Critical Reviews in Food Science and Nutrition, 55:1529–1551, 2015

ISSN: 1040-8398 print / 1549-7852 online
DOI: 10.1080/10408398.2012.705360

Selection Criteria for Water Disinfection Techniques in Agricultural Practices

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This paper comprises a selection tool for water disinfection methods for fresh produce pre- and postharvest practices. A variety of water disinfection technologies is available on the market and no single technology is the best choice for all applications. It can be difficult for end users to choose the technology that is best fit for a specific application. Therefore, the different technologies were characterized in order to identify criteria that influence the suitability of a technology for pre- or postharvest applications. Introduced criteria were divided into three principal components: (i) criteria related to the technology and which relate to the disinfection efficiency, (ii) attention points for the management and proper operation, and (iii) necessities in order to sustain the operation with respect to the environment. The selection criteria may help the end user of the water disinfection technology to obtain a systematic insight into all relevant aspects to be considered for preliminary decision making on which technologies should be put to feasibility testing for water disinfection in pre- and postharvest practices of the fresh produce chain.

Keywords Fresh produce, water disinfection, physicochemical parameters, cost-effectiveness, microbiological quality, disinfection by-products

INTRODUCTION

Fresh fruit and vegetables are recognized to be an important part of a healthy diet, as they provide necessary nutrients such as vitamins, minerals, fibers and antioxidants (De Giusti et al., 2010). Because the population becomes increasingly aware of this fact, the consumption of these food products has augmented. As convenience is a desired quality parameter these days, increased consumption is especially the case for prepacked, ready-to-eat fresh-cut produce (Heaton and Jones, 2008). Due to the increased fresh produce consumption, the risk of produce associated pathogens has become more relevant. Also changing consumer habits are of influence on the manifestation of fresh produce associated outbreaks. The demand for a wide choice of exotic fruit and vegetables, supplied year-round and made possible by increased global trade, has increased the number of potential vectors of food disease. In addition, consumers tend to buy fresh produce more often at large supermarkets instead of local stores, which makes it possible for a batch of pathogen infected produce to reach a larger number of consumers (Johannessen et al., 2002; Heaton and Jones, 2008). Fresh-cut produce is minimally processed, as it mostly involves only trimming, cutting, and washing, and thus contamination is not easily removed during processing. Therefore, the probability that this produce, once contaminated, reaches the consumer in contaminated state is relatively large.

There are a multitude of pathogens that have been associated with fresh produce including bacteria (*Salmonella* spp., *Listeria monocytogenes*, *E. coli* O157 and non O157 VTEC, *Shigella* spp., *Campylobacter* spp., *Yersinia enterocolitica*, *Clostridium* spp., *Bacillus cereus*., *Staphylococcus aureus*.), protozoa (*Cyclospora cayetanensis, Cryptosporidium* spp., *Giardia* spp.), viruses (Hepatitis A, norovirus), and

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helminths (Suslow et al., 2003; Steele and Odumeru, 2004; Chaidez et al., 2005; Doyle and Erickson, 2008; Pielaat et al., 2008; Mota et al., 2009; Behravesh et al., 2011; Danyluk and Schaffner, 2011; Keskinen and Annous, 2011; MacDonald et al., 2011; Verhoeff-Bakkenes et al., 2011). In a meeting by the Joint Food and Agriculture Organization/World Health Organization (FAO/WHO) Meetings on Risk Assessment of Microbiological Hazards in Foods (JEMRA) in 2008 concerning microbial hazards in fresh fruits and vegetables, the majority of the participating countries identified leafy greens as primary food group of concern, and either *Salmonella* spp., *Escherichia coli* O157:H7 or norovirus as the pathogens of greatest concern, due to their major occurrence (Doyle and Erickson, 2008; FAO/WHO, 2008; Franz and van Bruggen, 2008; Heaton and Jones, 2008).

Water is an important raw material in the fresh produce chain, as it is used in considerable amounts in many operations, including irrigation and application of pesticides and fertilizers in primary production, but also for rinsing, cooling, washing, and as transport medium in postharvest practices (FDA, 1998). Pathogens, potentially present in irrigation and wash water, can contaminate fruit and vegetables. Water can serve as source of or as a vector for transport of pathogens to plants and crops (Steele and Odumeru, 2004; Chaidez et al., 2005; Mota et al., 2009; Behravesh et al., 2011; Holvoet et al., 2012).

Several outbreaks have been traced back to the use of contaminated irrigation water. Irrigation water was believed to be involved in a European outbreak in 2006 of *Salmonella* Thompson caused by consumption of Italian rucola lettuce (Nygard et al., 2008). In a multistate outbreak of *Salmonella* Newport in the United States of America (USA) in 2005, associated with eating tomatoes, the strain responsible for the outbreak was isolated from pond water used to irrigate tomato fields (Greene et al., 2008). A nationwide outbreak of *Salmonella* enteric serotype Saint Paul in the USA in 2008 was traced back to agricultural water and serrano peppers on a Mexican farm, as well as jalapeño peppers (Behravesh et al., 2011). A large outbreak of *E. coli* O157 occurred in Sweden in 2005. The most likely source of the outbreak was lettuce that was irrigated by water from a small stream, which contained the strain involved with the outbreak (Söderström et al., 2008). In 2006, a multistate *E. coli* O157 outbreak occurred in the United States that was associated with the consumption of bagged spinach. The outbreak strain was isolated from one of the fields that produced the implicated spinach and in addition from river water, cattle feces, and wild pig feces on a ranch under one mile from the spinach field. A potential cause for the *E. coli* O157:H7 contamination of the spinach was that the river water functioned as vector between the contaminated feces and the irrigation wells used for irrigating the spinach field (CFERT, 2007). Outbreaks where norovirus was involved are numerous, and vehicles of norovirus include berries, fresh-cut fruits, lettuce, tomatoes, green onions, and other vegetables. One of the major routes of potential contamination of norovirus is the use of contaminated water for irrigation (Butot et al., 2009; De Giusti et al., 2010; Predmore and Li, 2011).

Outbreaks, traced to fresh fruits and vegetables, show that the quality of water used for pre- and postharvest practices is of importance to assure food safety. Furthermore, wash water may function as a vector for transfer of microorganisms from contaminated to uncontaminated produce within a batch and between different batches over time. Therefore, efficient water treatment of water intended for irrigation and postharvest practices and maintaining water quality during produce processing to avoid spread of produce associated pathogens to uncontaminated produce is necessary (Steele and Odumeru, 2004; Gil et al., 2009).

Water treatment in general aims to alter the water source in order to make it desirable for the end user. In most cases, a water treatment system aims to remove matter, which can be organic or inorganic, in soluble or particulate form, including microorganisms. Numerous treatment techniques have been developed for production of drinking water or process water and the treatment of wastewater. These can be chemical such as coagulation-flocculation processes or oxidation to remove color or refractory organics and increase biodegradability for subsequent biological processes. Water treatments can be physical, including sedimentation, air flotation, and granular and membrane filtration processes. They can also be biological where removal is achieved through utilization of microorganisms, such as slow sand filtration, biological oxidation of iron and manganese in drink water production, or the use of activated sludge processes in wastewater treatment for nutrient removal (Metcalf and Eddy, 2003; Crittenden et al., 2005). The focus of this paper is on water disinfection techniques, with the purpose of inactivating pathogenic microorganisms.

There are numerous chemical disinfectants that are applied in water disinfection such as ozone, chlorine dioxide, chlorine, hydrogen peroxide, and peracetic acid. Ultraviolet irradiation (UV) is a physical treatment that has been widely implemented for disinfection in the production of drinking water and wastewater treatment (Zimmer and Slawson, 2002; Sanz et al., 2007). Membrane filtration techniques are, besides their efficiency for removal of particles and organics from influent water sources, also very potent disinfection technologies (Madaeni, 1999).

Chlorination is globally the most applied water disinfection technique and in many countries it is extensively used to assure food safety of the produce because of the low cost, the good effectiveness against suspended vegetative bacteria, and it can be implemented in operations of any size (Suslow, 2001; Parish et al., 2003; Delaquis et al., 2004; Artés et al., 2009; Luo et al., 2011; Tomas-Callejas et al., 2012a). There are some major disadvantages associated with chlorine, i.e., formation of disinfection by-products (DBPs) in the water, the persistence of chlorine residuals with detrimental effects on aquatic life, the weakness of chlorination against protozoan parasites and some viruses, and the use of high chlorine concentrations can lead to chlorine gas formation which may affect worker comfort and health (Trussell, 1998; Lazarova et al., 1999; Suslow, 2004b; Saad et al., 2005; Hua and Reckhow, 2007; Shields et al., 2008; Tomas-Callejas et al., 2012c). This illustrates that chlorination is not the ultimate solution for all water disinfection practices and dependent on the objective, certain disinfection techniques will prove more suitable than others.

A variety of disinfection technologies is available on the market and the objective of this paper was to characterize water disinfection methods and to develop selection criteria to support the "fit for purpose" judgment of their use for water disinfection in irrigation practices, hydroponics, and produce processing washing and cooling operations.

Selection Tool Approach

An overview of relevant criteria for selecting a water disinfection technology in pre- and postharvest produce practices was composed based on available scientific literature, regulatory prescriptions, and guidance documents. A comprehensive approach for elaboration of the selection tool was taken, grouping the selection criteria into three main aspects, namely technological, managerial, and selection criteria related to sustainability (Figure 1).

The technological selection criteria encompass those factors that directly influence the required disinfection efficiency. Technological criteria relate to the water source and the opted water quality, the physicochemical and microbial parameters associated with the water source which will determine in turn the requirements of a disinfection method to achieve the opted water quality that is needed for a defined application. The technological criteria also include the process parameters of a water treatment that can be manipulated to improve the disinfection efficiency.

The managerial selection criteria include the capital and operational costs, factors related to the operation (e.g., complexity of the technology, required monitoring, and safety issues) and the legal considerations.

Last but not least, factors that determine the sustainability of the disinfection technology were also taken into consideration in the selection tool. Selection criteria related to sustainability comprise criteria for maintaining the disinfection technology (maintenance, choice of corrosion resistant construction materials, and supporting a reliable supply chain), equipment retrofitting and environmental considerations.

Selected disinfection technologies were evaluated on the defined criteria (Table 1). The disinfection technologies on which data is most prevalent in scientific and gray literature and thus taken up in this study were chlorine, chlorine dioxide, ozone, peracetic acid, hydrogen peroxide, membrane filtration, and UV.

Technological Criteria

Water Sources and Microbial Water Quality Used in Fresh Produce Practices

Approximately 70% of the global fresh water use is for irrigation practices. In developing countries, this increases to 95% of the available fresh water (Malato et al., 2009; Pedrero et al., 2010). Water used for irrigation may originate from multiple sources: rain water, ground water, surface water, wastewater, and in (semi) arid areas desalinated seawater or brackish groundwater are potential water sources for irrigation practices. To adapt to the increasing water shortages due to ground water depletion, applying alternative water sources for irrigation will gain importance in the future. Application of alternative water sources causes higher probability toward presence of pathogens and increases the pressure on governing water quality. Reconditioned wastewater and surface water are two abundant sources with potential to replace ground water as supplementary irrigation source for rainfall in periods of drought.

Rain and ground water are generally of good (yet less than potable) quality. The quality of rainwater depends in part on the microbial quality of the recipient, e.g., in the case of roof-harvested rainwater, it can be contaminated by pathogenic bacteria and protozoan parasites through the presence of bird and animal droppings on the roofs, especially right after relatively long periods of drought. Ground water (or bore hole water) is generally of good microbial quality although presence of pathogens is possible due to septic discharges, leaking sewer lines, or infiltration of surface water (Burch and Thomas, 1998; Ahmed et al., 2011). For example, analysis of groundwater from 448 samples in 35 states of the USA resulted in 4.8% positive samples for human enteric viruses (Abbaszadegan et al., 2003), while another study screened 50 household groundwater wells in Wisconsin, of which four were positive for human enteric viruses, three of them containing Hepatitis A virus (Borchardt et al., 2003).

Surface water is of lesser and more variable microbial and physicochemical quality as it is an open system, subject to discharges of (treated) wastewater, storm water runoff etc., e.g., the Missouri river may have fecal coliforms/100 ml that vary 4 log over a 100 mile stretch. Also for turbidity, great variations exist (Anderson and Davidson, 1997; Burch and Thomas, 1998; Steele and Odumeru, 2004). Disinfecting surface water before use in irrigation practices might be necessary, depending on the microbial quality.

Desalinated seawater is increasingly considered as a water source for irrigation practices. Although the costs of reverse osmosis membranes are high, the use of desalinated seawater might be economically feasible for high-value crops like greenhouse vegetables and flowers (Yermiyahu et al., 2007). Brackish groundwater can also be applied for irrigation when desalinated and using brackish groundwater for desalination is less energy consuming than applying seawater. However, the

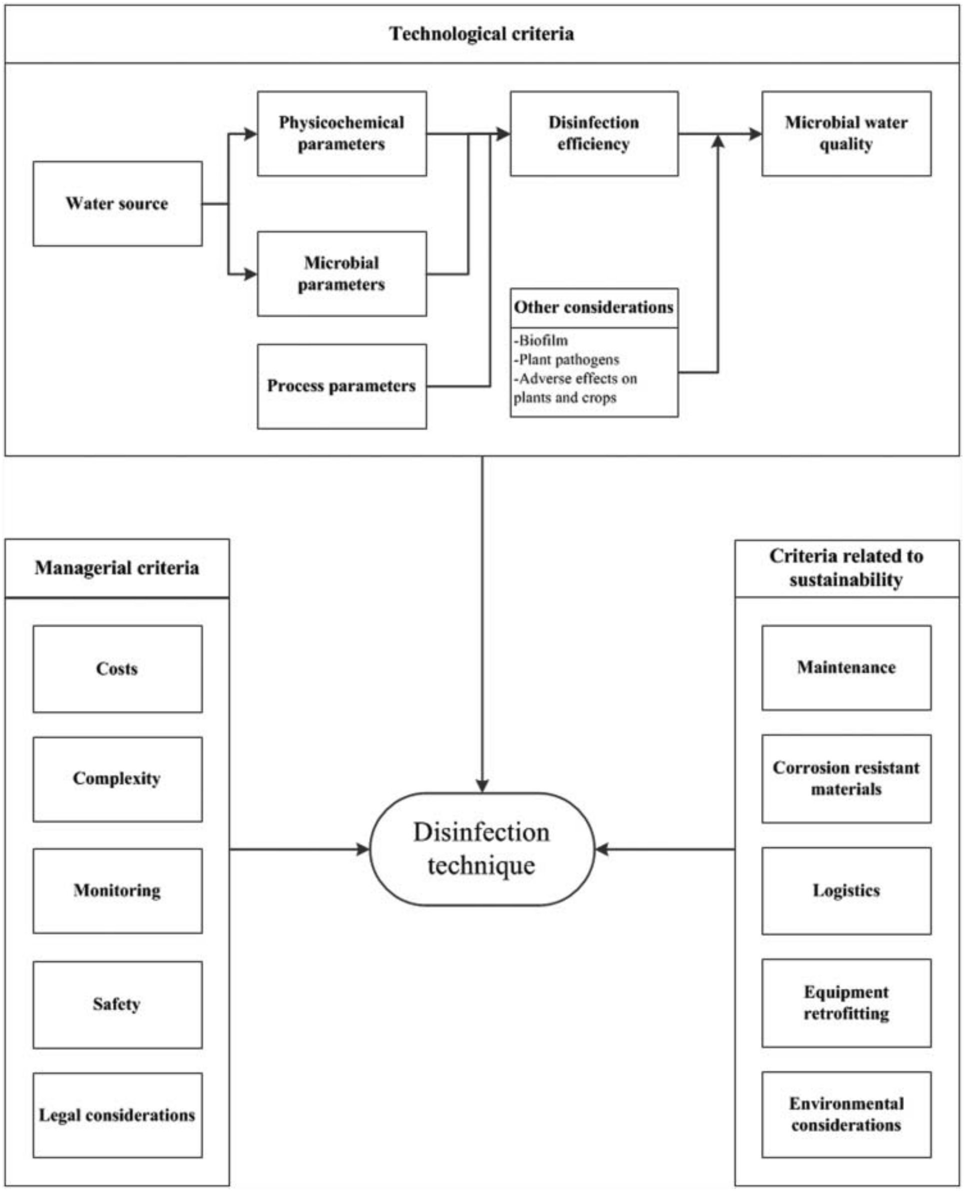

Figure 1 Overview of the selection criteria for choosing a water disinfection technique for pre- and postharvest practices.

fact that groundwater is a limited resource, as opposed to seawater, should be taken into consideration (Munoz et al., 2008).

Wastewater is of very poor physicochemical and microbial quality and requires intensive treatment (WHO, 1989; Steele and Odumeru, 2004; Pedrero et al., 2010). Primary and secondary water treatment processes can eliminate 1 to 3 log of enteric microorganisms with an additional 2 log by tertiary treatments, such as filtration techniques. Disinfection techniques should be applied if further elimination is required like in some irrigation practices (Liberti et al., 1999, 2000a, 2000b; Dell'Erba et al., 2004; Koivunen and Heinonen-Tanski, 2005a, 2005b; Ksibi, 2006; Falsanisi et al., 2006).

Indications on appropriate microbial quality for irrigation water can be obtained by consulting legal/regulatory requirements or in guides of good practices. Overall, the requirements for microbial water quality increase as the product progresses from field to final processing (Suslow, 2004b). Requirements enabling the use of water for unrestricted irrigation (i.e., for crops that are to be eaten uncooked) are usually more stringent than those for restricted irrigation (i.e., crops that are not to be eaten uncooked) (Steele and Odumeru, 2004). Most guidelines and regulations are heavily based on defined microbial standards, but ad hoc risk assessment strategies for managing health risks may also be effective (WHO, 1989; Blumenthal and Peasey, 2002; Carr et al., 2004), e.g., the latest guidelines by the WHO (anno 2006) for use of wastewater in agriculture have been revised substantially. The fecal coliform guideline has been replaced by guidelines based on

Table 1 Evaluated criteria of selected water disinfection technologies for pre-and postharvest applications

	Chlorine	Ozone	Chlorine dioxide	Peracetic acid	Hydrogen peroxide	Membrane Filtration	Ultraviolet irradiation
Technological criteria							
Vegetative bacteria	Good	Very good	Good	Good (1) [a]	Weak	Very good	Good
Bacterial spores	Weak	Moderate	Weak	[b](3)	Very weak	Very good	Weak
Viruses	Moderate [c]	Good [c]	Moderate [c]	Moderate (2) [c]	Very weak [c]	Very good [d]	Moderate [c]
Giardia	Weak	Good	Moderate	[b] (4)	Very weak	Very good	Good
Cryptosporidium	Very weak	Moderate	Weak	[b] (4)	Very weak	Very good	Good
Scale	All sizes	Medium to large	Medium to large	Small to medium	All sizes	Generally small to medium	All sizes
T	Better at higher T Not above 40°C	Better at low T Increased decomposition rate and decreased solubility at higher T	Better at higher T	Better at higher T	Better at higher T	< 80°C Lower viscosity at higher T, thus higher flux Higher T may promote biofouling	Better at lower T (of both water and lamp) to reduce fouling
pH	pH < 7 to assure presence of HOCl	6 (optimum) Higher decomposition rate at higher pH	Relatively constant in the range 3–9, Slightly better at alkaline pH	Relatively constant in the range pH 5, 5–8, 2 Reduced efficiency > pH 8,5	Better at lower pH Higher decomposition rate at alkaline pH	Working range 1–13 pH may influence fouling and electrostatic interactions of membrane with MO	No significant influence
Influence of suspended solids, organic matter, and reducing compounds	High	High	Medium No reaction with ammonia Overall less influenced than chlorine	Lower than other chemical disinfectants	High	Fouling Fouling and particle association may enhance retention capacity	High Particle shielding Reduction of UV transmittance
Managerial criteria							
Complexity of technology	Low to moderate (in case of gaseous chlorine)	High	Moderate to high	Low	Low	High	Low to moderate
Operational monitoring [e]	Chlorine pH T^f Ambient gaseous chlorine	O_3 (at generation, transfer to water, off-gass unit) [g] pH T^f	ClO_2 [g] T^f	Peracetic acid T^f	Hydrogen peroxide pH T^f	Transmembrane pressure or permeate flux Turbidity	UV intensity UV transmittance
Safety issues	Handling, storage, and transport Ambient gaseous chlorine	Exposure to high electrical voltages Ambient ozone and ozone leaks	Explosion due to ClO_2 build up in air Ambient ClO_2 Issues related to chlorine when used	Handling, storage, and transport	Handling, storage, and transport	Handling and disposal of chemicals for cleaning. Contaminated backwash (low risk)	Exposure to UV radiation and mercury during lamp disposal Electric shock (overall low risk)
Capital cost	Low	High	Moderate	Low	Low	High	Low to moderate

(*Continued on next page*)

Table 1 Evaluated criteria of selected water disinfection technologies for pre-and postharvest applications *(Continued)*

	Chlorine	Ozone	Chlorine dioxide	Peracetic acid	Hydrogen peroxide	Membrane Filtration	Ultraviolet irradiation
Operational cost	Low	High	Moderate	Moderate	Low	High	Low to moderate
Legal status in EU	Processing aid	Processing aid	Processing aid	Processing aid	Processing aid	Not applicable	Not applicable
Criteria related to sustainability							
Corrosive	Yes (all forms)	Yes	Yes but less than chlorine and ozone	Yes	Yes	Not applicable [h]	No
Maintenance	Low to moderate Issues: corrosion	High and careful Issues: corrosion and ozone electrode	High and careful Issues: corrosion	Low Issues: corrosion	Low Issues: corrosion	High and careful Issues: membrane	Low to moderate but careful Issues: lamp and sleaves
Storage	Yes	No, in situ	No, in situ Precursor storage	Yes [i]	Yes	Chemicals for cleaning	Chemicals for cleaning
Availability for developing countries/rural areas in general	NaOCl (high), gas (moderate, equipment only available in large cities), and $Ca(OCl)_2$ (moderate)	Very low, equipment needs to be purchased in developed countries	Very low, equipment needs to be purchased in developed countries	Relatively low, PAA is relatively expensive, in part due to limited production capacity, which could cause supply issues		Very low, equipment needs to be purchased in developed countries	Distant or rural areas dependent on external suppliers
Hazardous DBPs	Trihalomethanes (THMs) Haloacetic acids (HAAs) Aldehydes	Bromate and bromo-organic DBPs (dependent on bromide) Aldehydes	Less halogenated DBPs than chlorine (no THMs/THAAs) More iodinated DBPS (if iodine is present) Chlorite and chlorate Aldehydes	Negligible or low levels of aldehydes	Negligible or low levels of aldehydes	Not applicable	Normally none Nitrite with MP lamps if high nitrate concentration and/or very high UV MP doses are applied

[a]In order of decreasing disinfection efficiency 1 > 2 etc. (Kitis, 2004). [b]Relatively little is known. Liberti et al. (1999) observed low efficiency against protozoa in municipal treated wastewater. [c]Viral disinfection is quite dependent on virus type. [d]Microfiltration generally has a too great pore size to remove viruses, although certain properties of membrane, water matrix and microbial load can result in some retention capacity. Ultrafiltration can achieve very high retention of viruses. [e]Flow rate measurements are advisable in many disinfection practices, and indicate contact times for chemical disinfectants and UV. [f]Monitoring T might not be necessary when the process is T controlled or not subject to high fluctuations. [g]Additional monitoring of the in situ generation process. [h]RO treatment could lead to water with corrosive properties, [i]In situ generation by indirect electrosynthesis is possible (Chaenko et al., 2011).

attributable risks and disability-adjusted life years, and governments in developing countries have been given greater flexibility in applying guidelines (WHO, 2006).

Besides the microbial concerns, there are other water quality parameters which are of great importance for crop yield and proper operation of irrigation practices, some of which are shortly mentioned here. High salt contents may decrease the water uptake by the plant and reduce the rate at which water moves into the soil. Some specific ions such as boron are phytotoxic above certain concentrations, the tolerance level varying widely among crops. Also, possible formation of calcium scale, presence of particles or algae, originating from the water, can cause clogging of sprinkler orifices. The nutrient content of irrigation water may be advantageous or disadvantageous (overfertilization) on crop yield (Ayers and Westcot, 1989; Grattan, 2002; ILSI, 2008; Pedrero et al., 2010). Although ground water usually contains less organics than surface water, it may contain higher amounts of inorganic loads causing unpleasant colors and odors (e.g., hydrogen sulfide) (Burch and Thomas, 1998; Suslow, 2004a).

Water used in produce processing traditionally needed to be of potable quality (Council Directive 98/83/EC; USEPA, 2009), although more recently some flexibility has been provided by allowing the use of water of lesser quality if this use does not compromise food safety of the end product (FDA, 1998; Regulation (EC) 852/2004; 21CFR110, 2010). This can be understood as "suitability for intended use," meaning to adjust the water quality to the particular application. However, when determining suitability the judgment needs to be based on risk assessment for chemical and microbiological hazards, and the water use integrated in the Hazard Analysis and Critical Control Points (HACCP) principles (ILSI, 2008). Sources of potable water quality used in produce processing are mostly tap water obtained from municipalities and (treated) ground water (Nicolaisen, 2003; Xu et al., 2010). It is a normal practice to reuse water by recuperating, possibly treating (reconditioning) and recycling the washing and cooling water in processing operations and flume water in packing houses (Codex Alimentarius, 1999; Casani and Knochel, 2002; Lopez-Galvez et al., 2010a; Jacxsens, 2011).

Microbial, Physicochemical and Process Parameters

Microbial parameters. Ideally an implemented disinfection technique provides adequate performance against a broad range of microorganisms (Table 1). As these various types of microorganisms differ in morphology and physiology, disinfection mechanisms differ in their ability to successfully inactivate these different types of microorganisms. Variable resistance may also exist between different isolates of the same species (Hoff, 1986). As with other induced stresses, such as heat or antimicrobial components added to food, different growth conditions (e.g., medium, growth temperature) have influence on the vulnerability of the microorganism to water disinfection (Lee and Frank, 1990; Luh and Marinas, 2007). Also, microorganisms can potentially regrow after disinfection. This is especially the case with UV, as many microorganisms possess the ability to repair DNA damage by light-independent (i.e., dark repair) as well as light-dependent enzymatic mechanisms (Sanz et al., 2007; Locas et al., 2008). Regarding fresh produce practices, this is of particular concern when disinfected water is stored before use and can be avoided by maintaining a small disinfectant residual of a relatively stable disinfectant like monochloramine, or the less stable chlorine and chlorine dioxide (Neden et al., 1992; Momba et al., 1998, 2003; USEPA, 1999a).

Chemical disinfectants, such as ozone, chlorine, and hydrogen peroxide oxidize cellular components and their mechanism differs dependent upon the oxidation reduction potential, the targeted cellular components, solubility properties, and decomposition rate (Anderson et al., 1982; Hoff, 1986; von Gunten, 2003a; LeChevallier and Au, 2004; Dietrich et al., 2007; Pedersen et al., 2009). For chemical disinfectants, generally the resistance of microorganisms can be ranked as following: gram-negative bacteria $<$ gram-positive bacteria $<$ viruses $<$ bacterial spores and protozoan parasites.

UV causes the formation of pyrimidine-pyrimidine photoproducts in the genome, leading to errors when replication or transcription of the genome is executed (Wang et al., 2006). Vegetative bacteria are weak against UV, but in addition both *Giardia* and *Cryptosporidium* species have shown to have high vulnerability against DNA damage induced by UV irradiation, making UV an interesting technology to destroy these chemical oxidant resistant microorganisms. Viral resistance to UV is highly variable among different types of viruses, a phenomenon that is also the case with chemical disinfectants. Overall, bacterial spores, such as *Clostridium perfringens*, are very resistant against UV (Hijnen et al., 2006).

Membranes work through size exclusion and adsorption to remove pathogens from solution, but also solution-diffusion below certain pore sizes in the case of nanofiltration or reverse osmosis. Basically, microfiltration (pore size 0.1–10 μm) removes protozoan parasites and bacteria very efficiently based on size-exclusion, but it can also remove viruses to some degree due to adsorption and electrostatic repulsion between charged groups on the membrane and the virion. However, the presence of ultramicrobacteria (size reduction in low nutrient conditions) and the ability to deform or reduce cell volume, due to high pressure, of some bacteria may be a mechanism for bacterial passage through microfiltration membranes containing pores smaller than the average cell size. In addition, the uniformity of membrane pores is not perfect, resulting in the presence of larger than average pore sizes (Ghayeni et al., 1999; Delebecque et al., 2006). Ultrafiltration (pore size 5–100 nm) can remove viruses to high degrees and the even smaller nanofiltration and reverse osmosis membranes can provide virtually total pathogen retention.

(Rautenbach et al., 1997; Van der Bruggen and Vandecasteele, 2003; Wang et al., 2006). In reality, however, imperfections in the membrane and unit seals can occur, so total retention is never guaranteed by these technologies (Cooper and Straube, 1979; Van der Bruggen and Vandecasteele, 2003; Aguilar et al., 2008).

Besides the established water disinfection techniques, there are other technologies that have been and are being studied at present and which potentially could become mainstream technologies for water disinfection purposes.

Electrochemical disinfection is the inactivation of microorganisms through use of an electric current passing through water by means of suitable electrodes. Electrochemical disinfection comprises the generation of free chlorine (electrochlorination) and/or other free oxidants, depending the solute content of the water and the type of electrodes used (Kraft, 2008). Studies showed higher inactivation efficiency of electrochlorination compared to classic chlorination, because of production of these additional oxidants (Venczel et al., 1997; Feng et al., 2004; Li et al., 2004; Fang et al., 2006; Jeong et al., 2007; Bergmann et al., 2008; Martinez-Huitle and Brillas, 2008; Barashkov et al., 2010). Nevertheless, in chloride containing waters, chlorine generation is the predominant mechanism of electrochemical disinfection (Li et al., 2004; Schmalz et al., 2009).

Ultrasonication comprises a mechanical factor (shear stress caused by bubble implosion), a physical factor (high temperature and pressure) and a chemical factor (generation of OH radicals, H_2O_2, and other oxidants by pyrolysis), the latter which can be enhanced significantly in combination with titanium dioxide (Mason et al., 2003; Dadjour et al., 2006; Antoniadis et al., 2007; Shimizu et al., 2010). Ultrasound is overall quite inefficient for water disinfection as it requires high energy demands to achieve a reasonable disinfection (Scherba et al., 1991; Joyce et al., 2003; Blume and Neis, 2004; Furuta et al., 2004 Drakopoulou et al., 2009). However, it could be more suitable when larger volumes need to be treated and there is room for improvement in the geometry and overall design of sonication reactors (Gogate et al., 2007).

There has been considerable research in the field of advanced oxidation processes for oxidation of organic contaminants in water treatment, but also for inactivation of pathogens (Machado et al., 2007; Gerrity et al., 2009; Chong et al., 2010). For disinfection purposes, UV has been used for photolysis of hydrogen peroxide, peracetic acid or ozone, thus generating free radicals (Bianchini et al. 2002; Koivunen and Heinonen-Tanski, 2005a; Jung et al. 2008). Another disinfection mechanism of these combined techniques has been suggested: the multiple damage mechanism, meaning UV targets nucleic acids while the chemical disinfectant attacks cellular structures and enzymatic systems (Koivunen and Heinonen-Tanski, 2005a). Regarding advanced oxidation processes, there is a lot of interest in the possible synergistic effects on disinfection efficiency. Synergy implies that less chemicals or energy are needed to achieve a certain disinfection efficiency, which can reduce costs (Caretti and Lubello, 2003; Alkan et al., 2007).

Heterogeneous photocatalysis functions by inducing a series of oxidative and reductive reactions at a photocatalyst surface (often the semiconductor titanium dioxide) by photon energy (Chong et al., 2010). UV in combination with titanium dioxide was effective in reducing bacteria, moulds, and yeasts in fresh-cut vegetable wash waters (Selma et al., 2008b). Interesting to heterogeneous photocatalysis is also that solar radiation can be used as photon source for titanium dioxide photocatalysis (De la Hoz et al., 2009; Malato et al., 2009) In general, the main technical issue that obstructs commercialization of photocatalytic water treatments is the postrecovery of the catalysts particles after water treatment (Chong et al., 2010).

The above description of how efficiently microorganisms are inactivated by different disinfection technologies is not complete, as in practice disinfection efficiency is highly influenced by physicochemical parameters.

Physicochemical Parameters

Organic matter and other reducing compounds pose a chemical oxidant demand (Chang et al., 2000; Stampi et al., 2001; Pedersen et al., 2006; Dietrich et al., 2007) and soluble and particulate forms of organics, metals (e.g., iron), and some anions (e.g., nitrate and sulfites) absorb UV irradiation (USEPA, 2006) and cause fouling (Nessim and Gehr, 2006). Microorganisms can be shielded from UV irradiation by particles (measured as turbidity or suspended solids) (Li et al., 2009) or associate with particles, which causes diffusion resistance to chemical disinfectants (Dietrich et al., 2007). Surface water contains particles and organics originating from urban and industrial sources (Delpla et al., 2009), as well as from biota. Organics can be introduced by biota growing in water bodies by excretion or decay of these organisms but also by degradation of terrestrial vegetation (Volk et al., 2002). Considerable fluctuations in turbidity and organic matter may occur through seasonal changes that influence precipitation and surface runoff, imposing an additional challenge for treating surface water (Shresta and Kazama, 2007; Massé et al., 2011). The degree of accumulation of suspended solids and organic matter in postharvest washing operations, and thus the magnitude of influence on the disinfection efficiency, depends on the type of crop, the product to water ratio and the degree of water recycling (Humphries and Fleming, 1996; Luo, 2007; Selma et al., 2008a, 2008b). If the produce is prewashed before transport to the processing area, field soil on the produce and plant exudates released from harvest cuts are removed to some degree, which will reduce the disinfectant demand of the water (Suslow, 2000a).

Temperature enhances reaction kinetics and affects solubility of some chemical disinfectants (USEPA, 1999a).

Efficiency of physical disinfection techniques can also be affected to some degree by temperature (e.g., viscosity of water, fouling rates) (USEPA, 1999a, 2005).

The pH impacts the presence of chemical disinfectants in the medium. Some chemical disinfectants can decompose rapidly at certain pH values, e.g., ozone, (von Gunten, 2003b) or be present in less effective forms, e.g., peracetic acid in its less efficient dissociated form above pH 9 (Kitis, 2004). Furthermore, the pH may affect scaling/fouling rates, affecting UV irradiation (USEPA, 2006) or membrane filtration (Boerlage, 2001), the latter which is especially compromised in low pH and high ionic strength waters (Zularisam et al., 2006).

Process Parameters

Certain parameters can be manipulated to create a better functioning environment for disinfection i.e. process parameters. As mentioned, T and pH influence the disinfection process and control of these parameters can be beneficial (Table 1). During processing, wash water accumulates sugars, starches, other organic materials, and residual pesticides, and thus the process water may contain considerable amounts of chemical oxygen demand (COD) (Tarver, 2008). To achieve sufficient microbial abatements in highly turbid/organics loaded waters without having to apply excessive amounts of chemical disinfectants/power consumption or to prevent compromising normal operation, e.g., excessive membrane fouling, a pretreatment is sometimes a necessity (Collivignarelli et al., 2000).

Turbidity can readily be removed by rapid sand filtration, a process which can be enhanced by coagulation-flocculation processes, due to enlargement of the particles, resulting in better removal in the granular medium, with the additional effect of some microbial removal (Williams et al., 2007; Gitis, 2008; Shirasaki et al., 2010). Coagulation-flocculation-filtration has also the potential to partially remove dissolved organic material, thus lowering the COD load (Odegaard et al., 2009). More recently, the research to use biopolymers for coagulation-flocculation purposes has increased as these substances are natural low-cost products, not harmful for the environment and could be used in food processing operations (Renault et al., 2009; Fabris et al., 2010). Furthermore, there is a great amount of available technologies that are used or experimented with to remove COD and turbidity in water treatment including membrane processes, biodegradation (such as sequencing batch reactors, biological aerated filters, and membrane bioreactors), advanced oxidation processes, activated carbon, electrochemical oxidation, electrocoagulation, dissolved air flotation, and others (Stasinakis, 2008; Hyun Lee, 2009; Yoo Hsieh, 2010; Alvarez et al., 2011; Awang et al., 2011; Chen et al., 2011; Esparza-Soto et al., 2011; Gurel Buyukgungor, 2011; Mahvi et al., 2011).

Other Technological Considerations

Biofilms

Presence of biofilms is a persistent source of contamination that can lead to food spoilage or compromise food safety (Van Houdt and Michiels, 2010) and biofilms can also harbor microorganisms less prone to biofilm formation, potentially increasing the survival chances of pathogens. Biofilm formation on the produce itself is a main factor in the failure of decontamination practices to remove or inactivate human pathogens on produce surfaces (Annous et al., 2006). In addition, biofilm formation can also negatively influence the process (e.g., down time of the process, pressure drop in pipelines leading to decreased energy efficiency) and the equipment (corrosion).

Biofilms in fresh produce facilities can be controlled by regular disinfection. Sufficient prerinsing and cleaning to remove material deposits reduces the loss of applied chemicals during processing (Simões et al., 2010; Van Houdt and Michiels, 2010). There are some additional parameters that determine the efficiency of disinfectants against biofilms compared to bacteria in suspended state, such as diffusion capacity, reaction with exopolymeric substances, biofilm density and age, and fluid flow conditions (Gagnon et al., 2005; Jang et al., 2006; Vaid et al., 2010; Van Houdt and Michiels, 2010). This means that the most efficient disinfectant against planktonic cells in a certain case does not necessarily exhibit the best performance in preventing and destroying biofilms. For example, while chlorine is much more efficient in reducing free roaming heterotrophic bacteria than monochloramine, the relative efficiency of monochloramine to kill biofilm associated heterotrophic bacteria is much higher than that of chlorine, because the former does not readily react with exopolymeric substances allowing better penetration in the biofilm (LeChevallier et al., 1988). In general, biofilm associated microorganisms are —two to three orders of magnitude more resistant to disinfectants than planktonic ones (Simões et al., 2010).

The problem of biofilms is not limited to piping and surfaces in direct contact with the produce. Environmental pathogens that have been introduced in a processing facility can potentially spread throughout the facility if water is allowed to pool on the floor near equipment and employee walkways. This mechanism supposedly contributed in the spread of *Listeria monocytogenes* in a cantaloupe packing facility in southeast Colorado, which was implicated in a multi-state listeriosis outbreak in the USA in 2011. Applying good agricultural and management practices in processing facilities, such as avoiding water pooling and regular cleaning and disinfection should be used to control the introduction and spread of *Listeria monocytogenes* in processing facilities (FDA, 2011).

Control of Plant Pathogens

Regardless the increased attention for food-borne pathogens related to fresh produce, not in the least because of possible economic losses due to recall or trade restrictions, the economic problem of reduced crop yield that plant pathogens cause has been recognized since early in the last century. Control of plant pathogens is an important practice and the importance of this issue will increase with the growing implementation of recycling water in agriculture. These plant pathogens include *Phytopthora*, *Pythium*, fungi, bacteria, viruses and parasitic nematodes (Hong and Moorman, 2005). Protection from plant pathogens has been especially relevant in closed hydroponic systems due to recycling of nutrient solutions, leading to a higher risk for accumulation of (plant) pathogens. The conventional disinfection methods applied in hydroponics include heating, ozone, UV, iodine, hydrogen peroxide, and slow sand filtration (Ruina, 1995,1996; Ohtani et al., 2000). Other studied disinfection technologies for hydroponics include microfiltration (Ohtani et al., 2000), solar radiation (Osorio et al., 2005), peroxone (Langlais et al., 2001), and hydrogen peroxide/UV (Runia and Boonstra, 2004).

Disadvantages associated with certain disinfection techniques in hydroponics include: the energy consuming process of heating and cooling, the oxidation of iron and manganese by ozone resulting in precipitation and therefore the need of replenishing them in the nutrient solution, and the precipitation of oxidized ions on UV lamps (Ohtani et al., 2000; Déniel et al., 2006). As a proportion of the microbiota may be antagonistic toward plant pathogens, a technique capable of selectively eliminating pathogens while maintaining these beneficial microorganisms would contribute to suppressing plant diseases. Most disinfection methods do not possess this discriminating ability. Slow sand filtration, however, has shown promise as selective technique for maintaining beneficial microbiota while eliminating pathogens. In addition, it requires less energy and is less costly than established disinfection methods like ozone treatment (van Os, 1999; Déniel et al., 2004, 2006; Osorio et al., 2005; Martinez et al., 2010).

Adverse Effects of Disinfectants on Plants and Crops

It has been noted that the presence of too high concentrations of chemical disinfectants in hydroponic solutions can lead to stunted growth, root, and leaf damage, and effects on nutritional quality (Vines et al., 2003; Premuzic et al., 2007). Similarly, crop damage can occur when irrigating fields with reconditioned wastewater that contains disinfectant residuals, which is for example generally the case with wastewater containing more than 5 mg/L chlorine (Pedrero et al., 2010). In postharvest practices, the use of sanitizers in washing operations may also have negative effects on crops. If no proper process conditions are met, i.e., excessive concentration, contact time, and possibly temperature, all dependent on the disinfectant applied and the targeted crop, washing of produce with sanitizers may influence discoloration, off flavors, changes in nutrient content, softening of plant tissues, etc. (Delaquis et al., 2004; Allende et al., 2008; Tefera et al., 2008) and it may affect physiological processes such as respiration, enzymatic browning, and electrolyte leakage in fresh-cut produce (Vanderkinderen, 2009).

Managerial Criteria

Costs

When the needed degree of disinfection effectiveness is defined, the associated costs become the dominant factor in decision making. Capital investments to acquire the necessary equipment are supplemented by amortization costs, site specific constraints, and hiring consultants in order to implement the technology. Operational costs should be calculated in cost per cubic meter of treated water (USEPA, 1986; Kerwick et al., 2005) and include cleaning chemicals, supplies and other maintenance costs, equipment repairs, the storage of chemicals and spare parts, operator and management personnel costs, training of personnel, and power consumption (USEPA, 1986; Tzimas et al., 2006). Furthermore, shifts in the market situation influence total costs (Liberti et al., 2000b).

Exploitation scale influences the type of techniques that can be used. Some disinfection technologies have a too high investment or require excessive safety measures that are not feasible for small scale operations (Solsona and Méndez, 2003). However, feasibility can increase due to benefits of scale, e.g., ozone is generally unfeasible at low scale (Leverenz et al., 2006), yet better cost-effectiveness can be achieved at higher scale (Collivignarelli et al., 2000; Tzimas et al., 2006). Likewise, chlorine gas is the cheapest form of chlorine, but the equipment to operate gaseous chlorine is more expensive than sodium hypochlorite dosing systems. Because of this, chlorine gas tends to be used in greater facilities, while sodium hypochlorite is the chlorine disinfectant of choice in smaller ones (USEPA, 1999b). On the other hand, techniques which require relatively low, simple investments combined with relatively high chemical costs, like peracetic acid, are more cost-effective at lower scale than at larger scale (Collivignarelli et al., 2000; Kitis, 2004). Cost-effectiveness also depends upon the water quality, the needed pre-treatment, the imposed/aspired level of safety, the degree of automation, and local labor costs. During the evaluation of the scale-up from concept to a large operational process, care must be taken when extrapolating costs (Collivignarelli et al., 2000; Kerwick et al., 2005).

A cost-analysis for comparison of wash water disinfectants would provide valuable insight on the economical feasibility of different technologies. Garrett et al. (2003) performed a cost analysis for selected disinfectants. As chemical disinfectants can have significantly different reaction rates with water matrix constituents, the actual needed disinfectant dose can differ substantially among disinfectants because during operation the physicochemical wash water quality deteriorates very quickly. Due to lack of published information on comparing wash water disinfectants in actual washing operations, assumptions had to be made by Garrett et al. (2003). It was assumed that the water was of potable quality. Therefore, only the inherent disinfection capacity of the technologies was considered. In addition, the scale of operation was fixed to one size, and therefore, the possible increase of economical feasibility at higher scale of potent technologies which require high capital investments was not considered. This illustrates the necessity for additional research that compares the different technologies in actual postharvest washing conditions and which makes a cost analysis possible that considers influencing factors, i.e., the pathogens of concern, the amount of dissolved and particulate matter introduced in the wash water and the scale of operation. For example, Collivignarelli et al. (2000) performed a cost-analysis of disinfection systems for wastewater disinfection by applying different technologies on the same secondary effluent of a wastewater treatment plant and total costs were calculated for different plant sizes, which showed significant influence on costs. In the given case inactivation of total coliforms demanded higher concentration × contact time (CT) values for ozone than for peracetic acid and chlorine dioxide, again illustrating that physicochemical quality is significant when determining the needed disinfectant dose. A similar approach for investigation of costs of wash water disinfectants could be very valuable to the fresh produce industry.

Complexity

Complexity of the used technology and the aspired level of safety positively correlate with the required amount of operator skill and training (USEPA, 1999a). Disinfection techniques like ozone and chlorine dioxide are relatively high tech. This complexity translates in high and careful maintenance requirements and control systems (Salsona & Méndez, 2003), while simple systems for dosing, e.g., hypochlorite solutions or peracetic acid require much less maintenance and operating skills (USEPA, 1999a; Kitis, 2004). Complexity is not completely inherent to a defined disinfection technique. Considerable variations can exist between various designs of a disinfection technology, e.g., basic UV equipment is relatively simple, but more complex operating systems can be implemented to achieve energy savings or a higher safety level (Solsona and Méndez, 2003).

Higher degrees of automation will decrease the needed operator attention during normal operation, although during initial start-up, additional operator attention is needed to assist with functional and performance testing and to establish site-specific operation and maintenance procedures (USEPA, 2006). This reduced need for operating personnel can be beneficial in developed countries, whereas in regions with low labor costs, the application of labor-intensive, low automated techniques is more attractive.

Monitoring

Accurate monitoring and recording of disinfection procedures is an important component of a reliable postharvest food quality and food safety program (Suslow, 2004b). Monitoring of pathogens or indicator organisms should be done during pilot tests and initial start-up to validate the effectiveness of the process in general, i.e., to assess if the applied operational parameters guarantee sufficient kill-of or retention. Incorporation of water disinfection in the HACCP of the fresh produce operator confines the microbial monitoring to key points in the disinfection process, thus limiting needed laboratory resources through proper allocation (LeChevallier and Au, 2004). The relations between the operational, physicochemical parameters and the microbial inactivation, obtained during validation, can be used to establish a (continuous) monitoring system based on these rapidly measurable physicochemical parameters (USEPA, 1980, 1999c, 2006; Reith and Birkenhead, 1998; Madaeni, 1999; Cabassud et al., 2001) (Table 1).

In postharvest washing operations, the concentration of the wash water disinfectant should be measured as it decomposes by reacting with organic matter, and the pH if relevant. Based on these measurements, disinfectant and pH altering substances can be added. For example, free chlorine is often monitored with an (on-line) oxidation-reduction potential (ORP) control system. As the ORP is also dependent on the pH, it reflects not only the concentration of free chlorine, but also its state, i.e., the more lethal hypochlorous acid has a higher ORP than hypochlorite ion at the same concentration. ORP values of 650–700 mV, which correspond to about 3–5 ppm free chlorine, are considered to be sufficient for controlling suspended vegetative bacteria in the wash water, although in practice sometimes somewhat higher values are aimed, e.g., 850 mV (Suslow, 2004b; Barrera et al., 2012). Another example is the monitoring of membrane filtration, a technology which does not apply a measurable chemical concentration or a UV light intensity. When applying membrane filtration, e.g., for reconditioning purposes of wash water, monitoring is needed to assess both the status of the membrane and the microbial retention. A decreasing membrane flux, or alternatively, an increasing transmembrane pressure at a constant flow, indicates membrane fouling (Reith and Birkenhead, 1998; Madaeni, 1999; Cabassud et al., 2001). Microbial retention of membranes may be compromised by integrity breaches, i.e., leaks, which can be monitored indirectly by measuring the turbidity in the effluent (USEPA, 2005).

Safety

Worker safety issues due to the presence of hazardous compounds, danger of irradiation, possibility of electric shocks and proximity of water to electrical equipment, etc. need attention in the operation of disinfection systems (Solsona and Méndez, 2003; USEPA, 2006). When applying gaseous chemicals, like chlorine gas, chlorine dioxide, or ozone, ambient concentration levels in the workplace are regulated by law and should be monitored (USEPA, 1999a; Pascual et al., 2007; Tarrass et al., 2010; White, 2010;). Transport of strong oxidants, often in diluted solutions meaning only part of the transported weight is active compound, handling, storage and loss due to decomposition during storage, all generate costs and require safety management. This can be partially circumvented by using physical disinfection techniques or in-situ generation of chemical disinfectants. However, the latter requires additional capital investments, knowhow, and transport of precursor chemicals if applicable. In addition, storage of precursor chemicals is still necessary for chlorine dioxide and chlorine generation, and precursors can be hazardous compounds like hydrochloric acid or chlorine (USEPA, 1999a, 1999b, Solsona and Méndez 2003; Leverenz et al., 2006).

Safety measures, whether are not enforced by authorities, can directly influence decision making. For example, in the USA, Risk Management Program regulations, enforced by the United States Environmental Protection agency (USEPA), state that facilities, including agricultural establishments, that store, handle, and use chlorine in quantities greater than 2500 pounds, must develop and implement a program to prevent accidental release (40CFR68, 2010). These imposed measures contributed in part to the increased retro-fitting of wastewater treatment facilities from chlorination to UV disinfection (Johns et al., 2002). Another example is the increased use of sodium hypochlorite compared to chlorine gas. Despite chlorine gas being economically favorable for large scaled operations, several large facilities switched to hypochlorite to circumvent the transport of chlorine gas through populated areas (USEPA, 1999b).

Legal Considerations of Water Sanitation

In the European Union (EU), chemical disinfectants to control the microbial quality of wash water or produce are classified as processing aids. This implies that disinfectants can be introduced in the process water but also that washing of produce with sanitized water should be followed by a rinsing step of the produce with sanitizer free water. This is to make sure that levels of residual or byproducts that remain in the vegetable tissue pose no health risk and the disinfectant may not perform any function in the final product so only the unintentional presence of the sanitizer substance in the final product is allowed (Council Directive 89/107/EC; Council Directive 178/2002; Ölmez and Kretschmar, 2009). In the EU, the use of sanitizers is not uniformly allowed, because up till now legislation on processing aids is not harmonized at European Community level (Gil et al., 2009). For example, countries like France, Italy, Spain, and the United Kingdom allow the use of chlorine in washing processes (Artés and Allende, 2005; COT, 2006). In France, the use of chlorine is regulated by imposing limits for washing fruits and vegetables with sodium hypochlorite, stating that the concentration of free chlorine in the washing baths should not exceed 80 mg/L, the produce should be rinsed afterwards, and the adsorbed halogenated organics should not exceed 100 μg/kg produce (DGCCRF, 2009). However, the use of chlorine in fresh produce washing is prohibited in countries like Germany, The Netherlands, Denmark, and Belgium (Artés and Allende, 2005; Rico et al., 2007; Artés et al., 2009). As fresh produce is consumed raw and no complete inactivation step is performed, it is critical to control the washing process. A low amount of contaminated product poses a contamination risk on the entire lot during washing. Using large quantities of water does not remove the risk of cross-contamination (Gil et al., 2009; Lopez-Galvez et al., 2009). In addition, industry is driven toward washing large quantities of produce in a limited volume of water due to the high costs of potable water and wastewater treatment (Ongeng et al., 2006). Recent studies show that the use of chlorine does not result in significant presence of harmful DBPs on the final product (section 5.5). These arguments strongly suggest that the use of those wash water disinfectants which do not pose health risks at concentrations that eliminate cross-contamination, could be reconsidered in countries that prohibit this practice. Compounds for use as wash water disinfectant cannot be chosen solely based on microbial inactivation potential. Only those biocides that can be considered as processing aids are possible candidates for use as disinfectant. A list, though not a positive list, of antimicrobial substances that can be considered processing aids is provided in the "Inventory of substances used as processing aids," composed by the Codex Alimentarius commission on food additives (Codex Alimentarius, 2012). This document is not a Codex standard, but is meant as a reference tool.

In the USA, for raw agricultural commodities that are washed in, e.g., a fresh-cut facility, both the Food and Drug Agency (FDA) and the USEPA have judicial power. Sanitizers used for fresh produce are regulated as secondary direct food additives by the FDA, meaning they exhibit a technical effect during processing yet not in the finished product, although in some cases they are considered Generally Recognized As Safe (GRAS). Disinfectants are registered as pesticides with the USEPA (Gil et al., 2009; FDA, 2011).

If solely water disinfection is desired, quenching or simply avoiding excess residuals by proper dosing before (re)use of the water in washing steps could be suitable strategies for prevention of contact of disinfectants with produce and presence in the final product of residuals and/or resulting DBPs. In the case of water reuse, the water could be tapped from the washing bath for subsequent disinfection.

Criteria Related to Sustainability

Maintenance

Maintenance of disinfection equipment is necessary to avoid damage to the equipment, in order to maintain disinfection efficiency and normal operation. Maintenance consumes a certain amount of time (with possible downtime of the system), requires personnel, and has a certain cost. The various components of the system, e.g., meters, valves, piping need to be cleaned periodically for removal of organics, and iron, manganese, and calcium deposits if applicable, and parts should be replaced when necessary (USEPA, 1999a, 1999b; LeChevallier and Au, 2004). Dependent upon the technology, specific parts require careful attention by skilled technicians. Furthermore, the frequency of maintenance is related to site-specific conditions like the physicochemical water quality (Leverenz et al., 2006) and the amount of maintenance may also in part be dependent on the specific design of the disinfection technique. For example, due to the higher operating temperatures of UV medium pressure (MP) lamps compared to low pressure (LP) lamps, fouling is accelerated with certain water qualities, requiring a specific cleaning mechanism, i.e., on-line mechanical or on-line mechanical-chemical cleaning systems in order to be able to clean while maintaining operation (USEPA, 2006; Anonymous, 2008).

Corrosion Resistant Materials

The use of proper materials, resistant to the applied chemical oxidant, is critical to avoid rapid corrosion of the equipment and associated loss of structural integrity. Sediment formation of accumulating insoluble corrosion by-products can serve as habitat for microbes, as well as protect them from disinfectants (Tarrass et al., 2010; White, 2010). Use of corrosion preventing materials is especially important in parts of the system coming into contact with undiluted oxidant solutions, gasses, or precursor chemicals like strong acids, i.e., those parts preceding the actual dosing systems (USEPA, 1999a). Water treated by reverse osmosis attains aggressive properties as the ionic concentrations are very low and also pH decreases, so piping and other equipment subsequent to the reverse osmosis unit should be of adequate materials (USEPA, 2005; Pressdee et al., 2007).

Logistics

Crucial to sustaining, the disinfection process is maintaining an appropriate supply chain of chemicals and spare parts, a reliable electrical power source if necessary, and the possibility of technical support. Besides money issues, these factors are significant causes in the possible failure of water treatment facilities in developing countries, especially in rural areas (Burch and Thomas, 1998; Gadgil and Derby, 2003; Solsona and Méndez, 2003; Okpara et al., 2011).

Equipment Retrofitting

Water disinfection systems in general need to take the present design into consideration when implementing a new disinfection technique. As scientific knowledge and engineering experience evolves, new or improved technologies arise and efficient retro-fitting can help accomplish the effective implementation of a new technology into an existing system design (Lazarova et al., 1999). Is the new disinfection technique compatible with target water flow rates, with the system in general (e.g., is the available capacity of the electrical power distribution system sufficient for operating the new technique), what structural modifications might be needed and will there be enough space available for installing the new system (Johns et al., 2002; Pressdee et al., 2007)?

Environmental Considerations

In postharvest practices, a sustainable water disinfection system can be interpreted as one that negatively affects the environment as little as possible, minimizing DBPs formation and persistence of toxic residuals and generating less volumes of wastewater (i.e., allowing recycling) (Ölmez and Kretschmar, 2009).

Disinfectant residuals in wastewater effluents can have detrimental effects on the environment (Moore and Calabrese, 1980; Vedachalam, 2009). The formation and adverse effects of DBPs in drinking and wastewater from chlorine and other disinfectants has been well studied and depends on the type of disinfectant, the presence of organic matter, pH, bromide ion, and other environmental factors (Nieuwenhuijsen et al., 2000; Kitis, 2004; Dell'Erba et al., 2007; Hua and Reckhow, 2007; Richardson et al., 2007). On the contrary, production of DBPs during produce washing and wash water disinfection has up till now received little attention. Some studies were conducted to assess the formation of DBPs due to chlorine in vegetable wash water (COT, 2006; Klaiber, 2005; Lopez-Galvez et al., 2010a). These results suggest that under normal operating conditions actual transfer of chlorine DBPs to fresh produce would be insignificant. Lopez-Galvez et al. (2010a) noted that washing fresh-cut lettuce with 100 mg/L NaOCl during 30 min in wash water containing a COD of 700 mg O_2/L resulted in THMs concentrations that exceeded EU standards for drinking water, although no significant amounts were detected on the lettuce after rinsing, excluding any direct chemical danger toward the consumer. The production of DBPs in process wash water, the accumulation due to recycling, and the degree of transfer to the produce should receive additional attention. When deemed to be problematic, maintaining the physicochemical quality of the wash water by removal of precursor organic matter prior to disinfection, or applying technologies that generate less or no DBPs could be feasible strategies for lowering DBPs formation in washing operations (Hua and Yeats, 2010).

Use of disinfected wastewater in irrigation can augment the DBPs in ground water aquifers through infiltration. This may lead to DBPs accumulation and might have long term effects on the quality of ground water (Bouwer, 2000). Due to the accumulation of DBPs in ground water, now also legal limits of DBPs in treated wastewater are arising (e.g., by the Florida Department of Environmental Protection) in order to protect surface water quality and avoid accumulation of these compounds in the environment (Hua and Yeats, 2010). Akande et al. (2010) noted that up till now, little attention has been paid as to how the presence of DBPs in disinfected wastewater used for irrigation could affect crop performance, cause physiological changes, and the potential bioaccumulation of these compounds in edible plant tissues.

Sustainable development is increasingly employed in decision making. Future environmental and social implications are of importance when evaluating possible disinfection technologies for replacing chlorination. The impact of factors such as the generation and use of energy, transportation and storage of hazardous chemicals, and disposal of caustic chemicals and contaminated backwash from membrane processes should be considered (EPA Victoria, 2002; Kerwick et al., 2005).

DISCUSSION

The selection criteria may help the end user of the treatment to obtain a systematic insight into all relevant factors to be taken into account in preliminary decision making on which techniques should be put to feasibility testing for water disinfection in irrigation practices, hydroponics, and produce washing and cooling operations.

In primary production, water disinfection can be applied to control the microbial load in irrigation water in ponds, wells, and irrigation networks, in hydroponic and fertigation solutions in general, and for disinfecting wastewater destined for reuse in agriculture (Dell'Erba et al., 2004; De la Hoz et al., 2009; Martinez et al., 2010).

In postharvest practices, the application of disinfection consists mostly of decontaminating produce during processing and maintaining the microbial quality of washing and cooling water during processing, and in dump tanks and water flumes etc. in packing houses. Due to recycling operations, microorganisms may accumulate in the washing water and be present in higher concentrations on the end product (Luo, 2007; Doyle and Erikson, 2008; Holvoet et al., 2012).

When cross-contamination via wash water occurs, subsequent decontamination of the produce is less efficient than the inactivation of suspended microorganisms in wash water. This greater resistance is due to (i) adherence and colonization of produce surfaces, leading to biofilm formation (Huang et al., 2006), (ii) internalization in surface cuts, stomata, cracks, and crevices (Suslow, 2004b; Lopez-Galvez et al., 2010b; Luo et al., 2011), and (iii) attachment to hard to reach surfaces, e.g., decontamination of smooth apple surfaces is more efficient than irregular surfaces of lettuce leaves (Huang et al., 2006). Therefore, the foremost strategy of containing contamination should be maintaining a good microbial quality of the process water and efficiently reconditioning process water for reuse in order to allow higher recycling ratios of the processing water while still assuring food safety (Casani et al., 2005; Ölmez and Kretzschmar, 2009).

A set of water disinfection technologies on which considerable amounts of research has been published were chosen as cases for evaluation with the selection tool (Table 1). By evaluating available water disinfection technologies in the context of the specific application of the end user, a screening of the technologies can be executed. In order to make a selection, some hierarchy should be made to assess which criteria are most critical. Loo et al. (2012) constructed a methodology for emergency water treatment selection. They made use of a ranking system based on assigning weighing factors to criteria to adjust their relative importance, as well as defining scores for each criterion expressing the degree to which a certain criterion is met. The most favorable water treatment was than selected based on total weighted scores. Concerning the selection criteria for agricultural practices which were defined in this study, the amount of accumulated knowledge was considered insufficient to actually quantify the compliance with the criteria. Nonetheless, not all criteria are of equal importance so a ranking is possible. In addition, some criteria are simply essential and if not completely fulfilled the disinfection treatment is not fit for purpose. Those criteria were denoted as knockout criteria (Figure 2). Based on these criteria, a qualitative analysis can be done to assess fit for purpose status of water disinfection technologies.

Consider the case of a farmer in a developed country. The farmer can use water from a creek to supplement rainwater use. Suppose the amount of surface water needed is limited. Microbial analysis of the surface water indicates presence of *Cryptosporidium* and *Giardia* spp. Physicochemical analysis showed turbidity of 10–20 NTU and a COD of 30–60 mg O_2/L. All considered technologies can be applied and as such there are no legal constraints. When considering the inactivation potential, the presence of *Cryptosporidium* reduces the possible technologies to ozone, UV, and membrane filtration (micro or ultra filtration should suffice). All technologies are negatively influenced by the physicochemical load, ozone in inactivation efficiency, membrane filtration through fouling and UV through both, fouling resulting from both organics and inorganics such as iron or calcium. Nonetheless, all three technologies are expected to be able to provide the necessary disinfection efficiency, not considering the amount of chemicals or energy consumption it will require. The physicochemical load in this case is not particularly high, but a rapid sand filtration pretreatment would be beneficial for all three technologies, as, e.g., a turbidity < 10 NTU is recommended for UV disinfection (USEPA, 2006). In addition, a rapid sand filter may remove protozoan organisms to some degree, although an optimized coagulation process would be necessary to achieve a 2 log *Cryptosporidium* reduction (Gitis, 2008). Regardless the possibility for additional removal, particle removal would also reduce clogging of irrigation equipment. As it is a simple and low-cost pretreatment, implementation would be advisable in all cases. The farmer is situated in a developed country and it is presumed that the remaining technologies can be delivered and installed by the manufacturer, that technical support and

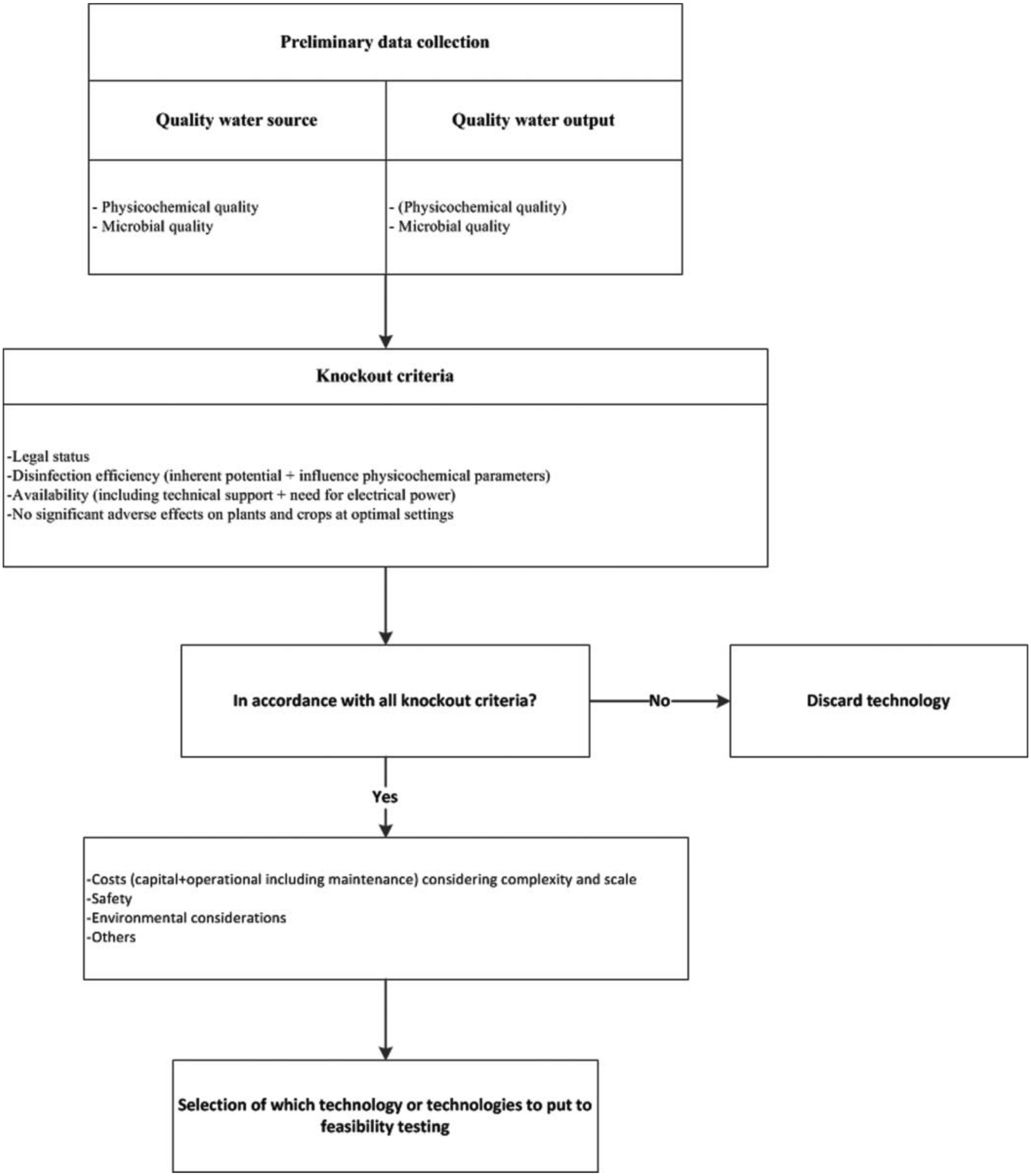

Figure 2 Methodology for applying selection criteria to decision making for water disinfection treatments in pre- and postharvest practices.

spare parts can be provided at all times and that electrical power is accessible. No chemical residual is generated with any of these technologies, so there is no adverse effect on the crops. However the lack of a residual implies that the irrigation piping should be regularly cleaned, as well as any recipients that serve as storage of disinfected surface water. As there are no further knock-outs, the three remaining technologies are evaluated further. Regarding costs, ozone and membrane filtration have a higher cost and require more expert knowledge than a simple UV unit, which is well suited for on-site, small scale treatment (Massé et al., 2011). As the farmer does not need to treat great amounts of surface water, such an investment might not be justifiable. Also, both membrane filtration and ozone generators have higher and more complex maintenance requirements, which might require technical assistance. In addition, membrane filtration creates a contaminated waste stream that must be treated with respect to the environment and ozonation might lead to production of bromate and bromoorganic DBPs in bromide-containing waters. There are some inherent safety issues, but proper design combined with periodic maintenance and creating awareness with the farmer could limit those. After evaluation of these technologies UV disinfection pretreated with a rapid sand filter seems best fit to be tested for this application, as it provides inactivation potential, is relatively low cost and has no environmental issues.

However, evaluating the selection criteria does not always reduce the number of technologies to one technology which is suspected to be best fit, e.g., a company wants to implement a disinfection barrier in order to eliminate the cross-contamination risk of bacterial pathogens when washing fresh-cut onions. The water is characterized by a quick accumulation of organic matter and turbidity and reaches high values (COD of 900 mg O_2/L and turbidity 70 NTU). The company is situated in a developed country. All technologies are allowed by legislation. Regarding inherent disinfection capacity, all considered technologies are able to inactivate vegetative bacteria efficiently, except for hydrogen peroxide which requires high CT values. To guarantee the absence of cross-contamination, presence of a residual in the washing water is obligatory, not considering the actual needed concentrations. A reconditioning strategy, meaning the water is treated before reuse, or otherwise stated, treating the water in another location then the lettuce is actually washed, can maintain the wash water quality but does not operate in situ and as such cannot fully guarantee the absence of cross-contamination. This implies that the technique has to be a chemical disinfectant and therefore membrane filtration and UV disinfection are discarded. The negative impact of organic matter on the remaining technologies can be ranked as following on a general basis: ozone > chlorine > chlorine dioxide > peracetic acid. However, ozone has the greatest inherent disinfection capacity of these technologies and through reaction, it can significantly reduce the organic load of fresh produce washing water (Selma et al., 2008a). Based solely on maintaining residual, peracetic acid can be expected to require the least amount of disinfectant. In theory, all four technologies will be able to avoid cross-contamination, it is only a matter of concentration. Availability is not an issue for any of the technologies as infrastructure, technical assistance, and electrical power are present. The potential for disinfectant concentrations, necessary to maintain water quality, to exhibit adverse effects on the produce is limited. Studies concerning influence on respiration, enzymatic browning, microbial degradation, etc. mostly utilized much higher residuals than necessary here because the goal was to decontaminate (Martinez-Sanchez, 2006; Allende et al., 2009; Vandekinderen, 2009; Tomas-Callejas et al., 2012b). Nonetheless, when testing a technology for in situ wash water disinfection, the potential impact on sensorial quality and shelf life should be assessed. Regarding costs, ozone will require a higher capital investment than the other technologies. Peracetic acid has the highest operational cost per mass unit of disinfectant. Ozone and chlorine dioxide generators require more careful maintenance than the chlorine and peracetic dosing units. All these factors contribute to the cost-effectiveness. The relation between the selection criteria "disinfection efficiency" and "costs" is not sufficiently characterized due to the lack of data on comparison of wash water disinfectants. Furthermore, there are some specific considerations for these technologies related to worker safety, the environment, and their impact on the operation. Use of ozone, chlorine dioxide, and gaseous chlorine will require ambient monitoring of concentrations in the working place to uphold worker safety. In addition the generation of ozone may require some restructuring in the workplace or an enclosed space where the ozone is generated. On that note, due to the rapid decomposition of ozone through reaction with water matrix constituents in combination with its off-site addition, it might be technically difficult to maintain a consistent dosage. Therefore, ozone might be better suited as reconditioning technique and less for maintaining a controlled residual in the washing bath. Peracetic acid has the least potential of producing DBPs, whereas chlorine, chlorine dioxide, and ozone can form primarily THMs, chlorite, and bromate respectively. In cases where restrictions are placed on presence of DBPs in the washing water, the DBPs generation by chlorine will be impacted greatly by organic matter, which is high in this case. The same is valid for chlorine dioxide, where reduction of chlorine dioxide leads to chlorite formation. For ozone, the primary concern is the amount of bromide in the tap water. Applying the knockout selection criteria leads to four possible disinfection technologies. Peracetic acid seems to possess the least additional disadvantages related to worker safety, related issues, and DBPs formation. Ozone has the most issues from an operational point of view, and based on the criteria, it seems to be the least suited for avoiding cross-contamination of the four technologies. As no weighing factors are present to quantify the impact of the criteria, no definite judgment can be made and pilot or full scale tests are needed to elucidate which technology is most suited.

Scientific literature relating to water disinfection in pre- and postharvest practices is relatively scarce. In preharvest practices, more research is needed towards disinfection of alternative water sources for irrigation use, because of the issue of groundwater shortages. Also, maintaining the water quality of hydroponic solutions is a relevant topic, and foremost towards techniques which selectively eliminate food-borne and plant pathogens. In postharvest practices both the prevention of cross-contamination during the washing process by applying sanitizers, and the reconditioning of used water for subsequent reuse are topics which should receive additional attention. In order to be able to perform a cost-analysis of postharvest washing processes, performance of relevant technologies should be assessed and compared, especially with consideration of the consumption rates of different disinfectants by organics present in the wash water. This to gain insight into the actual dosage that is needed to maintain residuals that prevent cross-contamination, in order to estimate the cost-effectiveness of different techniques.

CONCLUSIONS

Given that water quality is closely related to the safety of fresh produce, current information on water quality, water sources, and water disinfection systems applied in the fresh produce supply chain was reviewed. A variety of water disinfection technologies are currently available on the market but no single technology can be put forward as the perfect solution for all needs in water disinfection. It can be difficult for end users to choose the appropriate water treatment technology that is best fit for their purpose. Therefore, several water treatment technologies were characterized and selection criteria developed to support the fit for purpose judgment of their use for water disinfection in irrigation practices, hydroponics, and produce washing and cooling operations. All disinfection techniques have pros and cons, the appropriateness of the water treatment being dependent upon its cost-effectiveness. The inactivation effectiveness is determined by the inherent microbial inactivation ability of the disinfection technique, the target microorganisms and the physicochemical parameters of the water source to be treated. The associated costs are influenced by the capital investment of the technology, the inactivation effectiveness of the disinfection technique and the scale of operation. However, additional aspects such as maintaining a long-term successful disinfection operation, providing worker safety, possible adverse effects on the fresh produce and legal constraints need to be considered as selection criteria, as well as the impact of potential DBPs on human health, and the environment. The defined selection criteria can be applied by the end user as preliminary screening instrument in order to decide which technologies can be tested. The future accumulation of research that focuses on water disinfection in pre- and postharvest practices will allow improvement and refinement of this screening process.

FUNDING

The research leading to these results has been facilitated by the European Community's Seventh Framework Program (FP7) under grant agreement no 244994 (project VEG-i-TRADE).

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