overall security of the remedied water standard [99].

4.4. Electrochemical disinfection-ultrasound (ED-US)

When liquids are exposed to high-intensity US, acoustic cavitation occurs, forming an oxidizing environment [100]. The US causes low-pressure cavities to form, extend, and disintegrate. During this rapid collapse, temperatures of 5000 K and pressures of 1000 atm are generated, leading to the hot separation of H_2O into $^{\bullet}OH$ and the formation of different ROSs. These hot, chemical, and cavitation impacts are suitable for killing pathogens [101, 102]. However, relying solely on the US to kill microorganisms requires significant power, so it is more commonly used as an extra method alongside different methods for killing microbes. Combining the US and electrochemical devices could improve the oxidation method, increasing performance [2, 103, 104].

Combining ED and US technology produces ample oxidants to eliminate bacteria effectively [105]. Simultaneously, US enhances the production and distribution of these oxidants throughout the solution, breaking up clusters of microorganisms and facilitating better touch among the oxidant and the bacteria (**Fig. 7**) [106]. Additionally, US reduces the cell potential, and the turbulence caused by ultrasonic cavitation (UC) improves the transport of killing agent to the cells [107]. Investigators [108] discovered that the mass transfer process was enhanced when US and ED were combined with a dimensionally stable anode, preventing microbial assemblage. Such combined impact led to a killing rate that surpassed 200% of what could be reached by single killing techniques.

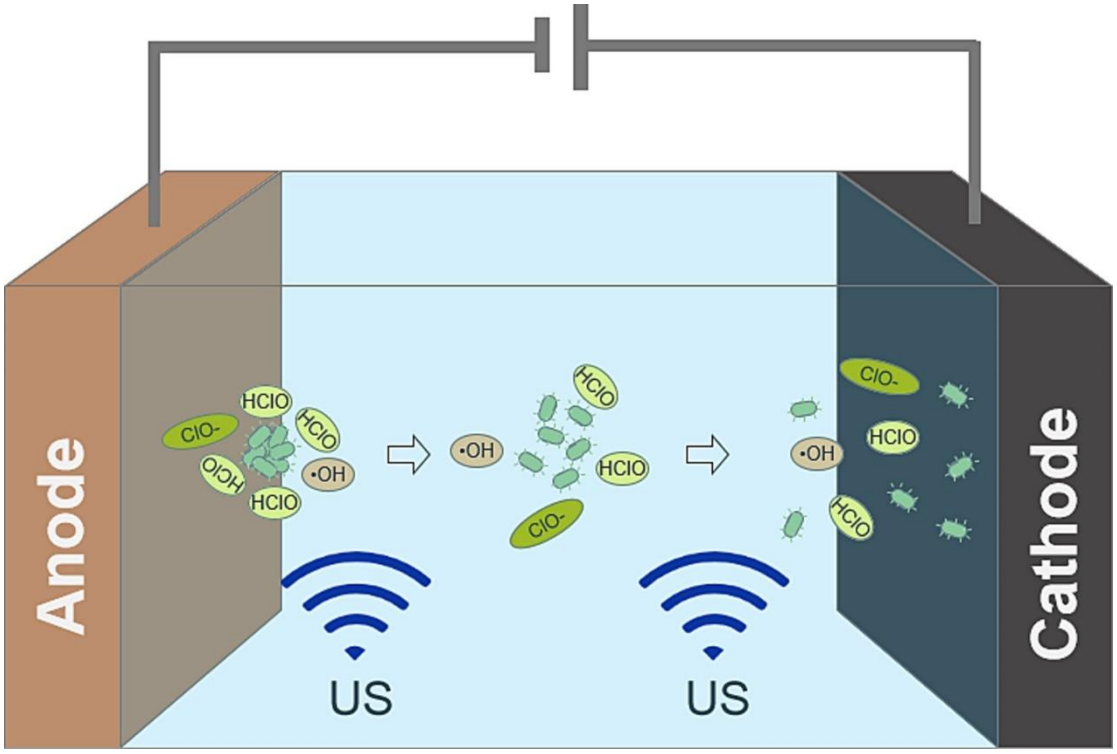

Fig. 7. Electrochemical disinfection-ultrasound (ED-US) synergistic killing route [2].

Scientists [109] researched ED-US and defined three implied pathways. The processes implicated in demobilizing *E. coli* cells encompass various mechanisms, such as DO induced by electrochemical means, IO, and the rupture of cells caused by the shear stress from the collapse of cavitation bubbles produced by US. The researchers credited the increased inactivation rate to the electrosorption of TiO_2 onto *E. coli*, which intensified the interplay between $^{\bullet}OH$ radicals formed acoustically on the surface of the TiO_2 anode and the *E. coli* cells.

The utilization of US in electrochemical processes prevents electrode passivation, as it effectively cleans the surface and strengthens the ED system [110, 111]. However, it is essential to acknowledge that US-induced cavitation can create localized high temperatures and pressures inside the water. Such circumstances could cause corrosive damage or mechanical wear to the EMR, especially when bubbles disintegrate at the surface, resulting in localized corrosion or breaking. Additionally, UC can lead to isolated temperature augmentations, which may influence the response of the EO method.

In summary, the combination of US and ED capitalizes on the merits of them, enhancing killing via numerous routes. Even if such approach could pose difficulties linked to EMRs, its general merits are clear: providing a performant solution for dealing with water. More investigations must should focus on adjusting working parameters, extending electrode lifespan, investigating reaction kinetics, and further exploring the synergistic mechanisms between ED and US [2].

4.5. Electrochemical disinfection-photocatalysis (ED-PC)

Electron movement from the valence band (VB) to the conduction band (CB) occurs if the photons' energy exceeds the typical band gap energy (E_g) of a semiconductor material [2]. This phenomenon conducts to the generation of photogenerated electrons (e_{CB}^-) and holes (h_{VB}^+), as indicated in Eq. (15) [112]. The interaction between electrons and adsorbed O_2 results in the formation of $O_2^{\bullet-}$ (Eq. (16)), while the water molecules' uptake by holes with decreasing features leads to the production of $^{\bullet}OH$ (Eq. (17)) [102]. Photocatalytic (PC) sterilization has attracted substantial interest thanks to its environmentally friendly nature and ability to eliminate many bacteria [30]. However, the limited efficiency in separating carriers (Eq. (18)) poses challenges to its overall effectiveness and practical application [113]:

$$\text{Semiconductor} + h\nu \rightarrow e_{CB}^- + h_{VB}^+ \quad (15)$$

$$e_{CB}^- + O_2 \rightarrow O_2^{\bullet-} \quad (16)$$

$$h_{VB}^+ + H_2O \rightarrow {}^{\bullet}OH + H^+ \quad (17)$$

$$e_{CB}^- + h_{VB}^+ \rightarrow h\nu \quad (18)$$

Combining ED with PC in the photoelectrocatalytic (PEC) disinfection process offers several advantages due to the combined effects of light-driven and electron-driven processes (**Fig. 8**). PEC enables the effective separation of carriers at higher energies, surpassing semiconductors' bandgap energy. This leads to longer lifetimes of electron-hole pairs and improved killing ability [2]. By applying a bias potential (BP) to the photocatalyst, PEC oxidation has revealed higher effectiveness than conventional PC via adjusting the employment of photogenerated holes [114, 115]. The BP extent influences the PEC effectiveness, even if it is essential to record that the number of photogenerated electrons is restricted. A saturation current is attained as soon as the BP exceeds a determined limit, causing the decomposition capability of PEC to level off [116]. Thus, regarding the PEC method, the conversion rate is not exclusively dependent on the applied potential. The overall effectiveness of the PEC oxidation is not exclusively attributed to one factor but rather a combination of several elements. These include the properties of semiconductors, the diffusion of light, the adsorption and desorption of reactants and products, and the magnitude of the EF in the space charge zone [117]. The efficiency of the PEC oxidation is determined through the intricate interplay of these factors.

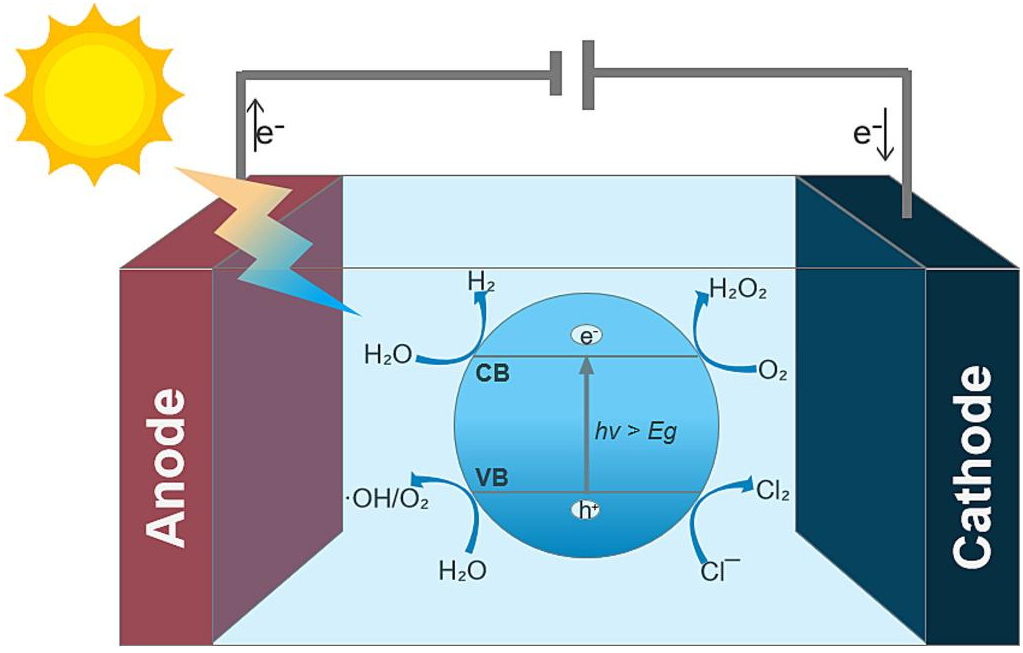

Fig. 8. Electrochemical disinfection-photocatalysis (ED-PC) synergistic disinfection pathway [2].

PEC involves the generation of electrically charged ROSs, RCSs, and photogenerated holes, all of which have the potential to cause damage to cell membranes, target cellular constituents, and create oxidative stress [2]. Investigators [118] examined the PEC-killing pathway and revealed that oxidative stress created by photogenerated H_2O_2 was the primary cause of bacterial cell inactivation and breakdown. Such oxidative stress overcomes the antioxidant ability of protective enzymes within the bacteria, leading to the infiltration of cytoplasmic tenor and biomolecules comprising essential proteins and nucleic acids, ultimately resulting in mineralization. Scientists [119] successfully deactivated *XL-1blue* (*E. coli*) using a TiO_2 P-25 running electrode below synthetic light, demonstrating the effectiveness of PEC in deactivating bacteria. Researchers [120] exhibited the PEC method's inhibitory effect on forming electron-hole pairs while enhancing the generation of hydroxyl radicals. In just 5 min, using an Ag-TiO_2 electrode successfully halted the growth of *Pseudomonas aeruginosa*, resulting in a six-fold decrease in treatment time juxtaposed to using PC alone.

In addition, the combination of electrochemical techniques and PC not only aids in the breakdown of the restricted number of halogens produced throughout electrochemical application but also improves the ED security [2]. Although PEC shows excellent potential in enhancing killing efficacy and security, the general price of the technique, including energy, electrodes, and UV lamps, stays relatively high, hindering its widespread implementation [117]. Utilizing solar energy to power the PC device presents an encouraging option to overcome this challenge. This procedure decreases dependence on traditional power sources, resulting in lower maintenance expenses and increased practicability of PEC implementations [121, 122].

4.6. Electrified membranes (EMs)-Electrochemical disinfection (ED)

By incorporating electroactivity as an extra membrane role, EMs can tackle challenges uniquely (**Fig. 9**) [123]. In addition to their conventional roles of separating solutes via steric hindrance and charge exclusion, EMs extend the

capabilities of membranes by utilizing various electron-based facts, including EO and reduction, electrophoresis, and EP [124]. As a result, EMs can effectively break down and transform pollutants while enhancing the removal of charged species through filtration techniques [123, 124].

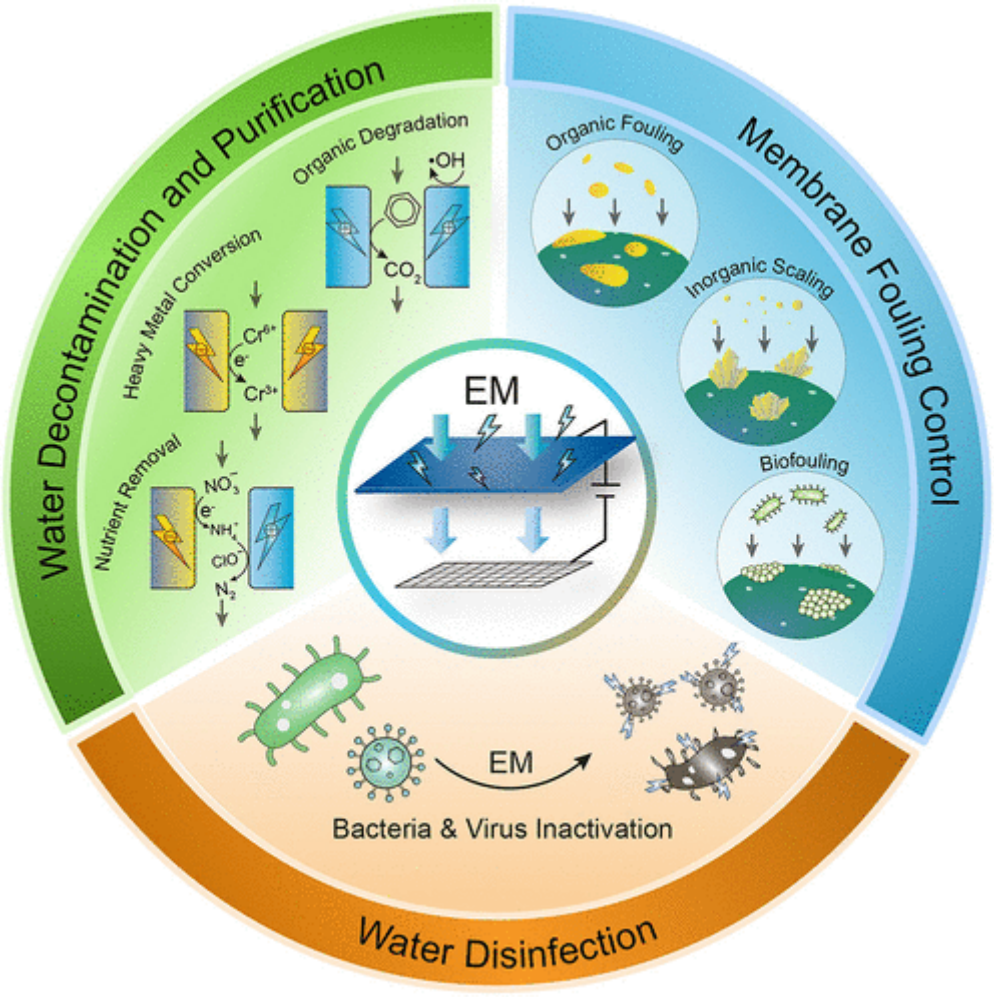

Fig. 9. Electrified membranes (EMs) offer a range of potential environmental applications, including water sanitation and cleaning, killing pathogens, and membrane fouling (MF) surveillance [123].

EM can eliminate contaminants and reduce membrane fouling (MF) and deposition via different electrochemical procedures [123]. For example, organic and biological pollutants can be degraded via electrochemical self-cleaning based on the *in-situ* formation of strongly oxidizing species like ROSs and RCSs. Additionally, the chemical and hydrodynamic environment near the membrane surface can be modulated by adjusting pH and electrolytic bubbling to reduce inorganic deposits. Besides using electrochemical reactions to prevent fouling, tuning membrane surface properties by applying voltage can give extra opportunities to diminish MF caused by organic substances, bacteria, and inorganic debris (**Fig. 10**).

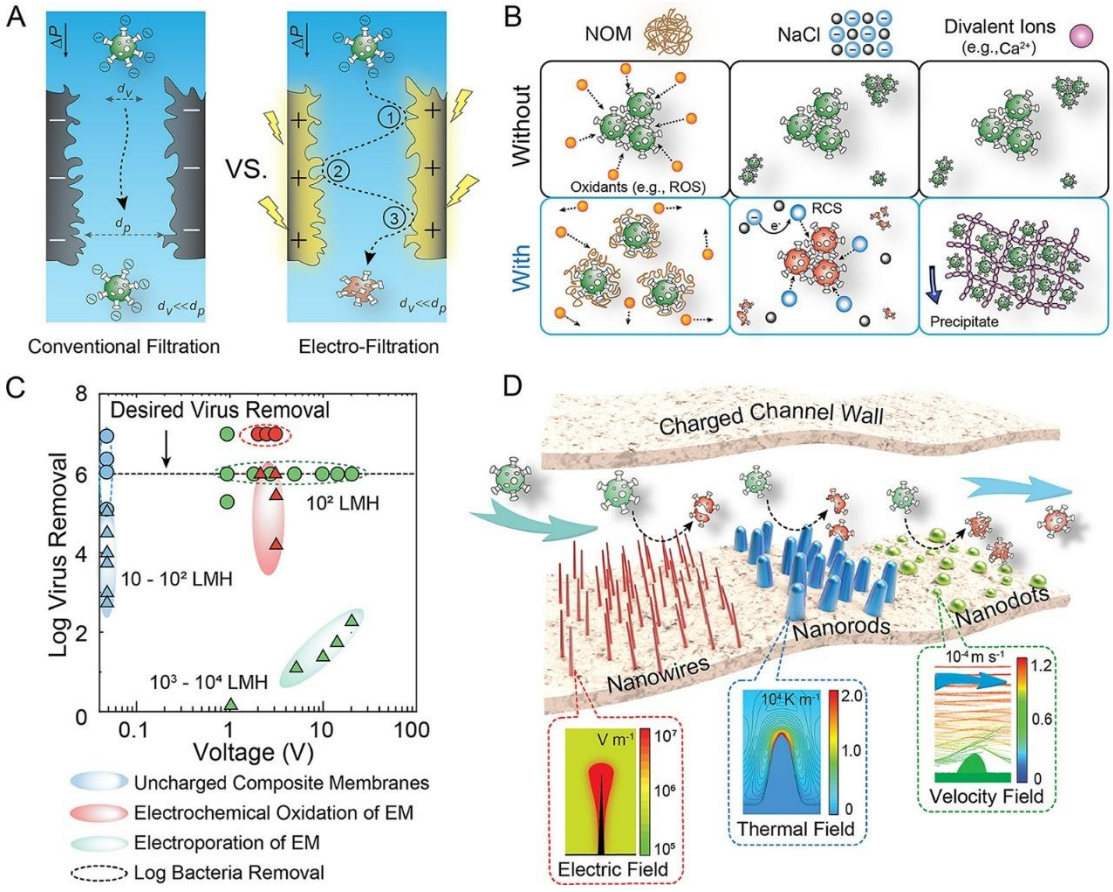

Fig. 10. Virus reduction and deactivation in electrified membrane (EM) filtration. (A) Schematic depicting viruses passing across a conventional, nonconductive membrane and deactivation by anodic EM filtration through direct oxidation (DO) and reactive-oxygen or -chlorine-species (ROSs/RCSs)-mediated indirect oxidation (IO). (B) Schematic illustrating the influence of solution chemistry on virus deactivation in EM filtration. Natural organic matter (NOM) competes with viruses for ROSs/RCSs consumption, which reduces deactivation performance. Solutions having an increased NaCl level encourage RCS generation in anodic filtration and boost virus deactivation. Divalent ions (like Ca^{2+}) promote virus agglomeration that facilitates virus removal by physical holdup and then (EO) via EMs. (C) Comparison of implemented voltage, water flux, and corresponding virus elimination efficacy in different types of flow-through filtration membranes. The water flux of membranes during virus deactivation is given as liters per square meter per hour (LMH). Solid and dashed ovals illustrate log virus (triangle) and bacteria (circle) deactivation below similar circumstances.

Electrified membrane-electrooxidation (EM-EO) considerably reaches desired virus deactivation with comparatively low voltage and moderate water flux. The model bacteria mainly employed are *E. coli* and *B. subtilis*. Data illustrated are mainly for MS2 and UZ1 viruses. (D) Increasing virus removal in anodic EM filtration with adjusted membrane electrode geometry. Engineered NW, nanorod, or nanodot additions to membrane geometries greatly augment nanoscale mass transport by locally amplifying the EF, concentrating reactants, augmenting temperature, and boosting flow convection [123].

Integrating EMs and ED could be a more robust method for purifying and treating water. The proposed apparatus could incorporate both processes into a single container [124].

4.7. Electrochemical water splitting (EWS)-electrochemical disinfection (ED)

Electrolytic water splitting (EWS) is an up-and-coming method for utilizing renewable energy sources and converting them into $H_{2(g)}$ and $O_{2(g)}$, which can be used as a clean and sustainable fuel [125]. However, it is crucial to maintain the detachment amidst $H_{2(g)}$ and $O_{2(g)}$ throughout the electrochemical process, especially when irregular renewable sources are involved (**Fig. 11**). Our previous research [126] delved into the advancements of separated electrolysis for water splitting and its capacity for facilitating other sustainable chemical processes (**Fig. 11**). One such process is ED of water, which shows great potential. We proposed implementing ED in the compartment that produces $O_{2(g)}$ during EWS while the other

compartment produces $H_{2(g)}$. Both processes share the use of electric current, but they operate in separate cells to ensure the production of $H_{2(g)}$ and $O_{2(g)}$ remains distinct [126].

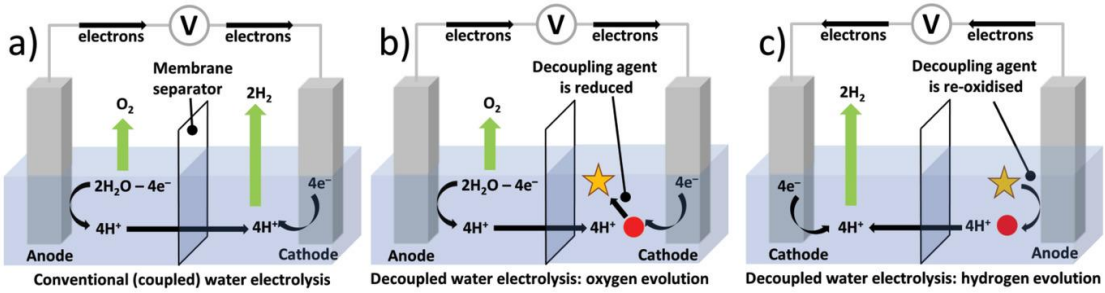

Fig. 11. A differentiation of a) traditional *vs.* b,c) decoupled water electrolysis under general acidic conditions [125].

In **Fig. 12**, three different decoupling strategies are depicted. Both arrangements **(A)** and **(B)** appear to be better options for generating hydrogen and oxygen and water treatment. Specifically, **Fig. 12(B)** showcases nickel (oxy)hydroxides as a solid-state redox mediator for separated water electrolysis [127]. On the other hand, **Fig. 12(C)** illustrates Walsh's bipolar electrode design for separated electrolysis [126].

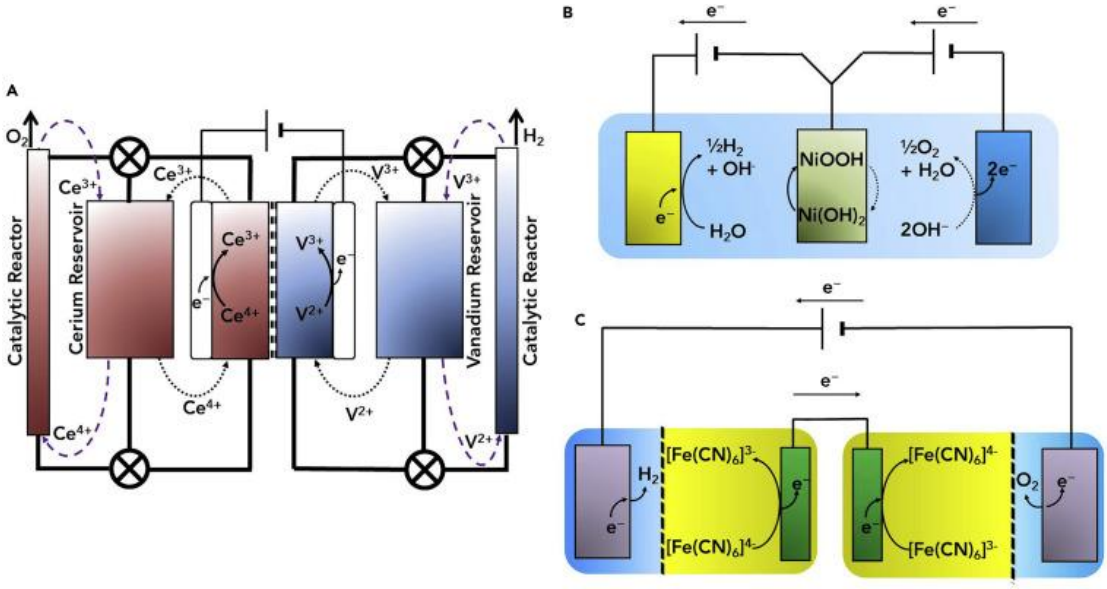

Fig. 12. Possible decoupling designs. (A) Girault's dual-circuit vanadium-cerium flow arrangement for flexible $H_{2(g)}$ generation or energy storage. (B) Separated water electrolysis employing nickel (oxy)hydroxides as a solid-state redox mediator. (C) Walsh's bipolar electrode design for separated electrolysis [127].

One proposed concept involves utilizing an EWS device to generate $H_{2(g)}$ in one cell and $O_{2(g)}$ in another cell, with the application of an EF and the passage of electric current disinfecting water. The inclusion of $O_{2(g)}$ would significantly increase the performance of the disinfection method. Practical tests will need to be conducted to identify the optimal dimensions and disinfection efficiencies [126].

4.8. Electrocoagulation (EC)/Electro-Fenton and electrochemical disinfection (ED)/filtration

Other most critical hybrid processes dealing with ED may be found in the literature such as EC/Electro-Fenton and ED/filtration [12, 128].

The electro-Fenton method, which involves the *in-situ* generation of $^{\bullet}OH$, is commonly associated with AOPs and is often recommended for wastewater treatment (**Fig. 13**). Studies have shown that the electro-Fenton method has superior disinfection effects compared to EC [12].

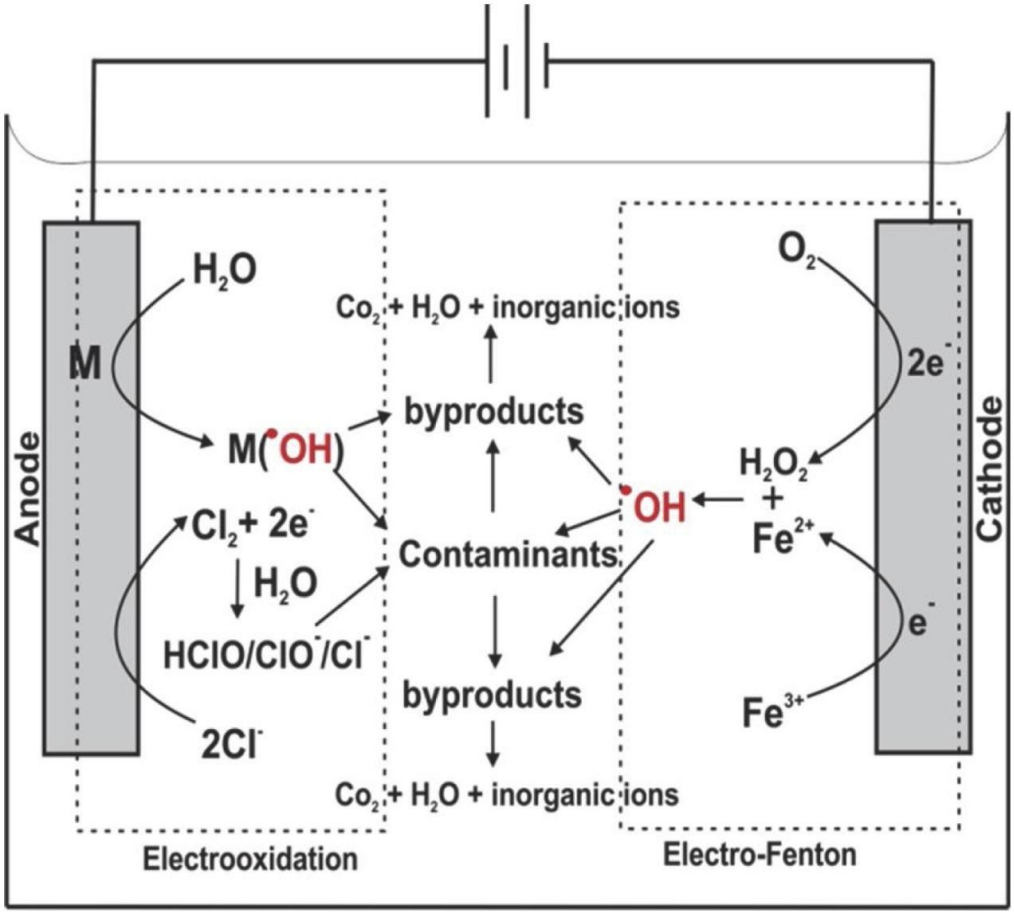

Fig. 13. A visual depiction illustrating the process of oxidant production in both electrooxidation (EO) and electro-Fenton processes [129].

Filtration has the potential to effectively remove organic matter and microorganisms by utilizing filters that have a specific distribution of pore sizes, including nanopore filters [130] (**Table 2**). This method allows for achieving disinfection performance through ED while minimizing the generation of by-products. Additionally, supplementary adsorption (Section 4.3) can be employed after the filtration process [12].

Table 2

Coagulation, decantation, filtration: Usual reduction performances and effluent quality [131].

Pathogens	**Reduction performance (%)**		
	Coagulation and decantation	**Rapid filtration**	**Slow sand filtration**
Total coliforms	74 - 97	50 - 98	>99.999
Fecal coliforms	76 - 83	50 - 98	>99.999
Enteric viruses	88 - 95	10 - 99	>99.999
Giardia	58 - 99	97 - 99.9	>99
Cryptosporidium	90	99 - 99.9	99

5. Hybridizing more than two separate methods simultaneously or consecutively

Finally, the effectiveness of combined and consecutive killing methods in deactivating microorganisms relies on specific working parameters. Certain substances or additives in the water can significantly impact the depletion and breakdown of pathogens. Various chemical and electrochemical reactions may occur depending on factors such as pH levels, cations or anions, different types of irradiations, US waves, temperature, organic matter concentration, viscosity, and flow direction. When optimizing and scaling up these combined technologies, it is crucial to address any issues carefully or dares related to each detail [132].

Achieving efficient commercial applications does not always require large-scale operations, as the bulk of the effluent can sometimes be lessened. Only small devices must be designed, developed, and constructed. A crucial challenge is creating autonomous ED setups turned on by renewable energy sources that require minimal maintenance. This would make diamond disinfection technologies more appealing for industrial use, even in remote areas. Additionally, every technique should undergo a techno-economic examination to reveal its competitiveness compared to traditional killing techniques such as chlorination [132].

Combining ED with other methods can improve its effectiveness and cost-efficiency. Hybridization involves using two separate methods simultaneously or consecutively. The EFT deactivates bacteria using EP, but generating a stable EF requires high voltages that can cause safety concerns. EC involves using sacrificial anodes to generate metal cations that aggregate suspended particles, allowing for their precipitation or the adsorption of dissolved pollutants. However, EC struggles to eliminate microorganisms. Integrating 3D electrodes into the traditional 2D electrode electrochemical reactors enables the effective combination of ED and adsorption processes. High-intensity US causes acoustic cavitation, creating an oxidizing environment that is adequate for disinfection.

The utilization of GAC after ED treatment has the potential to diminish the levels and harmful impacts of DBPs significantly. Additionally, there is a need for the exploration, experimentation, and promotion of secure multi-barrier methods such as solar disinfection through distillation, plasma discharge [133], nanotechnologies, and membrane processes. Despite their drawbacks, adsorptive methods and membrane techniques continue to be promising areas of investigation due to their affordability and simplicity of implementation [41].

6. Conclusions

To summarize, electrochemical disinfection (ED), as a promising approach, has demonstrated its importance and superiority in multiple areas. It eliminates bacteria by disrupting cell membranes, inducing cell death through oxidation, and utilizing self-acting electric fields (EFs). Advancements have been made in electrode material (EMR) selection and development, refining reaction conditions, and integrating ED with other processes. However, challenges remain, including significant initial investments and high energy requirements.

Future research should focus on improving electrocatalytic performance, assuring stability, and reducing the prices related to EMRs to facilitate the more extensive implementation of the ED technique. Recent advancements in materials science and nanotechnology will be central to this endeavor. Developing EMRs that are both catalytically efficacious and economically acceptable while also being practically stable and suitable for large-scale production will considerably accelerate the implementation of the ED method in treating water. Additionally, it is crucial to thoroughly examine possibly poisonous secondary products that may arise from the ED technique, particularly in vital usages such as drinking water disinfection.

Combining ED with other methods can improve its effectiveness and cost-efficiency. Hybridization involves using two or more separate methods simultaneously or consecutively. The electric field treatment (EFT) deactivates bacteria using electroporation (EP), but generating a stable EF requires high voltages that can cause safety concerns. Electrocoagulation (EC) involves using sacrificial anodes to generate metal cations that aggregate suspended particles, allowing for their precipitation or the adsorption of dissolved pollutants. However, EC struggles to eliminate microorganisms. Integrating 3D electrodes into the traditional 2D electrode electrochemical reactors enables the effective combination of ED and adsorption processes. High-intensity ultrasound causes acoustic cavitation, creating an oxidizing environment that is adequate for disinfection.

Further investigations into improving electrochemical reactors and optimizing electrochemical parameters are necessary to determine the most effective arrangements and circumstances for real-world wastewater treatment. Furthermore,

integrating the ED method with different killing methods encourages increasing killing performance, reducing energy consumption, and minimizing secondary product generation, a significant aspect of the next progress of the ED process.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflict of Interest

The authors declare that they have no conflict of interest.

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