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Electrochemical Disinfection Technology: Highlighting Advances and Outlooks

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ABSTRACT

Exciting findings have emerged from recent studies on using in situ electrochemical methods for water disinfection, demonstrating their effectiveness in deactivating microorganisms. However, significant precautions should be considered in future research to ensure a reliable drinking water supply. This viewpoint proposes strategies for evaluating the efficiency of disinfection processes, which will aid in advancing the readiness of this technology. Additionally, it explores the recent advancements in electrochemical disinfection (ED) techniques to avoid the generation of harmful disinfection by-products (DBPs) and examines how water composition affects treatment outcomes. Further research is needed to explore alternative materials and establish optimal operating parameters to avert DBP production. The effectiveness of hybrid and sequential disinfection methods depends on various factors, and small-scale devices powered by renewable energy sources present a significant challenge. The extensive use of chlorine conducted to the emergence of chlorine-resistant bacteria (CRB), threatening public health. The extensive use of chlorine has induced the emergence of chlorine-resistant bacteria (CRB) that threaten public health. Nanowire-assisted electroporation (EP) demonstrates remarkable stability when operating in complex water matrices. EP/Cl_2 effectively treats CRB in raw water, highlighting its potential use in real water matrices. Bacteria's vulnerability to RSs is well-documented, as their exposure can destroy proteins, DNA, and lipid membranes, ultimately causing cell demise. This characteristic makes the electrochemical production of RSs a highly appealing method for eliminating microorganisms during water treatment. It is crucial to prioritize expanding hybrid artificial intelligence (AI) technologies that could wholly employ the unique features of numerous AI technologies and deliver enhanced ED efficiency.

Keywords: Disinfection by-products; Antibiotic-resistant bacteria; Electrocoagulation; Solar disinfection; Antibiotic-resistant genes; Reactive oxygen species.

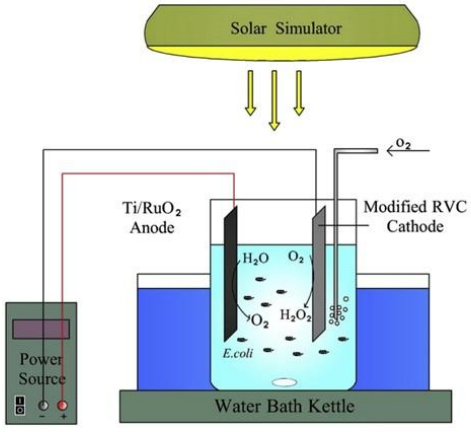
Highlights

- Future research must consider essential considerations to ensure a reliable, pathogen-free, and safe water supply.
- Developing electrochemical disinfection (ED) alternative materials and optimizing parameters to prevent toxic by-products formation.
- Nanowire-assisted electroporation (EP)/chlorine effectively treats chlorine-resistant bacteria.
- Bacteria establish their vulnerability to reactive species by destroying proteins and lipid membranes, ultimately causing cell demise.
- Developing hybrid artificial intelligence (AI) technologies that utilize the unique features of different AI technologies and deliver enhanced ED effectiveness.

Abbreviation

AC	Alternating (pulse) current	ER	Electrochemical reduction
AI	Artificial intelligence	FES	Flow-through electrode system
AOPs	Advanced oxidative processes	HA	Humic acid
AR	Antibiotic resistance	LEEF	Locally enhanced electric field
ARB	Antibiotic-resistant bacteria	LIG	Laser-induced graphene
ARGs	Antibiotic-resistant genes	PEAO	Piezoelectric aluminum oxide
BDD	Boron-doped diamond	PS	Activated persulfate
CRB	Chlorine-resistant bacteria	RVC	Reticulated vitreous carbon
DBPs	Disinfection by-products	RO	Reverse osmosis
DNA	Deoxyribonucleic acid	SEM	Scanning electron microscopy
DV	Direct voltage	SODIS	Solar disinfection
EC	Electrocoagulation	SWAV	Square-wave alternating voltage
ED	Electrochemical disinfection	RCSs	Reactive chlorine species
EFT	Electro-Fenton	RNSs	Reactive nitrogen species
EF	Electric field	RSs	Reactive species
EO	Electrochemical oxidation	RSSs	Reactive sulfur species
EP	Electroporation	ROSs	Reactive oxygen species
EPSs	Extracellular polymeric substances	UV	Ultraviolet

Graphical abstract



Integrating sunlight with H2O2 at renovated reticulated vitreous carbon (RVC) for killing pathogens

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1. Introduction

The lack of potable and safe water access affects approximately 20% of the global inhabitants, i.e., around 6.5 billion humans. This percentage is predicted to augment to 40% around 2050. Such an alarming situation will worsen, particularly considering the immense strain it will put on precious freshwater reservoirs. It is crucial to note that the challenges linked to water reserves are not solely centered around the quantity of water available but also the quality [1]. Various contaminants, including heavy metals, persistent organic and micro-pollutants, and pathogens, are infiltrating water sources, complicating water treatment. Consequently, efforts to contaminate previously clean water sources are driven by concerns for public health and the environment. It is imperative to develop practical, cost-effective, and reliable technologies that effectively demobilize pathogens and treat water from its source to its point of use without further straining nature or compromising persons through handling [2, 3].

When it comes to disinfection, it remains difficult to ensure safe water at an affordable price while minimizing energy consumption and maintaining effective control, all while avoiding further complications caused by the disinfection process itself [4]. Free chlorine is widely used as the primary disinfectant globally due to its effectiveness and cost efficiency [5]. It successfully eliminates or reduces the presence of various pathogens. Nevertheless, as fresh microbes persist and surge, there is a possibility that free chlorine may not be as effective, necessitating the use of alternative disinfectants [3].

Chlorine or chemicals could form poisonous disinfection by-products (DBPs) like trihalomethanes, chloroform, and haloacetic acids [3, 6]. These issues highlight the obligation to avoid chemicals and explore other processes [7]. Various chemical systems, including ozone (O_3), silver, copper, ferrate [8, 9, 10], iodine, bromine, hydrogen peroxide (H_2O_2) [11], and potassium permanganate, as well as physicochemical setups like TiO_2 photocatalysis [12] and photodynamic method, have been suggested as substitutes for chlorination to control waterborne pathogens in drinking water effectively. Additionally, novel treatment techniques such as ultrasonication [13], pulsed electric fields (EFs), irradiation, magnetically enhanced disinfection [14, 15], microwave setups, coagulation [16], decantation, and media or membrane filtration offer valuable options [17]. Another promising alternative is using ultraviolet (UV)-visible light to deactivate pathogens [18]. Electrochemical technologies have also experienced a renewed attention within engineers worldwide [19, 20, 21].

UV or sunlight exposure is suggested to disinfect water in plastic bottles and eliminate pathogens such as viruses, bacteria, and protozoa [11, 22, 23]. However, concerns have been raised about the potential health risks associated with chemicals released from the plastic material. Elevated organic matter levels and poor decontamination can lead to toxic DBPs and deficient demobilization of novel pathogens [24, 25, 26]. As a result, researchers are driven to suggest alternative water treatment methods that are safe, effective, and capable of addressing these challenges [27, 28, 29]. To achieve this, it is crucial to comprehend the pathways implicated in inactivating waterborne infectious agents and to create new disinfection approaches that offer the same or better benefits as chlorine and UV disinfection without adverse side effects [1, 30, 31]. Recent advancements in materials science provide hope for developing novel strategies, such as homogeneous or heterogeneous catalysis, to satisfy the growing demand for potable water and overcome the obstacles associated with water disinfection and decontamination.

Electrochemical disinfection (ED) is one of the growing applications for inactivating various pathogens [32]. Considering the fundamentals of its overall application, it has become one of the most exciting alternatives to chlorination. Reactive oxygen species (ROSs) produced in such devices prevent the generation of chlorine by-products by eliminating water-based sources of infection in potable water [17]. Scientists are dedicated to suggesting novel electrocatalytic materials and devices and studying the theoretical behavior of water interfaces to develop sophisticated ED processes.

As with chlorination, the ED effectiveness depends primarily on the effective production of the disinfectant and its oxidizing ability [33, 34, 35]. In chlorine-free water, the physically adsorbed hydroxyl radical M($^{\bullet}$OH) is generated by oxidizing water at the anode (M), according to Eq. (1) [3]:

$$M + H_20 \rightarrow M(^{\bullet}OH) + H^+ + e^- \quad (1)$$

$^{\bullet}$OH does not react selectively with various refractory organic substances or water-based pathogens with limited release rates [3]. Nonetheless, the effect of direct oxidation of M($^{\bullet}$OH) is restricted because of the minuscule existence of free radicals, reaction conflict, and the adsorption of a comparatively small number of microbes on the electrode. The quantity of M($^{\bullet}$OH) produced electrochemically depends on the type of electrocatalytic material employed [17, 36]. Consequently, forming electrochemically additional killing agents like chlorine/HClO/ClO^- (known as *active chlorine*), ClO_2, O_3 [37], H_2O_2, peroxydisulfate ($S_2O_8^{2-}$), peroxydicarbonate ($C_2O_6^{2-}$), peroxydiphosphate ($P_2O_8^{4-}$), chloramines, bromine, and

ferrates, in anodic, and rarer in cathodic reactions, is requested.

ED has utilized a range of electrodes, including metals, metal oxides, carbonaceous materials, and dimensionally stable anodes [38, 39, 40]. However, diamond electrodes like boron-doped diamond (BDD) are the most efficacious electrocatalytic materials when decomposing stubborn contaminants [3]. This is due to their ability to produce chlorine-based disinfection agents on-site, as shown in Eqs. (2)-(4), as well as their high production of ROSs, as demonstrated in Eqs. (1) and (5)-(8):

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

$$Cl_2 + H_2O \leftrightarrow HClO + Cl^- + H^+ \quad (3)$$

$$Cl_2 + 4H_2O \rightarrow 2ClO_2 + 8H^+ + 8e^- \quad (4)$$

$$^{\bullet}OH \rightarrow {}^{\bullet}O + H^+ + e^- \quad (5)$$

$$2{}^{\bullet}O \rightarrow O_2 \quad (6)$$

$$2{}^{\bullet}OH \rightarrow H_2O_2 \quad (7)$$

$$O_2 + {}^{\bullet}O \rightarrow O_3 \quad (8)$$

Also, additional oxidizing chemicals can be generated through the oxidation of sulfate (SO_4^{2-}) or bisulfate (HSO_4^-) following Eq. (9), bicarbonate (HCO_3^-) following Eq. (10), and phosphate following Eq. (11) producing $S_2O_8^{2-}$, $C_2O_6^{2-}$, and $P_2O_8^{4-}$, respectively [17, 41]:

$$2SO_4^{2-} \rightarrow 2SO_4^{\bullet-} \rightarrow S_2O_8^{2-} + 2e^- \quad (9)$$

$$2HCO_3^- \rightarrow C_2O_6^{2-} + 2H^+ + 2e\text{-} \quad (10)$$

$$2PO_4^{3-} \rightarrow P_2O_8^{4-} + 2e^- \quad (11)$$

This review highlights advances and outlooks on ED, such as (i) ED using a BDD anode, (ii) pathway and inherent menace of antibiotic-resistant bacteria (ARB) bearing last resort antibiotic resistance genes (ARGs) below electrochemical treatment, (iii) synergistic nanowire-assisted electroporation (EP) and chlorination for demobilizing chlorine-resistant bacteria (CRB), (iv) demobilizing domestic wastewater microbiota using single and sequential electrocoagulation (EC) and electro-Fenton (EFT) techniques, (v) laser-induced graphene (LIG) electrodes can generate highly localized chlorine in-situ during ED, (vi) routes behind EC as an ED technique, (vii) Integrating sunlight with H_2O_2 at renovated reticulated vitreous carbon (RVC) for killing pathogens, (viii) reactive species (RSs) produced electrocatalytically and their contributions in deactivating pathogens, (ix) flow-through electrode system (FES), and (x) applying artificial intelligence (AI) in disinfecting water.

2. Electrochemical disinfection (ED) employing a boron-doped diamond (BDD) anode

While diamond films show great potential as a practical material for creating potent disinfectants, a few limitations hinder their widespread use. In their study, Martínez-Huitle and Brillas [3] explored the basics and utilizations of novel electrochemical techniques that utilize BDD anodes, such as electrochemical oxidation (EO), for purifying drinking water contaminated with waterborne pathogens (**Fig. 1**). Their research highlighted the numerous benefits of these methods, marking a significant advancement in utilizing new technologies to enhance drinking water quality. However, it also challenges researchers, as electrochemical technologies encompass more than treatment methods. EO offers a solution for purifying drinking water. It paves the way for advancing alternative processes or integrating multiple methods that have reduced negative environmental impacts, commonly called process-integrated ecological protection. Martínez-Huitle and Brillas [3] highlighted the innovative application of EO using a BDD anode in endodontics and food quality supervision.

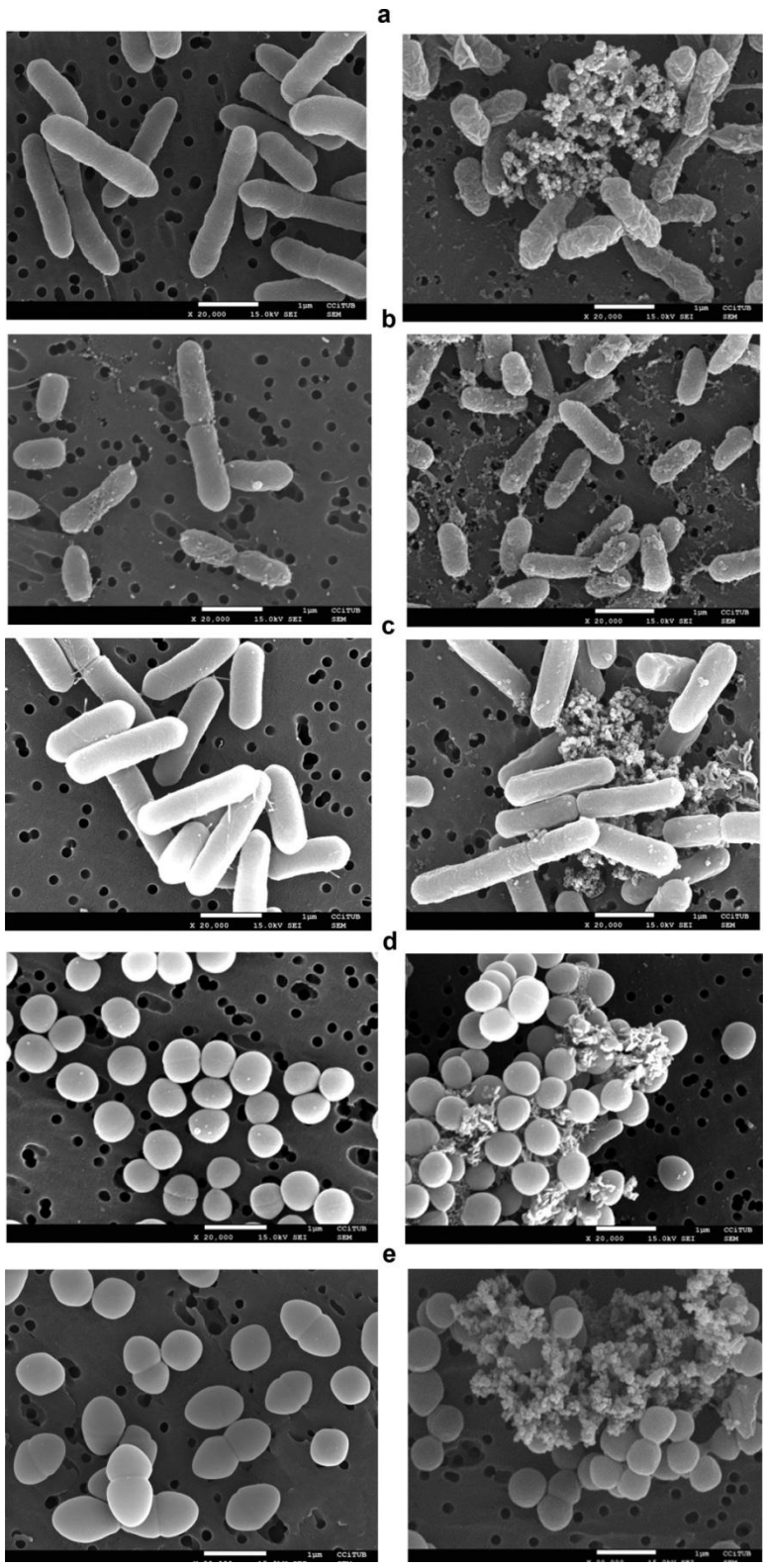

Fig. 1. Scanning electron microscopy (SEM) images for: (a) *Escherichia coli* (b), *Pseudomonas aeruginosa*, (c) *Bacillus atrophaeus*, (d) *Staphylococcus aureus,* and (e) *Enterococcus hirae* supported on polycarbonate membrane filters. Samples correspond to bacteria suspensions in 7 mM Na_2SO_4 at pH 7.0, before (left) and after (right) 45 min of EO treatment with a BDD/stainless steel cell at 33.3 mA/cm^2 and 25°C [42].

ED using diamond electrodes has shown promise in inactivating microbial cells by generating reactive oxidants [43]. BDD anodes have proven effective in EO, but their high cost and decreased efficiency with low pollutant concentrations hinder their industrial application. Further research is needed to explore alternative materials and establish optimal operating parameters to avert the production of poisonous by-products. The effectiveness of hybrid and sequential disinfection methods depends on various factors, and small-scale devices powered by renewable energy sources present a significant challenge. Collaborative efforts among analytical chemists, engineers, and electrochemists are necessary to implement and capitalize on these methods effectively [3].

3. Pathway and inherent menace of antibiotic-resistant bacteria (ARB) bearing last resort antibiotic resistance genes (ARGs) below electrochemical disinfection (ED)

The misuse of antibiotics has led to a significant surge in the number of ARGs, posing a grave menace to persons and the environment [44, 45, 46]. In a recent investigation performed by Meng et al. [47], the researchers examined the effectiveness and mechanism of electrochemical treatment on hospital wastewater containing six different bacteria carrying three last resort ARGs: *NDM*-1, *mcr*-1, and *tet*X. The findings revealed that the elimination performance of ARGs augmented as the voltage and electrolysis period were raised, with a maximum removal efficiency of up to 90%. The optimal treatment parameters were determined to be 3 V for voltage and 120 min for electrolysis. Factors such as temperature and pH had minimal impact on the electrochemical treatment process. To better comprehend the route governing the electrochemical treatment, the researchers employed scanning electron microscopy (SEM) and flow cytometry to examine the changes at macroscopic and microscopic levels. The results demonstrated that the electrochemical treatment induced significant alterations in cell membrane permeability and triggered a sequential progression of early and late cell apoptosis and necrosis. Furthermore, electrochemical treatment was found to have fewer inherent hazards when compared to conventional disinfection techniques. Applying this treatment resulted in a substantial decrease in the transfer frequencies of conjugative cells. It was observed that less than 1% of bacteria entered the viable but nonculturable state, and the conversion of intracellular ARGs to extracellular ARGs was less than 5% (**Fig. 2**). These findings offer valuable knowledge and serve as crucial points of reference for the future utilization of electrochemical treatment to eliminate ARB from hospital wastewater [47].

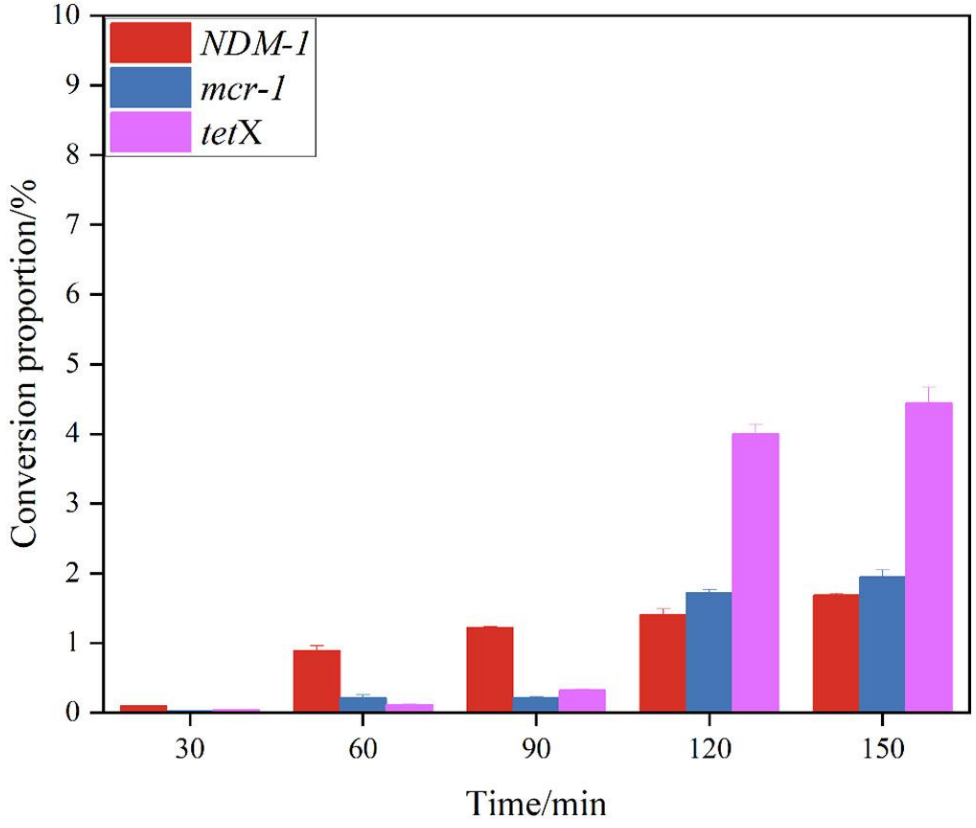

Fig. 2. Conversion rate of intracellular antibiotic resistance genes (ARGs) to extracellular ARGs [47].

Activated persulfate (PS) to deactivate ARB has recently gained attention. However, limited information is available on antibiotic resistance (AR) transmission hazards following ARB deactivation using activated PS. In this context, Zuo et al. [48] conducted batch experiments to study the inactivation of target ARB (specifically, *E. coli* K-12 bearing bla_{TEM}, *tet*R, and *aph*A) throughout disinfection with activated PS employing Fe/C microelectrolysis and UVA/LED irradiation. The results showed that following 60 min of disinfection under pH 5 with Fe/C activation of PS, there was a significant 5.3 logs reduction in ARB inactivation, compared to a 4.7 logs reduction with UVA/LED activation of PS. Further exploration of the mechanisms behind ARB inactivation revealed that both $O_2^{\bullet-}$ and $^1O_2$ were the main ROSs responsible for ARB demobilization. Additionally, the frequency of ARG conjugation transfer was higher (2.0×10^{-4}) following 20 min of disinfection with activated PS using UVA/LED, juxtaposed to a lower frequency (2.8×10^{-5}) with Fe/C activation of PS. On the other hand, the frequency of AR transformation following the disinfection process using Fe/C activation of PS was marginally more significant compared to the disinfection process using UVA/LED activation of PS. This observation aligns with the patterns observed in intracellular ROSs' levels and the permeability of ARB membranes. Moreover, complete inactivation of ARB was achieved after a 40-minute disinfection period using the integration of UVA/LED and Fe/C for PS activation, suggesting that the integration setup, as mentioned earlier, holds promise in preventing the transmission of AR in this particular study [48].

The use of milliampere-range current for electrochemical inactivation of bacteria is well-established. However, it is crucial to consider the potential sublethal effects on ARB because of poor mixing or energy-saving procedures through ED. The impact of these sublethal current intensities on plasmid transfer from ARB remains unknown. Li et al. [49] focused on the conjugal transfer of plasmid pKJK5 among *Pseudomonas putida* strains below circumstances simulating ED. As the implemented current augmented from 0 to 60 mA, the occurrence of culturable and membrane-intact donor and recipient cells reduced. However, both the density and frequency of transconjugants increased. Electrolytic generation of chlorine/HClO/ClO^- and $O_2^{\bullet-}$ led to the induction of ROSs generation. Additionally, a significant upregulation of the core oxidative stress defense gene ahp_{CF} was observed during increasing current density (CD). The expression of selected conjugation-related genes tra_E, tra_I, trb_J, and trb_L also considerably linked with CD. Consequently, the buildup of ROSs and the subsequent release of conjugation repression are the likely outcomes of exposure to non-lethal electric current [50]. These discoveries indicate that mild levels of current have the potential to increase the transfer of plasmids through conjugation, emphasizing the need for precise control over the conditions of electrodialysis to prevent the circulation of ARGs through conjugation.

4. Combined nanowire-supported electroporation (EP) and chlorination for demobilizing chlorine-resistant bacteria (CRB)

Chlorine disinfection, known for its cost-effectiveness and effective sterilization properties, is widely acknowledged as a prevalent disinfection method [51]. It offers the advantage of maintaining residual chlorine levels that can inhibit microbial regrowth over extended periods and distances within distribution systems up to the point of use [52, 53]. However, the extensive use of chlorine has led to the emergence of CRB [51], which threats public health by promoting pathogen-renewed expansion and biofilm generation in pipe reseau [54, 55]. Consequently, it is crucial to explore strategies for managing CRB in drinking water systems.

The mechanisms responsible for the deactivation of bacteria through the use of chlorine disinfectants involve either the oxidative destruction of cell membranes to increase cell permeability or the penetration of chlorine into cells to oxidize intracellular functional components, such as enzymes or deoxyribonucleic acid (DNA) [56, 57]. Bacteria that exhibit resistance to chlorine typically produce higher levels of extracellular polymeric substances (EPSs) that adhere to the cell surface compared to chlorine-sensitive bacteria [51]. These EPSs act as barriers to prevent chlorine from entering the cells or as reactive substances that consume chlorine [58]. Consequently, it is crucial to develop a strategy that enhances the permeation of chlorine into bacterial cells to ensure adequate exposure for effective deactivation of CRB.

Alternative approaches that combine chlorination with UV radiation have been created to improve the effectiveness of disinfection. These methods include UV/Cl_2, UV/free chlorine, and UV/NH_2Cl. The primary reason for their enhanced disinfection capabilities is their significantly greater oxidation capacity than traditional chlorine chemicals. Furthermore, by utilizing a combination of disinfection methods, it is possible to reach the wanted degree of killing pathogens while

simultaneously reducing the amount of chlorine needed and minimizing the production of DBPs [59, 60]. Despite these advantages, the effectiveness of these combined methods in eliminating CRB is hindered by the presence of EPSs, which create a barrier that competes with the oxidation mechanisms [51].

The lightning-rod impact on nanowires has the potential to significantly amplify the EF at their keen extremities. Building on this discovery, researchers developed EP disinfection using electrodes equipped with nanowire arrays [51]. This innovative approach utilizes a locally enhanced electric field (LEEF) generated by low-voltage driving (< 3 V) to deactivate both Gram-positive (G+) and Gram-negative (G-) microorganisms effectively [*61*, 62, 63]. When exposed to an EF exceeding 10^5 V/m, the lipid bilayer of bacteria undergoes rearrangement, forming irreversible or reversible pores. This membrane damage or cytoplasm leakage leads to bacterial inactivation [64, 65]. Notably, nanowire-assisted EP demonstrates remarkable stability when operating in complex water matrices. This suggests that the competitive oxidation of EPs has minimal impact on the effectiveness of EP disinfection. However, it is essential to acknowledge that the absence of steady disinfection capability hinders the application of individual EP for potable water storage and distribution.

In addition to the lethal EP pores that effectively deactivate bacteria, reversible EP pores result in minor cytoplasm leakage when the EF exposure is insufficient. However, these pores can be sealed rapidly because of the agility of the lipid membrane without compromising microbial existence. Recent studies have demonstrated that strong EFs that treat *Bacillus pumilus*, *Saccharomyces cerevisiae*, and *Chlamydomonas reinhardtii* cells can lead to irreversible pores on the stiff cell enclosure [51]. These EP-created pores on the cell enclosure and membrane can potentially disrupt the thick EPSs film that binds to the cell. Therefore, it can be inferred that the combination of EP and chlorination can create reversible EP-induced cell pores, which serve as channels for chlorine permeation and aid in the inactivation of CRB.

Lu et al. [51] conducted a study using Co_3O_4 nanowire-supported EP and Cl_2 (EP/Cl_2) to explore bacterial inactivation's combined effects and underlying mechanisms. To make a valid comparison, they included chlorine-sensitive *Escherichia coli* (*E. coli*, G-), while they chose *Bacillus cereus* (*B. cereus*, G+) and *Aeromonas media* (*A. media*, G-) as the chlorine-resistant strains due to their recurrent presence in water treatment devices and high resistance to chlorine [66, 67]. They examined the synergistic effects of EP/Cl_2 by varying EP voltages and chlorine injections and juxtaposed them to the consecutive EP and Cl_2 (EP+Cl_2) method and the single Cl_2 and EP techniques (**Fig. 3**). They elucidated the mechanisms behind the synergistic effects. Furthermore, they investigated the potential use of combined EP/Cl_2 in treating actual water resources.

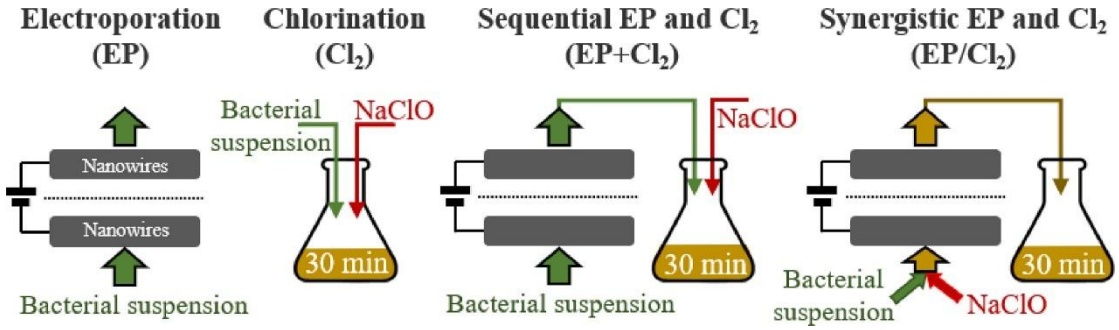

Fig. 3. Disinfection techniques of single electroporation (EP), single chlorination (Cl_2), consecutive EP and Cl_2 (EP+Cl_2), and combined EP and Cl_2 (EP/Cl_2) [51].

Integrating EP and Cl_2 disinfection, known as *synergistic EP/Cl_2*, has proven to be significantly more effective in inactivating various bacteria, comprising chlorine-resistant and sensitive microbes, and G+ and G- bacteria [51]. This superior efficacy is observed when juxtaposed to the single EP or Cl2 processes solo. The mechanisms behind this synergistic disinfection have been uncovered (**Fig. 4**). The presence of nanowires creates a LEEF, which induces the creation of pores on the cell enclosure, membrane, and EPSs layer. This, in turn, facilitates the permeation of chlorine and leads to oxidative destruction of cell constructions, ultimately resulting in microbial demobilization. The effectiveness of EP/Cl_2 has been demonstrated in the treatment of chlorine-resistant *B. cereus* in raw water, highlighting its potential usage in complex water matrices (**Fig. 5**) [51].

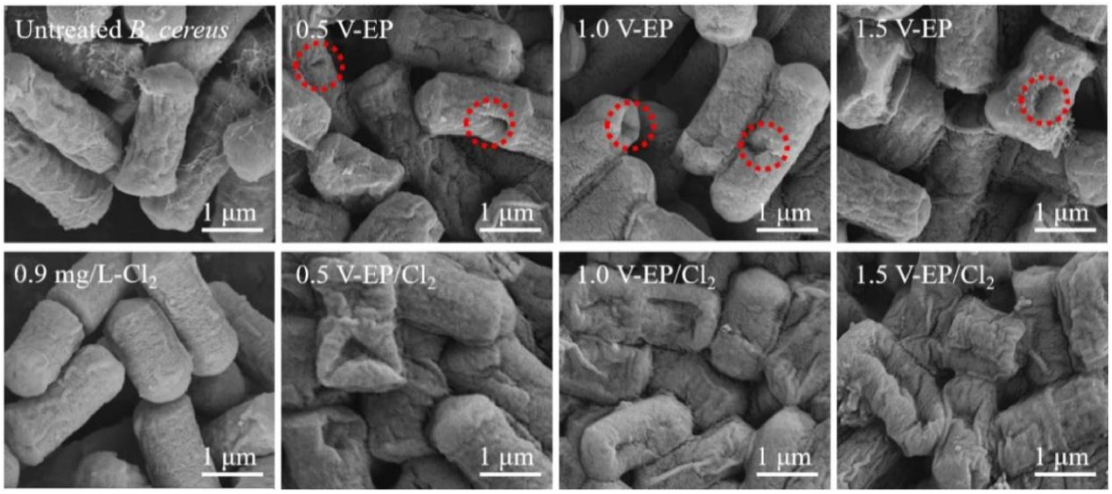

Fig. 4. Scanning electron microscopy (SEM) images of *B. cereus* before and following electroporation (EP), Cl_2, and EP/Cl_2 treatment [51].

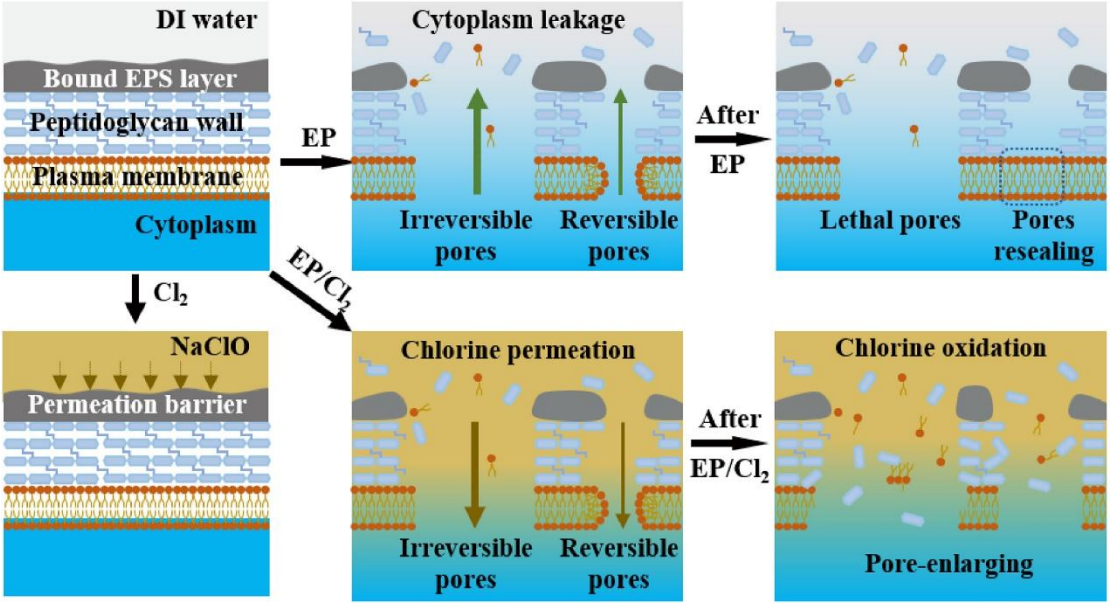

Fig. 5. Schematics of combined pathways of electroporation (EP)/Cl_2 for demobilizing chlorine-resistant bacteria (CRB) using Gram-positive (G+) bacterium [51].

In their study, Zhao et al. [68] developed a novel method for water disinfection using piezoelectric aluminum oxide (PEAO). By implementing ultrasonication, the piezo-catalytic disinfection system generated a powerful EF magnitude of 8.1×10^7 V/m on the surface of PEAO, pursued by induced *in-situ* EP of bacterial cell membranes, allowing for the penetration of ROSs, such as $^{\bullet}OH$ and singlet oxygen ($^1O_2$) [69], and H_2O_2. The proposed piezo-catalytic disinfection approach demonstrated remarkable efficacy against various microbes, surpassing the disinfection capabilities of an equivalent amount of preformed H_2O_2 by approximately 1000-fold. As a result, it significantly enhanced oxidant employment, improved killing pathogens' performance, and considerably reduced the generation of DBPs. Zhao et al. [68] showcased the usage and pathway of PEAO's *in-situ* flexible water disinfection method and hinted at its potential applications in other water treatment areas.

Dong et al. [70] aimed to enhance the properties of Cu_7S_4 nanowires developed on copper foam by applying a coating of *N*-doped carbon and Ag particles. This coating resulted in improved conductivity, localized field enhancement regions, and enhanced longevity and physical firmness of Cu_7S_4. Density functional theory calculations determined that diverse types of N doping led to variations in electron difference density and work function of the surrounding carbon, thereby

promoting high carrier transport capacity at the interface. Additionally, the presence of Ag anchored in *N*-doped carbon layers facilitated the adsorption of O_2. The material exhibited a band gap of 2.12 eV and demonstrated the ability to produce $O_2^{\bullet-}$ below energy excitation. Notably, when subjected to a voltage of 6 V and a water flow rate of 1000 mL/min, the material effectively achieved long-term water filtration sterilization of highly concentrated microbes. Even after continuous treatment for 8 h, the removal efficiency remained at an impressive 99%. These findings highlight the promising applications of this research in the future purification of heavily contaminated water sources.

As seen above, using nanowire-assisted EP has been widely adopted as a highly effective process for disinfecting drinking water at the point of use. However, its effectiveness when using direct voltage (DV, U) is hindered by two main factors: the limited microbial demobilization on the cathode and microbial adsorption-fouling on the anode. To address these limitations, Lu et al. [71] applied square-wave alternating voltage (SWAV, ±U) to the nanowire electrodes, which allowed for the periodic reversal of the cathodic/anodic polarity and their interactions with microbes. This reversal process proved highly beneficial, promoting cell demobilization and enhancing fouling resistance. When comparing the performance of DV supply to SWAV supply, Lu et al. [71] observed a progressive reduction in cell demobilization due to biofouling on the nanowire anode below DV supply. On the other hand, SWAV supply assured fixed and performant treatment, resulting in approximately 2 logs more significant cell demobilization. Additionally, the energy consumption was significantly reduced, with approximately 3 times lower energy consumption (ranging from 0.32 to 11.3 Wh/m^3/log at 1.0 to 3.0 V) for various types of bacteria, including G- bacteria (*E. coli* and *Acinetobacter schindleri*) as well as G+ bacteria (*Enterococcus faecalis* and *B. cereus*). These results were consistent across different water sources. The primary cause of microbial demobilization at voltages < 3.0 V was determined to be EP on nanowire interfaces with LEEFs. It was discovered that cell migration, adsorption, and desorption on the nanowire interface were regulated by the reversion of electrophoretic and electrostatic attractions under SWAV application, resulting in cell inactivation and fouling resistance on both nanowire electrodes. This significant finding establishes a steady and performant strategy for killing microorganisms through nanowire-assisted EP.

As affirmed above, the $^{\bullet}$OH-dominated electrochemical process has emerged as a promising disinfection technology due to its high efficiency, eco-friendly nature, and absence of DBPs. However, there have been inconsistent reports regarding the disinfection performances of G+ and G- bacteria in systems dominated by $^{\bullet}$OH. To comprehensively understand these differences, Zhang et al. [72] fabricated a Fe-Co/CA cathode and a Ru-Ir/Ti anode investigating the responses of G+ and G- bacteria. At a CD of 22.73 mA/cm^2, *E. coli* was demobilized entirely during 45 min, and approximately 2 logs of *Staphylococcus aureus* were also eliminated. Interestingly, the sublethal laceration observed in *E. coli* was more pronounced than *S. aureus*. However, when *E. coli* and *S. aureus* coexisted, the killing efficacies were hindered for both bacteria. Furthermore, the subcellular deterioration inflicted on *E. coli* and *S. aureus* differed. The treatment increased the cell surface hydrophobicity of both bacteria. However, *E. coli* augmented negative zeta potential following the ED, contributing to its enhanced disinfection. On the other hand, *S. aureus* experienced a decrease in negative zeta potential, leading to significant accumulation. Through the analysis of malondialdehyde levels, phosphate concentration, lactate dehydrogenase leakage, protein degradation, total organic carbon (TOC) levels, nucleic acid degradation, and observation under SEM, it was evident that the cell wall and cell outer membrane served as the primary defense against disinfection dominated by $^{\bullet}$OH. The resistance of *S. aureus* can be attributed to the substantial thickness and rigidity of its cell wall and the stable structure of peptidoglycan within its cells.

5. Demobilizing domestic wastewater microbiota using sole and consecutive electrocoagulation (EC) and electro-Fenton (EFT) techniques

Anfruns-Estrada et al. [73] worked on assessing and comparing the disinfection capabilities of two distinct electrochemical processes: EC [74, 75, 76, 77] and EFT. Specifically, they investigated the effectiveness of these technologies in treating primary and secondary effluents derived from domestic sources. Indicator microorganisms were examined in wastewater treatment plants. Using an EC system with a Fe/Fe cell operating at 200 A/m^2 and natural pH, it was possible to achieve a removal of over 5 logs for *E. coli*, reducing the final concentration of coliphages and eukaryotes to below one bacterium/mL in approximately 60 min. However, heterotrophic bacteria, enterococci, and spores showed more excellent resistance to elimination. The primary effluent, which contained higher levels of TOC entrapped within

flocs, exhibited a higher removal rate due to easier entrapment of the microbiota. EFT treatment, utilizing a BDD anode and an air-diffusion cathode to generate on-site H_2O_2, was initially conducted at pH 3.0, resulting in significant or complete demobilization of pathogens within 30 min. EFT proved more performant in removing microorganisms than EC, as the Fenton reaction generated $^{\bullet}OH$ that facilitated more excellent microorganism removal. The secondary effluent, with lower TOC content, experienced faster disinfection due to more electrogenerated oxidants attacking the microorganisms. The disinfection of wastewater using EFT was proven achievable even at the natural pH level of around 7.

This process exhibited a comparable reduction of active microorganisms due to the combined effects of active chlorine generated by EFT [79] and coagulation with $Fe(OH)_{2(s)}$ [80]. A consecutive treatment of EC [81] and EFT, with each process lasting 30 min, was found to be more effective for a more efficient approach to decontaminating and disinfecting urban wastewater [73].

6. Laser-induced graphene (LIG) electrodes can generate highly localized chlorine *in-situ* during electrochemical disinfection (ED)

LIG has become popular in ED thanks to its practical ability to kill microorganisms using low voltages, even if the precise antimicrobial mechanisms of LIG electrodes are still not fully understood. Zhang et al. [82] focused on shedding light on the various mechanisms that work together to deactivate bacteria during ED with LIG electrodes. These mechanisms include oxidant production, pH changes (specifically, the elevated alkalinity linked with the cathode), and electro-adsorption on the electrodes. Such routes could participate in killing pathogens if microbes are near the electrode. Interestingly, the demobilization of bacteria near the electrode surface was not a function of reactive chlorine species (RCSs).

In contrast, RCSs were likely the primary origin of antimicrobial impacts in the volume suspension (i.e., volumes ≥100 mL) [82]. Additionally, the level and spreading kinetics of RCSs in the suspension were found to be a function of voltage. At 6 V, RCSs reached an elevated level in the solution; however, at 3 V, RCSs were mainly found on the LIG surface and were not detectable in the solution. Nonetheless, LIG electrodes operated by 3 V attained a significant mitigation (5.5-logs) in *E. coli* following 120 min of application, in the absence of any noticeable chlorine, chlorate, or perchlorate in the solution. These findings suggest that LIG electrodes activated by low voltages have great potential for efficacious, energy-saving, and secure ED.

Shahnaz and Hayder [83] discussed graphene-based materials and their capability for antimicrobial utilizations in killing pathogens. These materials exhibit solid antimicrobial characteristics, efficiently preventing microbial fixation, impeding biofilm formation, and suppressing expansion.

They explored the pathways through which graphene-based materials exert their antibacterial effects, presenting them as promising avenues for mitigating microbial contamination in water sources. Their wide-ranging efficacy and capacity for improved filtration effectiveness make them an intriguing option. They focused on the efficiency, scalability, and cost-effectiveness of graphene-based antimicrobial process and shed light on the transformative potential of such materials in disinfection, offering enhanced water quality and the protection of public health.

7. Routes behind electrocoagulation (EC) as an electrochemical disinfection (ED) technique

Govindan et al. [84] suggested a comprehensive examination of the disinfection mechanism in the simple EC process. They reviewed and explained the mechanism by which EC removes biomass, including bacteria, viruses, and algae, delving into the impact of important operating parameters, such as dissolved matters and microbial cell enclosure constitution, on pathogens mitigation. They identified two main routes for bacteria removal throughout the EC method employing consumable electrodes (**Fig. 6**): physical removal through enntrapment of pathogens via EC flocs and sweep coagulation [6, 85], which is particularly effective against negatively charged biomass [85], as well as demobilization/reduction of microorganism cell enclosures through created ROSs (even if pieces of evidence remain required [86]) or direct interaction with the EF [87, 88]. These abatement mechanisms work independently and synergistically to achieve overall disinfection during the EC process [89, 90, 91].

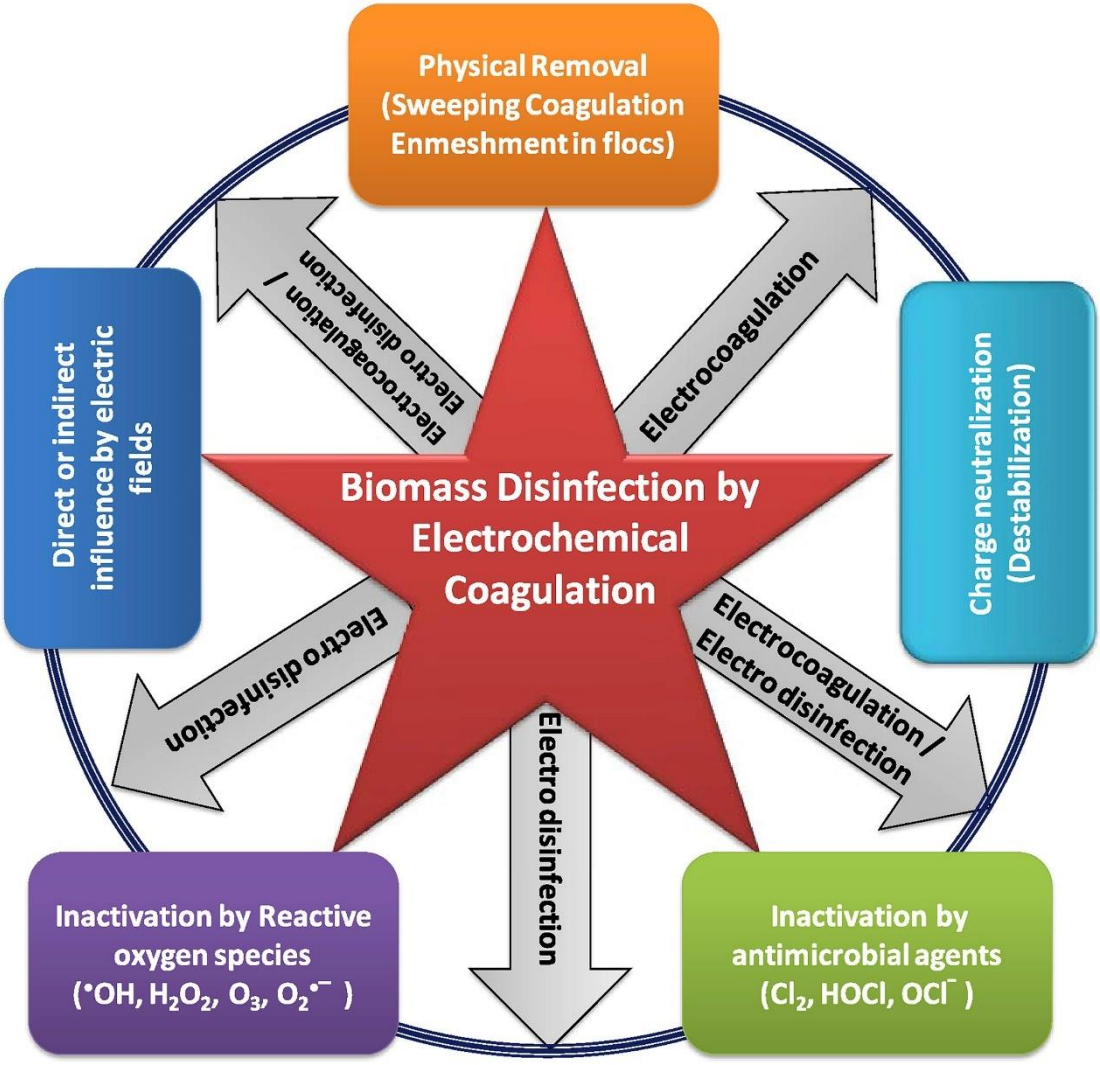

Fig. 6. Likely pathways of biomass killing phenomenon by electrocoagulation (EC) [84].

To gain a deeper comprehension of how the virus and algae are controlled, further experiments on the removal of algae and viruses are necessary [92]. Ultimately, it is crucial to conduct more extensive research on biomass reduction through EC to strengthen this assertion [93, 94].

8. Integrating sunlight with H_2O_2 at renovated reticulated vitreous carbon (RVC) for killing pathogens

The need for extended handling periods limits the effectiveness of solar disinfection (SODIS) [95, 96]. Due to the low levels of electrolytes in water, it is challenging to produce an adequate amount of H_2O_2 for killing microbes through electrochemical reduction (ER). To address this issue, researchers [97] explored the combination of SODIS and ER. They used an anodized RVC cathode (**Fig. 7**) and analyzed its performance using SEM (**Fig. 8**) and X-ray photoelectron spectroscopy. They examined the roles of both the ER and SODIS in killing pathogens and the effects of CD and humic acid (HA). They revealed that the modification of the RVC cathode resulted in adding oxygen-bearing functional groups and a twofold increase in H_2O_2 production. When they applied the combined technique to eliminate *E. coli*, the initial enumeration of about 10^6 colony-forming units (CFUs) per mL dropped under the observation beginning (< 4 CFUs/mL) following 120 min. Compared to SODIS and ED alone, the hybrid method demonstrated a 60% and 20% reduction in disinfection time, respectively. By increasing the current, the duration of treatment was shortened from 150 to 90 min despite the higher power use. Disinfection was enhanced with a small level of HA (1 mg/L). However, a relatively high concentration of HA (4 mg/L) hindered the demobilization of *E. coli*. The residence period was decreased from 120 to 90 min by increasing the temperature from 20 to 40°C, and the electricity consumption per log of *E. coli* decreased from 102.2

to 64 Wh/m^3. Jin et al. [97] provided evidence that integrating SODIS and H_2O_2 electrogeneration is an efficient and energy-saving approach to remove microbes.

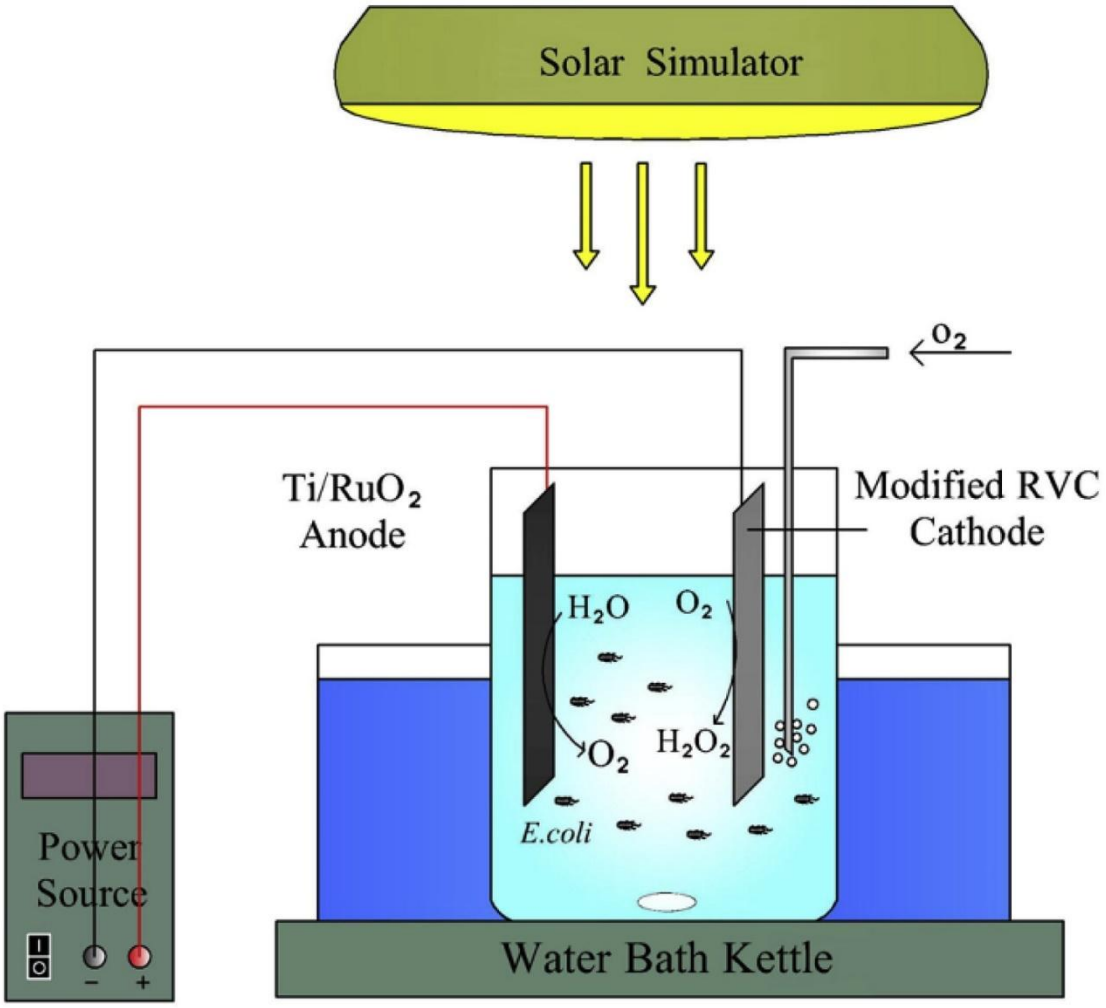

Fig. 7. Configuration of the device employed by Jin et al. [97].

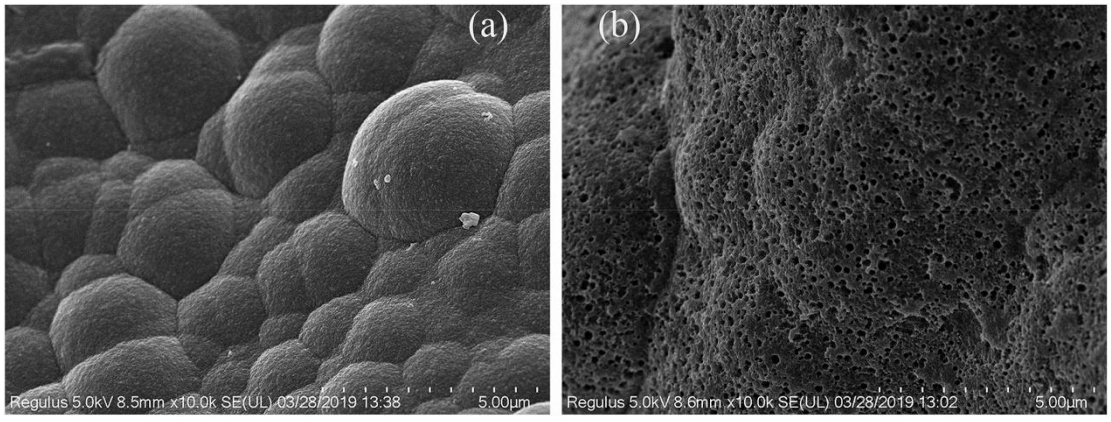

Fig. 8. Scanning electron microscopy (SEM) images of (a) the unaltered reticulated vitreous carbon (RVC) and (b) altered RVC electrodes [97].

9. Reactive species (RSs) produced electrocatalytically and their contributions in deactivating pathogens

As seen above, controlling microbes can be effectively achieved through electrochemically generated RSs. Nichols et al. [98] presented a comprehensive overview of recent advancements in the electrocatalytic production of RSs and their usage in eliminating bacteria. They focused on the selective formation of RSs and the interplays between microorganisms and these RSs, including exploring the mechanisms by which RSs act on microorganisms and the innate responses of microorganisms to these RSs.

In addition to the traditional chlorination method, water disinfection can be achieved through chemical processes that involve oxidation to remove contaminants [98]. Advanced oxidation processes (AOPs) like ozonation and UV light have efficiently dealt with water. Another sustainable approach to efficient water disinfection is electrochemistry, which becomes increasingly viable as renewable electricity sources become more prevalent [99]. While AOPs primarily focus on producing highly oxidizing substances like $^{\bullet}OH$, recent research has also explored the electrochemical generation of various other RSs for water treatment (**Fig. 9(a)**). These include ROSs, such as $O_2^{\bullet-}$, and H_2O_2, RCSs, reactive nitrogen species (RNSs), and reactive sulfur species (RSSs). Bacteria's vulnerability to RSs is well-documented, as their exposure can destroy proteins, DNA, and lipid membranes, ultimately causing cell demise [98]. This characteristic makes the electrochemical production of RSs a highly appealing method for eliminating microorganisms during water treatment (**Fig. 9(b)**).

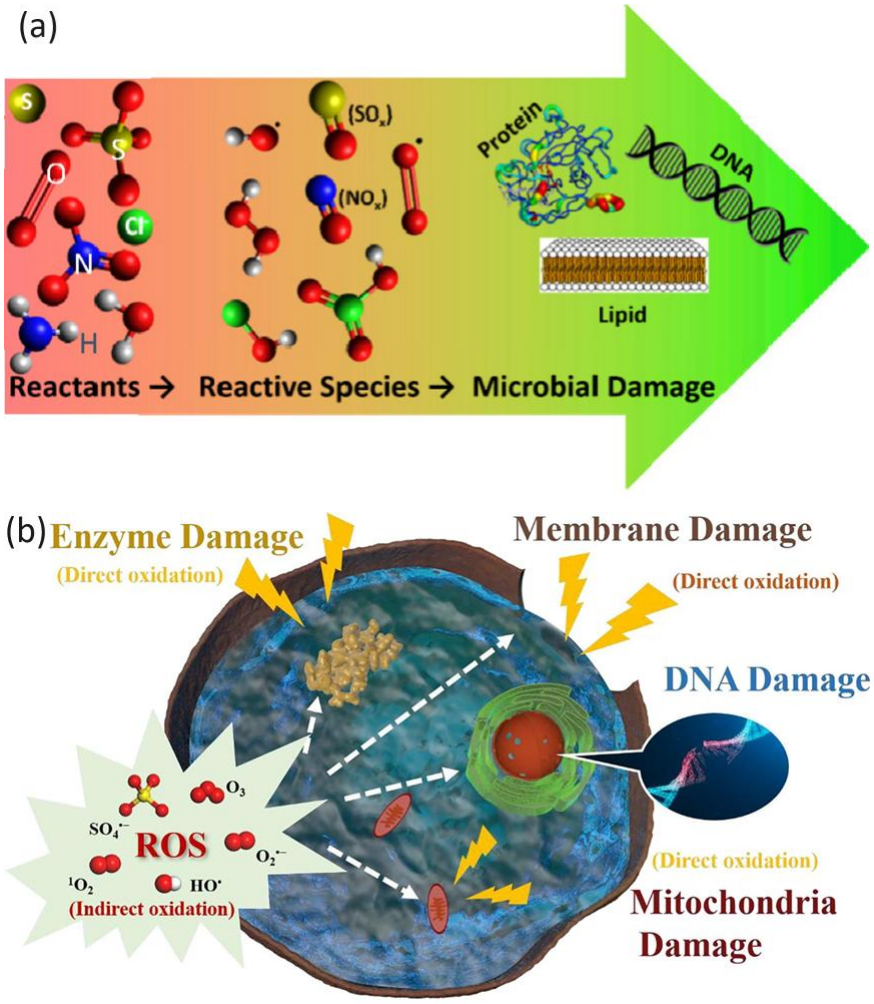

Fig. 9. (a). Illustrative depiction of reactive species (RSs) electrosynthesis and corresponding targets for bacterial harm. Spheres illustrate oxygen (red), hydrogen (grey), chlorine (green), sulfur (yellow), and nitrogen (blue) atoms [98]. (b). Depiction of the demolition of the cell envelope, enzyme, and deoxyribonucleic acid (DNA) by diverse reactive oxygen species (ROSs) [100].

Compared to photocatalysis, electrochemical RSs generation offers numerous benefits. One notable advantage is its capability to effectively disinfect various types of polluted water, even turbid or cloudy, which would hinder the transmission of light required for photocatalytic treatment. Additionally, electrochemical devices allow for precise control of the energy input, as they rely on electricity for decontamination. Further examination of the advantages and disadvantages of electrochemical RSs generation is given elsewhere [98].

As discussed above, extensive research into the impact of ROSs and RCSs on the failure of bacterial cells has played a vital role in developing EO disinfection techniques. Zhang et al. [82] utilized fresh Na_2SO_4 and a chloride-containing solution to form ROSs and RCSs individually. Applying a CD of 14.4 mA/cm^2, 5 logs in *E. coli* were significantly reduced after 60 min of application in the fresh Na_2SO_4 solution. In contrast, the inactivation of *E. coli* occurred within 15 min in the chloride-containing solution, considering that the primary level was approximately 7.5 logs. The EO disinfection process heavily relies on damaging the cell membrane. When a CD of 3.6 mA/cm^2 was applied, around 1.1 logs cells were harmed, approximately 37 times higher than the number of demobilized cells after 5 min of resdience in the fresh Na_2SO_4 solution. The demobilization of *E. coli* in the fresh Na_2SO_4 electrolyte was attributed to $^{\bullet}OH$ and $O_2^{\bullet-}$, while hypochlorite controlled the chloride-containing solution. Notable changes were noticed on the treated cells, with no discernible differences between the effects of ROSs and RCSs. In contrast, the ROSs primarily target total protein, not RCSs. The variations in absorbance, TOC, and potassium ion leakage showed minor disparities. The degradation of nucleic acid substances is evident in the ED process, but further investigation is required to understand the impact on nucleic acid fragments.

The utilization of anodic oxidation to eliminate unconsumed H_2O_2 in the occurrence of Cl^- has been identified as an effective ED method, ensuring the bacterial protection of handled water [101]. HOCl, formed at the anode, oxidizes H_2O_2 to produce $^1O_2$. Although $^1O_2$ is widely recognized as a crucial disinfectant in SODIS, its role in ED has not been previously reported. The presence of $^1O_2$ was established by detecting $^1O_2$ monomol release employing a near-infrared imaging setup. During the anodic oxidation of H_2O_2 with Cl^-, the level of $^1O_2$ could attain 1.64 pM. In the inactivation of *E. coli*, $^1O_2$ has a significant contribution, while HOCl only plays a minor role due to its low concentration in the occurrence of 1 mM H_2O_2. For instance, the combined demobilization of *E. coli* by H_2O_2 alone and micro-concentration HOCl contributes to approximately 2 logs in 60 min, whereas $^1O_2$ alone accounts for around 3 logs. Moreover, there was a considerable decrease in the creation of chlorinated DBPs, and the rapid degradation of HOCl by H_2O_2 was advantageous. These results hold promise for decentralized water treatment systems utilizing H_2O_2 and present an innovative approach to ED, as electrochlorination encounters challenges similar to those of traditional chlorination methods [101].

10. Flow-through electrode system (FES): A practical procedure for controlling biofouling in reverse osmosis (RO) membranes for treating domestic used water

Arising ED processes promise to control biofouling in reverse osmosis (RO). Nonetheless, the performance and pathway of these techniques below low-voltage circumstances following flow-through conditions are still poorly understood [102]. In this context, Wang et al. [103] investigated the impact of an FES utilizing both direct current (DC) and alternating pulse current (AC) on the control of biofouling in RO. Contrasted to chlorine utilization, the AC-FES group demonstrated a significantly higher normalized flux at the starting phase of biofouling growth, with a 67% flux on Day 5 compared to the control group's 56%. As the biofouling progressed, the normalized fluxes of both groups became more similar, showing minimal differences until the 20th day. Following a gentle chemical cleaning, the AC-FES group exhibited the most outstanding chemical purifying performance at 58%, indicating that its foulant was more easily eliminable and the biofouling was more changeful. The DC-FES group also displayed cleanable biofouling layers. Analysis of the fouling layers' morphology revealed that differences in thickness and compactness were the main factors influencing fouling behavior. Additionally, four fouling-related genera significantly correlated with the degree of biofouling.

AC-FES is a viable substitute for chlorine utilization in controlling biofouling in RO systems. It offers lower operating costs compared to chlorine disinfection and promotes the formation of a biofouling layer that is easier to clean and less severe through two key advantages (**Fig. 10**): firstly, it reduces the renewed expansion capability of microbes following treatment, resulting in reduced initial fouling; secondly, it alters the bacterial population, favoring organisms with weaker

biofilm generation capabilities. In conclusion, AC-FES shows excellent promise as an effective method for biofouling control in RO systems [103].

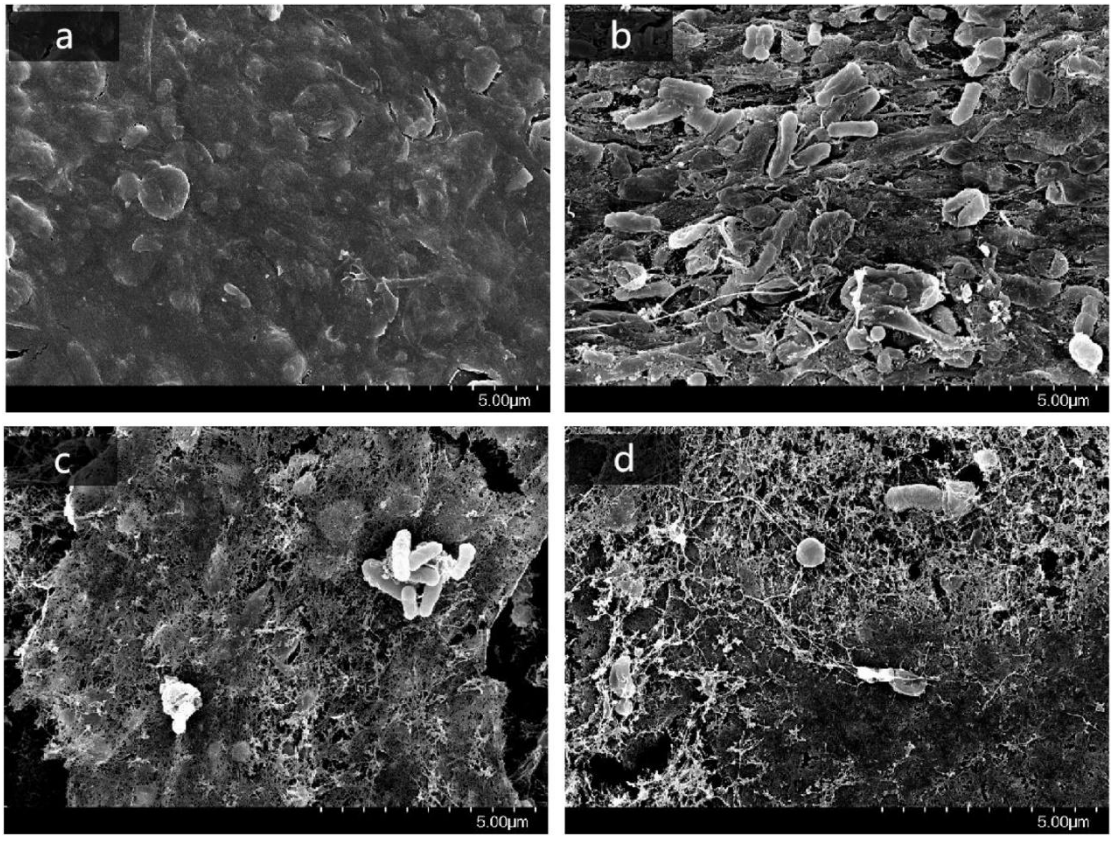

Fig. 10. Scanning electron microscope (SEM) images of the fouled layer. (a) Control, (b) Cl_2, (c) direct current (DC)-flow-through electrode system (FES), (d) alternating pulse current (AC)-FES [103].

As discussed above, the emergence of electrochemical flow-through setups as an encouraging process for addressing universal dares is due to their improved mass transfer and uncovered energetic sites, which surpass conventional parallel plates and flow-by dispositions. These setups are recently being examined for different water treatment methods. In recent years, there has been a rapid augmentation in exploration on the implementations of electrochemical flow-through setups in water handling, resulting in significant advancements. Feng et al. [104] summarized the progress made in this field and highlighted the key achievements.

Tanaka et al. [105] developed a novel electrochemical system to disinfect seawater utilizing a titanium electrode coated with platinum in a honeycomb pattern (**Fig. 11**). Cell suspensions containing fish pathogens were distributed in a device with ten series of such electrodes. The flow rate was set at 200 mL/min, and an applied voltage of 1.0 V *vs.* Ag/AgCl reference electrode was maintained. After a treatment period of 3 h, the distributed pathogens were neutralized entirely.

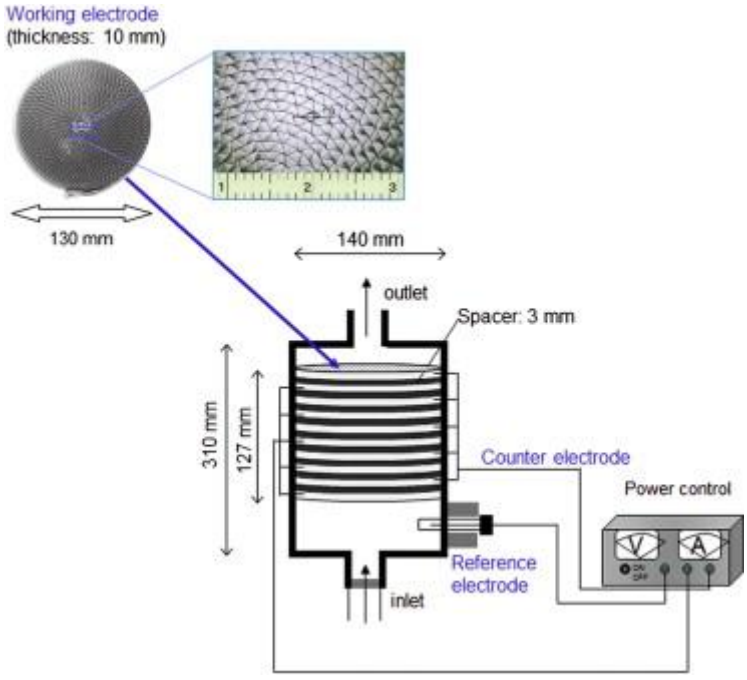

Fig. 11. A flow reactor was designed with honeycomb titanium electrodes coated in platinum [105].

Seawater electrolysis through the operation resulted in the generation of residual chlorine, which was measured to be below 0.1 mg/L. Furthermore, an assessment using a diphenyl-1-pyrenylphosphine fluorescent test indicated that the electrochemical treatment likely induced lipid peroxidation in the cell membranes of the demobilized microbes, potentially due to the presence of ROSs. These electrodes were arranged in a stack within the reactor [105].

11. Applying artificial intelligence (AI) in disinfecting water

Traditional disinfection models could not effectively deal with complex nonlinear circumstances and furnish instantaneous responses due to water quantity and quality fluctuations through treatment. However, AI techniques have shown great promise in accurately predicting and adjusting outputs promptly, as they can capture intricate variations. Ding et al. [106] utilized CiteSpace to analyze and examine AI's application in water disinfection. They explored its use in traditional disinfection processes and investigated its potential in novel methods. Additionally, they discussed the implementation of AI in controlling the generation of DBPs and predicting disinfection residue, including examining unregulated DBPs (**Fig. 12)**. Current research indicates that fuzzy logic-based neuro systems, among various AI techniques, demonstrate superior control performance in water disinfection. However, it is essential to note that a single AI technology cannot fully support its implementations in large-scale water treatment facilities.

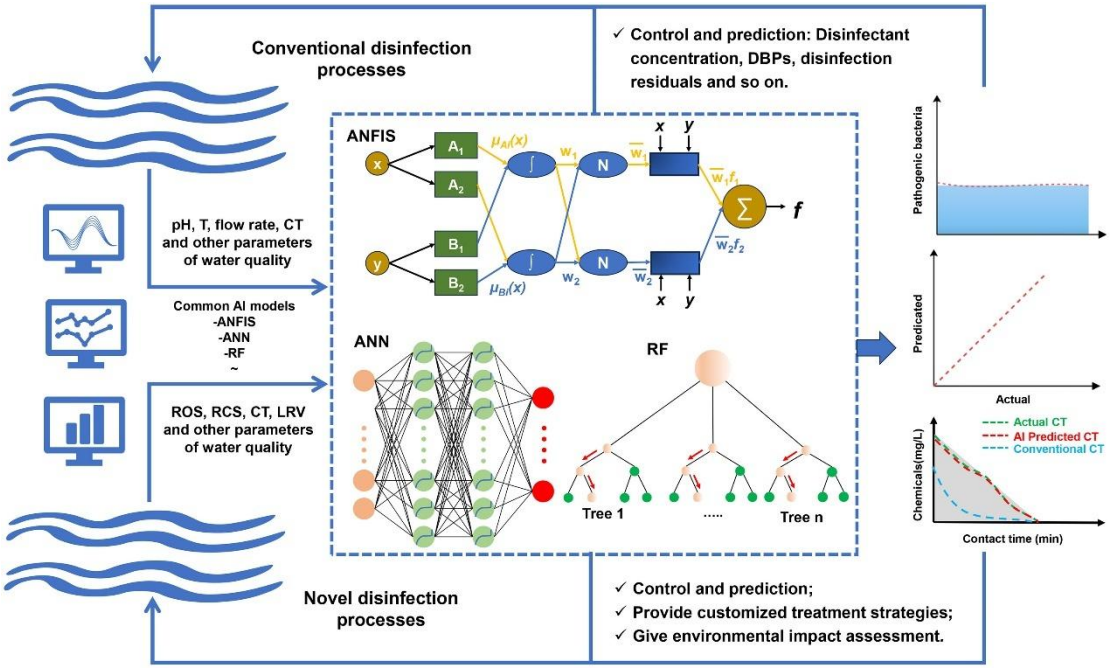

Fig. 12. Applying artificial intelligence (AI) in disinfecting water technology [106].

It is crucial to prioritize expanding hybrid AI technologies that could totally employ the unique features of several AI technologies and deliver enhanced performance. This comprehensive review offers valuable insights into the applications of AI in water disinfection and the mitigation of dangers associated with disinfection processes [106].

We hope to implement such approaches in the field of ED.

12. Conclusions

This review was dedicated to highlight advances and outlooks on electrochemical disinfection (ED). The main points drawn may be listed as below:

Ensuring drinking water safety is an essential requirement for any water supply system. The most cost-effective method for achieving this is through chemical treatment using chlorine. However, this process has the drawback of generating toxic disinfection by-products (DBPs) that are not ideal for safe water. O_3-founded methods have proven efficacious in eliminating most microbes, but it is crucial to assess the contents of the purified water to identify any potentially toxic DBPs. Solar disinfection (SODIS) presents an economical and environmentally friendly alternative as it requires minimal chemical usage. Similarly, sono-founded water treatment setups likewise minimize the need for chemicals, although the operating costs are slightly higher than traditional methods. UV-based processes are highly recommended for optimal results when combined with efficient illumination systems.

The potential of graphene-based materials in dealing with water is immense. These materials possess exceptional antibacterial properties that effectively hinder the growth, attachment, and formation of biofilms by bacteria, thereby improving water quality and reducing the dangers associated with waterborne diseases. Graphene-based materials are impressive. Furthermore, when integrated into membrane processes, graphene-based materials enhance efficiency by efficiently eliminating pathogens and various pollutants from water. The outstanding graphene characteristics position it as an up-and-coming option for applications in dealing with water. The future of graphene-based materials in the field of water purification looks encouraging.

It is vital to closely control the creation of chemicals when utilizing ED. It is possible to reduce or eliminate DBP formation by carefully fine-tuning operational parameters and incorporating additional treatments. However, further research is needed to understand how DBPs form in water with varying compositions, which may be encountered in incoming water sources. This research will help devise effective strategies to prevent the production of harmful substances.

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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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