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General Interest

Microbiological Reduction Strategies of Irrigation Water for Fresh Produce

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ABSTRACT

Irrigation water can be a source of pathogenic contamination of fresh produce. Controlling the quality of the water used during primary production is important to ensure food safety and protect human health. Several measures to control the microbiological quality of irrigation water are available for growers, including preventative and mitigation strategies. However, clear guidance for growers on which strategies could be used to reduce microbiological contamination is needed. This study evaluates pathogenic microorganisms of concern in fresh produce and water, the microbiological criteria of water intended for agricultural purposes, and the preventative and mitigative microbial reduction strategies. This article provides suggestions for control measures that growers can take during primary production to reduce foodborne pathogenic contamination coming from irrigation water. Results show that controlling the water source, regime, and timing of irrigation may help to reduce the potential exposure of fresh produce to contamination. Moreover, mitigation strategies like electrolysis, ozone, UV, and photocatalysts hold promise either as a single treatment, with pretreatments that remove suspended material, or as combined treatments with another chemical or physical treatment(s). Based on the literature data, a decision tree was developed for growers, which describes preventative and mitigation strategies for irrigation-water disinfection based on the fecal coliform load of the irrigation water and the water turbidity. It helps guide growers when trying to evaluate possible control measures given the quality of the irrigation water available. Overall, the strategies available to control irrigation water used for fresh produce should be evaluated on a case-by-case basis because one strategy or technology does not apply to all scenarios.

HIGHLIGHTS

- Guidelines and regulations on water quality for agriculture use vary by region.
- Control of irrigation water source, regime, and timing are preventative strategies.
- Electrolysis, ozone, UV, and photocatalysts are mitigative strategies.
- A decision tree can help prioritize control measures for growers.

Key words: Decision tree; Food safety; Growers; Irrigation water criteria; Pathogenic microorganisms; Water disinfection

Several foodborne outbreaks associated with pathogens in fresh produce have been reported in the past years *(38, 138)*. Fresh produce can become contaminated with pathogens at any step in the supply chain and often because of environmental or human factors. To protect human health, supply chain actors should prevent or mitigate foodborne pathogens early in the fresh produce supply chain to avoid further growth or cross-contamination at subsequent stages in the chain. Potential vectors and routes of microbiological contamination during the primary production of fresh produce include animals or insects, soil, manure, organic fertilizers, equipment, workers, and water. In particular, irrigation water and harvest washing water have been identified as key sources of pathogenic contamination for fresh produce *(116, 119)*. Fresh produce with the greatest vulnerability for contamination include low foliar crops (e.g., lettuce, spinach, other leafy-green vegetables), root crops (e.g., onions), off-ground crops (e.g., tomatoes), and fruits because they are vulnerable to multiple sources of contamination, are grown in the open field, and can be consumed raw *(119)*.

Good agricultural practices aim to provide safe food for actors further along the supply chain, such as industry, retailers, and consumers. GLOBALG.A.P. is a worldwide private standard that provides guidelines for primary production processes to ensure good agricultural practices. Among those guidelines are water management and control measures, which, e.g., aim to prevent pathogenic contamination in water and focus on irrigation requirements, irrigation and fertigation management, water quality, the supply of irrigation and fertigation, and water storage facilities *(47)*. In addition, water quality should comply with published guidelines of the World Health Organization

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(WHO) and local legislation. Although these standards highlight the need for water management, tangible recommendations regarding the application of control measures are lacking. Overall, there is a need for specific suggestions on measures that growers can take to reduce microbiological contamination coming from irrigation water.

This study aims to evaluate (i) pathogenic microorganisms of concern related to fresh produce and water; (ii) microbiological criteria of water, namely, when intended for agricultural purposes; and (iii) preventative and mitigative microbial reduction strategies for irrigation water use during the primary production of fresh produce. These aims subsequently provide additional information and suggestions for control measures that growers can take during primary production to reduce pathogenic contamination coming from water sources. Based on the literature data, a decision tree was developed to provide suggestions on the control measures that growers can take during primary production to reduce pathogenic contamination coming from irrigation water.

PATHOGENIC MICROORGANISMS RELATED TO FRESH PRODUCE AND IRRIGATION WATER

Bacterial, parasitic, and viral pathogens have been linked to outbreaks of produce-associated illness. The following section describes the most important pathogens. Irrigation water has been identified as a source of contamination, and examples of produce outbreaks that trace back, or are related to, irrigation water are provided. Moreover, characteristics such as the infectious dose, incubation period, sources, and mode of transmission of the pathogens are summarized in Table 1. In addition, several factors that can affect the survival and growth of pathogens, as well as the relationship between produce type and pathogen, are described.

Three important bacteria responsible for foodborne illnesses are pathogenic *Escherichia coli, Listeria monocytogenes,* and *Salmonella enterica*. Major sources of water contamination by *E. coli* and *Salmonella enterica* are similar: wildlife, livestock, and humans *(119)*. Notably, Shiga toxin–producing *E. coli* is responsible for several disease outbreaks related to contaminated foods. One prominent Shiga toxin–producing *E. coli* example was the 2011 Germany *E. coli* O104:H4 outbreak with fenugreek sprouts. Recently, a 2018 multistate outbreak of *E. coli* O157:H7 in the United States was linked to romaine lettuce. Environmental water samples from the growing region of the lettuce were linked to the *E. coli* found in those affected. In total, 210 people were reportedly infected. Ninety-six people were hospitalized, and five deaths were reported *(22)*. In general, bacterial pathogens have been associated more frequently with outbreaks in fresh produce than have outbreaks from parasites and viruses *(11)*. Additional examples in which irrigation water (or agricultural water) was traced back as the source or found to be indistinguishable from the outbreak strain include an outbreak of *E. coli* O157:H7 in romaine lettuce *(23)*; enterohemorrhagic *E. coli* in salad *(29)*; *L. monocytogenes* in sprouts *(17)*; *Salmonella* in alfalfa sprouts *(19)*; *Salmonella* Saintpaul in peppers *(13)*; and *Salmonella* Newport in tomatoes *(49),* among others. *E. coli, L. monocytogenes,* and *Salmonella enterica* can result in different symptoms with incubation times ranging from hours to weeks; however, the infectious dose for *E. coli* O157:H7 and *Salmonella enterica* can be as low as 10 CFU *(97, 98, 111, 112)*. Although these numbers are higher for *L. monocytogenes,* individuals with a high risk of infection, e.g., the young, the old, women who are pregnant, or immunocompromised persons, are more susceptible (Table 1).

In addition to pathogenic bacteria, parasites, such as *Cryptosporidium* spp., *Giardia,* and *Cyclospora* spp., have also been associated with fresh produce outbreaks. *Giardia* is a microscopic parasite that can spread in various ways, but water is the most common mode of transmission. Irrigation waters can be contaminated with *Giardia (103)*. For example, significant correlations were found between *Giardia* and *Cryptosporidium* densities and water-quality parameters such as turbidity and total and fecal coliform levels *(70)*. No correlation could be observed between the presence of *Cryptosporidium* and populations of fecal coliforms or *E. coli (116)*. When considering recent foodborne outbreaks, in 2019, a multistate outbreak of *Cyclospora cayetanensis* in the United States occurred in which 241 people were reported infected after eating fresh basil. The likely source of the outbreak was fresh basil exported from Mexico. *Cyclospora* transmission occurs when infected feces contaminate food or water *(118)*. Other outbreaks have been linked to raspberries, possibly because of water contaminated with *C. cayetanensis (110)*.

In addition to pathogenic bacteria and parasites, viruses, such as norovirus and hepatitis A, have been associated with fresh produce outbreaks. The estimated health risks of viral contamination in the soft-fruit supply chains and in lettuce are generally low. The contribution that virus contamination has to irrigation or rinsing water is less than the contribution of hand contact by the grower of the produce *(8)*. In 2010, an outbreak in Denmark of norovirus and enterotoxigenic *E. coli* was linked to contaminated lettuce. Although the source of the outbreak was not identified, it was speculated that contamination from human fecal matter, possibly via contaminated water, might have been the source *(34)*. Other outbreaks in which hepatitis A was linked to contaminated irrigation water included those with lettuce *(54, 105)*.

Certain factors, such as intrinsic, extrinsic, and implicit factors, as well as the complex interactions among these factors, can affect the survival and growth of pathogens in fresh produce. Intrinsic factors include the type of produce and the presence of antimicrobial substances, whereas extrinsic factors include environmental aspects, such as temperature or conditions in the field during cultivation or harvest. Implicit factors can include the competition or interaction among microorganisms, nutrient sources or limitations, stress tolerance, and the ability to internalize in produce. For instance, the natural competition of different microorganisms in water is important because that may affect pathogen presence given the effect on the type and concentration of nutrients or disinfectant residuals in the water *(90)*. In addition, in general, pathogens will survive, but not grow, on the outer surface of fresh produce because

TABLE 1. *Characteristics of pathogens linked to outbreaks of produce-associated illness*

Pathogen	Infectious dose	Incubation period	Sources, mode of transmission	References
Bacteria				
E. coli O157:H7	10–1,000 CFU	1–10 days (median 3–4 days)	Animal and human feces; contaminated food (e.g., raw or undercooked meat products, raw milk, apple juice) and water; cross-contamination during food preparation	*97, 111, 135*
Salmonella enterica	<10–10^7 CFU	5–72 h	Animal and human feces; contaminated water and foods such as meat, poultry, milk, and egg products; infective animals, feed, or humans.	*98, 112*
Shigella spp.	10–200 CFU	1–7 days	Fecal-oral route; contaminated water or food, such as salad, chicken, and shellfish; person-to-person by anal sexual contact; flies may be a vector	*14, 93, 129, 139*
Listeria monocytogenes	10,000,000–100,000,000 CFU (healthy host) 100,000–10,000,000 CFU (YOPIs)[a]	1 day–4 wk (typical), yet can be several months	Environment (ubiquitous), including soil, sewage, vegetation, water, and food processing environments; contaminated foods, such as meat products, including cured meats like smoked fish, dairy products like unpasteurized raw milk, soft cheeses, and ice cream; produce, such as celery, sprouts, and cantaloupe; transmission from mother to fetus (transplacental transfer) or during childbirth (via birth canal); transmission from diseased animals to humans	*18, 60, 95*
Clostridium botulinum	Oral (serotype A): 0.001 µg/kg bw adults	12–72 h	Environmental, spores exist in environmental sources, such as the soil, river, and seawater. Foodborne: contaminated foods, associated with foods, including low-acid–preserved vegetables that have undergone poor processing, storage, or improper perseveration	*61, 91, 134*
Parasites				
Cryptosporidium spp.	132 oocysts (healthy host), as low as 1–5 oocysts for immunodeficient persons	2–10 days (average 7 days)	Fecal-oral route; direct contact with infected humans or animals; contaminated food (such as raw milk, raw meat, raw produce) or water; aerosols	*15, 62, 96*
Giardia	10 cysts	1–3 wk	Fecal-oral route (person-to-person); contaminated food or water	*16, 32, 58, 94*
Cyclospora spp.	10–100 oocysts	2–11 days	Contaminated water or food (such as raspberries, basil, and lettuce); contact (direct or indirect) with contaminated soil	*21, 99*
Viruses				
Norovirus	<10 virions	10–50 h	Fecal-oral route (person-to-person); environment, contaminated surfaces, food (such as bivalve shellfish, fresh produce, ready to eat foods), water (incl. ice), fomites, and aerosols (incl. that from vomit)	*20, 63, 100*
Hepatitis A	unknown	14–50 days (average 28–30 days)	Fecal-oral route; transmission from close contact with the infected person; contaminated food and water (less-frequent transmission) and transfusion of blood or blood products (rare transmission). Waterborne outbreaks (infrequent) are associated with sewage-contaminated or inadequately treated water.	*59, 92, 136*

[a] YOPIs, young, old, pregnant, and immunocompromised persons.

of the protective character of the plant's natural barriers *(53)*. Under some circumstances, pathogens that may be present in the irrigation water can enter intact fruit through the blossom or stem. Research has shown that internalization of *E. coli* O157:H7 was not observed when lettuce leaves were inoculated with 4.4 log CFU per leaf, but when inoculated with 6.4 log CFU per leaf, internalization occurred *(31)*. The internalization of *E. coli* via the roots of a plant is rare, e.g., it has been shown that *E. coli* does not persist longer than a week *(31, 33)*. The internalization of pathogenic bacteria in tomatoes was shown to occur when immersed in contaminated water, despite the similar temperatures of the product and the water *(57)*. In brief, intrinsic, extrinsic, and implicit factors, as well as the complex interactions among those factors, can affect the survival and growth of pathogens in produce.

As far as a relationship between produce type and the pathogen of concern, several European Food Safety Authority (EFSA) reports regarding food of nonanimal origin ranked fresh produce-pathogen combinations that are often linked to foodborne disease have been published *(38–40)*. This research demonstrated that norovirus is often detected in fruit; mostly berries were of concern. Sprouts were mostly contaminated with *Salmonella,* whereas tomatoes were found to be susceptible to both *Salmonella* and norovirus. Red peppers and tomatoes were more susceptible to *Salmonella* contamination than were green crops *(77)*. Both tomatoes and leafy greens, such as parsley and lettuce, were susceptible to *Salmonella* and *E. coli*. Notably, the presence of human pathogens can differ depending on the cultivar *(77)*.

MICROBIOLOGICAL QUALITY CRITERIA OF WATER

Because water is an important contamination source, criteria on the microbiological quality of (treated) wastewater to be used for agriculture, recreational water, irrigation water, and drinking water have been described in several guidelines and regulations worldwide (Table 2). When assessing water quality for agricultural practices, *E. coli* concentrations in water are used as a hygiene indicator. This organism was found to be a suitable index organism for *Salmonella enterica* and Shiga toxin–producing *E. coli,* but to a lesser extent for *Campylobacter* spp. *(24)*. Values to assess the microbiological quality of water are commonly expressed in fecal coliforms rather than total coliforms. The term *fecal coliforms* concerns the coliforms that live in the intestinal tract of many animals and humans, whereas the term *total coliforms* is used as a general indicator of potential contamination with pathogenic organisms.

GLOBALG.A.P. specifies that the water quality to treat or wash produce before and after harvest stages should meet microbiological standards for drinking water as defined by the WHO. Treated wastewater used at the preharvest stage should meet the WHO microbiological guideline for the safe use of treated wastewater in agriculture. WHO guidelines for the use of wastewater in agriculture have indicated that, for the irrigation of crops that are likely to be eaten uncooked, a geometric mean of ≤1,000 CFU/100 mL has been recommended *(126)*. Since then, a more recent WHO guideline for unrestricted wastewater used in agriculture has recommended different criteria, based on the type of crop and irrigation (Table 2) *(130)*.

According to the European guidelines on recreational waters (e.g., of rivers, lakes, and coastal waters), different criteria for inland and coastal or transitional waters are provided. For inland waters, including lakes and rivers, concentrations of *E. coli* are recommended to be <900 CFU/100 mL, whereas, for coastal and transitional waters, concentrations <500 CFU/100 mL of *E. coli* have been proposed *(36)*. Guidelines from the WHO and the United States are presented for comparison (Table 2).

The Council of the European Union lays down the quality of water intended for human consumption in Directive 98/83/EC, indicating microbiological parameters of 0 CFU of *E. coli* per 100 mL and 0 CFU of enterococci per 100 mL, with exceptions for water sold in bottles or containers *(35)*. Guidelines from the WHO and the United States are presented for comparison (Table 2).

The European Commission has provided a notice on guidelines for addressing microbiological risks in fresh fruit and vegetables (FFVs) at primary production through good hygiene, wherein a matrix on the microbiological risk assessment of agricultural water is provided *(37)*. During preharvest and harvest, for FFVs that are to be eaten uncooked and where the irrigation water comes into direct contact with the edible portion of the crop, there is an indicator fecal contamination target value of *E. coli* of 100 CFU/100 mL. For FFVs that are to be eaten uncooked and where the irrigation water does not come into direct contact with the edible portion of the crop, or for FFVs that are to be eaten cooked and where the irrigation water comes into contact with the edible portion of the crop, there is an indicator fecal contamination target value of *E. coli* of 1,000 CFU/100 mL. Finally, for FFVs that are to be eaten cooked and where the irrigation water does not come into direct contact with the edible portion of the crop, there is an indicator fecal contamination target value of *E. coli* of 10,000 CFU/100 mL *(37)*. When required, e.g., if the results of the water source indicate a potential problem, growers should take action to reduce the risk to consumers and carry out further testing to verify the effectiveness of those actions *(37)*.

Regular water analysis is particularly important for produce that is not cooked before consumption when the edible part of the crop is in contact with water, and when a water source vulnerable to contamination such as wastewater, surface water, or reclaimed water is used. Testing frequencies of a minimum of three samples during the growing season and a minimum of five samples per year are recommended in guidance documents *(47, 117)*. It remains to be determined whether this is sufficient.

In the United States, under the Food Safety Modernization Act produce safety rule, definitions for agricultural water and its intended use have been described. Requirements for water quality are established based on *E. coli*. For instance, "no detectable generic *E. coli* in 100 mL of agricultural water" is a criterion that is described for some uses of agricultural water, whereas numerical criteria for agricultural water to be used directly on growing produce (except for sprouts) is based on a geometric mean of ≤126 CFU of *E. coli* per 100 mL of water and a statistical threshold of ≤410 CFU of *E. coli* in 100 mL of water *(117)*.

MICROBIOLOGICAL REDUCTION STRATEGIES

To reduce the probability of pathogenic contamination associated with fresh produce from contaminated irrigation

TABLE 2. *Guidelines and legislation for the microbiological quality of treated wastewater, recreational water, irrigation water, and drinking water*

Country/region	Criteria (CFU/100 mL)[a]	Document type	Reference(s)
(Treated) wastewater			
WHO (unrestricted)[b]		Guideline	*130*
Root crops[c]	$\leq 10^3$ *E. coli* ≤ 1 helminth eggs (no./L)		
Leaf crops[d]	$\leq 10^4$ *E. coli*		
Drip irrigation, high-growing crops[e]	$\leq 10^5$ *E. coli*		
Drip irrigation, low-growing crops[f]	$\leq 10^3$ *E. coli*		
Italy	<10 *E. coli* and absence of *Salmonella*	Regulation	*25, 119*
Spain	<100 *E. coli*	Regulation	*2, 119*
Recreational waters (coastal and fresh waters)			
WHO	<500 enterococci	Guideline	*128*
EU[g]	Inland waters: <330 enterococci or <900 *E. coli* Coastal and transitional waters: <185 enterococci or <500 *E. coli*	Guideline	*36*
United States	<35 enterococci or <126 *E. coli*	Guideline	*114*
Irrigation water (for all water types)			
Canada	<100 fecal coliforms 1,000 total coliforms	Guideline	*109, 119*
Canada (British Columbia)	200 fecal coliforms 77 *E. coli* <20 fecal streptococci	Guideline	*109, 119*
EU	Between 100 and 10,000 *E. coli*	Guideline	*37*
Drinking water			
WHO	<1 *E. coli*	Guideline	*132*
EU	0 *E. coli* 0 enterococci For water in bottles or containers:[a] 0 *E. coli*/250 mL 0 enterococci/250 mL 0 *Pseudomonas aeruginosa*/250 mL Colony count 22°C: 100 CFU/mL Colony count 37°C: 20 CFU/mL	Directive	*35*
The Netherlands	0 *E. coli* 0 enterococci	Decree	*108*
United States	0 for total coliforms, fecal coliforms, and *E. coli*	Regulation	*115*

[a] Unless stated otherwise.
[b] The use of treated wastewater to grow crops usually eaten raw.
[c] That may be eaten uncooked.
[d] Nonrooted salad crops, including vegetables eaten uncooked, e.g., lettuce, cabbage.
[e] Crops that are grown aboveground that generally do not touch the soil, e.g., fruit trees, olives.
[f] Nonrooted crops grown low or near the soil surface.
[g] EU, European Union.

water, preventative and mitigation strategies can be applied. Preventative strategies aim to reduce or prevent the exposure of fresh produce to contaminated irrigation water. Mitigation strategies aim to reduce the pathogenic load of the irrigation water by pretreatment of irrigation water with chemical or physical methods before application.

Preventative strategies. With the aim to reduce exposure of fresh produce to contaminated irrigation water, it is vital that the irrigation water source, regime, and time are well selected. These three preventative strategies are further elaborated in the following sections.

(i) Selection of irrigation water source. Selecting the appropriate irrigation source as a preventive measure has a substantial effect on the microbial exposure of fresh produce. The probability of finding pathogenic microorganisms is shown to be greatest in untreated wastewater, whereas surface water and recycled or reclaimed water have shown to have an intermediate probability *(76, 85)*. Waters with a low probability of contamination are tap water, groundwater, and rainwater *(76, 86)*. Groundwater has a stable composition over time and contains fewer impurities. Surface water originates from rivers, canals, lakes, ponds, reservoirs, or open wells. These sources are in direct contact with the environment, and therefore, variable in composition in place and time; hence, care should be taken when using such sources. For example, water quality can worsen after periods of heavy rainfall or flooding if water has been in contact with other sources of contamination (e.g., animal feces, sewage, and runoff water). Environmental conditions are shown to influence the potential of bacterial pathogens; in water, pathogens have been reported to be influenced by environmental conditions, such as water temperature, pH, oxygen, and organic and inorganic nutrient types *(90)*. These variables are important to consider when selecting the irrigation source.

When selecting an irrigation source, the turbidity of the water should also be considered since it may be related to pathogen prevalence. Turbid water often leads to sediment disturbance-generating particles and nutrients in the water. Particulates in water are a concern because microbes are particulates, and nonmicrobe particulates may serve as indicators of pathogen presence or protect pathogens from disinfectants *(27)*. Higher counts of fungus-like oomycetes were found to be associated with higher turbidity levels in creeks; for example, research demonstrated that an average increase in 2.4 nephelometric turbidity units (NTUs) led to an average increase of 29 CFU/L oomycetes for creek water samples *(66)*. Activities upstream of surface water, including rivers, streams, and creeks, can increase water turbidity and can rapidly change the level of contaminants, thereby affecting overall water quality. The relationship between pathogens like *Salmonella* and biological or physicochemical indicators is complicated because clear correlations between these are not consistent. McEgan et al. *(78)* reported that *E. coli* was a reasonable predictor of *Salmonella* levels in surface water in Florida, and at some studied sites, physicochemical parameters, including turbidity, oxidation-reduction potential, and conductivity, were predictors of *Salmonella* in surface water. However, when physicochemical parameters across studied sites were aggregated, there was no clear correlation. In another study, Francy et al. *(44)* studied the presence and absence of bacterial pathogen gene markers (for *E. coli, eaeA*; for *Shigella, ipaH*; for *Salmonella, spvC*) at inland Ohio waters. Authors observed that when data for several parameters were combined (rainfall, conductivity, turbidity, water temperature, and model probability), there was a relationship with at least one of the genes mentioned above, but an inconsistent relationship with *E. coli* concentrations. Overall, water quality parameters, as well as other data, such as site properties and precipitation, may help predict the pathogen prevalence of water for irrigation purposes. For growers, their activities, including the location thereof, which may negatively influence the water turbidity, can also be considered when selecting an irrigation water source.

The extent to which enteric pathogens survive in irrigation water varies substantially depending on the quality and origin of the water *(120)*. Studies on the irrigation water quality of eight Belgian lettuce producers confirm that surface water quality is unpredictable *(119)*. *E. coli* values for surface water collected from rivers in this study were within the range of 1.5 to 3.3 log CFU/mL. Another study concluded that irrigation waters of different origins can transmit enteric pathogens differently and affect the ability of the pathogens to survive and grow on the lettuce *(120)*. Competition with resident aquatic microbiota influences pathogen behavior. In addition, persistence and survival on produce are variable, ranging from 1 day to 4 weeks on leafy greens *(119)*. Given these variations, strategies should focus on prevention to decrease the probability of potential pathogenic contamination.

Apart from selecting the most appropriate irrigation source, other strategies to control the microbiological irrigation water quality include decreasing pathogen inflow from reservoirs and input sources. Examples of pathogen input sources are runoff, sewage discharge, direct deposition, infiltration, and sideward flow in shallow soils *(85)*. In one study, storage of rainfall water in a raised pond with elevated edges reduced mean *E. coli* concentrations 1.7 log CFU/100 mL compared with a pond that is not protected to prevent runoff *(26)*. In another study, analysis of New York surface waters showed ponds to be positive for *E. coli, Salmonella,* and oomycetes. Creeks were most often positive for oomycetes, whereas canals contained unambiguously low amounts of microorganisms *(66)*.

In brief, when selecting an irrigation water source, consider the possibility of pathogen inflow from reservoirs and input sources as well as the other variables mentioned above, such as water origin and type, influencing environmental factors, and activities that may contribute to increased water turbidity.

(ii) Irrigation regime. The irrigation regime, along with the amount of water used for irrigation, can influence the availability of niches, where pathogens may persist and/or multiply under field and postharvest conditions *(46)*. During preharvest irrigation, moisture on the plant from irrigation may promote growth and survival of bacterial populations. When the plant is in direct contact with the irrigation water, the probability of contamination is greatest. Contact can be avoided through “indirect” irrigation practices (furrow or drip, subsurface, etc.) because these are a better choice compared with spray or surface irrigation *(46)*. A study evaluated the survival of *E. coli* in lettuce fields when bacteria were introduced, showing that drip and furrow irrigation reduced survival on produce slightly after inoculation as compared with spray irrigation. In trials involving inoculation of *E. coli* in the field, a consistent observation was that leaves of plants that were sprinkler irrigated were positive 1 to 3 days after the introduction of the bacteria, whereas furrow- and drip-irrigated plants were negative for *E. coli* in most evaluations *(43)*. With drip irrigation, compared with overhead spraying, pathogen transfer onto low-growing crops (e.g., root crops, lettuce) was reduced by up to 2 log. For higher-growing crops (e.g., tomatoes), a 4-log reduction was observed *(131)*. Hence, the irrigation method can influence the bacteria transfer rate. Nevertheless, even though another study did not show a clear link between the type of irrigation system and contamination with bacterial pathogens *(88),* there may be other factors that influence the irrigation regime and pathogen contamination. For example, Marvasi et al. *(77)*

found that the irrigation regime–dependent differences were dependent upon the season and the weather.

Drip irrigation is a precise and controllable method that has been shown to be a preferable method to that of spray or surface irrigation. Nevertheless, the longevity of such a system is affected by system management, maintenance protocols, and source water quality. These aspects should not be ignored. For example, the use of reclaimed water contains many nutrient salts, particles, organics, microorganisms, and other substances; thereby, increasing the likelihood of emitter clogging *(71)*. This effect would then make the method less effective and could consequently introduce an opportunity for pathogenic contamination. Overall, when properly applied and managed, indirect irrigation methods may help to reduce the potential exposure of fresh produce to contaminated irrigation water.

(iii) Timing of irrigation. In addition to irrigation water source and regime, another important variable that can help to reduce the exposure of fresh produce to contaminated irrigation water is the timing. The effects that the temperature and season or weather may have, as well as the timing of the irrigation, are described.

During preharvest, when the temperature of the irrigated water or soil is increased, there was a reduced survival of *E. coli*. Field studies were performed in Arizona, where survival of *E. coli* was measured after its introduction into lettuce fields by sprinkler or furrow irrigation. The study showed that, in winter, the persistence of *E. coli* in soil was around 2.5 weeks, whereas, in summer, the estimated survival was around 5 days *(43)*. Interestingly, lower chances for bacterial introduction in the field are expected during times in which more prolonged survival occurred. A seasonal effect for the presence of pathogens and indicator bacteria has also been shown in water samples. They tend to be more detectable during months with higher temperatures when the fresh produce is maturing *(55)*. This effect is most likely because of environmental factors, such as wildlife intrusion, irrigation frequency, and insect activity *(72)*.

Another study reviewed the effects that weather has on the concentration of indicator bacteria on fresh produce, which was determined by evaluating the mean and maximum temperature as well as precipitation for 1 week up to 1 month before harvest *(87)*. Results substantiated how precipitation data could predict produce contamination, in this instance, for that of spinach contamination with *E. coli* at preharvest. In short, farm management, environment, and weather were found to be important to reduce produce contamination *(87)*. Further research has been performed to define the effect of weather dynamics in the period between contamination and sampling on the presence and concentration of bacteria on fresh produce. Precipitation ($\leq$0.64 cm) that occurs 3 days before sampling correlated with both the presence and the highest counts of *Salmonella* (175 CFU/100 mL) according to a study on fruit and vegetable crops in New York *(66)*. After rainfall, microbial populations increased by 1.5 to 3 log CFU/g on lettuce leaves *(42)*. Overall, temperature and season, including weather conditions, such as precipitation, have a role in the potential contamination of produce. Thus, strategies that aim to reduce the potential effect that these conditions may have on the presence of pathogens should be considered.

One control measure that can be considered during preharvest is the timing of last water irrigation. It has been observed that the timing of last water irrigation from natural sources, such as rainwater or surface water, was shown to critically affect the postharvest microbial population of fresh produce *(42, 43)*. To be able to reduce the microbial load, the challenge is to increase the irrigation interval up to the threshold at which quality and yield are not yet compromised because of moisture stress. A recent study reported that the timing of irrigation was a key risk factor for the presence of *L. monocytogenes,* namely, that isolated *L. monocytogenes* was significantly greater in fields irrigated 3 days versus that of at least 10 days before sample collection *(125)*. Authors suggested that refraining from irrigation within 3 days of harvest may reduce the probability of produce contamination.

Despite this advice, another study concluded that cessation for 3 days before the harvest was inadequate to exclude the possibility of viable *E. coli* O157:H7 cells on spinach or rocket *(3)*. The amount of time to apply between last irrigation and harvest allows for pathogenic microorganisms to die off on the field. In another study, Kisluk and Yaron *(69)* determined that the persistence of *Salmonella enterica* serotype Typhimurium on parsley occurred for at least 48 h after irrigation with water containing low concentrations (approximately 300 CFU/mL). Furthermore, irrigation with water containing *Salmonella* Typhimurium at 8.5 log CFU/mL, representing heavily contaminated water, resulted in the persistence of bacteria for at least 4 weeks. The population steadily declined during the first 2 days with a *Salmonella* Typhimurium reduction of approximately 2 log CFU/g *(69)*. Overall, contamination was affected by pathogen quantity in the irrigation water and timing between irrigation and harvest *(69)*. In terms of control, the U.S. Food and Drug Administration (FDA) *(116)* advises a preharvest interval of irrigation for a maximum of 4 days. Although the timing of irrigation is a relevant factor that warrants further research, preventing irrigation water contamination is nonetheless critical. Given a systematic literature review by Park et al. *(88)* on risk factors for produce at preharvest, authors found that repeated irrigation, including spray irrigation, was associated with an increased likelihood of produce contamination, and thus, reducing microbial contamination of irrigation water was a notable preventative control strategy. In summary, these findings show that the timing of irrigation is important to control during the preharvest period to reduce the exposure of fresh produce to contamination.

Mitigation strategies. Water treatment strategies at the primary production stage can include sedimentation, coagulation, flocculation, filtration, and disinfection. Several mitigation strategies that may help to improve the microbial quality of irrigation water include disinfection by chemical treatments, such as chlorine dioxide, electrolysis, and chemical oxidation. Physical disinfection treatments that can be performed include the use of UV, ultrasound (US), or filtration *(45)*. Most strategies are not effective in removing all types of microbiological agents but lead to a reduction in the overall level of pathogenic microorganisms. The appropriate water-treatment method for each situation can depend on multiple factors, including technological, managerial, and sustainability criteria *(121)*. The following sections describe water disinfection technologies whose efficacy on the reduction of fecal coliforms was seen as possibly advantageous for use during primary production.

(i) Removal of suspended material. The turbidity of the surface water is caused by suspended particles and floating debris, including organic matter, clay, sand, and silt. Microorganisms can colonize the surface of particles, such as sediment, which can then provide a protective barrier for survival *(124)*. Hence, it is important to remove suspended material from irrigation water before use. Groundwater and drinking water have turbidity levels below 1 NTU. Turbidity values above 5 NTUs become perceptible to the eye *(4)*. Water sources with moderate plant and animal life can have NTUs up to 10 *(50)*. Floating debris can easily be removed. The type of suspended residues in the water and the required degree of purification will determine the method of choice. Several methods may be implemented to remove suspended matter from runoff water, including sedimentation, flocculation, and coagulation.

Sedimentation through gravity is a slow, but economical, process. Most suspended material will settle out of the water in a collection basin or sedimentation pond within a few hours up to several days. During flocculation, a combination of alum, ferric sulfate, or a polymer is added to the water to flocculate the suspended particles resulting in a rapid (ca 5 min) sedimentation of clay *(84)*. Coagulation occurs when a chemical (such as alum or ferric) is added to water to destabilize colloidal suspensions. Decreasing pH (to levels as low as 4 or 5) increases the feed rate of coagulants *(64)*.

Several treatment processes are often combined to remove suspended matter. These include, in general, coagulation and filtration and may require a flocculation tank or a pressure vessel after the coagulation addition. Filtration methods that require influent water should have a turbidity of <5 to 10 NTUs and color of <20 to 30 color units *(82)*. For irrigation water with many suspended particles, removal of suspended material is recommended as a pretreatment measure to ensure subsequent proper membrane or cartridge filtration. For *Cryptosporidium* removal, studies have shown that coagulation pretreatment most influenced the effectiveness of subsequent conventional treatment processes *(7, 28)*.

(ii) Filtration. Filtration is mainly applied to remove particulate matter and some dissolved material from the water. Filtration systems effective in removing most microorganisms have a small pore size and need a prefilter with a larger pore size to reduce turbidity by filtering out particles. Particulates that are smaller than the membrane pore size can transfer through, meaning it is important to realize the size of the microorganism targeted for the filtration strategy. Bacteria are about 1 μm in size, whereas viruses have a size of 0.02 to 0.4 μm and are much smaller (Table 3). Microfiltration and ultrafiltration membranes (approximately 0.1 μm) remove sediment and bacteria; ultrafiltration membrane filters (approximately 0.01 μm) may also remove viruses. Nanofiltration (approximately 0.001 μm) or reverse osmosis (<0.0005 μm) is very efficient in removing microorganisms. Microporous ceramic membranes are used in developing countries for water purification with a filtration speed of 1 to 3 L/h and an efficiency of reducing *E. coli* concentrations 4 log or more depending on coating thickness *(73)*. Membranes, cartridges, or sand can be used as a filter.

Membrane filtration can be performed using two operating procedures: either with a constant flux, or with pressure. Depending on the module design, the water passes in different ways through the membrane. In dead-end filtration, the suspended solids remain on the feed side of the membrane. In a configuration with inside-out filtration, feed water enters the inside of the capillaries or tubular membranes. With cross-flow filtration, often used for water with a high concentration of suspended solids, a small part of the water permeates through the membrane, and most flows across the membrane. Membranes for liquid filtration can be made of different types of material. Ceramic membranes can be made of aluminum, titanium, or silicon carbide, whereas polymeric membranes can be composed of cellulose acetate, nitrocellulose, or polyamide.

Cartridge filters are a simple and lightweight option for filtration, especially for small systems. Cartridge filtration is a physical process in which the water flows from outside to inside (a vessel), whereby the water is strained through porous media *(82)*.

Slow sand filtration effectively removes turbidity and pathogenic organisms *(10)*. If the turbidity is <1 NTU, a reduction of 2 to 4 log infectious units of enteric viruses and 1 to 3 log units of coliforms (CFU) can be achieved *(83)*. A disadvantage is that an extensive land area is required for this low-flow operation, meaning the technique may be less practical in areas in which space is an issue (e.g., in The Netherlands). Sand filtration of irrigation water led to an *E. coli* reduction of about 0.7 log CFU in groundwater (pumped from boreholes) and about 0.3 log CFU in rainwater (collected from stored ponds) at fields in Belgium during the summer and fall. In comparison, sand-filtration–treated groundwater and rainwater had a lower estimated probability of *E. coli* in strawberries in the summer and fall periods. Overall, the presence of *E. coli* in irrigation water is influenced by irrigation water type and lack of prior treatment (untreated versus sand filtration) *(26)*. Rapid sand filtration is effective in removing large suspended particles causing turbidity (usually <0.1 to 1 NTU) but is ineffective in removing bacteria. The method is mostly used in combination with other pretreatment and posttreatments.

In general, all filtration methods are effective in the removal of pathogenic microorganisms. However, the efficiency of particle and microorganism removal differs

TABLE 3. *Shape and size of microorganisms*

Pathogen	Shape	Particle size (μm)	Reference
Bacteria			
Escherichia coli	Rod	1–3	*102*
Salmonella enterica	Rod	0.7–1.5 by 2.0–5.0	*98*
Shigella spp.	Rod	1–6 length 0.3–1 diam	*80*
Listeria monocytogenes	Rod	0.5–2 length 0.5 diam	*95*
Clostridium botulinum	Rod	0.3–20 by 1.5–20	*52*
Parasites			
Cryptosporidium parvum			
Oocyst	Spherical	4–6 diam	*96*
Giardia lamblia			
Cyst	Oval	10–20 length 7–10 wide 0.3–0.5 thick	
Trophozoite	Tear-drop	9–21 length 5–15 wide 1–2 thick	*94*
Cyclospora spp.			
Oocyst	Spherical	8–10 diam	*99*
Viruses			
Norovirus	Round, nonenveloped	0.027 diam	*100*
Hepatitis A	Icosahedral, nonenveloped	0.027–0.032 diam	*92*

depending on the filter type used, the module design, and the operating procedure. For small systems, membrane filtration and cartridge filtration are most suitable. Membrane filtration costs are relatively high, and knowledge on how to properly use the technology is needed.

(iii) Chlorination. Chlorine is a common form of disinfection, which is effective against harmful bacteria, viruses, and *Giardia* but has a limited effect against *Cryptosporidium (5)*. Chlorination is cost-effective, but safety precautions are needed during operation and maintenance. Chlorine treatments of irrigation water can be performed with chlorine-based disinfectants, such as sodium hypochlorite, calcium hypochlorite, or chlorine dioxide *(5)*.

The concentration of chlorine typically used for irrigation is 2 mg/L with a contact time of a few minutes. The concentration of sodium hypochlorite required to eliminate bacterial pathogens ranges from 0.1 to 4 mg/L with a contact time of 1 to 10 min *(101)*. At higher concentrations, shorter contact times are needed to prevent toxic effects on plant growth but still be efficient in removing microorganisms. One study showed up to a 2.5-log CFU reduction can be achieved with higher doses (70 mg/L) of sodium hypochlorite. The same study also showed that chlorine dioxide is more effective for disinfection. Lower doses (5 mg/L) were required for chlorine dioxide (contact time 1 to 5 min) leading to a total psychrotrophic plate count reduction of >5 log at process wash water chemical oxygen demand of 500 and 750 mg/L *(113)*. Bacteria attached to biofilm surfaces are more resistant to chlorination than free bacteria are. Only limited research has been conducted on effective control methods for biofilms. Research recommends water pH monitoring, a parameter that influences the corrosive properties of chlorine, during flushing of drip lines with chlorine. This measure would lead to a better understanding of the conditions that may lead to an increase in bacterial load in irrigation water distribution systems *(9)*.

Research into the effects of the long-term effect from water chlorination for irrigation is limited. According to Lonigro et al. *(75),* the cultivation of lettuce in pots with chlorinated water showed that the accumulation of organohalogenated compounds in the soil was related to the chlorine concentration in the water. The effects included the eventual loss of soil fertility and bioaccumulation of organohalogenated compounds into the edible parts of the crop *(75)*. Another study, however, showed that the use of chlorine dioxide (<1 mg/L) as a water disinfection treatment of irrigation water had a low impact on the soil and bacterial communities of baby spinach *(89)*.

If the water contains high amounts of organic matter, as may be the case for unfiltered irrigation water, chlorination should be avoided because of the formation of hazardous disinfection by-products. When attacked by chlorine radicals, carcinogenic products, such as trihalomethane and other organic disinfection by-products, may form *(68)*. Unlike chlorine, the reaction of chlorine dioxide reacts slower with organic matter; however, compared with chlorine, chlorine dioxide maintenance costs are typically higher. Filtration or coagulation before chlorination is needed to reduce the probability of carcinogenic by-product formation. Other techniques able to eliminate trihalomethanes are carbon filters and reverse osmosis units.

The Netherlands is one of the few European Union countries in which chlorine is not commonly used for disinfection of drinking water; instead, physical process treatments, such as sedimentation, filtration, and UV disinfection are performed *(106)*. Drinking water in The Netherlands should contain a maximum value of 0.3 to 2 mg/L free chlorine after chlorination *(79)*. A WHO provisional guideline value for chlorine in drinking water of 0.7 mg/L has been proposed *(127, 133)*.

(iv) Electrolysis. Electrolyzed water is another disinfection water pretreatment method that can help to reduce microbial contaminations. It is generated by applying an electric current to a dilute saltwater solution. The electrolytic process uses a membrane cell and produces very acidic electrolyzed water. Alternatively, with a nonmembrane cell, diluted hydrochloric acid is used to produce slightly acidic electrolyzed water containing chlorine (10 to 30 mg/L). The acidity of the water, the oxidation potential, and concentration of chlorine lead to reduced survival of bacteria such as *E. coli, Listeria,* and *Salmonella*. Electrolysis has been reported to have strong activity against most pathogenic bacteria and is recognized as a safe and relatively quick method, given a water flow of around 3.6 L/h *(48, 65)*. Moreover, combined strong acidic electrolyzed water and alkaline electrolyzed water have stronger sterilization ability than single acidic electrolyzed water or slightly acidic electrolyzed water *(51)*. A cooling system for the electrolysis reactor and cooling and control of chlorine storage are recommended to achieve production of minimal amounts of chlorine *(104)*.

(v) Chemical oxidation. For inactivation of protozoan parasites in water systems, ozone is a more effective chemical disinfectant than chlorine dioxide or chlorine *(32)*. Capital and operational costs and the complexity of the technology and maintenance are relatively high compared with other treatments, such as chlorine usage *(101)*. Scientific reports that document the feasibility and performance of on-farm water treatment with ozone are scarce.

Application of hydrogen peroxide (H_2O_2) may be another pretreatment technique to consider because it quickly decomposes in fresh produce-processing water. Van Haute et al. *(122)* tested the disinfection efficacy of H_2O_2 (500 mg/L) in combination with the stabilizing substance Bacsan (10 mg/L Cu). The authors observed the greatest log reductions of aerobic psychrotrophic plate count and *E. coli* at that concentration. For example, during trials with that ratio in artificially made process wash water (chemical oxygen demand, 848 mg O_2/L), after 30 min, there was a 4.5-log reduction in aerobic psychrotrophic plate count and >5-log reduction in *E. coli (113, 122)*.

Furthermore, the application of ozone and H_2O_2 can also be combined during water treatment. Sommer et al. *(107)* reported a 6-log reduction in *E. coli* and viral pathogens during water treatment pilots with 2.5 mg/L ozone and 1.5 mg/L H_2O_2. The ozone/hydrogen peroxide process showed good microbicidal efficacy *(107)*.

(vi) UV treatment and solar-driven disinfection. Various methods exist for harnessing photonic energy to drive solar disinfection: UV, photocatalysis, photosensitizers, and solar disinfection (SODIS) *(74)*. Disinfection with short-wavelength UV light irradiation (UV-C) is effective against bacteria, protozoa, and most viruses. UV application requires energy and regular replacement of UV lamps. UV chambers for treating irrigation water are designed to dose UV light at a given flow rate. Because UV systems are most effective when the water is clear and free of suspended particles, surface water will often need to be filtered to ensure efficacy. However, Jones et al. *(67)* described a 99.9% inactivation (3 log) even at relatively high turbidity levels (20 NTU) with a UV dose of 14.2 mJ/cm^2. Generally, as the turbidity increased, the UV effectiveness decreased. Reported log reductions ranged from 10.0 to 6.1 for bacterial pathogens and from 5.0 to 4.2 for *Phytophthora capsici (67)*. Dissolved solids in the water, such as iron, can also absorb UV light and decrease UV transmittance.

By performing filtration (60 μm filter) before UV radiation (dose 60 mW/s/cm^2) for fresh produce processing water (chemical oxygen demand 800 mg/l), a total psychrotrophic plate count log reduction of 4.5 CFU/mL could be observed, while UV treatment on the same sample that was not prefiltered showed a total psychrotrophic plate count log reduction of 3.5 CFU/mL. Performing filtration (with 10 and 60 μm) before UV treatment at lower doses <20 mW/s/cm^2 reduced the bacterial load only slightly (<0.6 CFU/mL) *(113)*.

Compared with bacterial pathogens, UV radiation is less efficient in inactivating protozoan parasites, such as *Giardia* and *Cryptosporidium,* that can be present in surface water (but are mostly absent from groundwater systems) *(81)*. It has been shown that UV radiation at 10 mW/s/cm^2 kills *Giardia* cysts effectively, whereas encysting parasites and trophozoites can recover from UV treatment at 50 and 100 mW/s/cm^2, respectively *(30)*.

Once water is disinfected with UV, it should be used immediately and not stored for later use in tanks because recontamination can occur, e.g., from backflow or biofilms because there is no residual disinfectant in the water after treatment. UV treatment is not appropriate for irrigation situations requiring very high volumes. The volume of water that can be treated at one time is limited because of the small path length through which UV can penetrate water *(81)*.

Titanium dioxide (TiO_2) is an effective material showing photocatalytic capability. When exposed to light (UV-light-emitting diode, solar irradiation, mercury medium pressure lamp), it functions as a catalyst, altering the rate of a chemical reaction. Under ideal conditions, photocatalysts are predicted to be able to treat up to 30 L/m^2/s water for *E. coli* for 2-log reduction and 10 L/m^2/s water for a 2-log reduction of viral pathogens (MS2 bacteriophage). For the more resistant *Cryptosporidium,* treatment up to 3 L/m^2/s is possible. At the laboratory scale, around 2 L/m^2/s can be treated. The performance of UV-C light-emitting diodes is around 10 L/m^2/s for a 2-log reduction of *Cryptosporidium* and *E. coli*. This treatment is not effective for viruses. Photosensitizers show, in contrast, a very high treatment capacity (approximately 700 L/m^2/s) for viruses compared with *E. coli* and *Cryptosporidium*. The efficiency of viral reduction by photosensitizers was, however, not reported in that article *(74, 137)*.

SODIS uses solar radiation (UV-A light and temperature) to destroy pathogenic bacteria and viruses present in the water. It is a simple water-treatment method that can be used to disinfect small quantities of water with low turbidity. However, the technique is slow, with a waiting period between 6 and 12 h, is weather dependent, and is applicable to only small volumes. The water-treatment capacity of SODIS is about 0.0005 L/m^2/s *(12)*. On the other hand, it does not require investments. It has been shown that in <30 min, about 1 L of water can be disinfected by reducing the concentration of pathogenic microorganisms by 4 log units *(12)*. Possibly, the addition of specific additives has the potential to decrease the relatively long inactivation time *(41, 74)*.

(vii) Ultrasound. US uses cyclic sound pressure with a frequency higher than the upper limit of human hearing. US treatment can reduce the presence of microbial pathogens on produce and in irrigation water. When applied to irrigation water, microbial loads of *E. coli* can be reduced by about 0.5 log units compared with untreated water *(123)*.

US can be combined with other techniques, such as heat, UV, and electrolysis. Continuous-flow US and UV treatment of wastewater showed about a 4-log reduction of fecal coliforms *(140)*. For removal of pathogens on produce, continuous US combined with heat showed a 5-log reduction of inoculated *Listeria (6)*. Electrolyzed water combined with ultrasonication for 15 min at 210 W led to a 4.4-log reduction of *E. coli* O157:H7 on lettuce, whereas 5 min of US eliminated the pathogen on tomatoes *(1)*.

Overall control strategies. Based on the literature studied, a decision tree was drafted (Fig. 1), which describes potential control strategies that growers can take for irrigation water disinfection, based on the fecal coliform load of the irrigation water and water turbidity, to help farmers in choosing water-treatment technologies or ways to reduce exposure of produce to contaminated water.

Microbial reduction strategies should be applied when the water does not meet the requirements for fresh produce. When the microbial load is intermediate (defined as 100 to 1,000 CFU/100 mL in Fig. 1), it is recommended to lower the levels. According to the literature, electrolysis, ozone, UV, and photocatalysts hold promise, either as single treatments with pretreatments that remove suspended material, or as combined treatments, with another chemical or physical treatment method(s) (Fig. 1). Additional research is required to quantify the optimal dosage and procedure or the field performance of the different techniques. The chance that produce becomes contaminated by water with a high microbial load depends on variables, such as the type of irrigation strategy used and whether the produce is grown in greenhouses or on the open field. Several risk-reduction strategies can be performed when irrigation water is contaminated with pathogenic microorganisms, e.g., exposure of produce to contaminated water can be reduced and/or the water can be pretreated (Fig. 1). Some measures can be applied more immediately than others, such as switching to tap water, SODIS, or, if possible, prolonging the preharvest interval. Others may be envisaged in the longer term, such as changing irrigation systems, using soil-less growing systems, or water pretreatment.

The inactivation effectiveness of several disinfection techniques has been evaluated; the range of microbial reduction was 1 to 5 log CFU for single treatments and 4 to 9 log CFU for combined disinfection treatments. The efficiency of microbial removal or inactivation depends greatly on the physicochemical parameters of the water source, such as its turbidity, temperature, pH, and organic load. Most techniques reduce all types of microbial (target) organisms, but efficiency differs for pathogenic bacteria, protozoa, and viruses. Combining diverse methods allows broader antimicrobial action and increases the efficacy. For water pretreatment procedures to be effective in reducing pathogens, a low (<5 NTU) to middle (5 to 10 NTU) turbidity level is important. When the water has a middle or high (>10 NTU) turbidity level, the removal of suspended solids is recommended. Turbidity can, in situations in which suspended materials in the water are caused by runoff, be used as an indicator of microbial water quality *(56)*.

According to current worldwide guidelines for microbial water quality of irrigation water, levels should be <1,000 CFU of fecal coliforms per 100 mL. When contamination levels are slightly higher than indicated by the current guidelines, single treatments should be sufficient. When aiming for levels as indicated by drinking water guidelines, double purification is needed.

CONCLUSIONS AND RECOMMENDATIONS

This study reviewed the knowledge on pathogenic microorganisms of concern related to fresh produce and water, microbiological criteria of irrigation water, as well as preventative and mitigative microbial reduction strategies for irrigation water use during the primary production of fresh produce. The decision tree developed in this study provides suggestions to select control measures that growers can take during primary production to reduce pathogenic contamination coming from irrigation water.

Various water-disinfection technologies are currently available on the market. Electrolysis, ozone, UV, and photocatalysts hold promise either as single treatments, with pretreatments that remove suspended material, or as combined treatments with another chemical or physical treatment(s). Knowledge on the range of bacterial contamination during growing and harvest, as well as the range of water capacity used over time for irrigation, needs to be collected from producers to better estimate which control options to employ. Regular monitoring of water sources would, therefore, be useful. Such research on the water quality and distribution system can be used not only to determine optimal dosage and application of the disinfection technique in field conditions but also to estimate its

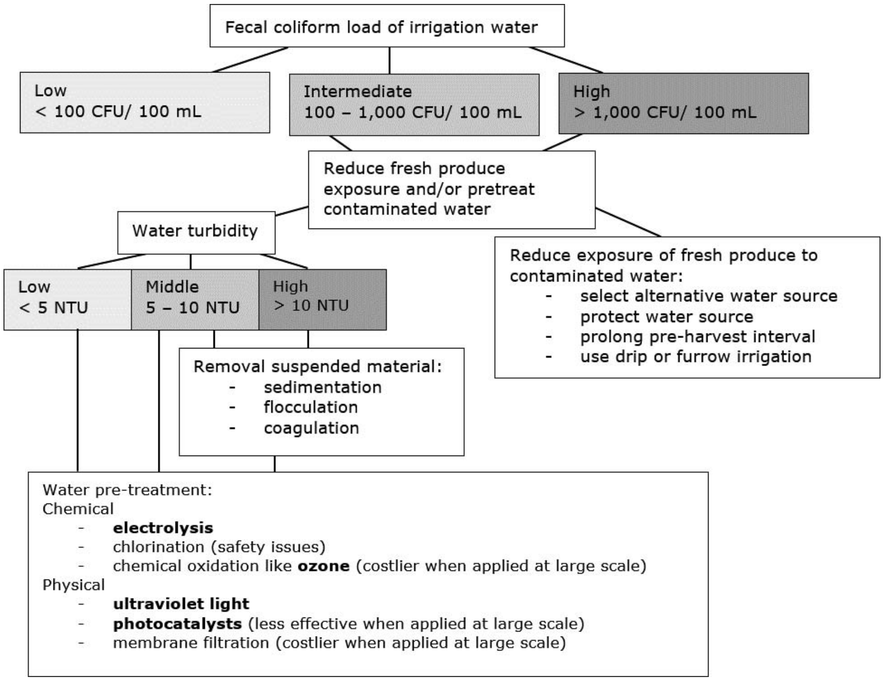

FIGURE 1. *Decision tree of prevention and mitigation strategies when the average concentration of fecal coliforms in the irrigation water samples is intermediate or high, as judged from regular inspections of the water source. Values selected to divide samples into low, middle, or high categories are dependent on the fecal coliform concentration, which is based on guidelines used by GLOBAL G.A.P. taken from the World Health Organization (WHO) standards on wastewater. Values for turbidity level are indicative.*

cost-effectiveness. Additional information on the water treatment capacity needed could be obtained from producers because this can help better access the technology to the various production scales and farm sizes at which the technology can be applied. Overall, the most effective preventative and mitigation strategies depend on multiple factors and should be assessed on a case-by-case basis.

Besides the microbial efficacy of a water disinfection technique, other criteria related to the technological (e.g., safety issues of the techniques and treatment capacity), managerial (e.g., costs and the complexity of the technology), and sustainability (e.g., the reusability of the water) can be considered. Future research can focus on evaluating the feasibility of several criteria of water-disinfection technologies to better assess case-specific questions. In addition, further research focusing on promising water-disinfection methods, including, e.g., the combination of methods in preharvest practices that allow improvement and refinement of water quality in agriculture are warranted. The effectiveness of the different prevention and mitigation strategies, such as water-disinfection technologies or combinations thereof, should be validated under laboratory conditions and in field studies. Combined approaches tend to show increased effectiveness in reducing fecal coliforms. Combining techniques, however, creates an increased complexity that may require skilled personnel and standardized guidelines for proper operation. Consequently, by using a combination of techniques, costs may increase. Data on the capacity of water that can be treated in a specified time window using combined methods are also needed to better decide among mitigation methods.

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