Irrigation Water as Source of Foodborne Pathogens on Fruit and Vegetables

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ABSTRACT

Awareness is growing that fresh or minimally processed fruit and vegetables can be sources of disease-causing bacteria, viruses, protozoa, and helminths. Irrigation with poor-quality water is one way that fruit and vegetables can become contaminated with foodborne pathogens. Groundwater, surface water, and human wastewater are commonly used for irrigation. The risk of disease transmission from pathogenic microorganisms present in irrigation water is influenced by the level of contamination; the persistence of pathogens in water, in soil, and on crops; and the route of exposure. Groundwater is generally of good microbial quality, unless it is contaminated with surface runoff; human wastewater is usually of very poor microbial quality and requires extensive treatment before it can be used safely to irrigate crops; surface water is of variable microbial quality. Bacteria and protozoa tend to show the poorest survival outside a human host, whereas viruses and helminths can remain infective for months to years. Guidelines governing irrigation water quality and strategies to reduce the risk of disease transmission by foodborne pathogens in irrigation are discussed.

The transmission of foodborne illness by pathogens present on foods of animal origin, such as meat, poultry, and raw milk, is well established, but awareness is growing that fresh or minimally processed fruit and vegetables can also be sources of pathogenic bacteria, protozoa, viruses, and helminths (170). Pathogenic bacteria include Campylobacter spp., Clostridium botulinum, Clostridium perfringens, enterotoxigenic Bacillus cereus, Escherichia coli O157:H7 and other Shiga toxin–producing E. coli, Listeria monocytogenes, Salmonella spp., Shigella spp., enterotoxigenic Staphylococcus aureus, Vibrio cholerae, and Yersinia enterocolitica. Pathogenic protozoa include Cyclospora cayetanensis, Cryptosporidium parvum, Giardia lamblia, and Entamoeba histolytica. Pathogenic viruses include hepatitis A, enteroviruses, echoviruses, rotaviruses, and Norwalk-like viruses. The nematode (roundworm) Ascaris lumbricoides is an example of a helminth pathogen that can be transmitted by food. Although some pathogens, such as B. cereus, S. aureus, C. perfringens, C. botulinum, and L. monocytogenes, are commonly found in the environment and on fruit and vegetables, the presence of most of these pathogens is indicative of recent human or animal fecal contamination.

Fruit and vegetables can become contaminated with pathogenic microorganisms by contact with soil or improperly composted manure, irrigation or postharvest washing with contaminated water, or contact with infected food handlers (34). Sources of irrigation water include groundwater, surface water, and human wastewater. Groundwater is located in aquifers beneath the earth’s surface. Surface water includes that of various freshwater sources, such as ponds, lakes, rivers, and creeks. Wastewater refers to human sewage and is commonly used for irrigation in countries where water is limited, including Canada and the United States. The use of wastewater irrigation can increase the available water supply and provide important nutrients for crops, but improperly treated wastewater can contain high levels of foodborne pathogens.

This review presents evidence that pathogens present in irrigation water could contaminate fruits and vegetables. The potential risk of human infection from this contamination is evaluated in the context of both current guidelines of recommended microbial quality for irrigation water and evidence of persistence of foodborne pathogens in the environment and on fruit and vegetables. Intervention strategies designed to minimize the risk of disease from foodborne pathogens in contaminated irrigation water are also discussed.

IRRIGATION WATER AS A SOURCE OF FOODBORNE PATHOGENS ON FRUIT AND VEGETABLES

Incidence of foodborne pathogens on fruit and vegetables. Surveys were performed in several countries to determine local prevalences of pathogenic microorganisms on fruit and vegetables (33). The pathogens investigated in these surveys included Campylobacter spp. (53, 87, 92, 104, 112, 118, 136, 157), E. coli O157:H7 (40, 78, 92, 104, 112, 136, 144, 175), enterotoxigenic S. aureus (40, 78, 157), enterotoxigenic B. cereus (157), L. monocytogenes (24, 52, 69, 78, 92, 104, 109, 112, 121, 136, 137, 145, 149, 152, 157, 171), Salmonella spp. (57, 64, 77, 78, 92, 104,
112, 133, 136, 144, 151, 157, 160), Shigella spp. (92, 144), Y. enterocolitica (112, 126, 137, 149), Cryptosporidium spp. (109, 117, 129), C. cayetanensis (117, 129), Giardia spp. (109, 129), E. histolytica (109), Ascariis spp. (133), and foodborne viruses (70). Incidences of pathogenic microorganisms determined in several of these surveys were summarized in a recent review of pathogens on fruit and vegetables (31). The proportions of produce that were contaminated with foodborne pathogens varied with the pathogen being investigated and the country in which the study was performed.

The incidence of foodborne pathogens on produce in developed countries is generally low. A survey of 1,564 vegetable samples from farmers’ markets and supermarkets in Canada detected Campylobacter spp. on 1.6 to 3.3% of vegetables (118). A survey of pathogenic bacteria present in a variety of vegetables from farmers’ markets and supermarkets in the United States reported one enterotoxigenic B. cereus and one enterotoxigenic S. aureus in 40 vegetable samples (157). The presence of bacteria that produce enterotoxin suggested a possible threat to human health. The same study detected L. monocytogenes in 6 of 127 vegetable samples (4.7%) but did not detect Salmonella spp. or Campylobacter spp. in these samples. A survey of 1,000 samples of supermarket vegetables in Washington state found L. monocytogenes in 11.4% of samples tested (69), and 1.5% of 200 mushroom samples in Seattle, Wash., were found to contain Campylobacter spp. (53). In a sampling of 890 fresh produce samples in Norway, three contained L. monocytogenes, and four contained enterotoxigenic S. aureus, but no Salmonella or E. coli O157:H7 were detected in any of the samples (78). In a study determining the incidence of parasites on 475 fruit and vegetable samples in Norway, 19 (4%) were positive for Cryptosporidium cysts and 10 (2.1%) were positive for Giardia cysts (129). B. cereus was detected in 17 of 81 (20.1%) vegetable samples in Japan, but the enterotoxigenicity of these samples was not determined (81). No L. monocytogenes isolates were obtained from these same samples.

In developing countries, the incidence of foodborne pathogens on fruit and vegetables can be much higher, particularly in countries in which irrigation with untreated or insufficiently treated wastewater is common. L. monocytogenes was detected in 7 of 66 (10.6%) samples of thoroughly washed market produce in India (121), in 5 of 22 (22%) leafy vegetables and 6 of 7 (85%) samples of bean sprouts in Malaysia (24), and in 8 of 103 (7.8%) vegetable samples in Spain (52). S. aureus was detected in 70 (58.3%) and Salmonella spp. were detected in 34 (28.3%) of 120 samples of fruit and vegetables obtained from markets in India (160). In a sampling of 129 lettuce crops in Brazil, high fecal coliform counts were reported in 22 (17%) crops, Salmonella spp. were found in 4 (3.1%) crops, and parasites were found in 17 (13.1%) crops (150). Salmonella spp. were detected in 68% of 120 lettuce samples and 72% of 89 fennel samples purchased from retail outlets in Italy and in 8.7% of bean sprouts in Thailand (57, 77). A survey of foodborne pathogens in fresh produce in Costa Rica found evidence of Cryptosporidium cysts in 1.2 to 8.7% of vegetables, Giardia intestinalis cysts in 2.5 to 5.2% of vegetables, and E. histolytica in 2.5 to 6.2% of vegetables (109). The same study reported that 20% of 50 cabbage salad samples contained L. monocytogenes, and that at least 3 of these samples tested positive for either hepatitis A virus or rotavirus. The presence of foodborne pathogens on produce that is normally consumed raw is of particular concern because the potential for human illness is much higher than when the pathogens are present on foods that will be cooked.

**Disease outbreaks caused by contaminated fruit and vegetables.** Numerous disease outbreaks linked to contaminated fruit and vegetables have been summarized in recent reviews (31, 33, 94, 139). These outbreaks emphasize the effect that contaminated produce can have on human health. The risk of disease transmission is increased when fruit and vegetables are consumed raw. Outbreaks of E. coli O157:H7 in the United States in Montana and Connecticut and of S. sonnei in Sweden and other European countries and increases in numbers of hepatitis A infections in Kentucky and in Sweden were associated with the consumption of lettuce or green salad (2, 63, 73, 82, 111, 132). Tomatoes were implicated in large multistate outbreaks of Salmonella infection in 1990, 1993, and 1999 in the United States (49, 68), Salmonella spp., E. coli O157:H7, B. cereus, L. monocytogenes, Y. enterocolitica, and Shigella spp. were implicated in sprout-associated illnesses (14, 96, 113, 123, 153, 168), including an outbreak of E. coli O157:H7 in Japan linked to consumption of radish sprouts that affected approximately 10,000 people (106). Cucumber, watercress, onions, parsley, spinach, coconut, cilantro, and celery have also been implicated in foodborne disease outbreaks (11, 20, 41, 51, 154, 155, 158, 167).

Fruit can act as vehicles for disease transmission. Unpasteurized orange juice and apple cider were implicated in multiple outbreaks of Salmonella, E. coli O157:H7, and Cryptosporidium infection (8, 12, 46, 47, 74, 107). Fresh fruit were implicated in outbreaks of Salmonella Saphra, Norwalk virus, Calicivirus, and the parasite C. cayetanensis (66, 71, 72, 108). Frozen fruits were the source of hepatitis A virus and calicivirus in two different outbreaks (76, 122).

**Irrigation water as a source of foodborne pathogens.** Evidence that contaminated irrigation water might be a source of foodborne pathogens on fruit and vegetables can be found in epidemiological investigations of food poisoning outbreaks, experimental studies examining E. coli O157:H7 contamination of lettuce, and observations of increased incidence of disease in areas practicing wastewater irrigation with little or no wastewater treatment. Irrigation water was implicated in outbreaks of E. coli O157:H7 infection from contaminated lettuce and C. cayetanensis infection from contaminated lettuce and raspberries (2, 71). Irrigation water was implicated as a source of E. coli detected on cabbage seedlings irrigated with sewage-contaminated water because none were found on seedlings in an adjacent field irrigated with municipal water (162).

Experimental studies examining contamination of lettuce with E. coli O157:H7 demonstrated that irrigation wa-
ter could effectively transmit *E. coli* to lettuce plants (142, 161). Contact with soil was not required for the lettuce plants to become contaminated, suggesting that the bacteria were taken up through the root system. In addition, the *E. coli* was visualized throughout the lettuce tissues, including areas that would be inaccessible to postharvest washing. These studies emphasize the importance of using good-quality irrigation water for ready-to-eat crops.

Evidence that pathogens present in irrigation water can contaminate not only fruit and vegetables but can also cause disease in humans is found in greater incidences of disease observed in populations practicing wastewater irrigation in which the wastewater receives little or no treatment before use. A large study performed in central Mexico compared the incidence of diarrheal disease and *A. lumbricoides* infections with the microbial quality of the irrigation water in 2,320 households practicing irrigation with either untreated wastewater, treated wastewater effluent from interconnected reservoirs, or natural rainfall (44). Rates of diarrhea and *A. lumbricoides* infection were significantly higher in households irrigating with untreated wastewater than in households irrigating with rainfall alone. There was no increase in diarrhea observed in households irrigating with reservoir effluents, suggesting that the improvement in microbial quality of this water was sufficient to prevent disease transmission. Other studies reported that higher incidences of *Salmonella* infection among children in Morocco, enteric disease in agricultural settlements in Israel, typhoid fever in Santiago, Chile, and *A. lumbricoides* infection in Mexico were associated with wastewater irrigation or irrigation with river water containing untreated sewage (indirect wastewater irrigation) (1, 45, 59, 169).

### IRRIGATION WATER QUALITY

**Guidelines for the microbial quality of irrigation waters.** Counts of total coliforms, fecal coliforms, *E. coli*, fecal streptococci, and nematode eggs are the microbial indicators most commonly used by water quality guidelines to dictate irrigation water quality. Because total coliform and fecal coliform counts can enumerate bacteria of nonfecal origin, *E. coli* counts are now considered a better measure of fecal contamination of water (29, 42, 54, 56, 75, 110). Fecal streptococci survive longer in the environment than fecal coliforms, suggesting that they could be a useful indicator for the presence of long-lived excreted viruses. Nematode eggs are used to estimate the risk of infection from *Ascaris* spp., *Trichuris* spp., and hookworms from treated wastewater in regions where these organisms are endemic (36, 169).

Guidelines governing the microbial quality of irrigation water vary considerably between countries and between groundwater, surface water, and human wastewater sources of water. The quality of water recommended for irrigation of crops likely to be consumed raw is often higher than that for processed or fodder crops. A partial summary of the levels of microbial indicators recommended in water quality guidelines is shown in Table 1.

Guidelines for wastewater irrigation quality are among the strictest, reflecting the high numbers of human pathogens present in untreated wastewater. The U.S. Environmental Protection Agency (EPA) manual *Guidelines for Water Reuse* recommends an absence of detectable fecal coliforms in wastewater used to irrigate crops likely to be eaten uncooked and less than 200 fecal coliforms per 100 ml in that used to irrigate processed or fodder crops (7). California, a state with a long history of wastewater reuse, specifies fewer than 2.2 total coliforms and no fecal coliforms per 100 ml of water for unrestricted irrigation of crops that are eaten raw (37). These standards are similar to those set by the EPA for drinking water (21). In contrast, the *Revised Guidelines for the Safe Use of Wastewater and Excreta in Agriculture and Aquaculture*, published by the World Health Organization (WHO), allows up to 1,000 fecal coliforms per 100 ml in that used to irrigate processed or fodder crops. A partial summary of the guidelines for wastewater irrigation quality is published by the World Health Organization (WHO), allows up to 1,000 fecal coliforms per 100 ml in that used to irrigate processed or fodder crops. A partial summary of the microbial quality of irrigation water for ready-to-eat crops.
cal coliforms per 100 ml of water; one viable intestinal nematode egg per liter of water for unrestricted irrigation of fresh vegetables, spray-irrigated fruit, parks, lawns, and golf courses; and up to 100,000 fecal coliforms per 100 ml of water for restricted irrigation of crops that are processed before consumption (36).

Guidelines for the microbial water quality of surface water tend to be more lenient than those for wastewater because many human-specific pathogens present in wastewater are usually absent from surface water (60). In Canada, where most irrigation is with surface or groundwater (100), the Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses, published by the Canadian Council of Ministers of the Environment (13), recommends a maximum of 1,000 coliforms per 100 ml and 100 fecal coliforms per 100 ml of irrigation water. Although these standards are widely accepted in Canada, some provinces also publish their own irrigation water quality standards (6, 9, 15, 170). An EPA guideline for surface water recommends fewer than 1,000 fecal coliforms per 100 ml of surface water, including river water, for irrigation of crops (5).

Differences among guidelines reflect widespread uncertainty about the actual risk of disease transmission from pathogens in irrigation water and economic restrictions on available water quality. The wastewater irrigation standards recommended by the EPA are based on the premise that if pathogenic microorganisms can be detected in irrigation water, they pose a potential public health risk. These standards reflect a zero-risk approach to preventing transmission of disease from foodborne pathogens. The WHO guidelines, in contrast, are based on the actual risk of disease transmission predicted from epidemiological studies of disease levels in exposed populations and a model-generated risk assessment that calculates the level of water treatment required to keep the level of increased infections to $10^{-4}$ infections per person per year (36). Although high-quality irrigation water is always desirable, in some countries, the economic costs associated with treating wastewater to achieve this high level of quality is prohibitive (141).

Studies evaluating the microbial quality of irrigation waters. The microbial quality of irrigation water depends largely on the source of the water. Groundwater is generally of good microbial quality unless it is contaminated with surface runoff, surface water is of variable microbial quality, and human wastewater is usually of very poor microbial quality and requires extensive treatment before it can be used safely for irrigation of crops.

In a survey of approximately 1,300 well water (groundwater) samples obtained from farms in Ontario, Canada, 31% of the wells exceeded the level of 10 total coliforms per 100 ml recommended for drinking water, 20% of the wells contained fecal coliforms, 17.6% of the wells contained E. coli, and 14.8% of the wells contained fecal streptococci (134). A study of well water samples in Nebraska found that 37% of samples contained fecal coliforms at levels of up to 950 fecal coliforms per 100 ml of water (58). A study of well water in Saudi Arabia reported that 5% of the wells contained high levels of fecal coliforms (3).

Groundwater can become contaminated by sources of contamination close to a well or by surface water seeping through a poorly fitting well head. In Argentina, horticultural activity, urban solid waste disposal, and sewage disposal were all shown to contribute to groundwater pollution (101). Another study in Argentina reported that a high prevalence of E. coli in well water was a result of the relatively shallow depth of the wells and the proximity of the wells to a cesspool (99).

Surface waters, including ponds, lakes, rivers, and streams, are much more susceptible than groundwater to contamination with pathogenic microorganisms. Sewage discharges, septic tank contamination, storm drains, and industrial effluents can all contaminate surface waters. On-site sewage disposal systems were associated with the occurrence of human pathogens in coastal waters in areas of high population density in Florida (91). Water from rivers or lakes that contain raw sewage or improperly treated sewage can contain hepatitis A, noroviruses, or enteroviruses (poliomyelitis, echoviruses, and coxsackieviruses) (28). Runoff from feedlots, manure piles, or crops fertilized with manure can also cause fecal contamination of surface waters. The presence of grazing cattle next to a creek in Colorado was found to increase levels of fecal coliforms and fecal streptococci in creek water by a factor of 1.6 to 12.5 (65). Fecal contamination of stream water from Virginia was mainly a result of the presence of cattle, and following the installation of fencing to restrict access of cattle to surface waters, fecal coliform levels were reduced 94% (67).

Wildlife and birds can also contribute to contamination of irrigation water. Wild birds harbor several pathogens in their intestinal tracts, including Campylobacter spp., Salmonella spp., V. cholerae, Listeria spp., and E. coli O157: H7 (61, 79, 90, 95, 124, 163). Birds were shown to contribute to fecal contamination of surface waters in New York (4).

Numerous studies have examined the prevalence of fecal indicator organisms and specific foodborne pathogens in surface waters. A survey of surface water from six irrigation districts in Alberta, Canada, found that 8% of irrigation water samples had more than 100 fecal coliforms per 100 ml (48). Salmonella were isolated from the Cornwallis River in Nova Scotia, Canada, downstream from meat and poultry processing plants (105) and were detected in 6.2% of surface water samples in Greece (25). Non-O1 V. cholerae were detected in surface waters of the United States, Brazil, Japan, and India (119, 127, 156, 159). Shiga toxin–producing E. coli serotype O121 was reported from lake water in Connecticut (103), and E. coli serotype O157: H7 that was associated with infections was isolated from a lake in Oregon (84). Several studies have reported the presence of Campylobacter species in surface waters in various countries (38, 39, 43, 50, 131, 138). C. parvum and Giardia cysts have been reported in several studies of surface waters in Canada, the United States, and Japan (89, 114, 115, 130, 164, 172).
Untreated human wastewater can contain high numbers of pathogenic microorganisms. It has been estimated that 1 liter of municipal sewage from a developing country might contain 5,000 enteroviruses, 7,000 Salmonella spp., 7,000 Shigella spp., 1,000 V. cholerae, 4,500 E. histolytica, and 600 A. lumbricoides (60). There is no excess disease risk associated with the use of properly treated wastewater for irrigation of crops, and crops irrigated with treated wastewater do not show the presence of pathogens on their surface (83). The microbial characteristics of human wastewater and its use in crop irrigation have been discussed extensively in other publications and will not be examined in detail here (35, 60, 140, 146).

SURVIVAL OF FOODBORNE PATHOGENS IN IRRIGATION WATER

The presence of foodborne pathogens in irrigation water suggests a potential risk of disease transmission if fruit or vegetables irrigated with this water are consumed by humans. The true risk of disease caused by pathogenic microorganisms in irrigation water, however, will depend on numerous variables, including the excreted load of the pathogen, its latency period before it becomes infectious, its persistence in the environment and on foods, its ability to multiply outside a mammalian host, its infectious dose for humans, and the host response (60). The ability of a pathogen to survive in the environment and on fruit and vegetables is an important determinant in the risk of human infection.

The viabilities of most pathogens in the environment decrease over time (7). Numerous studies examining the survival of individual pathogens in water, sewage, and soil at 20 to 30°C, were summarized by Feachem et al. (60). Bacteria, including fecal coliforms, Salmonella spp., and Shigella spp., usually survived fewer than 30 days in water and sewage; E. histolytica cysts usually survived fewer than 15 days and enteroviruses fewer than 50 days, whereas A. lumbricoides eggs could survive many months. Bacteria and viruses likely survive longer in groundwater than in surface water because groundwater tends to be cooler, is protected from sunlight, and has less microbiological and biological activity (60). In soil, bacteria, including fecal coliforms, Salmonella spp., and Shigella spp., usually survived fewer than 20 days, E. histolytica cysts fewer than 10 days, and enteroviruses fewer than 20 days, whereas A. lumbricoides eggs usually survived many months. Parameters influencing the persistence of pathogenic microorganisms in water, sewage, and soil were temperature, pH, moisture, antagonism from soil microflora, and exposure to sunlight (60). Of these parameters, temperature appeared to have the most significant effect (86, 93, 128, 165, 173). These survival times suggest that bacteria and protozoa present in surface water that is not contaminated with human sewage should be relatively short-lived, whereas viruses and helminths in wastewater should persist longer in the environment. Other studies, however, reported much longer survival times for E. coli O157:H7 in river water and in bovine feces, emphasizing the need for caution in interpreting these generalized survival times (62, 102, 166).

Feachem et al. (60) also summarized numerous studies examining the survival of pathogenic microorganisms on the surfaces of fruits and vegetables. Bacteria, including fecal coliforms, Salmonella spp., and Shigella spp., usually survived fewer than 15 days on crop surfaces, E. histolytica cysts fewer than 2 days, enteroviruses fewer than 15 days, and A. lumbricoides eggs fewer than 30 days. A more recent review by Beuchat (33) further details what is known about the survival of pathogenic microorganisms on the surfaces of fruits and vegetables after harvesting, including the contribution of biofilms to the survival of these microorganisms.

The shorter survival times of pathogenic microorganisms on crops, versus those for water and soil, reflect an increased exposure to sunlight and desiccation for pathogens on crop surfaces. Several studies showed a significant reduction over time in the levels of pathogenic microorganisms on vegetables irrigated with poor-quality water, suggesting that survival of pathogens is poor on vegetable surfaces (23, 26, 30, 55). In one study, however, rainfall was associated with an increase in pathogen numbers, suggesting that the pathogenic microorganisms remained viable in the soil and were able to recontaminate vegetables during rainfall (30). As occurs in the environment, cooler temperatures promote survival of pathogenic microorganism on fruit and vegetables. E. coli O157:H7 survived on the surface of harvested lettuce for up to 15 days when it was stored at 4°C (32) and on the surface of harvested fresh and frozen strawberries for at least 1 month (85, 174). Rotaviruses inoculated onto the surface of harvested vegetables maintained viability for up to 30 days at 4°C (27), and poliovirus survived on different foods under typical refrigeration conditions for 8.4 days to more than 2 weeks (88).

REDUCING THE RISK OF FOODBORNE PATHOGEN TRANSMISSION IN IRRIGATION WATER

Several strategies can reduce the risk of disease transmission from pathogenic microorganisms on fruits and vegetables. These include improving the microbial quality of irrigation water before its application, restricting the use of poor-quality irrigation water to crops that are not likely to be consumed raw, drip or surface irrigating, and postharvest washing of fruits and vegetables.

The approaches used to improve the microbial quality of irrigation water depend on the type of water used for irrigation and the final water quality desired. Groundwater is usually of very good microbial quality and does not require any treatment. Untreated municipal wastewater, in contrast, contains high levels of pathogenic and nonpathogenic microorganisms and requires extensive treatment to render it suitable to apply to crops for human consumption. In addition to intensive wastewater treatment at sewage treatment plants, low-cost biological treatments, such as waste stabilization ponds (120), work well in warm climates where land is not limited and can effect a 2- to 3-log reduction in fecal coliform levels (97, 98). Wastewater treatments have been reviewed extensively elsewhere (60, 120) and will not be examined here.

Surface water is usually of intermediate microbial qual-
ity and might require treatment for application to crops consumed raw, according to some guidelines, but treatment options for irrigation with surface water are limited. Filtration, chlorination, ozonation, exposure to ultraviolet light, electronic beam processing, and heat treatment all can potentially reduce the levels of microorganisms in irrigation water, but the use of these treatments might not be practical and their costs could be prohibitive (16–19). Chlorine is the disinfecting agent most commonly used for combined sewage overflows and have turbidities similar to that of irrigation water. However, the effectiveness of chlorine is reduced in water with high levels of organic matter (147), chlorine can react with organic matter to yield potential carcinogens (147), and the long-term effects of chlorine and other disinfectants on crops and soil are unknown. Sunlight has been proposed for disinfection of drinking water in developing countries (80), but it might not be practical in temperate regions where land is limited.

Because treatment options are limited, it is better to prevent contamination of surface water. Although controlling surface water contamination from nonpoint sources, such as birds and wildlife, is extremely difficult, the effect of other sources of contamination, such as manure used as fertilizer and runoff from feedlots, can be reduced by following good agricultural practices (125). These practices include keeping irrigation sources away from livestock, such as cows and poultry; identifying upstream uses of surface waters that are used for irrigation, such as streams and rivers; and ensuring that manure applied to fields does not run into irrigation sources.

When access to good-quality irrigation water is limited, one alternative is to treat crops that are not consumed raw, such as forage crops, with a lower quality irrigation water and using a higher quality, and usually more expensive, water for crops such as lettuce and tomatoes which are eaten with little or no processing. This approach has been tried in several countries (6, 7, 45, 120, 169). A crop restriction program in areas of Chile, where river water used for irrigation is highly contaminated because of sewage discharges, resulted in a significant reduction in incidence of hepatitis, typhoid, and other gastrointestinal diseases (169). An alternative to crop restriction might be to irrigate with lower quality wastewater early in the growing season while irrigating with better quality water closer to harvest, thus allowing pathogens present in the lower quality water to die off before harvesting the crops. This approach should be used with caution, however, because pathogens present in soil might contaminate crops irrigated with clean water if soil is splashed on the crops (30), and the length of time required for pathogens deposited in soil and on crops by irrigation with poor-quality water would need to be determined accurately.

The method of irrigation can influence how effectively pathogens present in irrigation water are transmitted to plant surfaces. Drip irrigation or surface irrigation can minimize contact of crops with contaminants present in irrigation water, compared with spray irrigation, because the edible portions of plants are not wetted directly. In a risk assessment–based study of wastewater irrigation for vegetables, the use of subsurface drip irrigation instead of spray irrigation was predicted to reduce risk of infection by two to three orders of magnitude (116). Other studies demonstrated reduced transmission of pathogens in irrigation water to vegetables when drip irrigation was used (135, 143). The EPA also recommends that drip irrigation be used when fecal coliforms are found in irrigation water (7).

Postharvest washing of fruit and vegetables is commonly used to reduce the microbial load on produce. Washing should be with potable water; common postharvest wash treatments include chlorine, chlorine dioxide, ozone, peroxide, and peroxyacetic acid (10, 148). Although postharvest washing is a valuable way to reduce the microbial load on produce, pathogenic microorganisms present on plant surfaces in natural plant contours, openings, and harvest and trimming wounds can escape the antimicrobial effects of postharvest washing (148). Lettuce seedlings experimentally irrigated with water containing E. coli were found to contain E. coli throughout the lettuce tissues, including the inner tissues, which would be inaccessible to postharvest washing (143). It was reported that E. coli O157:H7, for example, could not be eliminated from lettuce by washing in chlorinated water (32). It is preferable, therefore, to prevent initial contamination of fruit and vegetables by pathogenic microorganisms than to try to remove them after harvest.

A major disadvantage of either crop restriction or irrigation water quality monitoring is that a strong institutional framework is required to monitor and enforce compliance. Certification programs in which the produce label states that it was produced under safe conditions have been suggested as a means of avoiding low compliance rates (22). Certification of crops that were directly monitored for the presence of pathogens, as was done recently in Brazil, is a more costly alternative (150).

**GENERAL RECOMMENDATIONS**

There is a growing awareness that good-quality irrigation water is an important factor in the production of safe fruit and vegetables. As population levels increase, demand on limited water resources will increase while the quality of available water decreases. Information on how best to utilize declining water resources while maintaining food safety will be vital. Areas that would benefit from further investigation include research into simple and inexpensive methods for improving the microbial quality of marginal irrigation water at the farm level and a quantitative assessment of the risk of disease from pathogens present in surface water and groundwater used to irrigate crops, similar to the assessment used to develop the WHO Guidelines for the Safe Use of Wastewater and Excreta in Agriculture and Aquaculture (97).

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