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Making waves: Pathogen inactivation by electric field treatment: From liquid food to drinking water

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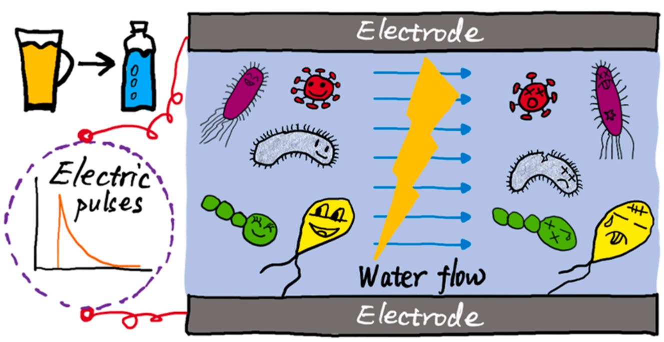
GRAPHICAL ABSTRACT



Both our water and food can be contaminated by pathogenic microorganisms. Most of the pathogens present in water can also be found in food, and *vice versa* (Acheson, 2009). These waterborne and foodborne pathogens have posed enormous health concerns and economic loss to society globally. Thus, the approaches to control and inactivate pathogens are of great interest in both water treatment and food production.

Electric field treatment (EFT) has shown great potential in the processing of liquid food such as juice, alcoholic, and dairy products. As a non-thermal process, EFT will not affect the flavor, texture, and nutrient of the food if the processing temperature is controlled (McAuley et al., 2016). EFT systems available on the market can process up to 10,000 L of liquid food per hour. The cost for the pathogen inactivation of beverages is estimated to be 10 Euro·ton^{-1}, which is already affordable in some circumstances. A commercial EFT system usually contains a treatment chamber (batch or continuous), a pulse generator, and its accessories encapsulated in a stainless-steel box for safety concerns. The footprint is usually a few m^2, primarily depending on its treatment capacity and the size of the pulse generator. Although training is still needed for the users, the friendly user interface and protection accessories have made EFT devices easy and safe to operate. In a survey article, EFT is named the top three most significant technology currently available by food professionals from industry, academia, and government (Jermann et al., 2015). EFT is also rated the third to be of the most commercial importance in ten years (Jermann et al., 2015).

The investigation of EFT in liquid food processing has mainly focused on the development of more reliable EFT systems for larger-scale applications. Such development is primarily driven by three objectives: (1) providing a more uniform electric field in order to avoid localized overheating, (2) reducing the applied voltage in order to lower the overall energy consumption, and (3) developing more stable electrodes in order to minimize electrochemical reactions, electrode erosion, and contamination of products (Buckow et al., 2011; Experton and Martin, 2018; Experton et al., 2016; González-Sosa et al., 2014; Huo et al., 2016, 2018; Knoerzer et al., 2012; Masood et al., 2018, 2017; Peng et al., 2017; Zhou et al., 2020a). In addition, researchers have studied the

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inactivation mechanisms, the influence of processing parameters on the performance, and the inactivation efficiency of EFT against different bacteria in different liquid foods (Arroyo et al., 2010; Jeyamkondan et al., 1999; Kotnik et al., 2003; Mahnič-Kalamiza et al., 2014; Mañas et al., 2001; Montanari et al., 2019; Sharma et al., 2014; Somolinos et al., 2008; Timmermans et al., 2014; Toepfl et al., 2007, 2006).

Nevertheless, EFT has rarely been studied as a water disinfection technique, let alone large-scale industrial applications. Notably, EFT employs a physical process, *i.e.*, electroporation, to inactivate pathogens, which avoids the formation of harmful disinfection by-products (DBPs) associated with chemical disinfection. Therefore, the objectives of this article are to (1) introduce EFT for pathogen inactivation, (2) discuss the feasibility of EFT for water disinfection, (3) identify the major obstacles and propose potential solutions, and (4) point out future research directions.

1. Overview of EFT

EFT has been applied as a pathogen inactivation method for several decades. As a non-thermal physical process, EFT avoids the use of chemicals and the production of harmful DBPs, possessing an intrinsic advantage over chemical disinfection methods (Jeyamkondan et al., 1999; Raso-Pueyo and Heinz, 2010). In a most conventional EFT, the liquid to be treated flows through a treatment chamber consisting of two parallel plate electrodes (Huang and Wang, 2009; Jeyamkondan et al., 1999). The typical distance separating the two parallel electrodes ranges from 1 to 10 mm (Rezaeimotlagh et al., 2018; Sharma et al., 2014; Timmermans et al., 2014; Walter et al., 2016). High-voltage electric pulses (up to several tens of kilovolts) with short durations (typically in microseconds) are applied between the electrodes to generate a strong electric field with minimal electrochemical reactions (Chang and Park, 2010). The strong electric field is expected to induce irreversible electroporation that damages the cell membrane and thus cell inactivation.

The theory of electroporation was established primarily using bacteria as the model microorganisms (Weaver and Chizmadzhev, 1996). A resting transmembrane potential (TMP, typically in the range of tens of millivolts) is maintained across the bacteria lipid bilayer membrane due to the distribution of charged ions inside *versus* outside of the membrane (Felle et al., 1980; Stratford et al., 2019). When a bacterial cell is placed in an electric field, an additional TMP, *i.e.*, ΔTMP, is induced (Kotnik et al., 2015). When the electric field is strong enough, the TMP exceeds the breakdown threshold, and thus electroporation occurs: the conductivity and permeability of the bacterial membrane increase, and electroporated pores are formed on the membrane (Chang and Reese, 1990; Weaver and Chizmadzhev, 1996). The breakdown TMP threshold ranges from ~250 mV to 1 V, depending on the characteristics of the microbes (size, shape, and orientation in the field, *etc.*) (Jeyamkondan et al., 1999). Initial electroporation is reversible: microbial cells reseal the pores and heal themselves, and thus maintain their activities (Kotnik et al., 2015). As the TMP increases, electroporation gradually evolves from reversible to irreversible (Weaver and Chizmadzhev, 1996). In this case, the electroporated cells cannot reseal and lose their viability, causing microbial inactivation (Kotnik et al., 2015).

Applying EFT for pathogen inactivation has multiple advantages. As a physical process, EFT does not require the addition of chemicals nor theoretically generate harmful DBPs (Weaver and Chizmadzhev, 1996). EFT is capable of inactivating a wide variety of pathogenic microorganisms because EFT targets microbial lipid bilayer structures (Gusbeth et al., 2009). EFT can be a fast treatment process to achieve high pathogen inactivation efficiency if the electric field strength is strong, because irreversible electroporation can happen in a few microseconds or less (Shahini and Yeow, 2013). In terms of operation, EFT only relies on electricity and does not need the transportation and storage of chemicals. Meanwhile, EFT does not introduce secondary pollution in terms of odor, sound, or light (Weaver and Chizmadzhev, 1996).

2. Feasibility of EFT for water disinfection

The pathogen inactivation processes for drinking water and liquid food share the same goal of achieving a high inactivation efficiency against a broad spectrum of pathogens. Nevertheless, drinking water and liquid food have different properties (Table 1). In a conventional drinking water treatment process, the source water to be disinfected usually has a nearly neutral pH (6~8), low conductivity (200~2000 $\mu s \cdot cm^{-1}$), and low total solid concentration ($< 50\ mg \cdot L^{-1}$) (Fernández et al., 2018; Gusbeth et al., 2009; Mañas et al., 2001; Seratlić et al., 2013). Liquid food to be processed can be much more complex. For example, fruit juice is usually acidic with a pH of 2~5 (Huang et al., 2014; Majstorović et al., 2017; Rezaeimotlagh et al., 2018). The viscosity of dairy products can be much higher than that of drinking water (Table 1) (Cregenzán-Alberti et al., 2015; Jaeger et al., 2009; Mañas et al., 2001; McAuley et al., 2016).

Theoretically, EFT for water disinfection can achieve efficacy at least similar to that for liquid food processing, because pathogens found in water are similar to those in liquid foods, and the physicochemical properties of water are also within the range of those for liquid foods. In addition, drinking water is relatively nutrient-deficient compared to liquid food, making the pathogens more difficult to survive. Drinking water also typically has fewer particles and organic molecules that can protect pathogens from inactivation by shading or other mechanisms. Therefore, higher pathogen inactivation efficiency can actually be expected when EFT is used in water.

3. The major barrier and potential solutions for the implementation of EFT for water disinfection

The high cost associated with the extensive energy consumption is the major barrier of EFT for liquid food processing (Rodriguez-Gonzalez et al., 2015). This concern will be more significant when applying EFT for water disinfection because drinking water is typically less valuable than liquid food. According to the literature, the specific energy consumption of EFT for liquid food processing is 40~1000 $kJ \cdot L^{-1}$, assuming the liquid density is 1 $kg \cdot L^{-1}$ (Saldaña et al., 2010; Timmermans et al., 2014; Walter et al., 2016), which is significantly higher than that of some other technologies that mainly consumes electrical energy for water disinfection (*e.g.*, 20~100 $J \cdot L^{-1}$ for UV and 20~150 $J \cdot L^{-1}$ for ozone) which has been adopted and optimized for decades (Chang et al., 2008).

Compared to liquid food processing, the energy consumption of EFT for water disinfection can potentially be lower, because the conductivity of drinking water is significantly lower than that of liquid food (Table 1), indicating that the energy unintentionally diverted for heat generation is largely reduced. Nevertheless, efforts are still needed to further reduce the energy consumption of EFT to make it affordable for water disinfection.

The general idea to reduce the energy consumption of EFT is to operate the process at lower voltages. When the operating voltage is lower, energy conversion efficiency for pulse generation is typically higher. In addition, side electrochemical reactions and unintentional heating can also be reduced. Nevertheless, according to the current theory of electroporation, the electric field strength needs to reach a threshold value to cause irreversible electroporation, *i.e.*, cell inactivation. Therefore, high electric field strength needs to be maintained while lowering the operating voltages, which has been realized by two different strategies.

First, we can reduce the distance between the electrodes for the flow-by EFT systems (electric field direction perpendicular to the fluid flow, Fig. 1a) or apply "co-field" or "converged" configurations for the flow-through EFT systems (electric field direction parallel to the fluid flow, Fig. 1b) (Eveke and Brunkhorst, 2004; Evrendilek and Zhang, 2005). In both cases, the treated fluid needs to flow through narrower channels, which will result in a higher risk of clogging and require more energy to

Table 1
Typical characteristics of drinking water sources and liquid food.

	Examples	pH	Conductivity ($\mu S \cdot cm^{-1}$)	Viscosity (mPa·s)*	Other parameters of concern	References
Drinking water sources	Natural surface water (*e.g.*, river, lake, & stormwater)	6–8	200–2000	~1	TSS (normal range 0–50 $mg \cdot L^{-1}$), turbidity (normal range under 10 NTU), water activity, & buffer ability	(Arroyo et al., 2010; Fernández et al., 2018; Gusbeth et al., 2009; Liu, 2017; Mañas et al., 2001; Seratlić et al., 2013)
	Alcoholic beverages (*e.g.*, wine & beer)	3–6	300–3000	0.7–3.0	Alcohol concentration (0.05–15%) & sugar content (1–200 $g \cdot L^{-1}$)	(Aadil, 2015; Evrendilek, 2004; González-Arenzana, 2015; Majstorović et al., 2017; Puértolas, 2009; Van Wyk, 2019)
Liquid food	Dairy products (*e.g.*, milk, cream, & ovalbumin)	6–7	1000–40,000	2 (milk)–100 (cream, 50% fat)	Fat (0–4%) & protein (~3%) component	(Bermúdez-Aguirre, 2012; Jaeger et al., 2009; Mañas et al., 2001; McAuley et al., 2016; Sharma et al., 2014)
	Juices of different fruits	2.5–6	1000–3000	2 (diluted)–200 (concentrated)	Sugar content (13–23 Bx)** & acidity	(Huang et al., 2014; Majstorović et al., 2017; Rezaeimotlagh et al., 2018)

* The viscosity values reported are at room temperature (18–25 °C).
** Degrees Brix (symbol Bx): 1 Bx is 1 gram of sucrose in 100 g of solution. For solutions containing dissolved solids other than pure sucrose, the Bx only approximates the dissolved solid content.

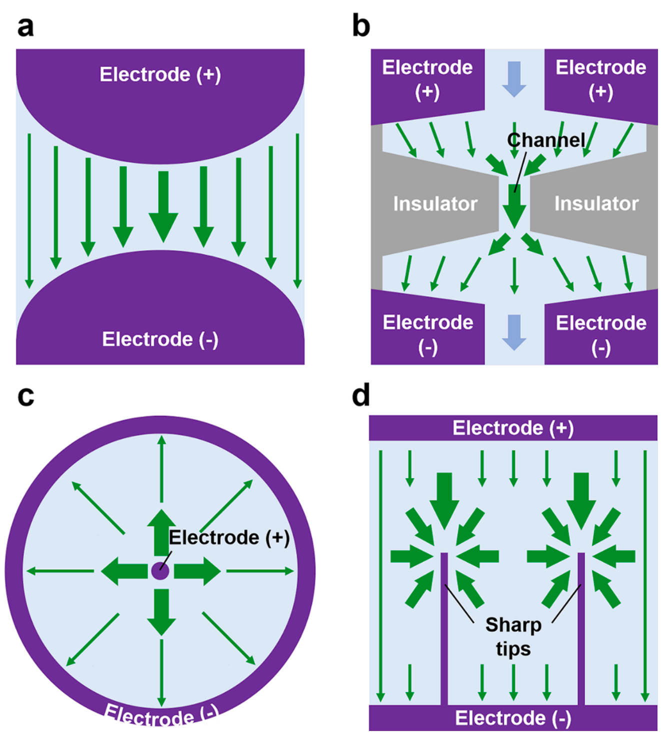

Fig. 1. Schematics of different strategies to achieve enhanced electric field. Green arrows represent the direction of electric field, and the thickness of the arrow indicates the strength of the electric field (*i.e.*, regions of enhanced electric field are presented by the thicker arrows). Blue arrows show the direction of water flow. (**a**) Electric field can be enhanced by reducing the distance between two electrodes. Water flows by the electrodes. (**b**) A co-field configuration can increase the electric field strength inside the narrow channel of the insulator. Water flows through the electrodes. (**c**) and (**d**) shows two different scales for locally enhanced electric field treatment (LEEFT). (**c**) Macro-scale enhancement by a coaxial electrode design. The center electrode is usually assigned positive, since the electrophoretic force can be utilized to transport the negatively-charged bacterial cells closer to the center region. Water flows by the electrodes. (**d**) Micro-scale enhancement by sharp tips on the electrode surface. The schematic is for demonstration and not to scale. The modification (*e.g.*, nanowires) can be very small compared with the bulk electrode and cannot be visualized by naked eyes. Water can flow either through or by the electrodes (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

push the fluid through (Huang and Wang, 2009). This strategy has been investigated in food processing for many years, and the knowledge gained from these studies can be applied for water treatment. As drinking water usually has fewer solid components and lower viscosity than most liquid foods (Table 1), EFT systems for drinking water disinfection may apply narrower channels than those for liquid food processing. Nevertheless, the throughput of the system will be limited, and may not be practical for large-scale applications.

Another strategy to achieve high electric field strength with low operating voltages is applying locally enhanced EFT (LEEFT). The design goal of conventional EFT is to achieve a uniform electric field and avoid dead zones so that all pathogens in the system can be inactivated simultaneously. Differently, LEEFT aims to enhance the electric field locally and to transport pathogens to these regions by various forces (*e.g.*, hydrodynamic, electrophoretic, and dielectrophoretic) to achieve high-efficiency disinfection. The electric field can be enhanced locally at two different levels. At the macro-scale, coaxial electrodes instead of parallel electrodes can be applied (Fig. 1c). With this configuration, the electric field is stronger when closer to the center electrode. Secondly, the electrode surface can be modified with micro-scale structures with sharp tips (*e.g.*, nanowires) (Fig. 1d). Attributed to the "lightning-rod" effect, the electric field near the tips is significantly stronger (Poudineh et al., 2014). Simulation results show that the electric field strength can be enhanced by at least 3–4 orders of magnitude (Liu et al., 2014).

Different from the first strategy that has been applied for food processing, LEEFT was first developed for water treatment and has demonstrated high-efficiency disinfection (Huo et al., 2018; Zhou et al., 2020b, 2020c). When both synthetic and natural water samples dosed with model bacteria are treated by LEEFT, inactivation efficiencies of >6 logs have been realized with applied voltages as low as 1 V (Zhou et al., 2020b). During LEEFT, pathogens will be exposed to the locally enhanced electric field and inactivated, but the bulk water is only exposed to the background electric field with much lower strength. This paradigm-shifting strategy makes the LEEFT intrinsically a very low energy-consuming process. At the bench-scale, the specific energy consumption of 1~5 $J \cdot L^{-1}$ has been achieved according to the operating current and voltage (Huo et al., 2016; Zhou et al., 2020c). Nevertheless, the development of LEEFT is still at a very early stage, and many challenges still need to be addressed before its real-world applications. More discussion on LEEFT can be found in recent publications that talk about electrode materials, electrode lifetime, concerns of secondary contaminants, etc. (Zhou et al., 2020b; Zhou et al., 2020c).

4. Future research and perspectives

Much higher energy consumption of EFT compared with competing technologies is still the major barrier to overcome for water disinfection.

Even though the above-mentioned two strategies have been applied to dramatically reduce the energy consumption in bench-scale prototypes, implementation in full-scale EFT systems requires much more effort. For example, the lifetime of the nanowire-modified LEEFT electrode is still too short and needs significant improvement. Meanwhile, researchers also need to look for other strategies that can reduce the energy consumption of EFT, such as improve the energy efficiency of pulse generation and minimize heat generation.

Besides the major barrier in energy consumption, there are other aspects of applying EFT for water disinfection that need future investigation. Food scientists have intensively studied the influence of liquid property parameters, including temperature, pH, conductivity, water activity, and protein and fat components, on the performance of EFT (Arroyo et al., 2010; Fernández et al., 2018; Somolinos et al., 2008; Timmermans et al., 2014). For the applications in drinking water disinfection, more studies are needed to investigate the influence of specific water quality characteristics such as turbidity and alkalinity, as well as inorganic ions (*e.g.*, Ca^{2+}, Mg^{2+}, HCO_3^{-}, and SO_4^{2-}) and dissolved organic matters (*e.g.*, humic acids) that commonly exist in natural water bodies. Most existing studies of EFT for water disinfection used a handful of common model bacteria. More investigation is needed on different microorganisms, including pathogenic bacteria, bacterial spores, viruses, and protozoa. The reactor of the EFT also needs to be rationally designed for water treatment. Computational fluid dynamics can be used to access the flow regime and pressure drop, which could be beneficial for the optimization of the reactor configuration. In addition, different from liquid food processing that is typically conducted at industrial scales by the manufacturers, drinking water disinfection can be applied not only in large centralized treatment plants but also through the water distribution pipelines and at the point of use for individual houses. Drinking water disinfection is also needed for remote places without grid power (*e.g.*, islands, ships, submarines, space stations, and developing areas) or emergency situations when the grid power is disrupted (*e.g.*, earthquakes and hurricanes). Therefore, specific challenges will need to be addressed for EFT to be adopted for drinking water disinfection at different scales and under different scenarios.

Promoting the implementation of EFT in drinking water disinfection requires the collaboration of water treatment scientists and engineers with other experts from multiple disciplines. For example, microbiologists can strengthen the understanding of the electroporation process in different water matrix, which provides fundamental knowledge to the mechanism of pathogen inactivation in EFT. Electrical engineers can design and optimize the pulse generator and control circuits specifically for water treatment. Mechanical engineers can improve the cooling system in those EFT systems with overheating issues. Material scientists can develop new electrodes with higher stability, lower cost, and/or specific surface features to provide the electric field enhancement effect. Food scientists who have applied EFT for liquid food processing can also share their acquired knowledge and experience and provide insights into the EFT for drinking water disinfection.

5. Conclusions

The next-generation water disinfection technologies should minimize the use of chemicals, the consumption of energy, and the impact on the environment, while having high resilience for different application scenarios (Deng, 2021; Shannon et al., 2010). We believe that EFT has the potential to become a competitive candidate in the technology toolbox for next-generation water disinfection. After analyzing both the feasibility and challenges of EFT for water disinfection, we offer the following insights:

1) As a physical process, EFT holds intrinsic merit comparing to chemical methods: the microbial inactivation by electroporation introduces no DBPs to the treated water.
2) The operation of EFT only relies on electricity, which is very easy to transport compared with chemical disinfectants, and can also be generated on-site to ensure resilience.
3) Even though the cost of electricity keeps dropping and can potentially be very low in the future, the energy consumption of EFT devices is still much higher than that of current water disinfection techniques, which becomes the major barrier of EFT. Potential solutions include redesigning the device configuration and electrode materials (*e.g.*, LEEFT).
4) With further development, EFT is promising to be applicable in the water treatment systems with reasonable cost to provide safer and more reliable drinking water.

Declaration of Competing Interest

The authors declare no conflict of interest for this study.

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