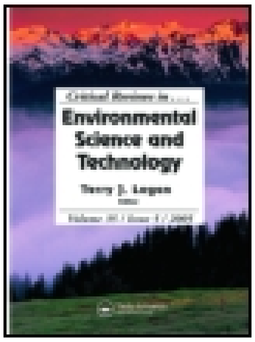


Critical Reviews in Environmental Science and Technology

ISSN: 1064-3389 (Print) 1547-6537 (Online) Journal homepage: https://www.tandfonline.com/loi/best20

Disinfection options for irrigation water: Reducing the risk of fresh produce contamination with human pathogens

Catherine E. Dandie, Abiodun D. Ogunniyi, Sergio Ferro, Barbara Hall, Barbara Drigo, Christopher W. K. Chow, Henrietta Venter, Baden Myers, Permal Deo, Erica Donner & Enzo Lombi

CRITICAL REVIEWS IN ENVIRONMENTAL SCIENCE AND TECHNOLOGY
https://doi.org/10.1080/10643389.2019.1704172

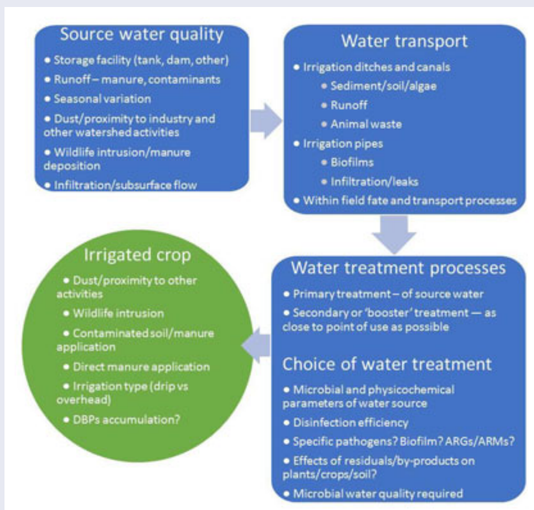
Disinfection options for irrigation water: Reducing the risk of fresh produce contamination with human pathogens

Catherine E. Dandie [a], Abiodun D. Ogunniyi [a], Sergio Ferro [b], Barbara Hall[c], Barbara Drigo[a], Christopher W. K. Chow [d], Henrietta Venter [e], Baden Myers [d], Permal Deo [e], Erica Donner [a], and Enzo Lombi [a]

[a]Future Industries Institute, University of South Australia, Mawson Lakes, South Australia, Australia; [b]Ecas4 Australia Pty Ltd, Mile End South, South Australia, Australia; [c]Plant Health and Biosecurity, SARDI, Adelaide, South Australia, Australia; [d]Natural and Built Environments Research Centre, School of Natural and Built Environments, University of South Australia, Mawson Lakes, South Australia, Australia; [e]School of Pharmacy and Medical Sciences, University of South Australia, Adelaide, South Australia, Australia

ABSTRACT

The growing health and economic burden posed by foodborne pathogens has stimulated global interest in the development of safe, affordable, effective and environmentally-sustainable irrigation water treatment technologies. This review critically compares the potential of existing and emerging methods for disinfection of irrigation water to reduce pathogenic microbial loads on high-risk vegetables and minimally processed fresh produce. We explore electrochemical disinfection and electrolyzed oxidizing water as alternatives to traditional chlorination, and identify hydrodynamic cavitation as an emerging disinfection strategy worthy of further investigation in this context. In addition, we assess the state of the knowledge regarding the impact of current water sanitation strategies on the ecological dynamics of plant and soil microbes and the potential induction of viable but nonculturable cells. Increased research in these areas could translate into substantial improvement in the overall quality and value of fresh produce, while maintaining environmentally-sustainable irrigation water usage.



KEYWORDS Foodborne pathogens; irrigation water disinfection; viable-but-non-culturable

CONTACT Catherine E. Dandie cathy.dandie@unisa.edu.au Future Industries Institute, University of South Australia, Mawson Lakes, South Australia, Australia.

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/best.

Supplemental data for this article can be accessed on the publisher's website.

1. Introduction

Crop agro-ecosystems are at the heart of the food–energy–water nexus, accounting for ∼70% of total freshwater withdrawal in the world (Food and Agriculture Organization of the United Nations (FAO), 2015). As an example, irrigated agriculture accounted for 58% of all water use in Australia in 2015–16 (ABS, 2017), and projected agricultural water demand is set to increase by 50% by 2050 (AWA, 2017). The increasing demand for water to support food production is a global trend that is significantly exacerbating pressure on water resources. Thus, alternative irrigation water sources are increasingly sought, and the quality and safety of those supplies must be ensured to safeguard future water and food safety.

1.1. Microbiological contamination of irrigation water and pathogen transfer to food

Irrigation water can be obtained from a range of water sources and the potential for microbiological contamination needs to be carefully considered. Table 1 lists the range of available water sources for irrigation and their relative risk of microbial contamination. In the case of irrigated food crops, particularly minimally processed foods such as lettuce, spinach, parsley and other leafy greens, opportunistic and human pathogens are of particular concern. Despite increasing efforts to improve sanitation, outbreaks linked to microbial contamination of minimally processed foods continue to occur around the world. In some instances, these outbreaks have been associated with pathogens that are uncommon in these foods, for example, *Salmonella* spp. and *Listeria monocytogenes* in cantaloupes, prepacked lettuce, and baby spinach leaves (FSANZ, 2016; Zhu, Gooneratne, & Hussain, 2017). Pre-harvest water supplies (i.e., irrigation water) and postharvest water (i.e., washing water) have previously been identified as the main sources of contamination in produce associated with illness (FSANZ, 2011), and the growing use of whole genome sequencing in outbreak investigations is providing increasing evidence for the role of contaminated irrigation water in pathogen outbreaks (Hoelzer, Switt, Wiedmann, & Boor, 2018). It is clear that contaminated irrigation water can transfer pathogens to edible produce (Jongman & Korsten, 2017; Markland, Ingram, Kniel, & Sharma, 2017) and leafy greens are especially vulnerable to contamination with opportunistic human pathogens because they have large surface areas, are often grown in close proximity to soil, are irrigated intensively, and are mostly consumed raw (De Keuckelaere et al., 2015).

Given the above, it is evident that in some settings effective sanitation of irrigation water is paramount in ensuring the safety of edible produce. Guideline values for pathogens in irrigation water have historically been

Table 1. Irrigation water sources and their potential for microbial contamination.

Water source	Potential for microbial contamination	References
Municipal/potable water	Low risk (treated to potable use standards), but cost and volumes required might be prohibitive	Uyttendaele et al., 2015
Surface water (incl. rivers, streams, creeks, lakes, dams and reservoirs)	High risk, with many potential sources of contamination, incl. wildlife or stock intrusion and fecal deposition, sewage or septic discharges and industrial effluents; high turbidity from suspended solids	Jones, Worobo, & Smart, 2014; Steele & Odumeru, 2004
Groundwater	Generally considered low risk, but overextraction of groundwater and contamination of shallow aquifers contributes to higher potential risk	Bradford & Harvey, 2017; Van Haute et al., 2015
Harvested rainwater	High risk of contamination by animal feces and organic debris; volumes required might be prohibitive except for small-scale applications	Dobrowsky, De Kwaadsteniet, Cloete, & Khan, 2014
Recycled wastewater	High initial microbial content but generally low risk with sufficient and appropriate treatment	Allende & Monaghan, 2015
Untreated wastewater/indirect wastewater reuse	High risk; prevalent because of insufficient wastewater treatment infrastructure in expanding urban areas	Thebo, Drechsel, Lambin, & Nelson, 2017

framed around fecal contamination and associated indicators (i.e., fecal coliforms), with the WHO guideline value of ≤1,000 colony forming units of fecal coliforms per 100 ml in wastewater for irrigation (World Health Organization (WHO), 1989). Other guidelines might be more specific and restrictive, specifying *E. coli* rather than coliforms (i.e., <1 *E. coli* per 100 ml of recycled wastewater; E.P.H.C., 2006) or targeting other pathogens (absence of *Salmonella* required in 100% of samples in recent EU legislation; European Commission, 2019). The impetus or trigger for irrigation water treatment should be derived from relevant local guideline values and microbial risk assessment of the potential pathogen exposure from contaminated crops (Uyttendaele et al., 2015).

The intention of this review is to critically assess the literature relating to existing methods for disinfection of irrigation water for food crops. The information presented is mainly focused on bacterial pathogens, whilst acknowledging that there are substantial disease burdens associated with other pathogens such as viruses, protozoa and helminths (Ramírez-Castillo et al., 2015). Where there is limited information on the application of treatments specifically to irrigation water, we have drawn on literature assessing the application of sanitation technologies in other scenarios and their potential for adoption for irrigation water treatment.

1.2. Human health effects of contaminated fresh produce and mechanisms of pathogen contamination

There are substantial human health effects of contaminated fresh produce—for instance, between 2004 and 2013, over one third of foodborne illnesses in the USA were from the consumption of contaminated fresh produce (Fischer, Bourne, & Plunkett, 2015). Considering that the World Health Organization (WHO) reported a global burden of 600 million cases of foodborne illness in 2010 (420,000 resulting in death), the importance of water sanitation during the pre- and postproduction of fresh produce should not be ignored (World Health Organization (WHO), 2015b).

Pathogen survival on plant surfaces has been clearly demonstrated, especially in biofilms, as has the internalization of pathogens into plant tissues – i.e., endophytes (Berg, Eberl, & Hartmann, 2005; Berg et al., 2013; Hardoim et al., 2015; Lim, Lee, & Heu, 2014). In fact, many opportunistic human pathogens colonizing fresh produce have an endophytic lifestyle, using vegetables as an alternative host to survive in the environment and as a vehicle to colonize human and animal hosts once ingested (Mendes, Garbeva, & Raaijmakers, 2013). Critically, the endophytic interaction leads to difficulties for postharvest decontamination of fresh produce (Berger et al., 2010). Therefore, while treatment of irrigation water might be effective in reducing the incidence of pathogen contamination through direct transfer of pathogens from irrigation water to plant surfaces and soil, changes in agricultural management practices might also be required to reduce the potential for endophytic pathogen colonization from contaminated soil and/or manure-based fertilizers.

In addition to the general risks to human health associated with pathogen contamination in food, the heightened risks posed by antimicrobial resistant microorganisms and antimicrobial resistance genes, particularly when associated with pathogenic microorganisms, is also of key relevance (Thanner, Drissner, & Walsh, 2016). Antimicrobial resistance is a major concern worldwide and is recognized by the WHO as a "global health security emergency", prompting the World Health Assembly to develop a Global Action Plan on antimicrobial resistance (World Health Organization (WHO), 2015a). A number of areas specifically highlighted as antimicrobial resistance research needs have been documented and many of them are directly relevant to food irrigation water supply (Wuijts et al., 2017), e.g., the identification of treatment technologies that can remove antibiotics and other antimicrobial agents, their metabolites, antimicrobial resistant microorganisms and antimicrobial resistance genes in water.

1.3. Strategies to reduce contamination of fresh produce

To reduce the potential for pathogen contamination of fresh produce, selection of an appropriate water source and/or pretreatment of irrigation water is critical (De Keuckelaere et al., 2015). Irrigation practices and distribution networks must be maintained to the highest possible standards to ensure that the potential for contamination is minimized. As with drinking water treatment, a multiple barrier approach is recommended to ensure that irrigation water quality remains high even in the event of failure or suboptimal performance of individual treatment modules (NHMRC & NRMMC, 2011). On-site treatment of irrigation water could represent an important component of a multiple barrier approach, especially in the context of irrigation with recycled water.

2. Treatment technologies for irrigation water

Water treatment for potable use and wastewater treatment for reuse or discharge draw on a range of different treatment technologies, many of which are potentially applicable to irrigation water treatment. A multitude of factors can affect the choice of irrigation water treatment technology (Figure 1). Selection criteria for treatment technologies can generally be broken down into three categories—technological, managerial, and sustainability

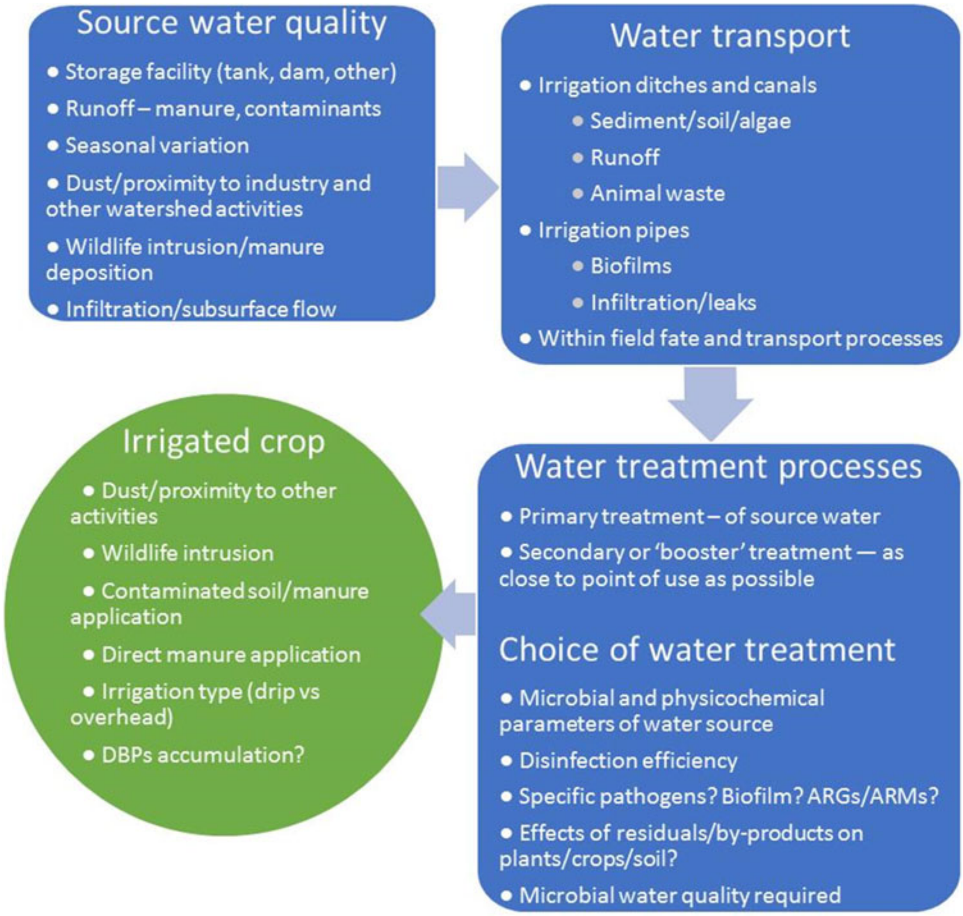


Figure 1. Factors affecting irrigation water quality and selection of water treatment processes to improve the microbial safety of fresh produce. ARGs: antimicrobial resistance genes; ARMs: antimicrobial resistant microorganisms; DBPs: disinfection byproducts.

related (Van Haute, Sampers, Jacxsens, & Uyttendaele, 2015). Technological criteria include the quality of the water source (e.g., microbiological load, temperature, pH, turbidity, suspended solids, organic matter content), distribution system characteristics, required water quality (in terms of physical and microbiological parameters), and water treatment parameters (i.e., treatment time and dose). Managerial criteria include the upfront and operational costs, complexity of operation, monitoring, and safety issues (in terms of chemical handling, storage, production of disinfection by-products (DBPs) and DBP accumulation in plants). Sustainability criteria cover maintenance, monitoring, environmental considerations and associated costs.

Generally, treatment approaches can be separated into clarification and disinfection processes. Clarification processes can be classified as follows: physical/mechanical methods, like screening, slow sand filters and membrane filtration treatment; biological methods, such as biofilters; and chemical methods, such as coagulation and flocculation. Disinfection processes can involve the application of chemicals, such as chlorine, ozone (O_3), peroxyacetic acid (PAA), or hydrogen peroxide (H_2O_2), or might be based on non-chemical disinfection methods like ultraviolet (UV) irradiation.

Traditional treatment technologies and potential but largely untested treatment technologies for irrigation water are outlined below and the advantages and disadvantages of each process are summarized in Tables 2 and 3. As the scientific literature about on-site disinfection of irrigation water is rather limited and generally targeted toward plant pathogens rather than human pathogens (Raudales, Parke, Guy, & Fisher, 2014), this review also draws on parallel literature and examples from other applications such as potable water and wastewater treatment when necessary.

2.1. Traditional water treatment technologies

The advantages and disadvantages of traditional water treatment technologies are summarized in Table 2 and there have been several recent reviews covering many of these technologies in detail (Chahal et al., 2016; Hai, Riley, Shawkat, Magram, & Yamamoto, 2014; Hoslett et al., 2018; Jhaveri & Murthy, 2016; Kitis, 2004; Majsztrik et al., 2017; Martínez, Pérez-Parra, & Suay, 2011; Raudales et al., 2014; Scarlett et al., 2016; Yang, Li, Huang, Yang, & Li, 2016). Chlorination and UV irradiation are widely applied, mostly because of their low relative cost and convenient application.

Chlorination can be applied in gaseous form (Cl_2) or as hypochlorite (OCl^-) in either liquid or tablet form; it is well characterized, economical and effective against a broad range of pathogens. Optimum treatment conditions occur at pH 6, where the active form of undissociated hypochlorous acid is most prevalent. Hypochlorite treatment is relatively easy to implement for irrigation systems and has been widely applied in large-scale irrigation water treatment (Allende & Monaghan, 2015; Gil et al., 2015; Suslow, 2010). The disadvantages of chlorine treatment are mostly associated with the formation of DBPs, whose formation could be greater in irrigation water with high organic matter content, which would also have a high chlorine demand.

UV treatment efficacy can be substantially affected by water quality, turbidity and flow rate. Turbidity can reduce the penetration of UV irradiation, thus prefiltration or the use of thin films is required. Because of the lack of residual, there is significant potential for regrowth of pathogens after UV treatment, via photoreactivation mechanisms. UV is certified for

Table 2. Traditional water treatment technologies.

Treatment type	Mechanism	Target organism(s)/contaminants	Advantages	Disadvantages
Physical/Mechanical treatment technologies				
Coagulation/flocculation	Inorganic metal coagulants (i.e., aluminum sulfate or ferric chloride) Polymeric coagulants Organic polyelectrolytes Composite inorganic–organic coagulants Natural compounds (i.e., chitosan)	Turbidity/suspended solids Organic matter Phosphorus Cryptosporidium Giardia Viruses Bacteria	Targets larger pathogens that are not targeted by or susceptible to many other disinfection processes Nutrient removal reduces nutrient source for pathogen growth/survival	Must be optimized for specific water source in terms of pH, dosage, temperature, ionic strength and treatment and settling times Insufficient log removal of pathogens for unrestricted irrigation Substantial expertise required Generates sludge that must be disposed of appropriately No residual
Slow bed sand filtration	Pore size and depth of sand bed (straining and adsorption) Biofilm (or *Schmutzdecke*) (predation, starvation, lysis, reactive oxygen species)	Turbidity/suspended solids Bacteria Fungi (spores)	Low cost, low technology approach to provide substantial improvement in water quality Limited expertise required to implement and maintain	Large footprint Clogging requires regular maintenance and filter downtime Insufficient log removal of pathogens for unrestricted irrigation May not provide sufficient throughput for large scale irrigation No residual
Membrane filtration	Membrane pore size Microfiltration (MF: 0.1–1.0 μm) Ultrafiltration (UF: 5–100 nm) Nanofiltration (NF: 1–10 nm) Reverse osmosis (RO: ∼0.1 nm) Pressure	Particles (MF/UF) Dissolved contaminants (NF/RO) Protozoa (MF) Bacteria (MF/UF) Viruses (UF/NF/RO) ARGs? (NF/RO?)	Removal of all contaminants possible Potential for contaminant-specific applications	High expertise required to run and maintain Fouling/clogging requires backwashing, regular maintenance and membrane replacement Membrane failure can be catastrophic and hard to detect Costly to install and maintain No residual
Ultraviolet (UV) irradiation	Broad spectrum (i.e., UV-C 200–280 nm) or specific wavelength (i.e., 254 nm) DNA/RNA adsorption, production of thymine dimers, inhibition of replication, protein damage	Bacteria Viruses Protozoa Fungi	Widely used in drinking and wastewater treatment Effective against a wide range of pathogens Easy to install and maintain No DBPs UV-LED technology should lead to treatment innovation Can be combined with advanced oxidation processes	No residual Potential for pathogen regrowth, limiting opportunity to store treated water Effectiveness limited in turbid water

Disinfection processes				
Ozone (O_3)	Ozone (O_3) Free radicals	Bacteria Viruses Protozoa?	Generally regarded as safe for food industry use High oxidizing potential Decomposes upon exposure to oxygen	Can generate DBPs in reaction with organic matter (non-halogenated organic products, bromate) High cost of installation Residual O_3 must be removed from excess water and disposed of safely Potential phytotoxicity
Peroxyacetic acid (PAA) ($C_2H_4O_3$)	Acetic acid (CH_3COOH) Hydrogen peroxide (H_2O_2)	Bacteria Biofilms Fungi Spores Viruses Protozoan cysts	Easy to use and common for post-harvest treatment Broad-spectrum of activity and effective at low concentrations Relatively insensitive to organic loading, total suspended solids, ammonia, nitrite and phosphates No quenching (dechlorination) requirement Low formation of DBPs such as THMs and HAAs relative to chlorination Small dependence on pH; effective under a wide temperature range Strong oxidizing properties; requires short contact time	Potential microbial regrowth from higher organic content in effluent (acetic acid in PAA formulation and as breakdown product) High concentrations required to inactivate bacterial spores and protozoan cysts High initial purchase cost due to limited production capacity Formation of iodo-DBPs possible, which are highly cyto- and genotoxic Limited research into pre-harvest applications
Chlorine dioxide (ClO_2)	Chloride (Cl^-) Chlorite (ClO_2^-) Chlorate (ClO_3^-)	Multidrug-resistant bacteria Mycobacteria Protozoa Biofilms Fungi Bacterial and fungal spores Viruses	Potent across a wide pH range High oxidation capacity Does not generate DBPs such as THMs, HAAs, dioxins, furans, but can generate chlorates Does not leave odor or taste nuisance	Concerns around worker safety Efficacy is affected by high organic load and inorganic water content Concerns over transport of precursor chemicals (risk of explosion and instability) Unstable during on-site generation Sensitive to light and high temperatures Chlorate DBP generation
Chlorination/Hypochlorite	HOCl ClO^-	Bacteria Biofilms Fungi Algae Viruses	Widely used, well characterized and easy to implement Less hazardous than chlorine gas (Cl_2) Can be generated on site, reducing need for transport and handling of hazardous chemicals	Formation of DBPs (THMs, HAAs) in reaction with organic matter or during production (chlorate) Conc. solution (12%–15%) hazardous to workers – high pH, corrosive, burns Unstable On-site generation can produce hydrogen, an explosion hazard Potential phytotoxicity Inactivation in the presence of high organic matter

DBPs: disinfection byproducts; THMs: trihalomethanes; HAAs: haloacetic acids; LED: light emitting diode.

use in organic treatment regimens and largely used in conventional closed greenhouse systems (Dorais et al., 2016).

All currently available technologies have several advantages and disadvantages (Table 2), such that it is difficult to provide generalized recommendations. The main advantages of the physical/mechanical treatments is that they do not form DBPs; disadvantages include the lack of residual disinfectant, and the requirement for pretreatment to reduce the potential for clogging with filtration and increase the efficacy of UV treatment. The advantages of chemical sanitation treatments are that, in some cases, residual disinfection can be maintained throughout the distribution system, thus reducing the risk of pathogen regrowth. The main disadvantages of chemical sanitation treatments are 1) the formation of DBPs, which are generally formed during the reaction of oxidants with organic matter; 2) the maintenance of residual disinfection during storage; 3) the handling and transport of dangerous chemicals, and 4) the expertise required to run and maintain complex water treatment technologies. The application of chemical disinfectants requires careful monitoring and process control to ensure suitable residual disinfectant concentration and avoid phytotoxicity (Allende & Monaghan, 2015). In addition, depending on the source, irrigation water might have high organic matter content, meaning that the formation of DBPs and their potential for plant accumulation should be carefully considered when selecting treatment technologies.

Given the above, the identification and investigation of treatment technologies that 1) generate no or minimal DBPs; 2) provide some residual disinfection without resulting in phytotoxicity or increasing the risk of antimicrobial resistance; and 3) are simple to implement with no additional chemicals required, is a high priority in a world with increasing regulation of irrigation water and food production. The potential for point-of-use water treatment is also appealing, so that storage/transfer time is minimized and the water is of the highest quality directly prior to crop application in the field.

2.2. Potential irrigation water treatment technologies

We have identified several treatment technologies (Table 3) that have the potential to address some of the concerns outlined above, whilst also acknowledging that in many cases multiple treatment technologies in combination will likely be the best scenario for effective irrigation water treatment. The common feature through all of the methods outlined below is that they have an element of advanced oxidation processes, because of the generation of reactive oxygen species (ROS), particularly hydroxyl radicals ($HO^{\bullet}$), for the degradation/oxidative attack on organic material including

Table 3. Potential irrigation water treatment technologies.

Treatment type	Active constituent(s)	Target organism(s)	Advantages	Disadvantages
Hydrodynamic cavitation	Mechanical generation and subsequent collapse of vapor bubbles, causing aggressive physico-chemical environments, under high temperature and pressure	Bacteria and viruses Cyanobacterial cell disruption Removal of pharmaceuticals and pesticides Degradation of organic pollutants (e.g. textile dyes)	Can be combined with UV treatment and other AOPs Reactor design is simple, scalable and easy to operate High energy efficiency No chemicals required	Most effective under acidic conditions which favors generation of hydroxyl radicals Requires optimization of configuration for each application No residual No available research for irrigation water use
Electrolyzed oxidizing (EO) water	Hypochlorous acid (HOCl) Hypochlorite (ClO^-) Hydrogen peroxide (H_2O_2) Ozone (O_3)	Bacteria Biofilms Fungi Algae Viruses	Wide applicability in health, food, agriculture Scalability for small, medium and large applications Some EO water technologies such as NEW are pH neutral and require no hazardous chemical usage, therefore non-corrosive and non-hazardous NEW is nontoxic, the electrodes do not contain ruthenium	High initial set-up cost Inactivation in the presence of high organic matter, which might require more brine and increase cost Potential different kill rates/ concentration against a variety of micro-organisms Formation of DBPs (THMs, HAAs) in reaction with organic matter
Electrochemical treatment	Hypochlorous acid (HOCl) Hypochlorite (ClO^-) Hydrogen peroxide (H_2O_2) $^{\bullet}OH$ Ozone (O_3)	Bacteria Biofilms Fungi Algae Viruses	Easy set up Requires no hazardous chemical usage Transport, storage or dosage with chemicals is not required Disinfection strength can be adjusted according to on-site demand	High initial reactor cost Efficacy dependent on water pH, temperature, suspended solids, microbiological load, organic matter The amount of chloride ions needed will vary depending on the water quality Potential for DBPs untested Level of on-going maintenance uncertain

DBPs: disinfection byproducts; THMs: trihalomethanes; HAAs: haloacetic acids; NEW: neutral electrolyzed water; AOP: advanced oxidation process; UV: ultraviolet.

pathogenic microorganisms. The $HO^{\bullet}$ molecule has the highest oxidizing potential of all oxidizing agents used in water treatment (Deng & Zhao, 2015).

2.2.1. Hydrodynamic cavitation

Hydrodynamic cavitation (HC) is a technique with a range of potential applications in water treatment and environmental remediation (Zupanc et al., 2019). First characterized in the 19th century, research has shown that HC treatment can generate localized high temperature and pressure hot spots under nearly ambient 'bulk' conditions. Previously, ultrasound was the main method used for producing cavitation but the adoption by industry has been poor because of the cost and extensive expertise required to operate the equipment successfully. HC is a cheaper and simpler alternative than the ultrasound-based process; the cavitation is produced by the rapid constriction and subsequent expansion of a liquid through a Venturi or orifice plates under controlled conditions (Ciriminna, Albanese, Meneguzzo, & Pagliaro, 2016; Dular et al., 2016). As the fluid flows through the constriction, HC occurs in regions where the (hydro)static pressure drops below the vapor pressure of water, causing evaporation and the formation of vapor bubbles (Figure 2). On return to regions of normal static pressure, vapor re-condenses and cavitation bubbles collapse, leading to the formation of very short lived (μs) but also very aggressive physico-chemical microenvironments characterized by very high temperature (>1,500 °C), pressure (>69 MPa), and turbulence (100 m s^{-1} micro jets; Tao, Cai, Huai, Liu, & Guo, 2016), all while the bulk water environment remains at ambient conditions. Reactive oxygen species (ROS; including $HO^{\bullet}$ and $HO_2^{\bullet}$ radicals), while generated during cavitation, can also be added (H_2O_2, O_3) to further enhance organics removal during water treatment applications (Jusoh, Aris, & Talib, 2016; Raut-Jadhav et al., 2016; Tao et al., 2016).

Research has shown the potential beneficial uses of HC for remediation of contaminated waters, with applications including: elimination of refractory organic pollutants (Petkovšek et al., 2013; Tao et al., 2016); disinfection and pathogen destruction (Dular et al., 2016; Li, Song, & Yu, 2014; Tao et al., 2016; Torabi Angaji & Ghiaee, 2015); removal of oxyanions (As, Se) and pharmaceuticals (Zupanc et al., 2013, 2014); and recovery of base/precious metals from mine waters (Kirpalani, Singla, Lotfi, & Mohapatra, 2016).

HC can be used as a stand-alone process or in conjunction with UV (Zupanc et al., 2013), and H_2O_2 treatments (Rajoriya, Carpenter, Saharan Virendra, & Pandit Aniruddha, 2016). The main drawback of this treatment technology is the lack of residual disinfection, which might mean that it is best used in combination with another form of disinfection, or

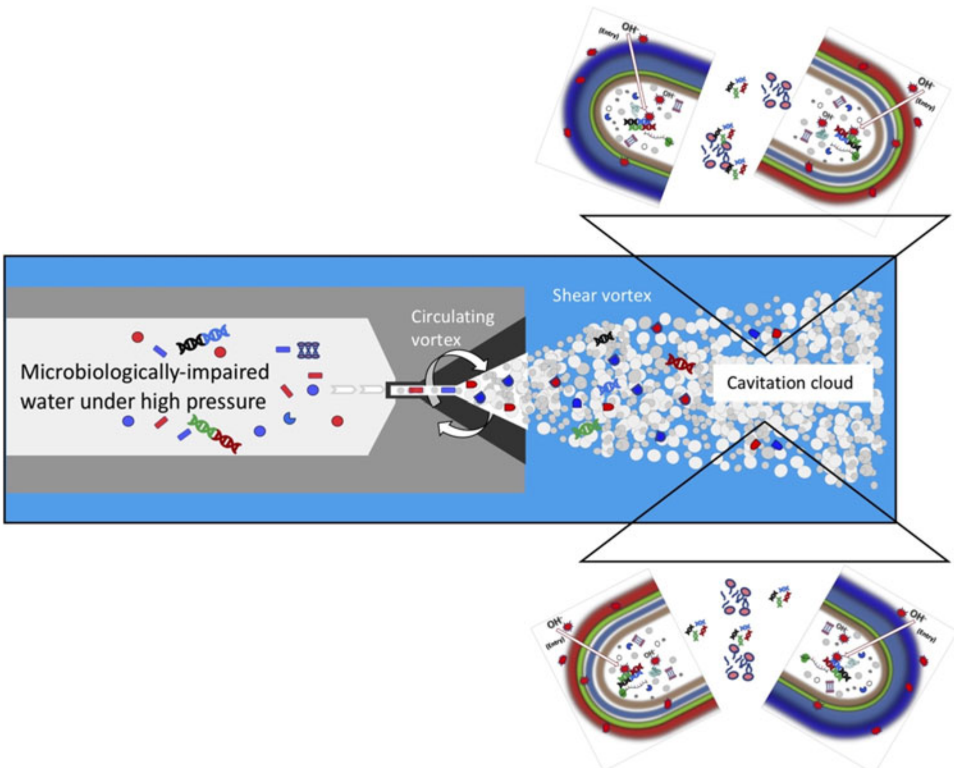


Figure 2. Principles of hydrodynamic cavitation. Formation and collapse of vapor bubbles from liquids in orifices or Venturi occur rapidly under very high temperature and high pressure changes, resulting in very high energy densities and generating hydroxyl radicals, leading to pathogen destruction.

implemented as a point-of-use water treatment. Also, given the paucity of reports in the literature, various issues such as the potential for clogging at the constriction point and the durability of the cavitation chamber need to be considered. On the other hand, the simple reactor design, easy operation, high energy efficiency and scalability have made this technology attractive for deployment (Tao et al., 2016). The review by Zupanc et al. (2019) summarized recent research on the effects of cavitation on a range of organisms, including bacteria (both Gram negative and Gram positive), cyanobacteria, algae, fungi, yeast and viruses, whilst also highlighting the many limitations of research in this area. Despite the potential of this technology, much research is required to optimize HC treatment for application to irrigation water and ensure optimal pathogen inactivation.

2.2.2. Electrolyzed oxidizing (EO) water

EO water is obtained through the electrolytic treatment of brine (water containing NaCl or KCl salts; Bakhir, 1985). In the presence of chloride,

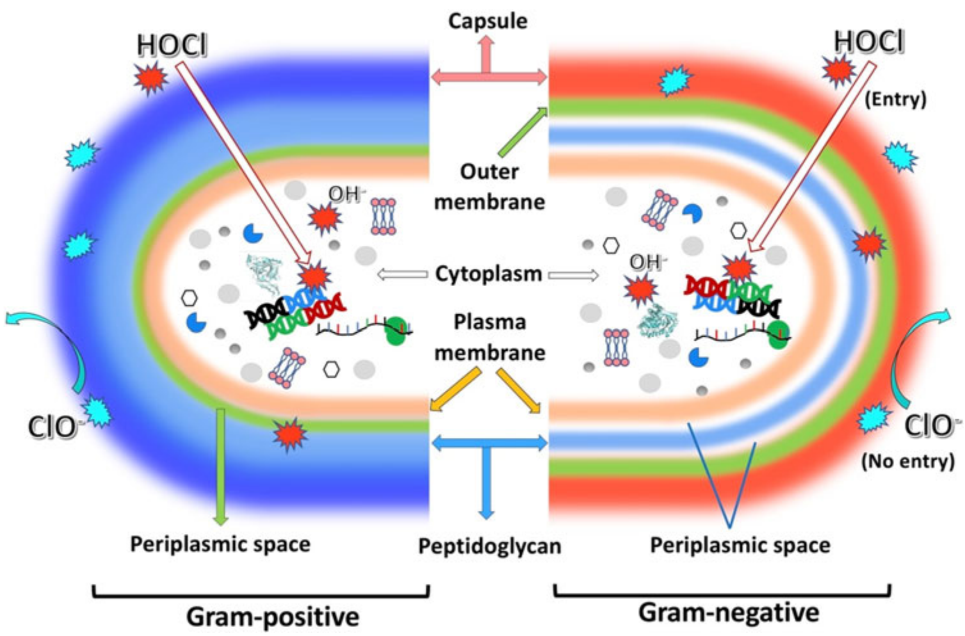


Figure 3. Schematic representation of the abilities of hypochlorous acid (HOCl) and hypochlorite (ClO^-) to kill Gram-positive and Gram-negative bacteria. The potent activity of HOCl is due to its dual cidal action on bacterial cells: HOCl is electrically neutral and can passively diffuse through the cell wall and plasma membrane into the cytoplasm where it attacks constituents including nucleic acids, proteins and lipids. HOCl is also able to directly destroy the cell wall and plasma membrane through its oxidizing action. However, ClO^- is unable to penetrate the cell and only exerts its cidal action on the bacterial cell surface.

active chlorine (sodium hypochlorite or hypochlorous acid) and ROS (O_3, H_2O_2) are formed, which are toxic to microorganisms (Figure 3). The resulting concentrated solution (300–500 mg l^{-1} active chlorine) can then be diluted into water for disinfection treatment. Electrolysis in a 2-chamber system generally results in both an acidic anolyte and an alkaline catholyte, while a 4-chamber system produces a pH-neutral anolyte, NEW (Bohnstedt, Surbeck, & Bartsch, 2009; Ferro, 2015; Migliarina & Ferro, 2014; Quadrelli & Ferro, 2010).

The main active component in the disinfection activity of EO water is free chlorine. ROS are also produced but their action is limited by their short half-life. The EO water activity will largely depend on the pH, oxidation reduction potential (ORP) and available chlorine concentration (Rahman, Khan, & Oh, 2016). Similar to traditional chlorination treatments, the optimal activity of free chlorine generated in the electrolytic process occurs when the pH of the EO water is around 6. Of the various types of EO water available, NEW (pH 6.5–7.5) is arguably the most promising as it contains predominantly HOCl. This compound is uncharged and poorly solvated by water molecules and as such it is able to penetrate bacterial cell walls and oxidize polysaccharides (Bonfatti et al., 2000). EO waters with extremes of pH are likely to damage infrastructure and cause phytotoxicity and are therefore less suitable for agricultural applications.

Several studies have described the activity of EO waters against suspensions of target human pathogens (*E. coli*, *Salmonella* spp. and *Listeria* spp.; Supplementary information Table S1) where substantial log reductions in viable microorganisms were obtained with treatment under a range of conditions of exposure time, pH, temperature, available chlorine and ORP (Rahman et al., 2016). However, there are limited published applications of the use of EO technology in treating irrigation water. Grech and Rijkenberg (1992) found that micro-emitter-based irrigation to treat citrus root pathogens with acidic EO water at 40–50 μg ml^{-1} active chlorine did not result in chlorine-induced phytotoxicity in field-grown plants. Similarly, the use of acidic EO water as a foliar spray (free chlorine of 54–71 mg l^{-1}) on a variety of bedding plants grown under greenhouse conditions demonstrated very little to no phytotoxicity to the plants while exhibiting rapid killing of pathogenic fungi such as powdery mildews and gray molds (Buck, van Iersel, Oetting, & Hung, 2003). Zarattini, De Bastiani, Bernacchia, Ferro, and De Battisti (2015) reported that the use of NEW at up to 500 mg l^{-1} on tobacco plants and apple trees produced no phytotoxic effects but unexpectedly triggered the molecular defenses of plants. NEW was effective at inactivating norovirus, showing >5-log reduction in suspension with NEW at 250 mg/l free chlorine, but increasing organic load or reduced NEW concentrations were less effective at reducing the viral load (Moorman, Montazeri, & Jaykus, 2017).

Similar to other chlorination treatments, organic matter has a detrimental effect on the efficacy of EO water (Jo, Tango, & Oh, 2018; Stevenson, Cook, Bach, & McAllister, 2004) and can result in the formation of DBPs, although few studies have investigated this in detail (López-Gálvez, Andujar, et al., 2018). Chlorates can also be produced during the electrolysis process itself; this can be controlled by the choice of electrode material, electrolyte composition, applied current, pH and temperature (López-Gálvez, Andujar, et al., 2018). As an alternative to traditional chlorination treatments, the technology is easy to implement and safe to use, with no dangerous chemicals required; however, the production of DBPs is still a concern and further research is required to determine the type and levels of DBPs produced and their potential accumulation in plants.

2.2.3. Electrochemical disinfection

Electrochemical disinfection is achieved by passing an electric current through the water under treatment, using suitable electrodes, without the addition of exogenous salts (Kraft, 2008). At the phase boundary between

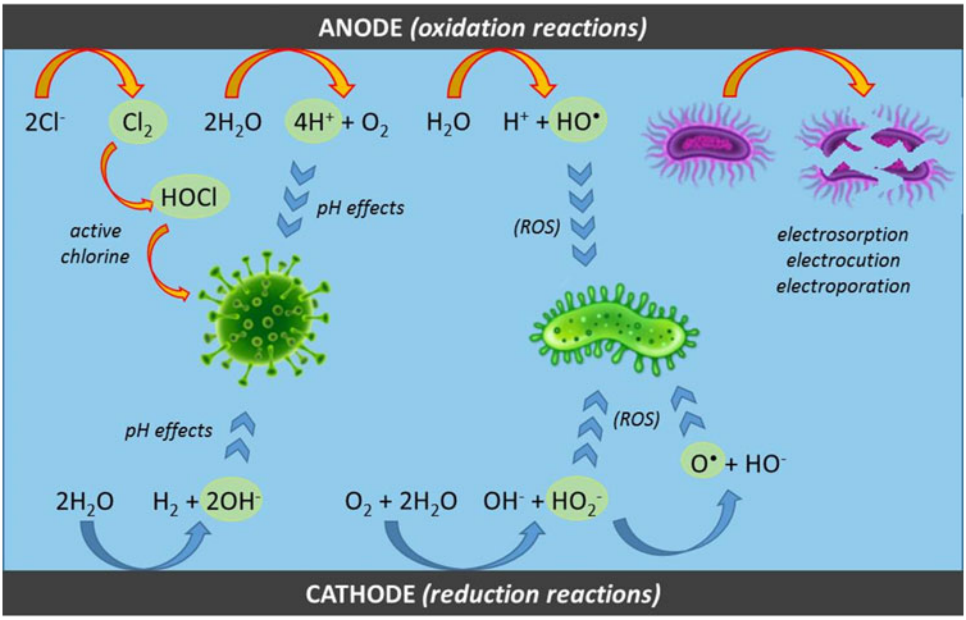


Figure 4. Reactions that occur at the anode and cathode during electrochemical disinfection of water. ROS: reactive oxygen species.

the electrodes and the water, the electric current leads to the electrochemical production of disinfecting species from the water itself (for example, ROS) or from species dissolved in the water (most notably chloride is oxidized to free chlorine; Figure 4; Kerwick, Reddy, Chamberlain, & Holt, 2005). Sufficient free chlorine can be produced to efficiently disinfect water even at low chloride concentrations (less than 100 mg l^{-1}; Kraft, 2008). The disinfection efficacy of the electrochemical approach is thought to be higher than that of chlorination due to the formation of ROS such as hydroxyl radicals ($^{\bullet}OH$), atomic oxygen ($^{\bullet}O$), H_2O_2, and O_3 (Delaedt et al., 2008; Diao, Li, Gu, Shi, & Xie, 2004). Yet, the short lifetime of most of the ROS in solution means that they are only active inside the electrochemical reactor. While most disinfecting agents are produced at the anode, H_2O_2 may also be produced at the cathode, as a product of oxygen reduction (Stoner, Cahen, Sachyani, & Gileadi, 1982).

The inactivation efficacy of electrochemical disinfection systems depends on several factors, including the electrochemical cell configuration, electrode material, water composition, the nature of the target microorganism, flow rate and current density (Jeong, Kim, & Yoon, 2009; Martínez-Huitle & Brillas, 2008). The main process leading to electrochemical water disinfection relies on the electrosynthesis of disinfecting agents, however other phenomena such as the electrosorption of bacteria on the electrode surface (with consequent direct interaction), electrocution, and electroporation might play a role in the process (Matsunaga, Nakasono, Kitajima, &

Horiguchi, 1994; Matsunaga, Okochi, & Nakasono, 1995; Nakasono, Nakamura, Sode, & Matsunaga, 1992). After electrosorption, inactivation of microorganisms can result from the direct electrochemical oxidation of intracellular coenzyme-A, leading to decreased respiration and consequent cell death (Matsunaga et al., 1992). Electrochemical treatment was shown to result in oxidation of viral capsid proteins, leading to loss in structural integrity and viral inactivation (Shionoiri, Nogariya, Tanaka, Matsunaga, & Tanaka, 2015).

An interesting feature of the electrochemical disinfection approach is that the local concentration of the active agents (i.e., within the diffusion layer that forms at each electrode surface) can exceed the average concentration found in the water leaving the reactor by one or two orders of magnitude (Stoner et al., 1982). Consequently, the local concentration can be high enough to destroy highly resistant microorganisms, even if the concentration of active species in the treated water is kept at a low level. When compared with chemical disinfection methods, electrochemical water disinfection has the advantage that no transport, storage or dosage with disinfectants is required. In addition, the disinfection strength can be adjusted according to the on-site demand by adjusting the current. The technology is easy to install and could be integrated into irrigation systems where required. While electrochemical water disinfection has great potential for point-of-use irrigation water treatment, the amount of chloride ions needed, the effect of the water pH, temperature, presence of suspended solids, microbiological load, high organic matter, nature of the electrode material and the potential to produce DBPs need to be carefully evaluated. De Battisti, Formaglio, Ferro, Al Aukidy, and Verlicchi (2018) observed the formation of chlorate and perchlorate during electrochemical disinfection of groundwater, but that the concentrations of these DBPs was lower than the appropriate guideline values.

3. Other considerations in the choice of irrigation water treatment methods

There are many other issues that should be considered when choosing an appropriate irrigation water treatment method. These include potential health risks such as antimicrobial resistance and DBP accumulation, and application concerns such as cost, water quality and application methods.

The treatments described in this review have generally focused on bacterial pathogens, however, the control and treatment of other pathogen types is important. Viral pathogens such as hepatitis A and norovirus have been associated with several recent outbreaks on fresh or frozen berries and other fresh produce such as leafy greens and salads (Chatziprodromidou, Bellou, Vantarakis, & Vantarakis, 2018). Viral pathogens can be introduced to fresh produce during preharvest operations (from contaminated irrigation water) or during postharvest manipulation (from infectious food handlers or contaminated process/washing water). Thus the role of irrigation water in virus transmission and the efficacy of the disinfection treatments investigated in this review against viral pathogens should be an important focus of future research (Hedberg, 2016).

Disinfection is a key component in successfully controlling pathogen populations in water but has also been linked in some studies to the selection of antimicrobial resistance (Rizzo et al., 2013) and reduced efficacy/increased resistance over time. Recent studies have implicated both DBPs and residual disinfectants in the induction of antimicrobial resistance and horizontal transfer of antimicrobial resistance genes (Li & Gu, 2019). Multidrug resistant opportunistic and human pathogens are an emerging worldwide threat to human health that can be transmitted through a variety of sources, including as foodborne pathogens (Baker, Thomson, Weill, & Holt, 2018). These risks should be carefully considered in the risk–benefit analysis of any proposed disinfection strategy, particularly where this is linked directly to human food.

The accumulation of DBPs in plants and potential health effects also need to be carefully considered (Dannehl, Schuch, Gao, Cordiner, & Schmidt, 2016; López-Gálvez, Andujar, et al., 2018) and this is an area that would benefit from more research. Dannehl et al. (2016) found that using potassium hypochlorite as the disinfectant in a recirculating hydroponic system, resulted in higher chlorate content in the tomatoes being grown than the current European maximum residue limit. Similarly, overhead irrigation with EO treated water resulted in accumulation of chlorates in lettuce to above the maximum residue limit (López-Gálvez, Andujar et al., 2018).

Cost is obviously an important factor in the decision-making process (Raudales, Fisher, & Hall, 2017; Van Haute et al., 2015), but because of its variability at local, national and international scale, it is difficult to draw broad conclusions. Significant research gaps also exist in terms of the practical application of water treatment to irrigation water and potential impacts in the field and beyond. The variability of irrigation water quality and quantity, crops and scale of production also makes it difficult to identify an optimal treatment arrangement that will be suitable for all potential users. For each water source and treatment configuration, the efficacy (in terms of pathogen reduction) and safety (in terms of DBPs production and/or accumulation in plants) should be independently verified to ensure compliance with the relevant guidelines. For instance, water with high turbidity might not be suitable for UV treatment; and water with high dissolved organic matter content could be problematic for chlorine treatment because of the potential for DBPs and high chlorine demand, resulting in reduced disinfection efficacy. The irrigation method (i.e., drip *vs.* overhead) might also considerably affect the risk of pathogen or DBP uptake from treated water.

Below we provide some perspective on two important considerations for both human and plant health, which are induction of the viable but nonculturable (VBNC) state in microbial populations, and the potential effect of treated waters on soil and plant microbial communities.

3.1. Induction of VBNC microorganisms

Microbial populations can exist in a VBNC state, a survival strategy used by many Gram-positive and Gram-negative bacteria in response to adverse environmental conditions (Ferro, Amorico, & Deo, 2018; Ramamurthy, Ghosh, Pazhani, & Shinoda, 2014). There have recently been several works published investigating the potential for induction of VBNC cells during water disinfection processes (Lin, Li, Gu, Zeng, & He, 2016; López-Gálvez, Gil, Meireles, Truchado, & Allende, 2018; Zhang, Ye, Lin, Lv, & Yu, 2015). This might be of particular concern in low-quality irrigation waters, where disinfection efficacy is compromised by organic matter content or other factors. Hence, investigation of irrigation water disinfection using only conventional microbial culturing techniques might overestimate the efficacy of the disinfection treatment if VBNC organisms are not specifically considered. This is because VBNC organisms do not grow when plated on culture media that would normally support their growth *in vitro*, rendering them difficult to detect by conventional means.

VBNC microbes have lipid-rich membranes, tend to be smaller than their non-VBNC counterparts, exhibit reduced metabolic activity, and display altered cellular changes including cell leakage, depletion of energy pools, and altered gene expression and DNA replication (Arzanlou, Chai, & Venter, 2017; Trevors, Bej, Mojib, van Elsas, & Van Overbeek, 2012). Importantly, under favorable conditions (such as through expression of a resuscitation-promoting factor), these organisms can be revived. For example, it has been shown that *L. monocytogenes* treated with distilled water entered into the VBNC state and became virulent after resuscitation using embryonated eggs (Cappelier, Besnard, Roche, Velge, & Federighi, 2007). It therefore cannot be excluded that VBNC pathogens may be present in treated irrigation water and that they may become virulent again at a later stage. Furthermore, several studies have shown that pathogens may still exert detrimental effects even when in a VBNC state. For instance, laboratory-induced VBNC *E. coli* O157:H7 cells produced Shiga-like toxins in a vero-cell microplate cytotoxicity assay, demonstrating a potential health hazard (Liu, Wang, Tyrrell, & Li, 2010). It has also been demonstrated that the VBNC state in *S. epidermidis* contributes to the formation and persistence of biofilms, resulting in tolerance to multiple antimicrobials and immune evasion (Cerca et al., 2011).

VBNC bacterial cells can be induced by many factors, including water sanitation treatments with H_2O_2 (Arana, Muela, Iriberri, Egea, & Barcina, 1992), chlorination (Oliver, Dagher, & Linden, 2005), high/low temperature (Patrone et al., 2013; Pawlowski et al., 2011), UV irradiation (Zhang et al., 2015), peroxide-based disinfectants such as PAA (Park, Lee, Bisesi, & Lee, 2014) and high-pressure CO_2 (Zhao, Bi, Hao, & Liao, 2013). A recent study showed that *E. coli* O157:H7 treated with acidic (pH 2.7–2.9 or pH 5.6–6.3) EO water could become VBNC and be resuscitated at available chlorine concentrations that resulted in no viable counts (30 mg l^{-1}; Zhang, Chen, Xia, Li, & Hung, 2018). Much higher concentrations of available chlorine (50 mg l^{-1}) were required to remove all VBNC cells. Green fluorescent protein-tagged *L. monocytogenes* and *S. enterica* Thompson became VBNC upon exposure to 12 mg l^{-1} and 3 mg l^{-1} chlorine, respectively (Highmore, Warner, Rothwell, Wilks, & Keevil, 2018). Thus, it is critical to investigate whether and under which conditions the various water treatment regimens induce VBNC cells in a microbial community and whether these organisms can become active again on crops or fresh produce postharvest. To fully characterize the induction of VBNC status by the various water treatment technologies, a combination of macromolecular and cellular techniques such as real-time PCR (DNA), transcriptomic (RNA) metabolic activity (protein, lipid, luminescence) measurements, fluorescence-based imaging flow cytometry, as well as morphometric analyses by transmission and scanning electron microscopy will be essential.

3.2. Effects of treated irrigation waters on soil and plant microbial communities

Soil-borne microbes constitute a major proportion of the resident organisms (the "microbiome") identified on fruit and vegetables. The vast majority of these are not responsible for spoilage but rather act as a "natural biological barrier" against plant opportunistic pathogens, which are often a smaller subset of the entire soil microbial community (Andrews & Harris, 2000; Barth, Hankinson, Zhuang, & Breidt, 2009; Janisiewicz & Korsten, 2002). Indeed, it has been shown that an inverse relationship exists between soil microbial diversity and the survival of an invading pathogen (van Elsas et al., 2012). Hence, it is important that the irrigation with treated water does not negatively alter the microbial ecology of soils as this could directly influence the plant microbiome (by altering the plant endophytic and phyllosphere microbial community) or indirectly by compromising organisms important for soil health (fertility and biocontrol) and thereby decreasing the health status of plants.

Many factors contribute to changes in the microbial ecology of soil, vegetables and fruits, including soil characteristics, climatic conditions and agronomic practices (Allende & Monaghan, 2015; Barth et al., 2009; Becerra-Castro et al., 2015; Berg & Smalla, 2009; Cluff, Hartsock, MacRae, Carter, & Mouser, 2014; Frenk, Hadar, & Minz, 2014; Zheng et al., 2017). Irrigation water quality also contributes to changes in microbial communities in soil and plants, especially in copiotrophic environments/ecosystems. For instance, Mañas, Castro, and de Las Heras (2009) reported significant increases in fecal streptococci, *Salmonella* spp., sulfite-reducing *Clostridium* spp. as well as total and fecal coliform counts in lettuce irrigated with minimally treated wastewater (using trickling filters), relative to control plants receiving potable water (groundwater). These findings indicate the potential deleterious effects of microbiologically impacted irrigation water on fresh produce. However, the use of tertiary water treatment regimes, such as final disinfection using UV light, chlorination and/or ultrasound, have been shown to effectively remove indicator microorganisms and pathogens to below limits of detection at the point of discharge (Pachepsky, Shelton, McLain, Patel, & Mandrell, 2011; Villanueva, Luna, Gil, & Allende, 2015). Therefore, it is critically important that good agricultural practices are implemented before, during and after harvest to maintain soil health and promote a balanced and functioning microbial community. These practices are defined in the Codex General Principles on Food Hygiene (Codex Alimentarius Commission, 2003) and aim at maximizing the quality of the crop harvested. However, a search through the literature reveals very few original manuscripts and/or reviews pertaining to changes in the microbial ecology of soil and foliar tissues after irrigation with treated irrigation water. Chevremont, Boudenne, Coulomb, and Farnet (2013) documented the changes in microbiological properties of soils irrigated with UV-LED treated wastewaters over a one-year period. When compared with watering with untreated wastewater, watering with the UV-LED treated wastewater resulted in decreased occurrence of fecal coliforms, and showed no deleterious effects on overall microbial diversity and function. Truchado, Gil, Suslow, and Allende (2018) recently investigated the effect of a low residual ClO_2 concentration (approx. $0.25\,mg\ l^{-1}$) in irrigation water on the soil microbiome and baby spinach phyllosphere bacterial community. Next generation sequencing demonstrated that while the composition of these microbiomes was not significantly altered, the relative abundance of specific bacterial genera was influenced. In particular, the relative abundance of

Pseudomonaceae and *Enterobacteriaceae* significantly decreased when the water was treated with ClO_2.

Our overall knowledge of how the microbial ecosystems in the soil and on the surface of each produce type are influenced by the treatment of irrigation water, especially when disinfectant residues are present, is still very limited. Considering the importance of the soil and plant microbiomes to directly and indirectly control the occurrence of both human and plant pathogens, more research effort is needed in this regard.

4. Conclusions

The need to utilize water bodies and sources with sub-optimal microbiological characteristics is anticipated to increase in line with increased demand for water by the agricultural sector and society in general. In the case of fresh produce, it is of paramount importance that the microbiological quality of the water is optimized to minimize the potential for pathogen outbreaks. A significant number of treatment technologies are available for the treatment of irrigation water and they include both physical and chemical treatments. At present, the use of sodium hypochlorite and UV disinfection are widely applied because of both cost and convenience. However, other treatments such as EO water and electrochemical water disinfection (which do not require addition of chemicals) could provide interesting alternatives. Hydrodynamic cavitation should also be considered and further investigated as, in addition to not requiring chemicals due to it being a “mechanical treatment process,” it may also mitigate disinfection-induced selection of resistant bacteria (which are often pathogenic), particularly if it is proven to also destroy resistance genes and not induce the VBNC state. As noted above, however, it is generally advisable that multiple treatments are used in conjunction in high-risk settings (e.g., salad crop production), in order to ensure continuity of high water quality even in the event of total or partial failure of individual treatment barriers. We propose the concept of multistep irrigation water treatment that could be implemented for on-farm sanitation, which could vary depending on the physico-chemical parameters of the water to be treated, level of contamination and the size and cost implications of the approach to be adopted.

While there is a significant body of work on the relative efficacy of various water treatments for production of clean water, there is little direct information on the microbial profiling of irrigation water. More critically, there is little data on the effects of microbiologically impacted irrigation water on the quality of fresh produce or its effects on soil microbial communities. Direct evidence, via specific in-field experiments and advanced molecular and cellular techniques, showing the effects of the various irrigation treatment regimens on the VBNC state as well as their effects on the dynamics of soil and microbial communities, particularly on high-risk vegetables, is warranted and paramount. Equally important is a thorough evaluation of the long-term effects and benefits of the irrigation treatment methods on soil sustainability, produce quality and overall farm productivity. Moreover, judicious implementation of environmentally-friendly treatment technologies that can effectively remove antibiotics and other antimicrobial agents, their metabolites, antimicrobial resistant microorganisms and antimicrobial resistance genes in irrigation water will improve the overall safety and value of minimally-processed foods.

Funding

This work was supported by Horticulture Innovation Australia (VG15068).

ORCID

Catherine E. Dandie http://orcid.org/0000-0002-8699-6894
Abiodun D. Ogunniyi http://orcid.org/0000-0001-9308-5629
Sergio Ferro http://orcid.org/0000-0003-0797-795X
Christopher W. K. Chow http://orcid.org/0000-0001-5829-8944
Henrietta Venter http://orcid.org/0000-0001-5569-7755
Baden Myers http://orcid.org/0000-0002-6120-5363
Permal Deo http://orcid.org/0000-0002-6477-9127
Erica Donner http://orcid.org/0000-0001-6465-2233
Enzo Lombi http://orcid.org/0000-0003-3384-0375

References

ABS. (2017). *Water account, Australia, 2015–16*. Belconnen, ACT: Australian Bureau of Statistics.

Allende, A., & Monaghan, J. (2015). Irrigation water quality for leafy arops: A perspective of risks and potential solutions. *International Journal of Environmental Research and Public Health*, *12*(7), 7457–7477. doi:10.3390/ijerph120707457

Andrews, J. H., & Harris, R. F. (2000). The ecology and biogeography of microorganisms on plant surfaces. *Annual Review of Phytopathology*, *38*(1), 145–180. doi:10.1146/annurev.phyto.38.1.145

Arana, I., Muela, A., Iriberri, J., Egea, L., & Barcina, I. (1992). Role of hydrogen peroxide in loss of culturability mediated by visible light in *Escherichia coli* in a freshwater ecosystem. *Applied and Environmental Microbiology*, *58*(12), 3903–3907.

Arzanlou, M., Chai, W. C., & Venter, H. (2017). Intrinsic, adaptive and acquired antimicrobial resistance in Gram-negative bacteria. *Essays in Biochemistry*, *61*, 49–59. doi:10.1042/EBC20160063

AWA. (2017). *Emerging challenges and opportunities to secure our water future* (Discussion paper). St. Leonards, NSW: Australian Water Association.

Baker, S., Thomson, N., Weill, F.-X., & Holt, K. E. (2018). Genomic insights into the emergence and spread of antimicrobial-resistant bacterial pathogens. *Science*, *360*(6390), 733–738. doi:10.1126/science.aar3777

Bakhir, V. M. (1985). *Regulating physical and chemical properties of technological aqueous solutions by unipolar electrochemical exposure and experience of its practical application* (PhD thesis). Kazan Institute of Chemical Technologies, Kazan, Tatarstan, Russia, 146 p.

Barth, M., Hankinson, T. R., Zhuang, H., & Breidt, F. (2009). Microbiological spoilage of fruits and vegetables. In W. H. Sperber & M. P. Doyle (Eds), *Compendium of the microbiological spoilage of foods and beverages, food microbiology and food safety*. New York: Springer Verlag.

Becerra-Castro, C., Lopes, A. R., Vaz-Moreira, I., Silva, E. F., Manaia, C. M., & Nunes, O. C. (2015). Wastewater reuse in irrigation: A microbiological perspective on implications in soil fertility and human and environmental health. *Environment International*, *75*, 117–135. doi:10.1016/j.envint.2014.11.001

Berg, G., Alavi, M., Schmidt, C., Zachow, C., Egamberdieva, D., Kamilova, B., & Lugtenberg, B. J. J. (2013). Biocontrol and osmoprotection for plants under salinated conditions. In F. J. De Bruijn (Ed.), *Molecular microbial ecology of the rhizosphere* (pp. 587–592). Hoboken, NJ: John Wiley & Sons, Inc.

Berg, G., Eberl, L., & Hartmann, A. (2005). The rhizosphere as a reservoir for opportunistic human pathogenic bacteria. *Environmental Microbiology*, *7*(11), 1673–1685. doi:10.1111/j.1462-2920.2005.00891.x

Berg, G., & Smalla, K. (2009). Plant species and soil type cooperatively shape the structure and function of microbial communities in the rhizosphere. *FEMS Microbiology Ecology*, *68*(1), 1–13. doi:10.1111/j.1574-6941.2009.00654.x

Berger, C. N., Sodha, S. V., Shaw, R. K., Griffin, P. M., Pink, D., Hand, P., & Frankel, G. (2010). Fresh fruit and vegetables as vehicles for the transmission of human pathogens. *Environmental Microbiology*, *12*(9), 2385–2397. doi:10.1111/j.1462-2920.2010.02297.x

Bohnstedt, R., Surbeck, U., & Bartsch, R. (2009). European Patent EP *1969159 B1*.

Bonfatti, F., Ferro, S., Lavezzo, F., Malacarne, M., Lodi, G., & De Battisti, A. (2000). Electrochemical incineration of glucose as a model organic substrate. Part 2: Role of active chlorine mediation. *Journal of the Electrochemical Society*, *147*(2), 592–596. doi:10.1149/1.1393238

Bradford, S. A., & Harvey, R. W. (2017). Future research needs involving pathogens in groundwater. *Hydrogeology Journal*, *25*(4), 931–938. doi:10.1007/s10040-016-1501-0

Buck, J. W., van Iersel, M. W., Oetting, R. D., & Hung, Y.-C. (2003). Evaluation of acidic electrolyzed water for phytotoxic symptoms on foliage and flowers of bedding plants. *Crop Protection*, *22*(1), 73–77. doi:10.1016/S0261-2194(02)00113-8

Cappelier, J. M., Besnard, V., Roche, S. M., Velge, P., & Federighi, M. (2007). Avirulent viable but non culturable cells of *Listeria monocytogenes* need the presence of an embryo to be recovered in egg yolk and regain virulence after recovery. *Veterinary Research*, *38*(4), 573–583. doi:10.1051/vetres:2007017

Cerca, F., Andrade, F., Franca, A., Andrade, E. B., Ribeiro, A., Almeida, A. A., … Vilanova, M. (2011). *Staphylococcus epidermidis* biofilms with higher proportions of dormant bacteria induce a lower activation of murine macrophages. *Journal of Medical Microbiology*, *60*(12), 1717–1724. doi:10.1099/jmm.0.031922-0

Chahal, C., van den Akker, B., Young, F., Franco, C., Blackbeard, J., & Monis, P. (2016). In S. Sariaslani & G. M. Gadd (Eds), *Advances in applied microbiology* (Vol. 97. pp. 63–119). San Diego, CA: Elsevier Academic Press Inc.

Chatziprodromidou, I., Bellou, M., Vantarakis, G., & Vantarakis, A. (2018). Viral outbreaks linked to fresh produce consumption: A systematic review. *Journal of Applied Microbiology*, *124*(4), 932–942. doi:10.1111/jam.13747

Chevremont, A. C., Boudenne, J. L., Coulomb, B., & Farnet, A. M. (2013). Impact of watering with UV-LED-treated wastewater on microbial and physico-chemical parameters of soil. *Water Research*, *47*(6), 1971–1982. doi:10.1016/j.watres.2013.01.006

Ciriminna, R., Albanese, L., Meneguzzo, F., & Pagliaro, M. (2016). Wastewater remediation via controlled hydrocavitation. *Environmental Reviews*, *25*(2), 175–183. doi:10.1139/er-2016-0064

Cluff, M. A., Hartsock, A., MacRae, J. D., Carter, K., & Mouser, P. J. (2014). Temporal changes in microbial ecology and geochemistry in produced water from hydraulically fractured Marcellus shale gas wells. *Environmental Science & Technology*, *48*(11), 6508–6517. doi:10.1021/es501173p

Codex Alimentarius Commission. (2003). *Recommended International Code of Practice—General principles of food hygiene* (CAC/RCP 1-1969 Rev. 4-2003). Rome: FAO/WHO.

Dannehl, D., Schuch, I., Gao, Y., Cordiner, S., & Schmidt, U. (2016). Effects of hypochlorite as a disinfectant for hydroponic systems on accumulations of chlorate and phytochemical compounds in tomatoes. *European Food Research and Technology*, *242*(3), 345–353. doi:10.1007/s00217-015-2544-5

De Battisti, A., Formaglio, P., Ferro, S., Al Aukidy, M., & Verlicchi, P. (2018). Electrochemical disinfection of groundwater for civil use – An example of an effective endogenous advanced oxidation process. *Chemosphere*, *207*, 101–109. doi:10.1016/j.chemosphere.2018.05.062

De Keuckelaere, A., Jacxsens, L., Amoah, P., Medema, G., McClure, P., Jaykus, L.-A., & Uyttendaele, M. (2015). Zero risk does not exist: Lessons learned from microbial risk assessment related to use of water and safety of fresh produce. *Comprehensive Reviews in Food Science and Food Safety*, *14*(4), 387–410. doi:10.1111/1541-4337.12140

Delaedt, Y., Daneels, A., Declerck, P., Behets, J., Ryckeboer, J., Peters, E., & Ollevier, F. (2008). The impact of electrochemical disinfection on *Escherichia coli* and *Legionella pneumophila* in tap water. *Microbiological Research*, *163*(2), 192–199. doi:10.1016/j.micres.2006.05.002

Deng, Y., & Zhao, R. (2015). Advanced oxidation processes (AOPs) in wastewater treatment. *Current Pollution Reports*, *1*(3), 167–176. doi:10.1007/s40726-015-0015-z

Diao, H. F., Li, X. Y., Gu, J. D., Shi, H. C., & Xie, Z. M. (2004). Electron microscopic investigation of the bactericidal action of electrochemical disinfection in comparison with chlorination, ozonation and Fenton reaction. *Process Biochemistry*, *39*(11), 1421–1426. doi:10.1016/S0032-9592(03)00274-7

Dobrowsky, P. H., De Kwaadsteniet, M., Cloete, T. E., & Khan, W. (2014). Distribution of indigenous bacterial pathogens and potential pathogens associated with roof-harvested rainwater. *Applied and Environmental Microbiology*, *80*(7), 2307–2316. doi:10.1128/AEM.04130-13

Dorais, M., Alsanius, B. W., Voogt, W., Pepin, S., Tüzel, İH., Tüzel, Y., & Möller, K. (2016). Impact of water quality and irrigation management on organic greenhouse horticulture. BioGreenhouse COST Action FA 1105. Retrieved from www.biogreenhouse.org

Dular, M., Griessler-Bulc, T., Gutierrez-Aguirre, I., Heath, E., Kosjek, T., Krivograd Klemencic, A., … Kompare, B. (2016). Use of hydrodynamic cavitation in (waste)water treatment. *Ultrasonics Sonochemistry*, *29*, 577–588. doi:10.1016/j.ultsonch.2015.10.010

E.P.H.C. (2006). *Australian guidelines for water recycling*. Managing health and environmental risks. Phase 1. National water quality management strategy 21. Natural Resource

Management Ministerial Council. Environment Protection and Heritage Council, Australian Health Ministers Conference Council, Canberra.
European Commission. (2019). *P8_TA(2019)0071. Minimum requirements for water reuse*. Retrieved from http://www.europarl.europa.eu/doceo/document/TA-8-2019-0071_EN.pdf
Food and Agriculture Organization of the United Nations (FAO) (2015). *FAO statistical pocketbook: World Food and Agriculture*. Rome: Food and Agriculture Organization of the United Nations.
Ferro, S. (2015). Electrochemical activated solutions. *The Australian Hospital Engineer*, *38*(2), 50–53.
Ferro, S., Amorico, T., & Deo, P. (2018). Role of food sanitising treatments in inducing the 'viable but nonculturable' state of microorganisms. *Food Control*, *91*, 321–329. doi:10.1016/j.foodcont.2018.04.016
Fischer, N., Bourne, A., & Plunkett, D. (2015). *Outbreak Alert! 2015: A review of foodborne illnesses in the US from 2004–2013*. Washington, DC: Center for Science in the Public Interest.
Frenk, S., Hadar, Y., & Minz, D. (2014). Resilience of soil bacterial community to irrigation with water of different qualities under Mediterranean climate. *Environmental Microbiology*, *16*(2), 559–569. doi:10.1111/1462-2920.12183
FSANZ. (2011). Supporting document 2: Review of foodborne illness associated with selected ready-to-eat fresh produce (December 2011). Proposal P1015. Primary Production & Processing Requirements for Horticulture. Barton, ACT: Food Standards Australia New Zealand.
FSANZ. (2016). Woolworths loose leaf lettuce product recall. Retrieved from http://www.foodstandards.gov.au/industry/foodrecalls/recalls/Pages/Woolworths-loose-leaf-lettuce.aspx
Gil, M. I., Selma, M. V., Suslow, T., Jacxsens, L., Uyttendaele, U., & Allende, A. (2015). Pre- and postharvest preventive measures and intervention strategies to control microbial food safety hazards of fresh leafy vegetables. *Critical Reviews in Food Science and Nutrition*, *55*(4), 453–468. doi:10.1080/10408398.2012.657808
Grech, N. M., & Rijkenberg, F. H. J. (1992). Injection of electrolytically generated chlorine into citrus microirrigation systems for the control of certain waterborne root pathogens. *Plant Disease*, *76*(5), 457–461. doi:10.1094/PD-76-0457
Hai, F., Riley, T., Shawkat, S., Magram, S., & Yamamoto, K. (2014). Removal of pathogens by membrane bioreactors: A review of the mechanisms, influencing factors and reduction in chemical disinfectant dosing. *Water*, *6*(12), 3603–3630. doi:10.3390/w6123603
Hardoim, P. R., van Overbeek, L. S., Berg, G., Pirttila, A. M., Compant, S., Campisano, A., … Sessitsch, A. (2015). The hidden world within plants: Ecological and evolutionary considerations for defining functioning of microbial endophytes. *Microbiology and Molecular Biology Reviews*, *79*(3), 293–320. doi:10.1128/MMBR.00050-14
Hedberg, C. (2016). Epidemiology of viral foodborne outbreaks: Role of food handlers, irrigation water, and surfaces. In S. Goyal & J. Cannon (Eds.), *Viruses in foods. Food microbiology and food safety* (pp. 147-163). Cham: Springer.
Highmore, C. J., Warner, J. C., Rothwell, S. D., Wilks, S. A., & Keevil, C. W. (2018). Viable-but-nonculturable *Listeria monocytogenes* and *Salmonella enterica* Serovar Thompson induced by chlorine stress remain infectious. *mBio*, *9*(2), e00540–18. doi:10.1128/mBio.00540-18
Hoelzer, K., Switt, A. I. M., Wiedmann, M., & Boor, K. J. (2018). Emerging needs and opportunities in foodborne disease detection and prevention: From tools to people. *Food Microbiology*, *75*, 65–71. doi:10.1016/j.fm.2017.07.006

Hoslett, J., Massara, T. M., Malamis, S., Ahmad, D., van den Boogaert, I., Katsou, E., … Jouhara, H. (2018). Surface water filtration using granular media and membranes: A review. *Science of the Total Environment*, *639*, 1268–1282. doi:10.1016/j.scitotenv.2018.05.247

Janisiewicz, W. J., & Korsten, L. (2002). Biological control of postharvest diseases of fruits. *Annual Review of Phytopathology*, *40*(1), 411–441. doi:10.1146/annurev.phyto.40.120401.130158

Jeong, J., Kim, C., & Yoon, J. (2009). The effect of electrode material on the generation of oxidants and microbial inactivation in the electrochemical disinfection processes. *Water Research*, *43*(4), 895–901. doi:10.1016/j.watres.2008.11.033

Jhaveri, J. H., & Murthy, Z. V. P. (2016). A comprehensive review on anti-fouling nanocomposite membranes for pressure driven membrane separation processes. *Desalination*, *379*, 137–154. doi:10.1016/j.desal.2015.11.009

Jo, H. Y., Tango, C. N., & Oh, D. H. (2018). Influence of different organic materials on chlorine concentration and sanitization of slightly acidic electrolyzed water. *LWT*, *92*, 187–194. doi:10.1016/j.lwt.2018.02.028

Jones, L. A., Worobo, R. W., & Smart, C. D. (2014). UV light inactivation of human and plant pathogens in unfiltered surface irrigation water. *Applied and Environmental Microbiology*, *80*(3), 849–854. doi:10.1128/AEM.02964-13

Jongman, M., & Korsten, L. (2017). Irrigation water quality and microbial safety of leafy greens in different vegetable production systems: A review. *Food Reviews International*, *34*(4), 308–328. doi:10.1080/87559129.2017.1289385

Jusoh, M. N. H., Aris, A., & Talib, J. (2016). Hydrodynamic cavitation using double orifice-plates for the generation of hydroxyl radicals. *Jurnal Teknologi*, *78*(11), 41–47. doi:10.11113/jt.v78.7164

Kerwick, M. I., Reddy, S. M., Chamberlain, A. H. L., & Holt, D. M. (2005). Electrochemical disinfection, an environmentally acceptable method of drinking water disinfection? *Electrochimica Acta*, *50*(25-26), 5270–5277. doi:10.1016/j.electacta.2005.02.074

Kirpalani, D. M., Singla, A., Lotfi, S., & Mohapatra, D. P. (2016). Cavitation Technology Development: A Paradigm Shift in Mining Effluent Treatment. Energy, Mining & Environment Portfolio, NRC, Québec Mines, November 21st to 24th, 2016.

Kitis, M. (2004). Disinfection of wastewater with peracetic acid: A review. *Environment International*, *30*(1), 47–55. doi:10.1016/S0160-4120(03)00147-8

Kraft, A. (2008). Electrochemical water disinfection: A short review. *Platinum Metals Review*, *52*(3), 177–185. doi:10.1595/147106708X329273

Li, D., & Gu, A. Z. (2019). Antimicrobial resistance: A new threat from disinfection byproducts and disinfection of drinking water? *Current Opinion in Environmental Science & Health*, *7*, 83–91. doi:10.1016/j.coesh.2018.12.003

Li, P., Song, Y., & Yu, S. L. (2014). Removal of *Microcystis aeruginosa* using hydrodynamic cavitation: Performance and mechanisms. *Water Research*, *62*, 241–248. doi:10.1016/j.watres.2014.05.052

Lim, J. A., Lee, D. H., & Heu, S. (2014). The interaction of human enteric pathogens with plants. *The Plant Pathology Journal*, *30*(2), 109–116. doi:10.5423/PPJ.RW.04.2014.0036

Lin, Y. W., Li, D., Gu, A. Z., Zeng, S. Y., & He, M. (2016). Bacterial regrowth in water reclamation and distribution systems revealed by viable bacterial detection assays. *Chemosphere*, *144*, 2165–2174. doi:10.1016/j.chemosphere.2015.10.071

Liu, Y., Wang, C., Tyrrell, G., & Li, X. F. (2010). Production of Shiga-like toxins in viable but nonculturable *Escherichia coli* O157:H7. *Water Research*, *44*(3), 711–718. doi:10.1016/j.watres.2009.10.005

López-Gálvez, F., Andujar, S., Marin, A., Tudela, J. A., Allende, A., & Gil, M. I. (2018). Disinfection by-products in baby lettuce irrigated with electrolysed water. *Journal of the Science of Food and Agriculture*, *98*(8), 2981–2988. doi:10.1002/jsfa.8796

López-Gálvez, F., Gil, M. I., Meireles, A., Truchado, P., & Allende, A. (2018). Demonstration tests of irrigation water disinfection with chlorine dioxide in open field cultivation of baby spinach. *Journal of the Science of Food and Agriculture*, *98*(8), 2973–2980. doi:10.1002/jsfa.8794

Majsztrik, J. C., Fernandez, R. T., Fisher, P. R., Hitchcock, D. R., Lea-Cox, J., Owen, J. S., Jr., … White, S. A. (2017). Water use and treatment in container-grown specialty crop production: A review. *Water, Air, and Soil Pollution*, *228*(4), 151. doi:10.1007/s11270-017-3272-1

Mañas, P., Castro, E., & de Las Heras, J. (2009). Irrigation with treated wastewater: Effects on soil, lettuce (*Lactuca sativa* L.) crop and dynamics of microorganisms. *Journal of Environmental Science and Health, Part A*, *44*(12), 1261–1273. doi:10.1080/10934520903140033

Markland, S. M., Ingram, D., Kniel, K. E., & Sharma, M. (2017). Water for agriculture: The convergence of sustainability and safety. *Microbiology Spectrum*, *5*(3):PFS-0014-2016. doi:10.1128/microbiolspec.PFS-0014-2016

Martínez, S. B., Pérez-Parra, J., & Suay, R. (2011). Use of ozone in wastewater treatment to produce water suitable for irrigation. *Water Resources Management*, *25*(9), 2109–2124. doi:10.1007/s11269-011-9798-x

Martínez-Huitle, C. A., & Brillas, E. (2008). Electrochemical alternatives for drinking water disinfection. *Angewandte Chemie International Edition*, *47*(11), 1998–2005. doi:10.1002/anie.200703621

Matsunaga, T., Nakasono, S., Kitajima, V., & Horiguchi, K. (1994). Electrochemical disinfection of bacteria in drinking water using activated carbon fibers. *Biotechnology and Bioengineering*, *43*(5), 429–433. doi:10.1002/bit.260430511

Matsunaga, T., Nakasono, S., Takamuku, T., Burgess, J. G., Nakamura, N., & Sode, K. (1992). Disinfection of drinking water by using a novel electrochemical reactor employing carbon-cloth electrodes. *Applied and Environmental Microbiology*, *58*(2), 686–689.

Matsunaga, T., Okochi, M., & Nakasono, S. (1995). Direct count of bacteria using fluorescent dyes: Application to assessment of electrochemical disinfection. *Analytical Chemistry*, *67*(24), 4487–4490. doi:10.1021/ac00120a010

Mendes, R., Garbeva, P., & Raaijmakers, J. M. (2013). The rhizosphere microbiome: Significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. *FEMS Microbiology Reviews*, *37*(5), 634–663. doi:10.1111/1574-6976.12028

Migliarina, F., & Ferro, S. (2014). A modern approach to disinfection, as old as the evolution of vertebrates. *Healthcare*, *2*(4), 516–526. doi:10.3390/healthcare2040516

Moorman, E., Montazeri, N., & Jaykus, L. A. (2017). Efficacy of neutral electrolyzed water for inactivation of human norovirus. *Applied and Environmental Microbiology*, *83*(16), e00653–17. doi:10.1128/AEM.00653-17

Nakasono, S., Nakamura, N., Sode, K., & Matsunaga, T. (1992). Electrochemical disinfection of marine bacteria attached on a plastic electrode. *Bioelectrochemistry and Bioenergetics*, *27*(2), 191–198. doi:10.1016/0302-4598(92)87042-S

NHMRC & NRMMC. (2011). In National Health and Medical Research Council & N.R.M.M.C. (Eds.), *Australian drinking water guidelines Paper 6 National Water Quality Management Strategy*. Canberra: Commonwealth of Australia.

Oliver, J. D., Dagher, M., & Linden, K. (2005). Induction of *Escherichia coli* and *Salmonella* Typhimurium into the viable but nonculturable state following chlorination of wastewater. *Journal of Water and Health*, *3*(3), 249–257. doi:10.2166/wh.2005.040

Pachepsky, Y., Shelton, D. R., McLain, J. E. T., Patel, J., & Mandrell, R. E. (2011). Irrigation waters as a source of pathogenic microorganisms in produce: A review. *Advances in Agronomy*, *113*, 75–141.

Park, E., Lee, C., Bisesi, M., & Lee, J. (2014). Efficiency of peracetic acid in inactivating bacteria, viruses, and spores in water determined with ATP bioluminescence, quantitative PCR, and culture-based methods. *Journal of Water and Health*, *12*(1), 13–23. doi:10.2166/wh.2013.002

Patrone, V., Campana, R., Vallorani, L., Dominici, S., Federici, S., Casadei, L., … Baffone, W. (2013). CadF expression in *Campylobacter jejuni* strains incubated under low-temperature water microcosm conditions which induce the viable but non-culturable (VBNC) state. *Antonie Van Leeuwenhoek*, *103*(5), 979–988. doi:10.1007/s10482-013-9877-5

Pawlowski, D. R., Metzger, D. J., Raslawsky, A., Howlett, A., Siebert, G., Karalus, R. J., … Whitehouse, C. A. (2011). Entry of Yersinia pestis into the viable but nonculturable state in a low-temperature tap water microcosm. *PLoS One*, *6*(3), e17585. doi:10.1371/journal.pone.0017585

Petkovšek, M., Zupanc, W., Dular, M., Kosjek, T., Heath, E., Kompare, B., & Širok, B. (2013). Rotation generator of hydrodynamic cavitation for water treatment. *Separation and Purification Technology*, *118*, 415–423. doi:10.1016/j.seppur.2013.07.029

Quadrelli, S., & Ferro, S. (2010). Electrochemical reactor. International Patent Application *WO 2010/055108*.

Rahman, S. M. E., Khan, I., & Oh, D.-H. (2016). Electrolyzed water as a novel sanitizer in the food industry: Current trends and future perspectives. *Comprehensive Reviews in Food Science and Food Safety*, *15*(3), 471–490. doi:10.1111/1541-4337.12200

Rajoriya, S., Carpenter, J., Saharan Virendra, K., & Pandit Aniruddha, B. (2016). Hydrodynamic cavitation: An advanced oxidation process for the degradation of bio-refractory pollutants. *Reviews in Chemical Engineering*, *32*(4), 379–411. doi:10.1515/revce-2015-0075

Ramamurthy, T., Ghosh, A., Pazhani, G. P., & Shinoda, S. (2014). Current perspectives on viable but non-culturable (VBNC) pathogenic bacteria. *Frontiers in Public Health*, *2*, 103. doi:10.3389/fpubh.2014.00103

Ramírez-Castillo, F. Y., Loera-Muro, A., Jacques, M., Garneau, P., Avelar-González, F. J., Harel, J., & Guerrero-Barrera, A. L. (2015). Waterborne pathogens: Detection methods and challenges. *Pathogens*, *4*(2), 307–334. doi:10.3390/pathogens4020307

Raudales, R. E., Fisher, P. R., & Hall, C. R. (2017). The cost of irrigation sources and water treatment in greenhouse production. *Irrigation Science*, *35*(1), 43–54. doi:10.1007/s00271-016-0517-5

Raudales, R. E., Parke, J. L., Guy, C. L., & Fisher, P. R. (2014). Control of waterborne microbes in irrigation: A review. *Agricultural Water Management*, *143*, 9–28. doi:10.1016/j.agwat.2014.06.007

Raut-Jadhav, S., Badve, M. P., Pinjari, D. V., Saini, D. R., Sonawane, S. H., & Pandit, A. B. (2016). Treatment of the pesticide industry effluent using hydrodynamic cavitation and its combination with process intensifying additives (H_2O_2 and ozone). *Chemical Engineering Journal*, *295*, 326–335. doi:10.1016/j.cej.2016.03.019

Rizzo, L., Manaia, C., Merlin, C., Schwartz, T., Dagot, C., Ploy, M. C., … Fatta-Kassinos, D. (2013). Urban wastewater treatment plants as hotspots for antibiotic resistant bacteria and genes spread into the environment: A review. *Science of the Total Environment*, *447*, 345–360. doi:10.1016/j.scitotenv.2013.01.032

Scarlett, K., Collins, D., Tesoriero, L., Jewell, L., van Ogtrop, F., & Daniel, R. (2016). Efficacy of chlorine, chlorine dioxide and ultraviolet radiation as disinfectants against plant pathogens in irrigation water. *European Journal of Plant Pathology*, *145*(1), 27–38. doi:10.1007/s10658-015-0811-8

Shionoiri, N., Nogariya, O., Tanaka, M., Matsunaga, T., & Tanaka, T. (2015). Capsid protein oxidation in feline calicivirus using an electrochemical inactivation treatment. *Journal of Hazardous Materials*, *283*, 410–415. doi:10.1016/j.jhazmat.2014.09.049

Steele, M., & Odumeru, J. (2004). Irrigation water as source of foodborne pathogens on fruit and vegetables. *Journal of Food Protection*, *67*(12), 2839–2849. doi:10.4315/0362-028X-67.12.2839

Stevenson, S. M. L., Cook, S. R., Bach, S. J., & McAllister, T. A. (2004). Effects of water source, dilution, storage, and bacterial and fecal loads on the efficacy of electrolyzed oxidizing water for the control of *Escherichia coli* O157:H7. *Journal of Food Protection*, *67*(7), 1377–1383. doi:10.4315/0362-028X-67.7.1377

Stoner, G. E., Cahen, G. L., Sachyani, M., & Gileadi, E. (1982). The mechanism of low-frequency a.c. electrochemical disinfection. *Bioelectrochemistry and Bioenergetics*, *9*(3), 229–243. doi:10.1016/0302-4598(82)80013-5

Suslow, T. V. (2010). Standards for irrigation and foliar contact water. An initiative of the Pew Charitable Trusts at Georgetown University. Peer-reviewed issue. Retrieved from http://www.producesafetyproject.org/admin/assets/files/Water-Suslow-1.pdf

Tao, Y. Q., Cai, J., Huai, X. L., Liu, B., & Guo, Z. X. (2016). Application of hydrodynamic cavitation to wastewater treatment. *Chemical Engineering & Technology*, *39*(8), 1363–1376. doi:10.1002/ceat.201500362

Thanner, S., Drissner, D., & Walsh, F. (2016). Antimicrobial resistance in agriculture. *mBio*, *7*(2), 7. doi:10.1128/mBio.02227-15

Thebo, A. L., Drechsel, P., Lambin, E. F., & Nelson, K. L. (2017). A global, spatially-explicit assessment of irrigated croplands influenced by urban wastewater flows. *Environmental Research Letters*, *12*(7), 074008. doi:10.1088/1748-9326/aa75d1

Torabi Angaji, M., & Ghiaee, R. (2015). Decontamination of unsymmetrical dimethylhydrazine waste water by hydrodynamic cavitation-induced advanced Fenton process. *Ultrasonics Sonochemistry*, *23*, 257–265. doi:10.1016/j.ultsonch.2014.09.007

Trevors, J. T., Bej, A. K., Mojib, N., van Elsas, J. D., & Van Overbeek, L. (2012). Bacterial gene expression at low temperatures. *Extremophiles*, *16*(2), 167–176. doi:10.1007/s00792-011-0423-y

Truchado, P., Gil, M. I., Suslow, T., & Allende, A. (2018). Impact of chlorine dioxide disinfection of irrigation water on the epiphytic bacterial community of baby spinach and underlying soil. *PLoS One*, *13*(7), e0199291. doi:10.1371/journal.pone.0199291

Uyttendaele, M., Jaykus, L.-A., Amoah, P., Chiodini, A., Cunliffe, D., Jacxsens, L., … Rao Jasti, P. (2015). Microbial hazards in irrigation water: Standards, norms, and testing to manage use of water in fresh produce primary production. *Comprehensive Reviews in Food Science and Food Safety*, *14*(4), 336–356. doi:10.1111/1541-4337.12133

van Elsas, J. D., Chiurazzi, M., Mallon, C. A., Elhottova, D., Kristufek, V., & Salles, J. F. (2012). Microbial diversity determines the invasion of soil by a bacterial pathogen. *Proceedings of the National Academy of Sciences USA*, *109*(4), 1159–1164. doi:10.1073/pnas.1109326109

Van Haute, S., Sampers, I., Jacxsens, L., & Uyttendaele, M. (2015). Selection criteria for water disinfection techniques in agricultural practices. *Critical Reviews in Food Science and Nutrition*, *55*(11), 1529–1551. doi:10.1080/10408398.2012.705360

Villanueva, M. V., Luna, M. C., Gil, M. I., & Allende, A. (2015). Ultrasound treatments improve the microbiological quality of water reservoirs used for the irrigation of fresh produce. *Food Research International*, *75*, 140–147. doi:10.1016/j.foodres.2015.05.040

World Health Organization (WHO). (1989). Health guidelines for the use of wastewater in agriculture and aquaculture. Retrieved from http://whqlibdoc.who.int/trs/WHO_TRS_778.pdf

World Health Organization (WHO). (2015a). Global action plan on antimicrobial resistance. World Health Organization. Retrieved from http://www.who.int/iris/handle/10665/193736

World Health Organization (WHO). (2015b). *WHO estimates of the global burden of foodborne diseases*. Geneva: World Health Organization.

Wuijts, S., van den Berg, H., Miller, J., Abebe, L., Sobsey, M., Andremont, A., … Husman, A. M. D. (2017). Towards a research agenda for water, sanitation and antimicrobial resistance. *Journal of Water and Health*, *15*(2), 175–184. doi:10.2166/wh.2017.124

Yang, R., Li, H., Huang, M., Yang, H., & Li, A. (2016). A review on chitosan-based flocculants and their applications in water treatment. *Water Research*, *95*, 59–89. doi:10.1016/j.watres.2016.02.068

Zarattini, M., De Bastiani, M., Bernacchia, G., Ferro, S., & De Battisti, A. (2015). The use of ECAS in plant protection: A green and efficient antimicrobial approach that primes selected defense genes. *Ecotoxicology*, *24*(9), 1996–2008. doi:10.1007/s10646-015-1535-4

Zhang, C. L., Chen, X., Xia, X. D., Li, B. M., & Hung, Y. C. (2018). Viability assay of *E-coli* O157: H7 treated with electrolyzed oxidizing water using flow cytometry. *Food Control*, *88*, 47–53. doi:10.1016/j.foodcont.2017.12.029

Zhang, S., Ye, C., Lin, H., Lv, L., & Yu, X. (2015). UV disinfection induces a VBNC state in *Escherichia coli* and *Pseudomonas aeruginosa*. *Environmental Science & Technology*, *49*(3), 1721–1728. doi:10.1021/es505211e

Zhao, F., Bi, X. F., Hao, Y. L., & Liao, X. J. (2013). Induction of viable but nonculturable *Escherichia coli* O157:H7 by high pressure CO_2 and its characteristics. *Plos One* , *8*(4): e62388. doi:10.1371/journal.pone.0062388

Zheng, J., Kase, J., De Jesus, A., Sahu, S., Hayford, A. E., Luo, Y., … Bell, R. (2017). Microbial ecology of fresh vegetables. Food and Drug Administration Papers, 18. U.S. Department of Health and Human Services Chapter 17, pp. 341–357.

Zhu, Q., Gooneratne, R., & Hussain, M. A. (2017). *Listeria monocytogenes* in fresh produce: Outbreaks, prevalence and contamination Levels. *Foods*, *6*(3), 21. doi:10.3390/foods6030021

Zupanc, M., Kosjek, T., Petkovsek, M., Dular, M., Kompare, B., Sirok, B., … Heath, E. (2013). Removal of pharmaceuticals from wastewater by biological processes, hydrodynamic cavitation and UV treatment. *Ultrasonics Sonochemistry*, *20*(4), 1104–1112. doi:10.1016/j.ultsonch.2012.12.003

Zupanc, M., Kosjek, T., Petkovsek, M., Dular, M., Kompare, B., Sirok, B., … Heath, E. (2014). Shear-induced hydrodynamic cavitation as a tool for pharmaceutical micropollutants removal from urban wastewater. *Ultrasonics Sonochemistry*, *21*(3), 1213–1221. doi:10.1016/j.ultsonch.2013.10.025

Zupanc, M., Pandur, Ž., Stepišnik Perdih, T., Stopar, D., Petkovšek, M., & Dular, M. (2019). Effects of cavitation on different microorganisms: The current understanding of the mechanisms taking place behind the phenomenon. A review and proposals for further research. *Ultrasonics Sonochemistry*, *57*, 147–165. doi:10.1016/j.ultsonch.2019.05.009

Supporting Information

Table S1: Efficacy of electrolyzed oxidizing water treatments on specific pathogens in suspension

Pathogen	Matrix/Active agent	Dose/contact time	Log reduction	Reference
Escherichia coli	PBS/ SAEW (20:1)	5–10 min; 60 ppm ACC; ORP +910 mV; pH 6.4; volume ratio 20:1	~8 log CFU/mL	Ye et al 2017
E. coli	TSB/ NEW (0.1/9.9 mL)	10 min; 20–100 ppm total residual chlorine; ORP +800-900 mV; pH 6.3–6.5; 25°C	6.1–6.7 log CFU/mL	Guentzel et al 2008
E. coli	0.85% NaCl/ LcEW (1/9 mL)	1 min; 5–10 mg/L ACC; ORP +660–700 mV; pH 6.8–7.4	4.9–5.3 log CFU/mL	Rahman et al 2012
E. coli O157:H7	[a]Culture/sterile water/NEW (1/1/8 mL)	5 min; 89 mg/L ACC; pH 7.99–8.19; ORP +745–771 mV; 23°C	>6 log CFU/mL	Deza et al 2003
E. coli (range of strains)	NECAW	30 s; 100 ppm FAC; ORP +864 mV; pH 7.0	>5 log CFU/mL	Yang et al 2013
Salmonella (range of strains)	NECAW	30 s; 100 ppm FAC; ORP +864; pH 7.0	>5 log CFU/mL	Yang et al 2013
Salmonella enteritidis	Culture/sterile water/NEW (1/1/8 mL)	5 min; 89 mg/L ACC; pH 7.99–8.19; ORP +745–771 mV; 23°C	>6 log CFU/mL	Deza et al 2003
Listeria monocytogenes	Culture/sterile water/NEW (1/1/8 mL)	5 min; 89 mg/L ACC; pH 7.99–8.19; ORP +745–771 mV; 23°C	>6 log CFU/mL	Deza et al 2003

Listeria monocytogenes (range of strains)	PW/NECAW (1/99 mL)	30 s; 50–100 ppm FAC; ORP +824–864; pH 7.0	>5 log CFU/mL	Yang et al 2013
Listeria innocua	Cells resuspended in NEW	10 min; 150 ppm ACC; ORP +840 mV; pH 6.9; 23°C	2.7 log CFU/mL	Feliciano et al 2012
Listeria innocua	Cells resuspended in AEW	10 min; 150 ppm ACC; ORP +1100 mV; pH 2.7; 23°C	4.7 log CFU/mL	Feliciano et al 2012
Listeria monocytogenes	TSB/ NEW (0.1/9.9 mL)	10 min; 20–100 ppm total residual chlorine; ORP +800–900 mV; pH 6.3–6.5; 25°C	6.1–6.7 log CFU/mL	Guentzel et al 2008
Listeria monocytogenes	0.85% NaCl/ LcEW (1/9 mL)	1 min; 5–10 mg/L ACC; ORP +660–700 mV; pH 6.8–7.4	5.2–5.6 log CFU/mL	Rahman et al 2012
Listeria monocytogenes	0.85% NaCl/NEW (1/9 mL)	30 s; 20 ppm total chlorine concentration; ORP +1100 mV; pH 7.0; 30°C	≥5 log CFU/mL	Arevalos-Sanchez et al 2012

NEW: neutral electrolyzed water; AEW: acidic electrolyzed water; SAEW: slightly acidic electrolyzed water; CFU: colony forming unit; ACC: available chlorine concentrations; NECAW: neutral electrochemically activated water; LcEW: low concentration electrolyzed water; ORP: oxidation-reduction potential; PBS: phosphate buffered saline; TSB: trypticase soy broth; PW: peptone water

[a] details of culture medium not provided.

References to Table S1:

Arevalos-Sanchez, M., Regalado, C., Martin, S.E., Dominguez-Dominguez, J., Garcia-Almendarez, B.E., 2012. Effect of neutral electrolyzed water and nisin on *Listeria monocytogenes* biofilms, and on listeriolysin O activity. Food Control 24, 116-122.

Deza, M.A., Araujo, M., Garrido, M.J., 2003. Inactivation of *Escherichia coli* O157:H7, *Salmonella enteritidis* and *Listeria monocytogenes* on the surface of tomatoes by neutral electrolyzed water. Letters in Applied Microbiology 37, 482-487.

Feliciano, L., Lee, J., Pascall, M.A., 2012. Transmission electron microscopic analysis showing structural changes to bacterial cells treated with electrolyzed water and an acidic sanitizer. Journal of Food Science 77, M182-187.

Guentzel, J.L., Liang Lam, K., Callan, M.A., Emmons, S.A., Dunham, V.L., 2008. Reduction of bacteria on spinach, lettuce, and surfaces in food service areas using neutral electrolyzed oxidizing water. Food Microbiology 25, 36-41.

Rahman, S.M.E., Park, J.H., Wang, J., Oh, D.-H., 2012. Stability of low concentration electrolyzed water and its sanitization potential against foodborne pathogens. Journal of Food Engineering 113, 548-553.

Yang, H., Feirtag, J., Diez-Gonzalez, F., 2013. Sanitizing effectiveness of commercial “active water” technologies on *Escherichia coli* O157:H7, *Salmonella enterica* and *Listeria monocytogenes*. Food Control 33, 232-238.

Ye, Z., Wang, S., Chen, T., Gao, W., Zhu, S., He, J., Han, Z., 2017. Inactivation Mechanism of *Escherichia coli* Induced by Slightly Acidic Electrolyzed Water. Science Reports 7, 6279.