Agricultural Water Use in U.S. Fresh Produce Growing Operations—Part I: Pathogen Presence and Persistence

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ABSTRACT

Throughout the United States, diverse water sources and delivery systems are used in fresh produce production from pre-planting through post-harvest operations. These operations include soil preparation, irrigation, agrochemical mixing, microclimate protection from freeze injury and sunscald, dust abatement on farm roads, harvesting activities, and cleaning and sanitizing of field equipment. Water used in produce operations comes from groundwater, surface water, or collected rainwater and is accessed from wells, rivers, creeks, streams, reservoirs, ponds, lakes, irrigation districts, municipal supplies, and private purveyors. Human pathogens that have been detected in water include bacteria, parasites, and viruses, many of which can survive in water for extended periods of time posing a food safety risk when contaminated water is used on or near produce crops. To fulfill mandates in the Food Safety Modernization Act, the U.S. Food and Drug Administration (FDA) has proposed risk-based regulations for agricultural water that are expected to be finalized within 2024. This review, the first part of a series on agricultural water in produce production, gives an overview of how agricultural water is used during production activities throughout produce growing regions in the United States and summarizes recent and seminal research relevant to pathogen prevalence and persistence in agricultural water.

INTRODUCTION

Historically, the major concerns of produce growers related to agricultural water were volume (i.e., how much would they need), source (i.e., would the supply for the growing season come primarily from the sky or the ground), and in some areas, cost or regulated availability of delivered water. These concerns have not subsided, and for some, such as the farmers in California's Central Valley, concerns have significantly increased as groundwater depletion increases (e.g., accelerating from 1.86 km^3/year in 1961 through 2021 to 8.58 km^3/year in 2019 through 2021) *(54, 70)*. In more recent times, growers have had additional concerns related to the microbial quality of agricultural water. Decades of testing data for drinking, environmental, and agricultural water have provided substantial evidence that human pathogens can survive in water *(10, 23, 24, 60, 68, 72, 76, 112, 119, 123, 137, 145)*. In addition, advancements in microbial detection methods and public health data collection systems have improved the ability of researchers to identify foodborne illness outbreaks and helped fuel industry awareness and knowledge of food safety risks related to agricultural water sources, production practices, and influences of commodity traits on pathogen attachment to and persistence on fresh produce.

As identification of foodborne illness outbreaks attributed to fresh produce contamination increased in the late 1990s, the U.S. Food and Drug Administration (FDA) increased their output of educational and guidance materials to assist industry in preventing human pathogen contamination *(12)*. The FDA's first guidance document on microbial hazards, *Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables (126)*, was published in 1998 followed by several commodity-specific guidance documents within the next decade *(127, 128)*. In December 2010, the U.S. Congress passed the Food Safety Modernization Act, which was signed into law in early January 2011 *(116)*. Nearly 5 year later in November 2015, following an extensive industry outreach effort, the FDA published the *Standards for the Growing, Harvesting, Packing, and Holding of Produce for Human Consumption (129)* or Produce Safety Rule (PSR). However, in December 2021 following considerable feedback from the industry, cooperative extension specialists, and other industry educators, the agency proposed revised PSR requirements related to agricultural water (subpart E) *(130–132, 136)*. As of this writing, the proposed subpart E revisions have not yet been finalized but are anticipated to be published in 2024.

Water use in produce production spans operations from preplanting through harvest (see *Table 1* for examples of agricultural water use). In the PSR, the FDA defines agricultural water as "water used in covered activities on

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covered produce where water is intended to, or is likely to, contact covered produce or food contact surfaces, including water used in growing activities (including irrigation water applied using direct water application methods, water used for preparing foliar crop sprays, and water used for growing sprouts) and in harvesting, packing, and holding activities (including water used for washing or cooling harvested produce and water used for preventing dehydration of covered produce)" *(132)*. The FDA's definition is specific and limited in scope by the regulations promulgated in the PSR. As used here, agricultural water includes a broader range of water activities that occur during the production and harvest of produce crops but does not include water use in activities performed away from the field (i.e., during packing and holding).

In the newly proposed subpart E, the FDA also includes a new definition for an agricultural water system, which it defines as "a source of agricultural water, the water distribution system, any building or structure that is part of the water distribution system (such as a well house, pump station, or shed), and any equipment used for application of agricultural water to covered produce during growing, harvesting, packing, or holding activities" *(132)*. Agricultural water distribution or delivery systems in produce growing operations across the United States span the spectrum from simple on-farm ponds or wells providing water via surface pipe systems over a few acres to complex systems where water is distributed to several hundred acres via a network of above- and below-ground canals and pipes.

Within an agricultural water system, the microbial quality of the water source has typically received more scrutiny than have other parts of the system. Water used in produce production and harvest activities may be surface water (e.g., rivers, ponds, lakes, creeks), groundwater (e.g., wells or springs), or rainwater collected in open or closed systems *(2, 11, 19, 90, 147, 148)*. In some cases, groundwater may become surface water when shallow well water breaches the soil surface or when groundwater is pumped into reservoirs before application to produce fields *(10, 43)*. According to a 2015 to 2016 U.S. Department of Agriculture survey of 4,618 U.S. produce growers, 50% of growers reported using well water for irrigation, whereas 19 and 12% used flowing and standing surface water, respectively *(4)*.

Agricultural water may come from on-farm sources or may travel to a farm from irrigation water districts and/or municipal or public water suppliers. On-farm sources include ponds, reservoirs, wells, rivers, creeks, and streams. In some produce-growing regions, extensive irrigation canal systems under the management of water districts distribute agricultural water to fields for irrigation and/or to drain excess water from fields *(16, 55, 98)*. Growing operations within or on the outskirts of urban areas often receive their water supplies from municipal sources, which are typically restricted to drip systems when used for irrigation *(55, 98)*. In areas where water sources are scarce or highly regulated, agricultural water may be supplied by private purveyors, and some water may be delivered to fields by tanker trucks *(55, 98)*.

Considering these diverse U.S. agricultural water sources and systems of varying complexities, creating regulations that effectively address the produce safety risks resulting from microbial hazards in agricultural water is no small task. In their proposed revisions to subpart E, the FDA uses a risk-based approach that encompasses routine monitoring, inspection, and maintenance of agricultural water sources and systems and annual written assessments of agricultural water applied directly to crops covered by the PSR. Monitoring, inspecting, and maintaining agricultural water systems have been essential elements of produce growers' food safety programs for numerous years, but the written agricultural water assessment requirement is new for growers and has raised many questions and concerns within the grower community and industry at large related to effectively meeting the objective of this requirement. The purpose of this series of review articles is to provide the produce industry with summarized scientific information that is pertinent to assessing microbial hazards posing a contamination risk to agricultural water and to assist growers in conducting agricultural water assessments. The primary objective of this first review in the series is to document pathogen prevalence in watersheds within produce-growing regions and agricultural water as reported over the past decade (2013 to 2023) and to provide growers with a better understanding of conditions that support pathogen persistence in water after contamination occurs.

AGRICULTURAL WATER USES

Irrigation systems are arguably the most complex component of agricultural water systems. Many U.S. growing operations, particularly those in western states, are in arid and semiarid regions that are completely or partially reliant on irrigation for crop production *(10, 55, 70, 115, 124)*. The U.S. Geological Survey estimated 118,131,000 gallons per day, equaling 37% of all U.S. water use, were used to irrigate U.S. farmland in 2015 *(28)*.

In U.S. regions dependent on irrigation for crop production, crops are irrigated using numerous types of systems, including gravity systems such as furrows or flooding and pressurized systems such as sprinklers and surface and subsurface drip *(10, 20, 35, 36, 86, 98, 115, 124)*. Between 1994 and 1998, irrigation systems in the United States shifted from gravity to pressurized systems, which now make up over two-thirds of all systems *(125)*. Configurations of irrigation systems vary from complex weblike networks to fingerlike extensions attached to a main pipe, ditch, or line. Based on water-to-crop contact, irrigation systems have varying potential to introduce human pathogens and/or promote human pathogen growth on unharvested crops *(Table 1)*. For example, microirrigation systems in an orchard are less likely

TABLE 1. Agricultural water uses by application methods during crop cultivation and growing operations

Crop activity	Application method(s)	Description	Contamination risk	Reference(s)
Soil preparation	Sprinklers	Water applied to prepare soil for groundwork, planting bed formation	Limited concern dependent on time interval, cropping cycle, and nature and source of any soil amendment additions	*115*
Germination, transplanting	Sprinkler irrigation, drip irrigation	Water applied following seed planting to support germination or transplant establishment	Limited contact with harvestable crop	*104, 115, 124*
Ground chemigation	Pesticides	Insecticides, fungicides, bactericides, herbicides injected into or spread on soil to kill pests or weeds that will affect plant growth and quality	Limited contact with harvestable crop	*104, 115, 124*
	Fertilizer	Nutrients applied to soil to support plant growth	Limited contact with harvestable crop	*104, 115, 124*
Irrigation	Overhead sprinkler	Water applied to plants from aerial pipes	Direct contact with harvestable crop	*36, 51, 104, 115, 124*
	Drip	Water applied to soil surface or upper plant root zone and surrounding soil through piping systems that may be above or below ground	Limited contact with harvestable crop; dependent on system integrity and maintenance (e.g., no spraying leaks from punctures or splits in the pressurized polymer delivery lines)	*36, 51, 104, 115, 124*
	Furrow	Water delivered in lateral ditches or gated pipe and flowing into the cropped field between crop rows; water reaches plant roots from soil percolation and absorption	Dependent on contact between harvestable plant leaf or fruit and furrow water	*36, 51, 104, 115, 124*
	Microsprinklers	Water sprayed onto crops or soil from above-ground small emitters mounted on vertical risers rather than from larger reciprocating emitters (sprinklers) on surface or overhead linear or center-pivot systems	Dependent on contact between harvestable fruit and the misting, aerosols, sprays	*36, 51, 104, 115, 124*

Table 1 continued on the next page.

TABLE 1. Agricultural water uses by application methods during crop cultivation and growing operations (cont.)

Crop activity	Application method(s)	Description	Contamination risk	Reference(s)
Foliar sprays, wetting	Pesticides	Water used to dilute insecticides, fungicides, and bactericides sprayed on plants to kill pests that will affect plant growth and quality	Direct contact with harvestable crop	*36, 51, 71, 73, 104, 107, 115, 124, 135*
	Fertilizer	Nutrients diluted with water and applied to plants for absorption through aerial portions (e.g., foliage)	Direct contact with harvestable crop	*36, 51, 71, 73, 104, 107, 115, 124, 135*
	Sun protection	Water applied to create evaporative cooling to prevent sunburn	Direct contact with harvestable crop	*51, 115*
	Frost injury protection	Water from overhead spray or micromisters to create ice on plants, generate heat from freezing, and build an insulating layer	Direct contact with harvestable crop	*36, 51, 115*
	Hydration, antitranspirants	Chemical solutions applied to crops to provide a water-impermeable layer to protect the plant by reducing transpiration resulting in damage and irreversible water loss	Direct contact with harvestable crop	*115*
	Growth regulators	Hormone-like substances in solutions applied at various stages of plant growth that affect plant development and maturation; may be used to enhance fruit yield, size, and quality (e.g., thinning)	Direct contact with harvestable crop	*115*
Dust abatement	High-volume flood or fan-spray bars	Water applied in dry conditions to unpaved ground and access roads surrounding fields to control dust created by equipment and wind	Depends on environmental conditions (e.g., wind) and contact with harvestable crop, primarily along farm road edges	*36, 115*

to contaminate tree fruit than are overhead sprinkler systems for irrigating row crops such as strawberries and lettuce *(35, 80, 110, 111, 144)*. *Table 1* summarizes how agricultural water is used during cultivation and growing operations in produce production and describes the associated risk of crop contamination related to those operations.

PATHOGEN PREVALENCE IN AGRICULTURAL WATER

Water can be a carrier of many human pathogens, including bacteria such as Shiga toxin-producing *Escherichia coli* (STEC), *Salmonella, Listeria monocytogenes, Shigella,* and *Campylobacter (1, 24, 37, 41, 53, 56, 57, 69, 72, 103, 109, 143)*; parasites such as *Cyclospora cayetanensis, Cryptosporidium parvum*, and *Giardia (27, 30, 31, 58, 79,* 85, *120, 143)*; and human enteric viruses such as hepatitis A and E and norovirus *(39, 102, 118, 122)*. When present in the environment, human pathogens can be introduced into an agricultural water system anywhere to and from the water source through its distribution and use.

Human pathogen prevalence in surface and ground agricultural water sources is attributed primarily to the proximity of these sources to pathogen sources in the surrounding environment and varies considerably among U.S. produce-growing regions, both in the types and levels of pathogens present *(3, 18, 24, 29, 110)*. As would be expected based on the risk of contamination, surface water in produce-growing areas has been studied far more extensively than has groundwater. In addition, pathogen presence and levels in surface water may vary seasonally and are undoubtedly related to and affected by other conditions and human activities in the surrounding environment. Surveys of agricultural water in locations around the United States and Canada also provide evidence that the distribution and prevalence of human pathogens (strains and species) differ among produce-growing regions *(82, 112)*.

Table 2 summarizes studies published between 2013 and 2023 that address watersheds in which produce-growing operations occur, and *Table 3* summarizes studies published in the same time frame that address agricultural water supplying produce farms. Studies of agricultural water used for irrigation on produce-growing ranches and farms *(Table 3)* typically indicate that human pathogens are less prevalent in irrigation water sources than they are in the surrounding regional watersheds *(Table 2) (10)*. Of the studies listed in *Tables 2 and 3*, water in surrounding watersheds had an overall pathogen prevalence of 33.3% and irrigation water used on produce farms had an overall pathogen prevalence of 17.9%. Of the three major human pathogens (*Salmonella*, *L. monocytogenes*, and pathogenic *E. coli*) surveyed in agricultural water studies, *Salmonella* and *L. monocytogenes* had the highest prevalences in agricultural watersheds and in agricultural water supplies for produce farms and pathogenic *E. coli* had the lowest.

Seasonality and temperature

Studies in which human pathogens such as *L. monocytogenes*, *Salmonella*, and STEC have been surveyed in agricultural water have frequently included evaluation of whether fluctuations in occurrence, levels, or strain diversity are seasonal. Seasonality encompasses weather conditions, wildlife, domestic animals, and cultivation activities that occur seasonally. For example, *L. monocytogenes* has been reported as consistently more prevalent in water when temperatures are cooler, most often during winter but also in early spring and/or late fall *(1, 24, 32, 82, 114)*. This pattern has been fairly consistent for surface waters surveyed across the country from New York, Maryland, and Virginia to California. Rivers (n = 147) and reclaimed water plants (n = 41) on Maryland's eastern shore and surface water (n = 120) on produce farms in Virginia had significantly higher *L. monocytogenes* prevalence in winter months than in summer *(1, 82)*. However, in Ohio, Ferguson et al. *(34)* reported higher *L. monocytogenes* prevalence in irrigation water from surface water sources (n = 69) in the summer than in fall and spring. These authors suggested that the difference was due to domestic animals having more frequent direct contact with surface water in summer months. On the west coast, Falardeau et al. *(32)* reported significantly higher *L. monocytogenes* prevalence in irrigation ditch water (n = 223) from agricultural areas in southern British Columbia in fall (22.9%) and winter (16.3%) than in spring (7.8%) and summer (3.7%). A survey of five watersheds (n = 1,405) within the California central coast region revealed two watersheds with higher *L. monocytogenes* prevalence in winter and spring months than in summer and fall months *(24)*. However, in three watersheds within the region, *L. monocytogenes* prevalence was not correlated with season *(24)*.

Seasonal trends in *Salmonella* prevalence throughout the United States and Canada were less consistent than trends for *L. monocytogenes*. In several studies of *Salmonella* prevalence, higher recovery rates were found in one season compared with others *(18, 40, 48, 65)*, whereas in other studies greater serotype diversity was found during a particular season *(48, 117)* or no seasonal association was found *(46, 79, 114, 117)*. Haley et al. *(48)* and Li et al. *(65)* both reported seasonal differences in *Salmonella* prevalence in their surveys of agricultural water in southern Georgia's Little River (n = 72) and Suwannee River (n = 170) watersheds, respectively. *Salmonella* prevalence was significantly higher in July, August, and September (summer) than in other months. In northern Georgia's Upper Oconee watershed, Cho et al. *(18)* also reported higher *Salmonella* prevalence in summer months over a 3-yr surface water survey (n = 688) from 2015 through 2017. In a survey of shallow wells on tomato farms along Virginia's eastern shore (n = 196), *Salmonella* was detected more often in weekly samplings during November and December than in other months throughout the 70-wk sampling period *(47)*. In their 5-yr survey of surface water (n = 2,979)

collected from six watersheds in Monterey County in California, Gorski et al. *(41)* reported higher levels of *Salmonella* in the spring than in the fall. They also found differences in seasonal recovery among *Salmonella* strains; Heidelberg and Senftenberg were isolated more often in winter, Infantis and Oranienburg were more common in spring, Enteritidis and Anatum were recovered more frequently in fall and spring, and Montevideo was more common in spring and summer. Studies of surface waters in eastern Virginia (n = 147 and 196), central Florida (n = 202), New York (n = 146), southern Ontario, Canada (n = 235), and lower mainland British Columbia (n = 223) revealed no association between *Salmonella* prevalence and season *(1, 32, 46, 78, 113, 117)*.

Because pathogenic *E. coli* is found less frequently in agricultural water than are *Salmonella* and *L. monocytogenes*, its prevalence is more difficult to correlate with season. Several studies in the produce-growing region of California's central coast were conducted to evaluate a possible association between pathogenic *E. coli* prevalence in water and season, but the results were inconclusive. In their study of *E. coli* O157 prevalence over three growing seasons in the region from May 2008 through October 2010, Benjamin et al. *(10)* found no significant association between season and *E. coli* O157 presence in water (n = 256) or sediment on farms or at public access areas within the watershed. In contrast, Cooley et al. *(24)* conducted a study over a 2-yr period from October 2011 to November 2013 in the same region with five times the sample size (n = 1,386) and reported significantly higher prevalence of *E. coli* O157 in water in the winter and spring than in the summer and fall. However, these authors did not find any seasonal difference in non-O157 pathogenic *E. coli* prevalence. In another central California study with a smaller sample size (n = 244) conducted from April 2008 to October 2010, significantly higher prevalence of pathogenic *E. coli* was found in January, February, and March when temperatures are cooler and rainfall is more frequent than in warmer summer months with typically fewer rainfall events *(23)*.

Like studies evaluating the association between seasonality and pathogen prevalence, studies evaluating water temperature also frequently revealed a correlation with pathogen prevalence or levels *(48)*. Many of the most prominent human pathogens causing foodborne illness (e.g., *L. monocytogenes, Salmonella*, and STEC) survive longer in water at lower temperatures due primarily to the slowing of their metabolic processes *(22, 92)*. However, as water temperatures become warmer, many pathogens become more metabolically active and resume reproduction *(62)*.

Some researchers have tried to more specifically determine whether pathogen prevalence is directly related to seasonal environmental conditions (e.g., precipitation, water temperature, and humidity) or to seasonal agricultural practices (e.g., runoff from soil amendment applications and cattle moved to nearby pasture). Thomas et al. *(117)* studied the seasonality of *Salmonella* prevalence in urban and rural streams in Ontario, Canada and found an association between season and *Salmonella* serotypes of human health significance in rural (agricultural) streams but not in urban streams, which suggests that agricultural activities are primarily responsible for *Salmonella* prevalence in these environments. Weller et al. *(140)* studied nine waterways providing water to commercial farms in Arizona and New York and also suggested that upstream activities related to farm production may have contributed to the seasonal variation in microbial water quality. Most likely seasonal weather effects (e.g., ambient temperatures and rainfall and related runoff) in conjunction with seasonal agricultural activities contribute to and influence pathogen prevalence. Seasonal weather conditions such as rainfall and runoff undoubtedly affect contamination of agricultural water by introducing pathogens or increasing pathogen levels and will be further discussed as contamination risk factors in a future article in this series on agricultural water.

PATHOGEN PERSISTENCE IN AGRICULTURAL WATER

Human pathogens can survive in water for extended periods of time and survive longer in environments with favorable conditions that reduce or eliminate competitors and provide sufficient nutrients and protection from predators *(7, 8, 13, 25, 37, 61, 138)*. Pathogens may also persist in agricultural water by entering a viable but nonculturable state or being enclosed in vesicles within free-living protozoa, and survival may be enhanced by adherence to sediment or aquatic plants and by the presence of agrochemicals, as discussed in more detail below *(5, 61, 69, 74, 75)*. Pathogens may persist longer in stagnant water or ephemeral waterbeds that contain water only when there is substantial rainfall than in continually flowing waterbodies. Chase et al. *(17)* studied an ephemeral river in Florida and observed significantly greater fecal coliform and *E. coli* levels under no-flow conditions than when the river flowed. Fecal coliform levels in the water column and sediments were negatively correlated with the time since the last rain event (i.e., as time between rain events increased, microbial levels decreased) *(17)*. Pathogens are removed from water by sedimentation, filtration, and absorption or from natural die-off due to UV exposure, temperature fluctuations, starvation, or predation *(61, 69, 146)*. Two recent reviews have taken in-depth looks at the ability of human pathogens to persist in water *(8, 37)*. Bell et al. *(8)* reviewed the persistence of STEC, *Salmonella*, *Campylobacter*, and *L. monocytogenes* in surface water sources. Gartley et al. *(37)* reviewed the published science on the prevalence and persistence of *L. monocytogenes* in irrigation water and the factors that contribute to *L. monocytogenes* contamination of various types of water sources. Here we briefly discuss published research findings on specific environmental conditions that may enhance the persistence of human pathogens in agricultural water sources after contamination occurs. In a

TABLE 2. Pathogen prevalence in agricultural watershed or region, 2013 to 2023 (potential agricultural water sources)

Pathogen	Sampling location	State, region	Total no. of samples (% positive)	Sample volume, type	Reference
Campylobacter	Streams	GA, Satilla River Basin	156 (62.0)	3-liter grab	*134*
Campylobacter	Streams	GA, South Fork Broad River watershed	120 (33)	4-liter grab	*14*
Escherichia coli O145	Reclaimed water from wastewater treatment plant	AZ	13 (7.1)	Moore swabs	*149*
E. coli O157	Public waterways	CA, Central Coast	860 (7.9)	Moore swabs	*118*
E. coli O157	Watershed (lakes, streams, rivers, ponds)	CA, Monterey County	1,386 (8.0)	Moore swabs	*24*
E. coli O157:H7	Agricultural recovery basins	CA	71 (0)	20-liter grab	*95*
E. coli O157:H7	CAFO[a] monitoring wells	CA, central valley	190 (1.1)	1 liter	*66*
E. coli O157:H7	Lakes, reservoirs	CA, central valley	257 (1.2)	20-liter grab	*93*
E. coli O157:H7	Agricultural recovery basins	FL	24 (0)	20-liter grab	*95*
E. coli O157:H7	Agricultural recovery basins	MS	12 (0)	20-liter grab	*95*
STEC	Lakes, reservoirs	CA, central valley	257 (8.9)	20-liter grab	*93*
STEC	Watershed (lakes, streams, rivers, ponds)	CA, Salinas Valley	131 (6.0)	Moore swabs	*68*
STEC	Streams	GA, South Fork Broad River watershed	90 (61)	4-liter grab	*14*
STEC	Untreated surface water (five nontidal fresh, one tidal brackish, two ponds)	Mid-Atlantic	426 (2.1)	10 liters pumped through a modified Moore swab	*53*
STEC, non-O157	Public waterways	CA, Central Coast	860 (9.4)	Moore swabs	*118*
STEC, non-O157	Watershed (lakes, streams, rivers, ponds)	CA, Monterey County	1,386 (11.0)	Moore swabs	*24*
L. monocytogenes	Public waterways	CA, Central Coast	860 (44.3)	Moore swabs	*118*
L. monocytogenes	Lakes, ponds, streams, rivers	CA, Central Coast	2,922 (41.9)	Moore swabs	*40*
L. monocytogenes	Nontidal fresh water (rivers)	MD, DE	123 (63.1)	Modified Moore swabs	*59*
L. monocytogenes	Brackish and fresh water	MD, eastern shore	147 (51.7)	10-liter grab	*1*
L. monocytogenes	Reclaimed water	MD, eastern shore	41 (0)	10-liter grab	*1*
L. monocytogenes	Pond, ditch, river, creek, stream	NY	51 (39.0)	250-ml grab	*114*
L. monocytogenes	Streams near produce production	NY, rural watershed	181 (15.0)	10-liter grab	*140*
L. monocytogenes	Streams near produce production	NY, rural watershed	86 (7.0)	Moore swabs	*140*
Salmonella	Reclaimed water from a wastewater treatment plant	AZ	13 (64.3)	Moore swabs	*149*
Salmonella	Agricultural recovery basins	CA	71 (23.9)	20-liter grab	*95*
Salmonella	Public waterways	CA, Central Coast	860 (59.7)	Moore swabs	*118*
Salmonella	CAFO monitoring wells	CA, central valley	190 (1.1)	1 liter	*66*
Salmonella	Lakes, reservoirs	CA, central valley	257 (26.1)	20-liter grab	*93*

Table 2 continued on the next page.

TABLE 2. Pathogen prevalence in agricultural watershed or region, 2013 to 2023 (potential agricultural water sources) (cont.)

Pathogen	Sampling location	State, region	Total no. of samples (% positive)	Sample volume, type	Reference
Salmonella	Watershed (lakes, streams, rivers, ponds)	CA, Monterey County	1,405 (65)	Moore swabs	*24*
Salmonella	Lakes, ponds, streams, rivers	CA, Monterey County	2,979 (56.4)	Moore swabs	*41*
Salmonella	Agricultural recovery basins	FL	24 (79.2)	20-liter grab	*95*
Salmonella	Rivers, lakes	FL, north	72 (23.6)	1-liter grab	*81*
Salmonella	Canals	FL, south	96 (28.1)	1-liter grab	*81*
Salmonella	Streams	GA, Satilla River Basin	299 (43.0)	3-liter grab	*134*
Salmonella	Streams	GA, South Fork Broad River watershed	105 (76)	4-liter grab	*14*
Salmonella	Rivers, streams	GA; NE, Upper Oconee watershed	688 (70.2)	1-liter grab	*18*
Salmonella	Nontidal fresh water	MD, DE	126 (84.1)	Modified Moore swabs	*59*
Salmonella	Brackish and fresh water	MD, eastern shore	147 (81.0)	10-liter grab	*1*
Salmonella	Reclaimed water	MD, eastern shore	41 (7.3)	10-liter grab	*1*
Salmonella	Pond and creeks in watershed	MD, eastern shore	48 (77.1)	40-liter grab	*9*
Salmonella	Agricultural recovery basins	MS	12 (100)	20-liter grab	*95*
Salmonella	Pond, ditch, river, creek, stream	NY	51 (14.0)	250-ml grab	*114*
Salmonella	Streams near produce production	NY, rural watershed	181 (44.0)	10-liter grab	*140*
Salmonella	Streams near produce production	NY, rural watershed	88 (57.0)	Moore swabs	*140*
Salmonella	Streams	NY, upstate	196 (40.0)	10-liter grab	*139*
Salmonella	Susquehanna River	PA, Susquehanna River Basin	112 (49)	10 liters	*26*

[a]CAFO, confined animal feeding operation.

forthcoming article in this series, we will discuss risk factors for the introduction of pathogens into agricultural water.

Sediment

Attachment to soil particles and/or algae plays a significant role in human pathogen persistence in water. Numerous studies have been conducted to explore sediment as a reservoir for bacteria in agricultural water and to report bacterial levels in sediment across the United States *(10, 72, 89–91, 95, 99)*. Hassard et al. *(52)* and Pachepsky and Shelton *(87)* summarized decades of research covering aspects of sediments that favor adherence of bacteria, the bacterial properties and soil fractions (particularly clay and silt but also sand with an established biofilm consortium) that allow for sediment adherence, and the environmental and stream conditions associated with bacterial load in sediment and resuspension in water.

Microbial water quality studies frequently have revealed that microorganisms are more concentrated and survive longer in sediment or algae than in the overlaying water *(6, 10, 17, 39, 69, 87, 89, 121)*. Sediment and water from irrigation and nonirrigation water sources on produce farms and from water sources in the surrounding area were tested for *E. coli* in a 30-mo water quality study on California's central coast *(10)*. With the exception of reservoirs, mean levels of *E. coli* in sediment were 5- to 48-fold higher than levels in water

TABLE 3. Pathogen prevalence in irrigation water, 2013 to 2023

Pathogen	Sampling location	State, region	Total no. of samples (% positive)	Sample volume, type	Reference(s)
Arcobacter	On-farm irrigation water from wells, surface water adjacent to farms	GA	23 (22.0)	10 liters	*34*
Arcobacter	On-farm irrigation surface water	OH	69 (45.0)	10 liters	*34*
Campylobacter	On-farm irrigation water from wells, surface water adjacent to farms	GA	23 (4.0)	10 liters	*34*
Campylobacter	On-farm irrigation surface water	OH	69 (0)	10 liters	*34*
Escherichia coli O157	Source water upstream of district control, point of diversion where the district takes control, irrigation delivery points within the district	CA, irrigation districts	187 (4.8)	1 liter	*94*
E. coli O157	Source water upstream of district control, point of diversion where the district takes control, irrigation delivery points within the district	CA, irrigation districts	45 (13.3)	10 liters	*94*
E. coli O157	Well water, reservoir, irrigation, standing water furrow, furrow ditch, drainage ditch, pond, standing water, stream, river, creek	CA, central coast	242 (0.4)	290-ml grab	*10*
E. coli O157	Farm stream, river, creek	CA, central coast	14 (21.4)	Moore swab	*10*
E. coli O157	Reservoir	CA, Salinas Valley	16 (18.8)	10-liter grab processed through an MMS[a]	*101*
E. coli O157	Irrigation canal	CA, San Joaquin Valley	83 (4.8)	10-liter grab processed through an MMS	*101*
E. coli O157	Farm ponds	GA, Suwannee River watershed	240 (14.6)	10-liter grab	*43*
E. coli O157	Surface water	PA, south-central and southeastern	153 (0)	1-liter grab	*29*
E. coli O157	Source water upstream of district control, point of diversion where the district takes control, irrigation delivery points within the district	WA, irrigation districts	330 (0.9)	1 liter	*94*
E. coli O157	Source water upstream of district control, point of diversion where the district takes control, irrigation delivery points within the district	WA, irrigation districts	104 (1.0)	10 liters	*94*
E. coli O157:H7	Irrigation water, standing water, creek, stream	CA	244 (0)	250-ml grab	*23*
Pathogenic *E. coli* (non-O157:H7)	Irrigation water, standing water, creek, stream	CA	244 (8.2)	250-ml grab	*23*

Table 3 continued on the next page.

TABLE 3. Pathogen prevalence in irrigation water, 2013 to 2023 (cont.)

Pathogen	Sampling location	State, region	Total no. of samples (% positive)	Sample volume, type	Reference(s)
STEC	Source water upstream of district control, point of diversion where the district takes control, irrigation delivery points within the district	CA, irrigation districts	187 (10.7)	1 liter	*94*
STEC	Source water upstream of district control, point of diversion where the district takes control, irrigation delivery points within the district	CA, irrigation districts	45 (11.1)	10 liters	*94*
STEC	On-farm irrigation water from wells, surface water adjacent to farms	GA	26 (0)	10 liters	*34*
STEC	Farm wells	MD, DE, NJ	72 (0)	1 liter	*88*
STEC	Farm ponds, streams, creeks	MD, DE, NJ	30 (0)	1-liter grab	*88*
STEC	Municipal or farm wells	NY	28 (0)	250-ml grab	*113*
STEC	Surface water	NY	146 (3.0)	250-ml grab	*113*
STEC	Irrigation water (farm pond, river, creek, stream, wells)	NY, 10 produce farms	18 (0)	250-ml grab	*141*
STEC	Nonirrigation water (ditch, river, creek, stream within 50 m of a sampled field)	NY, 10 produce farms	15 (7.0)	250-ml grab	*141*
STEC	On-farm irrigation surface water	OH	69 (3.0)	10 liters	*34*
STEC	Source water upstream of district control, point of diversion where the district takes control, irrigation delivery points within the district	WA, irrigation districts	330 (7.6)	1 liter	*94*
STEC	Source water upstream of district control, point of diversion where the district takes control, irrigation delivery points within the district	WA, irrigation districts	104 (10.6)	10 liters	*94*
L. monocytogenes	Irrigation canals	AZ	76 (4.0)	10-liter grab	*140*
L. monocytogenes	Irrigation canals	AZ	34 (0)	Moore swabs	*140*
L. monocytogenes	On-farm irrigation water from wells, surface water adjacent to farms	GA	26 (7.0)	10 liters	*34*
L. monocytogenes	River	Mid-Atlantic	66 (65.2)	10-liter modified Moore swab	*103*
L. monocytogenes	Municipal or farm wells	NY	28 (0)	250-ml grab	*113*
L. monocytogenes	Surface water	NY	146 (33.0)	250-ml grab	*113*
L. monocytogenes	Farm wells	NY	14 (0)	250-ml grab	*114*
L. monocytogenes	Surface water	NY	9 (25.0)	250-ml grab	*114*
L. monocytogenes	Irrigation water (ponds, wells)	NY, 10 produce farms	18 (12.0)	250-ml grab	*141*
L. monocytogenes	Nonirrigation water (ditch, river, creek, stream within 50 m of a sampled field)	NY, 10 produce farms	15 (53.0)	250-ml grab	*141*

Table 3 continued on the next page.

TABLE 3. Pathogen prevalence in irrigation water, 2013 to 2023 (cont.)

Pathogen	Sampling location	State, region	Total no. of samples (% positive)	Sample volume, type	Reference(s)
L. monocytogenes	Pond and stream	NY, Finger Lakes	132 (48.0)	250-ml grab	*7*
L. monocytogenes	Creek	NY, Freeville	52 (63.0)	250-ml grab	*142*
L. monocytogenes	Surface water (roadside ditch, irrigation intake in creek upstream of irrigation intake)	NY, produce farm upstate	27 (78.0)	250-ml grab	*49*
L. monocytogenes	On-farm irrigation surface water	OH	69 (22.0)	10 liters	*34*
L. monocytogenes	Farm wells	VA, eastern shore	48 (4.2)	4 liters	*46, 47*
L. monocytogenes	Farm ponds	VA, eastern shore	48 (27.1)	4-liter grab	*46, 47*
L. monocytogenes	Surface water (streams, rivers, creeks, ponds)	VA, eastern shore and mainland	120 (7.5)	1-liter grab	*82*
Salmonella	Irrigation canals	AZ	77 (34.0)	10-liter grab	*140*
Salmonella	Irrigation canals	AZ	33 (64.0)	Moore swabs	*140*
Salmonella	Source water upstream of district control, point of diversion where the district takes control, irrigation delivery points within the district	CA, irrigation districts	187 (41.7)	1 liter	*94*
Salmonella	Source water upstream of district control, point of diversion where the district takes control, irrigation delivery points within the district	CA, irrigation districts	45 (71.1)	10 liters	*94*
Salmonella	Irrigation system	CA, central coast	13 (7.7)	290-ml grab	*10*
Salmonella	Reservoirs	CA, Salinas Valley	4 (50)	10-liter grab processed through an MMS	*101*
Salmonella	Irrigation canal	CA, San Joaquin Valley	83 (0)	10-iter grab processed through an MMS	*101*
Salmonella	Irrigation water	FL, south	40 (37.5)	250-ml grab	*112*
Salmonella	On-farm irrigation water from wells, surface water adjacent to farms	GA	26 (4.0)	10 liters	*34*
Salmonella	Farm ponds	GA, Little River watershed, southern	48 (46.0)	6-liter grab	*50*
Salmonella	Deep on-farm well	GA, southern	26 (0)	1 liter	*3*
Salmonella	Farm ponds	GA, southern	83 (12.0)	1-liter grab	*3*
Salmonella	Farm ponds	GA, southern	507 (42.8)	4.5-liter grab	*64*

Table 3 continued on the next page.

TABLE 3. Pathogen prevalence in irrigation water, 2013 to 2023 (cont.)

Pathogen	Sampling location	State, region	Total no. of samples (% positive)	Sample volume, type	Reference(s)
Salmonella	Farm ponds	GA, Suwannee River watershed	170 (29.4)	10-liter grab	*65*
Salmonella	Farm ponds	GA, Upper Suwannee River watershed in southern GA and northern FL	635 (28.2)	10-liter grab	*72*
Salmonella	Farm wells	MD, DE, NJ	72 (0)	1-liter grab	*88*
Salmonella	Farm ponds and streams creeks	MD, DE, NJ	30 (0)	1-liter grab	*88*
Salmonella	Irrigation water (ponds, wells)	MD, eastern shore	60 (0)	1-liter grab	*9*
Salmonella	River	Mid-Atlantic	66 (78.8)	10-liter modified Moore swab	*103*
Salmonella	Reservoirs	NY	123 (43.0)	2 liter grab	*57*
Salmonella	Municipal or farm wells	NY	28 (0)	250-ml grab	*113*
Salmonella	Surface water	NY	146 (11.0)	250-ml grab	*113*
Salmonella	Farm wells	NY	14 (0)	250-ml grab	*114*
Salmonella	Surface water	NY	9 (13.0)	250-ml grab	*114*
Salmonella	Irrigation water from surface sources and wells	NY	381 (9.4)	250-ml grab	*112*
Salmonella	Irrigation water (ponds, wells)	NY, 10 produce farms	18 (6.0)	250 ml grab	*141*
Salmonella	Nonirrigation water (ditch, river, creek, stream within 50 m of a sampled field)	NY, 10 produce farms	15 (20.0)	250-ml grab	*141*
Salmonella	On-farm irrigation surface water	OH	69 (9.0)	10 liters	*34*
Salmonella	Surface water	PA, south-central and southeastern	153 (3.3)	1-liter grab	*29*
Salmonella	Farm wells	VA, eastern shore	196 (3.3)	4-liter grab	*46, 47*
Salmonella	Farm ponds	VA, eastern shore	196 (19.4)	4-liter grab	*46, 47*
Salmonella	Farm (experimental) ponds	VA, eastern shore	17 (64.7)	30-liter grab	*45*
Salmonella	Farm (experimental) ponds	VA, eastern shore	100 (12.0)	4-liter grab	*45*
Salmonella	Farm ponds	VA, eastern shore	400 (19.0)	1-liter grab	*123*

Table 3 continued on the next page.

TABLE 3. Pathogen prevalence in irrigation water, 2013 to 2023 (cont.)

Pathogen	Sampling location	State, region	Total no. of samples (% positive)	Sample volume, type	Reference(s)
Salmonella	Surface water (streams, rivers, creeks, ponds)	VA, eastern shore and mainland	120 (21.7)	1-liter grab	*82*
Salmonella	Source water upstream of district control, point of diversion where the district takes control, irrigation delivery points within the district	WA, irrigation districts	330 (16.4)	1-liter	*94*
Salmonella	Source water upstream of district control, point of diversion where the district takes control, irrigation delivery points within the district	WA, irrigation districts	104 (34.6)	10 liters	*94*
Salmonella (invA gene)	Farm ponds	FL, west-central	540 (4.8)	500-ml grab	*119*

[a]MMS, micromembrane system.

at each sampling location (standing water furrow, furrow ditch, drainage ditch, pond, standing water, and flowing waterbodies) *(10)*. Weller et al. *(140)* suggested that stream sediments may "act as an in-channel store of bacteria," which are released back into the water column when rain events cause sediment disturbances. Based on their flume model of an irrigation canal system, Sassi et al. *(100)* concluded that although resuspension of *E. coli* increased as the velocity of the overlaying water increased, the bacteria were also resuspended from sediment at low flow rates and not just when the sediment was disturbed.

However, not every study has revealed higher bacterial levels in sediment than in the overlaying water. In a 2-yr study of *Salmonella* in 10 irrigation ponds in the southeastern United States, *Salmonella* levels and prevalence in all 10 ponds were significantly higher in the water (0.29 most probable number [MPN]/liter, 37.4% of samples) than in pond sediment (0.22 MPN/liter, 17.0% of samples) *(72)*. *E. coli* levels also were higher in the overlaying water (6.26 MPN/100 ml) than in the sediment (4.44 MPN/100 ml). However, individually some ponds had significantly higher levels of *Salmonella* and *E. coli* in sediment than in water (e.g., in one pond, *E. coli* was 9.34 MPN/100 ml in water and 32.48 MPN/100 ml in sediment). Variability in study results underscores the importance of understanding the spatial and temporal dynamics of sediment-water interactions of each individual water source for effectively managing agricultural water.

Various researchers have focused their work on gaining a greater understanding of bacteria in sediment and, more specifically, the relationship between bacterial levels in sediment and in the overlaying water column. In a study modeling the effect of sediment on *E. coli* levels in water, water samples exceeding the standard of 126 MPN/100 ml had higher levels of *E. coli* in sediment than did water samples with *E. coli* levels below the standard *(121)*. In their flume model of an irrigation canal system, Sassi et al. *(100)* found no difference in the resuspension rate between *E. coli* and the much smaller MS2 coliphage, but they did find differences in *E. coli* resuspension related to the sediment's soil types. *E. coli* resuspension rates in clay sediments were significantly higher than those in sand. The authors suggested that this finding was likely due to the dynamics of sediment resuspension, transport, and resettlement rates rather than the properties (e.g., type and size) of the microorganisms themselves. Other researchers have corroborated the impact of sediment properties on bacterial resuspension in agricultural water. Garzio-Hadzick et al. *(38)* reported that in sediment with identical granulometric (sand, clay, and silt) composition, *E. coli* survived better in sediment with higher portions of fine particles and organic carbon. Perkins et al. *(96)* also found significant positive correlations between the abundance of pathogens and fecal indicators and the sediments that contained higher proportions of silt and/or clay and associated organic matter.

Although a microorganism's size may not have much impact on its resuspension into the water column, other properties of microorganisms affect their resuspension in water. In their study of Squaw Creek in Ames, IA, Liang et al. *(67)* found differences between 44 *E. coli* strains isolated from sediment and 33 strains isolated from the overlaying water. The *E. coli* strains isolated from stream sediment had signifi-

cantly greater hydrophobicity, greater extracellular polymeric substance protein and sugar concentrations, less negative net charge, and higher point of zero charge than did the *E. coli* isolates from stream water. Whether bacterial characteristics permit these organisms to adhere to sediment particles or whether contact with sediment induces bacterial characteristics necessary for adherence has yet to be determined.

Algae and aquatic plants

Similar to sediment, plant surfaces provide nutrients, sites for microbial attachment, and protection against damaging radiation and predators *(15, 18, 33, 84, 133)*. Because of health risks to the public during water recreation, the association of human pathogens with aquatic plants has frequently been studied in recreational waters. In Lake Michigan, high levels of *E. coli* and enterococci have been reported in Cladophora, a green alga that grows in dense strands and mats along the shoreline *(15)*. Blooms of algae and other select aquatic plant species appear to extend pathogen survival in water *(15, 18, 105, 133)*.

Mathai et al. *(77)* studied how *E. coli* populations in 10 freshwater lakes in Minnesota were affected by Eurasian watermilfoil, an invasive submerged macrophyte that has spread across thousands of lakes in North America. *E. coli* levels were generally elevated on the plants, peaking in June. Several potentially pathogenic bacteria, including members of the Enterobacteriaceae family and *Aeromonas, Yersinia,* and *Clostridium*, were present on the Eurasian watermilfoil at significantly greater levels than found in water samples. Source tracking biomarkers indicated the bacteria were predominantly from waterfowl feces *(77)*. In Florida, aquatic plants in a freshwater lake contained high levels (8.7×10^4 CFU/g) of fecal indicator bacteria (FIB), suggesting that the plants may serve as important reservoirs for these bacteria *(105)*. Sbodio et al. *(101)* observed that during periods of elevated temperatures in the summer in California, increased total coliform levels coincided with algae blooms in irrigation canals in the San Joaquin Valley and reservoirs on produce farms on the central coast.

Because of bacterial attachment to plants, researchers have studied the use of aquatic plants to remove pathogens contaminating agricultural water sources. Some plants remove pathogens from water better than other plants. Clairmont et al. *(21)* studied the ability of two species of wetland plants to remove *E. coli*, *Enterococcus* spp., and *Salmonella* from water in constructed wetlands and found that *E. coli* and *Enterococcus* removal varied based on the type of plant, but *Salmonella* thrived in the rhizoplane (roots and associated soil particles) of both plants. Other research corroborates preferential bacterial attachment to roots of a specific aquatic plant over those of other plants *(18, 133)*. Irrigation ditches and reservoirs often contain plants, but whether they remove pathogens from water or protect attached pathogens that could then contaminate the surrounding water has not been studied. Most likely, both functions are operating, and the dominant net effect will depend on multiple codependent or interacting factors.

Agrochemicals

Many agrochemical (e.g., synthetic, natural inorganic, organic, and biological) formulations used to enhance soil health, for crop protection (e.g., pesticides), and as plant nutrients or biostimulants are sold in a form that requires mixing and diluting with water for application. When the water used to mix the formulations is contaminated with human pathogens, pathogen survival in the solution may be beneficially or detrimentally affected by the class of agrochemical or a specific agrochemical. Agrochemicals may directly kill or injure pathogens (e.g., cause DNA, protein, oxidative, or membrane damage) or destroy their protective habitat and/or nutrients or may enhance pathogen survival by killing their predators or competitors or providing direct growth nutrients as part of the chemical formulation *(97, 106)*.

Staley et al. *(105, 107, 108)* reported primarily indirect effects on FIB and pathogenic *E. coli* in their studies of pesticides in agricultural water. Their research on atrazine's effect on *E. coli* suggested that the herbicide had no direct effect on *E. coli* survival but rather reduced algae in the water column, which led to redistribution of *E. coli* into sediment *(107)*. In studying the effects of the fungicide chlorothalonil on FIB and *E. coli* O157:H7 survival, these authors found that chlorothalonil indirectly elevated *E. coli* O157:H7 and FIB levels by reducing levels of predaceous protozoans *(108)*. These effects diminished over time as the chemical degraded or microorganisms adopted resistance. Ng et al. *(83)* evaluated naturally occurring microorganisms in 10 commercially available pesticides reconstituted in agricultural water from bore, dam, and river sources. After 48 h, the majority of pesticides supported the growth of naturally occurring microorganisms, including bacteria known to be human pathogens.

Mahovic et al. *(73)* and Lopez-Velasco et al. *(71)* investigated survival of *Salmonella* in pesticide solutions (23 commercial brands) commonly used on tomatoes grown on the eastern shore of Virginia and in California, respectively. Mahovic et al. *(73)* observed a 5.0-log reduction in *Salmonella* in the pesticide solution containing peracetic acid (PAA) as the active ingredient, but no other pesticide affected *Salmonella* populations in solution. Lopez-Velasco et al. *(71)* found that *Salmonella* growth was not hindered by most pesticides and that specific pesticides even supported the pathogen's growth in solution. *Salmonella* growth in pesticide solutions was also dependent on water composition and temperature. When the contaminated pesticide solutions were applied to plants during in-field production, *Salmonella* survived up to 15 days in 80% of plant samples. The researchers concluded that foliar application of pesticides may elevate the risk of contamination beyond that of the water source alone.

Gu et al. *(44)* inoculated greenhouse-grown tomato plants with *Salmonella* and evaluated the effects of pesticide (acibenzolar-S-methyl, PAA, copper hydroxide, and streptomycin sulfate) solutions on the pathogen's growth and survival in both whole and ground leaves up to 9 days after inoculation. Two days after inoculation, PAA and streptomycin sulfate reduced *Salmonella* levels on tomato leaves by approximately 5.0 and 4.0 CFU/g, respectively. At 2 days postinoculation, copper hydroxide application reduced *Salmonella* populations by 6.3 CFU/g in ground tomato leaves. At 6 and 9 days postinoculation, no significant differences in *Salmonella* populations were observed with any of the pesticide solutions. Although these experiments were performed on contaminated plants, similar effects would be expected, based on the findings of Lopez-Velasco et al. *(71)*, if *Salmonella*-contaminated water were used to create pesticide solutions. Although agrochemical effects have not been a major focus in produce-related agricultural water research, agrochemical concentrations, especially in environmental runoff or agricultural surface irrigation runoff (tailwater) blended with other water sources, could play a role in the contamination of agricultural surface water sources.

CONCLUSION

Agricultural water is used in various ways before and after and planting and harvesting activities. Use of agricultural water that is "safe and of adequate sanitary quality for its intended use" is the paramount requirement of the FDA's proposed agricultural water requirements (subpart E) of the PSR. Because agricultural water has long been known to pose a contamination risk to produce crops, monitoring the microbial quality of this water is a core element of produce growers' food safety programs. Human pathogens have been detected in numerous studies of waterbodies on U.S. produce farms and in the surrounding watersheds. Watersheds in produce-growing regions tend to have higher human pathogen detection rates than do on-farm waterbodies. Of public health concern is human pathogen persistence in agricultural water, because contamination of this water increases the likelihood of produce contamination when this water is used on crops. Research has provided a better understanding of the roles that plants, agrochemicals, and sediment play in the persistence of pathogens in water and the potential ways these roles could be exploited to improve agricultural water quality. As the produce industry awaits the finalization of PSR subpart E requirements, producers are moving ahead in their efforts to increase awareness and understanding of the science related to assessing and effectively managing microbial hazards that pose a risk to the food safety and adequate sanitary quality of agricultural water.

REFERENCES

1. Acheamfour, C. L., S. Parveen, F. Hashem, M. Sharma, M. E. Gerdes, E. B. May, K. Rogers, J. Haymaker, R. Duncan, D. Foust, M. Taabodi, E. T. Handy, C. East, R. Bradshaw, S. Kim, S. A. Micallef, M. T. Callahan, S. Allard, B. Anderson-Coughlin, S. Craighead, S. Gartley, A. Vanore, K. E. Kniel, S. Solaiman, A. Bui, R. Murray, H. A. Craddock, P. Kulkarni, R. E. Rosenberg Goldstein, and A. R. Sapkota. 2021. Levels of *Salmonella enterica* and *Listeria monocytogenes* in alternative irrigation water vary based on water source on the eastern shore of Maryland. *Microbiol. Spectr.* 9:e0066921.
2. Allard, S. M., M. T. Callahan, A. Bui, A. M. C. Ferelli, J. Chopyk, S. Chattopadhyay, E. F. Mongodin, S. A. Micallef, and A. R. Sapkota. 2019. Creek to table: Tracking fecal indicator bacteria, bacterial pathogens, and total bacterial communities from irrigation water to kale and radish crops. *Sci. Total Environ.* 666:461–471.
3. Antaki, E. M., G. Vellidis, C. Harris, P. Aminabadi, K. Levy, and M. T. Jay-Russell. 2016. Low concentration of *Salmonella enterica* and generic *Escherichia coli* in farm ponds and irrigation distribution systems used for mixed produce production in southern Georgia. *Foodborne Pathog. Dis.* 13:551–558.
4. Astill, G., T. Minor, and S. Thornsbury. 2019. Changes in U.S. produce grower food safety practices from 1999 to 2016. *Food Control* 104:326–332.
5. Badgley, B. D., F. I. M. Thomas, and V. J. Harwood. 2011. Quantifying environmental reservoirs of fecal indicator bacteria associated with sediment and submerged aquatic vegetation. *Environ. Microbiol.* 13:932–942.
6. Baker, C. A., G. Almeida, J. A. Lee, and K. E. Gibson. 2021. Pathogen and surrogate survival in relation to fecal indicator bacteria in freshwater mesocosms. *Appl. Environ. Microbiol.* 87:e0055821.
7. Belias, A., L. K. Strawn, M. Wiedmann, and D. Weller. 2021. Small produce farm environments can harbor diverse *Listeria monocytogenes* and *Listeria* spp. populations. *J. Food Prot.* 84:113–121.
8. Bell, R. L., J. A. Kase, L. M. Harrison, K. V. Balan, U. Babu, Y. Chen, D. Macarisin, H. J. Kwon, J. Zheng, E. L. Stevens, J. Meng, and E. W. Brown. 2021. The persistence of bacterial pathogens in surface water and its impact on global food safety. *Pathogens* 10:1391.
9. Bell, R. L., J. Zheng, E. Burrows, S. Allard, C. Y. Wang, C. E. Keys, D. C. Melka, E. Strain, Y. Luo, M. W. Allard, S. Rideout, and E. W. Brown. 2015. Ecological prevalence, genetic diversity, and epidemiological aspects of *Salmonella* isolated from tomato agricultural regions of the Virginia Eastern Shore. *Front. Microbiol.* 6:415.
10. Benjamin, L., E. R. Atwill, M. Jay-Russell, M. Cooley, D. Carychao, L. Gorski, and R. E. Mandrell. 2013. Occurrence of generic *Escherichia coli, E. coli* O157 and *Salmonella* spp. in water and sediment from leafy green produce farms and streams on the Central California coast. *Int. J. Food Microbiol.* 165:65–76.
11. Bihn, E. A., C. D. Smart, C. A. Hoepting, and R. W. Worobo. 2013. Use of surface water in the production of fresh fruits and vegetables: A survey of fresh produce growers and their water management practices. *Food Prot. Trends* 33:307–314.
12. Bland, R. 2021. History of produce safety. United Fresh Produce Association, Washington, D.C. Available at: History of Produce Safety 1-4-21.pdf (unitedfresh.org). Accessed 28 March 2023.
13. Bradford, S. A., V. L. Morales, W. Zhang, R. W. Harvey, A. I. Packman, A. Mohanram, and C. Welty. 2013. Transport and fate of microbial pathogens in agricultural settings. *Crit. Rev. Environ. Sci. Technol.* 43:775–893.

14. Bradshaw, J. K., B. J. Snyder, A. Oladeinde, D. Spidle, M. E. Berrang, R. J. Meinersmann, B. Oakley, R. C. Sidle, K. Sullivan, and M. Molina. 2016. Characterizing relationships among fecal indicator bacteria, microbial source tracking markers, and associated waterborne pathogen occurrence in stream water and sediments in a mixed land use watershed. *Water Res.* 101:498–509.

15. Byappanahalli, M. N., D. A. Shively, M. B. Nevers, M. J. Sadowsky, and R. L. Whitman. 2003. Growth and survival of *Escherichia coli* and enterococci populations in the macro-alga *Cladophora* (Chlorophyta). FEMS *Microbiol. Ecol.* 46:203–211.

16. Carlson, E. A., D. J. Cooper, D. M. Merritt, B. C. Kondratieff, and R. M. Waskom. 2019. Irrigation canals are newly created streams of semi-arid agricultural regions. *Sci. Total Environ.* 646:770–781.

17. Chase, E., J. Hunting, C. Staley, and V. J. Harwood. 2012. Microbial source tracking to identify human and ruminant sources of faecal pollution in an ephemeral Florida river. *J. Appl. Microbiol.* 113:1396–1406.

18. Cho, S., L. M. Hiott, S. L. House, T. A. Woodley, E. A. McMillan, P. Sharma, J. B. Barrett, E. S. Adams, J. M. Brandenburg, K. B. Hise, J. M. Bateman McDonald, E. A. Ottesen, E. K. Lipp, C. R. Jackson, and J. G. Frye. 2022. Analysis of *Salmonella enterica* isolated from a mixed-use watershed in Georgia, USA: Antimicrobial resistance, serotype diversity, and genetic relatedness to human isolates. *Appl. Environ. Microbiol.* 88:e0039322.

19. Chopyk, J., D. J. Nasko, S. Allard, A. Bui, T. Treangen, M. Pop, E. F. Mongodin, and A. R. Sapkota. 2020. Comparative metagenomic analysis of microbial taxonomic and functional variations in untreated surface and reclaimed waters used in irrigation applications. *Water Res.* 169:135395.

20. Christen, E., J. Ayars, J. Hornbuckle, and M. Hickey. 2006. Technology and practice for irrigation in vegetables. New South Wales Department of Primary Industries, Orange, New South Wales, Australia. Available at: Technology and practice for irrigation in vegetables (nsw.gov.au). Accessed 23 February 2023.

21. Clairmont, L. K., A. Coristine, K. J. Stevens, and R. M. Slawson. 2021. Factors influencing the persistence of enteropathogenic bacteria in wetland habitats and implications for water quality. *J. Appl. Microbiol.* 131:513–526.

22. Coffey, R., M. Paul, J. Stamp, A. Hamilton, and T. Johnson. 2018. A review of water quality responses to air temperature and precipitation changes. 2. Nutrients, algal blooms, sediment, pathogens. *J. Am. Water Resour.* Assoc. 55:844–868.

23. Cooley, M. B., M. Jay-Russell, E. R. Atwill, D. Carychao, K. Nguyen, B. Quiñones, R. Patel, S. Walker, M. Swimley, E. Pierre-Jerome, A. G. Gordus, and R. E. Mandrell. 2013. Development of a robust method for isolation of Shiga toxin–positive *Escherichia coli* (STEC) from fecal, plant, soil and water samples from a leafy greens production region in California. *PLoS One* 8:e65716.

24. Cooley, M. B., B. Quiñones, D. Oryang, R. E. Mandrell, and L. Gorski. 2014. Prevalence of Shiga toxin producing *Escherichia coli*, *Salmonella enterica*, and *Listeria monocytogenes* at public access watershed sites in a California central coast agricultural region. *Front. Cell. Infect. Microbiol.* 4:30.

25. Dean, K., and J. Mitchell. 2022. Identifying water quality and environmental factors that influence indicator and pathogen decay in natural surface waters. *Water Res.* 211:118051.

26. Deaven, A. M., C. M. Ferreira, E. A. Reed, J. R. C. See, N. A. Lee, E. Almaraz, P. C. Rios, J. G. Marogi, R. Lamendella, J. Zheng, R. L. Bell, and N. W. Shariat. 2021. *Salmonella* genomics and population analyses reveal high inter- and intraserovar diversity in freshwater. *Appl. Environ. Microbiol.* 87:e02594-20.

27. Díaz-Gavidia, C., C. Barría, D. L. Weller, M. Salgado-Caxito, E. M. Estrada, A. Araya, L. Vera, W. Smith, M. Kim, A. I. Moreno-Switt, J. Olivares-Pacheco, and A. D. Adell. 2022. Humans and hoofed livestock are the main sources of fecal contamination of rivers used for crop irrigation: A microbial source tracking approach. *Front. Microbiol.* 13:768527.

28. Dieter, C. A., M. A. Maupin, R. R. Caldwell, M. A. Harris, T. I. Ivahnenko, J. K. Lovelace, N. L. Barber, and K. S. Linsey. 2018. Estimated use of water in the United States in 2015. U.S. Geological Survey circular 1441. Available at: Estimated use of water in the United States in 2015 (usgs.gov). Accessed 19 April 2023.

29. Draper, A. D., S. Doores, H. Gourama, and L. F. Laborde. 2016. Microbial survey of Pennsylvania surface water used for irrigating produce crops. *J. Food Prot.* 79:902–912.

30. Durigan, M., H. R. Helen, and A. J. da Silva. 2020. Dead-end ultrafiltration and DNA-based methods for detection of *Cyclospora cayetanensis* in agricultural water. *Appl. Environ. Microbiol.* 86:e01595-20.

31. Duris, J. W., A. G. Reif, D. A. Krouse, and N. M. Isaacs. 2013. Factors related to occurrence and distribution of selected bacterial and protozoan pathogens in Pennsylvania streams. *Water Res.* 47:300–314.

32. Falardeau, J., R. P. Johnson, F. Pagotto, and S. Wang. 2017. Occurrence, characterization, and potential predictors of verotoxigenic *Escherichia coli, Listeria monocytogenes,* and *Salmonella* in surface water used for produce irrigation in the Lower Mainland of British Columbia, Canada. *PLoS One* 12:e0185437.

33. Fang, T., Z. Zhang, H. Wang, M. Rogers, and Q. Cui. 2022. Insights into effects of algae on decay and distribution of bacterial pathogens in recreational water: Implications for microbial risk management. *J. Environ. Sci.* (China) 113:92–103.

34. Ferguson, M., C. K. Hsu, C. Grim, M. Kauffman, K. Jarvis, J. B. Pettengill, U. S. Babu, L. M. Harrison, B. Li, A. Hayford, K. V. Balan, J. P. Freeman, G. Rajashekara, E. K. Lipp, R. S. Rozier, A. M. Zimeri, and L. S. Burall. 2023. A longitudinal study to examine the influence of farming practices and environmental factors on pathogen prevalence using structural equation modeling. *Front. Microbiol* 14:1141043.

35. Fonseca, J. M., S. D. Fallon, C. A. Sanchez, and K. D. Nolte. 2011. *Escherichia coli* survival in lettuce fields following its introduction through different irrigation systems. *J. Appl. Microbiol.* 110:893–902.

36. Food and Agriculture Organization of the United Nations and World Health Organization. 2021. Safety and quality of water used with fresh fruits and vegetables. Microbiological Risk Assessment Series 37. Food and Agriculture Organization of the United Nations, Rome. Available at: https://doi.org/10.4060/cb7678en. Accessed 21 April 2023.

37. Gartley, S., B. Anderson-Coughlin, M. Sharma, and K. E. Kniel. 2022. *Listeria monocytogenes* in irrigation water: An assessment of outbreaks, sources, prevalence, and persistence. *Microorganisms* 10:1319.

38. Garzio-Hadzick, A., D. R. Shelton, R. L. Hill, Y. A. Pachepsky, A. K. Guber, and R. Rowland. 2010. Survival of manure-borne *E. coli* in streambed sediment: Effects of temperature and sediment properties. *Water Res*. 44:2753–2762.

39. Givens, C. E., D. W. Kolpin, M. A. Borchardt, J. W. Duris, T. B. Moorman, and S. K. Spencer. 2016. Detection of hepatitis E virus and other livestock-related pathogens in Iowa streams. *Sci. Total Environ.* 566–567:1042–1051.

40. Gorski, L., M. B. Cooley, D. Oryang, D. Carychao, K. Nguyen, Y. Luo, L. Weinstein, E. Brown, M. Allard, R. E. Mandrell, and Y. Chen. 2022. Prevalence and clonal diversity of over 1,200 *Listeria monocytogenes* isolates collected from public access waters near produce production areas on the Central California coast during 2011 to 2016. *Appl. Environ. Microbiol.* 88:e0035722.

41. Gorski, L., A. S. Liang, S. Walker, D. Carychao, A. A. Noriega, R. E. Mandrell, and M. B. Cooley. 2022. *Salmonella enterica* serovar diversity, distribution, and prevalence in public-access waters from a Central California coastal leafy green–growing region from 2011 to 2016. *Appl. Environ. Microbiol.* 88:e0183421.

42. Gorski, L., S. Walker, K. F. Romanolo, and S. Kathariou. 2021. Growth and survival of attached *Listeria* on lettuce and stainless steel varies by strain and surface type. *J. Food Prot.* 84:903–911.

43. Gu, G., Z. Luo, J. M. Cevallos-Cevallos, P. Adams, G. Vellidis, A. Wright, and A. H. C. van Bruggen. 2013. Factors affecting the occurrence of *Escherichia coli* O157 contamination in irrigation ponds on produce farms in the Suwannee River watershed. *Can. J. Microbiol.* 59:175–182.

44. Gu, G., C. M. Murphy, J. Zheng, X. Nou, S. L. Rideout, and L. K. Strawn. 2023. Effects of fumigation on the reduction of *Salmonella enterica* in soil. *Foodborne Pathog. Dis.* 20:563–569.

45. Gu, G., L. K. Strawn, D. O. Oryang, J. Zheng, E. A. Reed, A. R. Ottesen, R. L. Bell, Y. Chen, S. Duret, D. T. Ingram, M. S. Reiter, R. Pfuntner, E. W. Brown, and S. L. Rideout. 2018. Agricultural practices influence *Salmonella* contamination and survival in pre-harvest tomato production. *Front. Microbiol.* 9:2451.

46. Gu, G., L. K. Strawn, A. R. Ottesen, P. Ramachandran, E. A. Reed, J. Zheng, R. R. Boyer, and S. L. Rideout. 2021. Correlation of *Salmonella enterica* and *Listeria monocytogenes* in irrigation water to environmental factors, fecal indicators, and bacterial communities. *Front. Microbiol.* 11:557289.

47. Gu, G., L. K. Strawn, J. Zheng, E. A. Reed, and S. L. Rideout. 2019. Diversity and dynamics of *Salmonella enterica* in water sources, poultry litters, and field soils amended with poultry litter in a major agricultural area of Virginia. *Front. Microbiol.* 10:2868.

48. Haley, B. J., D. J. Cole, and E. K. Lipp. 2009. Distribution, diversity, and seasonality of waterborne salmonellae in a rural watershed. *Appl. Environ. Microbiol.* 75:1248–1255.

49. Harrand, A. S., L. K. Strawn, P. M. Illas-Ortiz, M. Wiedmann, and D. L. Weller. 2020. *Listeria monocytogenes* prevalence varies more within fields than between fields or over time on conventionally farmed New York produce fields. *J. Food Prot.* 83:1958–1966.

50. Harris, C. S., M. Tertuliano, S. Rajeev, G. Vellidis, and K. Levy. 2018. Impact of storm runoff on *Salmonella* and *Escherichia coli* prevalence in irrigation ponds of fresh produce farms in southern Georgia. *J. Appl. Microbiol.* 124:910–921.

51. Harris, L. J., J. Bender, E. A. Bihn, T. Blessington, M. D. Danyluk, P. Delaquis, L. Goodridge, A. M. Ibekwe, S. Ilic, K. Kniel, J. T. Lejeune, D. W. Schaffner, D. Stoeckel, and T. V. Suslow. 2012. A framework for developing research protocols for evaluation of microbial hazards and controls during production that pertain to the quality of agricultural water contacting fresh produce that may be consumed raw. *J. Food Prot.* 75:2251–2273.

52. Hassard, F., C. L. Gwyther, K. Farkas, A. Andrews, V. Jones, B. Cox, H. Brett, D. L. Jones, J. E. McDonald, and S. K. Malham. 2016. Abundance and distribution of enteric bacteria and viruses in coastal and estuarine sediments—A review. *Front. Microbiol.* 7:1692.

53. Haymaker, J., M. Sharma, S. Parveen, F. Hashem, E. B. May, E. T. Handy, C. White, C. East, R. Bradshaw, S. A. Micallef, M. T. Callahan, S. Allard, B. Anderson, S. Craighead, S. Gartley, A. Vanore, K. E. Kniel, S. Solaiman, A. Bui, R. Murray, H. A. Craddock, P. Kulkarni, D. Foust, R. Duncan, M. Taabodi, and A. R. Sapkota. 2019. Prevalence of Shiga-toxigenic and atypical enteropathogenic *Escherichia coli* in untreated surface water and reclaimed water in the mid-Atlantic U.S. *Environ. Res.* 172:630–636.

54. Hrozencik, A., and M. Aillery. 2021. Trends in U.S. irrigated agriculture: Increasing resilience under water supply scarcity. EIB-229. U.S. Department of Agriculture, Economic Research Service, Washington, D.C. Available at: Trends in U.S. Irrigated Agriculture: Increasing Resilience Under Water Supply Scarcity (usda.gov). Accessed 24 May 2023.

55. Hrozencik, A. R., S. Wallander, and M. Aillery. 2021. Irrigation organizations: Water storage and delivery infrastructure. Available at: USDA ERS–Irrigation Organizations: Water Storage and Delivery Infrastructure. Accessed 24 May 2023.

56. Jokinen, C. C., H. Schreier, W. Mauro, E. Taboada, J. L. Isaac-Renton, E. Topp, T. Edge, J. E. Thomas, and V. P. J. Gannon. 2010. The occurrence and sources of *Campylobacter* spp., *Salmonella enterica* and *Escherichia coli* O157:H7 in the Salmon River, British Columbia, Canada. *J. Water Health* 8:374–386.

57. Jones, L. A., R. W. Worobo, and C. D. Smart. 2014. Plant-pathogenic oomycetes, *Escherichia coli* strains, and *Salmonella* spp. frequently found in surface water used for irrigation of fruit and vegetable crops in New York State. *Appl. Environ. Microbiol.* 80:4814–4820.

58. Kahler, A. M., M. C. Mattioli, A. J. da Silva, and V. Hill. 2021. Detection of *Cyclospora cayetanensis* in produce irrigation and wash water using large-volume sampling techniques. *Food Waterborne Parasitol.* 22:e00110.

59. Kim, S., Y. Pachepsky, S. A. Micallef, R. Rosenberg Goldstein, A. R. Sapkota, F. Hashem, S. Parveen, K. E. Kniel, and M. Sharma. 2023. Temporal stability of *Salmonella enterica* and *Listeria monocytogenes* in surface waters used for irrigation in the mid-Atlantic United States. *J. Food Prot.* 86:100058.

60. King, D. N., M. J. Donohue, S. J. Vesper, E. N. Villegas, M. W. Ware, M. E. Vogel, E. F. Furlong, D. W. Kolpin, S. T. Glassmeyer, and S. Pfaller. 2016. Microbial pathogens in source and treated waters from drinking water treatment plants in the United States and implications for human health. *Sci. Total Environ.* 562:987–995.

61. Korajkic, A., P. Wanjugi, L. Brooks, Y. Cao, and V. J. Harwood. 2019. Persistence and decay of fecal microbiota in aquatic habitats. *Microbiol. Mol. Biol. Rev.* 83:e00005-19.

62. Kritzberg, E., and E. Bååth. 2022. Seasonal variation in temperature sensitivity of bacterial growth in a temperate soil and lake. *FEMS Microbiol. Ecol.* 98:fiac111.

63. Leaman, S. M., S. Salas, R. E. Mandrell, T. V Suslow, M. T. Jay-Russell, and D. A. Davis. 2022. Environmental risk factors in the human pathogen transmission pathways between animal operations and produce crops. *Food Prot. Trends* 42:362–376.

64. Lee, D., M. Tertuliano, G. Vellidis, C. Harris, M. K. Grossman, S. Rajeev, and K. Levy. 2018. Evaluation of grower-friendly, science-based sampling approaches for the detection of *Salmonella* in ponds used for irrigation of fresh produce. *Foodborne Pathog. Dis.* 15:627–636.

65. Li, B., G. Vellidis, H. Liu, M. Jay-Russell, S. Zhao, Z. Hu, A. Wright, and C. A. Elkins. 2014. Diversity and antimicrobial resistance of *Salmonella enterica* isolates from surface water in southeastern United States. *Appl. Environ. Microbiol.* 80:6355–6365.

66. Li, X., E. R. Atwill, E. Antaki, O. Applegate, B. Bergamaschi, R. F. Bond, J. Chase, K. M. Ransom, W. Samuels, N. Watanabe, and T. Harter. 2015. Fecal indicator and pathogenic bacteria and their antibiotic resistance in alluvial groundwater of an irrigated agricultural region with dairies. *J. Environ. Qual.* 44:1435–1447.

67. Liang, X., C. Liao, M. L. Thompson, M. L. Soupir, L. R. Jarboe, and P. M. Dixon. 2016. *E. coli* surface properties differ between stream water and sediment environments. *Front. Microbiol.* 7:1732.

68. Liao, Y. T., I. A. Quintela, K. Nguyen, A. Salvador, M. B. Cooley, and V. C. H. Wu. 2018. Investigation of prevalence of free Shiga toxin–producing *Escherichia coli* (STEC)-specific bacteriophages and its correlation with STEC bacterial hosts in a produce-growing area in Salinas, California. *PLoS One* 13:e0190534.

69. Liu, H., C. A. Whitehouse, and B. Li. 2018. Presence and persistence of *Salmonella* in water: The impact on microbial quality of water and food safety. *Front. Public Health* 6:159.

70. Liu, P. W., J. S. Famiglietti, A. J. Purdy, K. H. Adams, A. L. McEvoy, J. T. Reager, R. Bindlish, D. N. Wiese, C. H. David, and M. Rodell. 2022. Groundwater depletion in California's central valley accelerates during megadrought. *Nat. Commun.* 13:7825.

71. Lopez-Velasco, G., A. Tomas-Callejas, D. Diribsa, P. Wei, and T. V. Suslow. 2013. Growth of *Salmonella enterica* in foliar pesticide solutions and its survival during field production and postharvest handling of fresh market tomato. *J. Appl. Microbiol.* 114:1547–1558.

72. Luo, Z., G. Gu, A. Ginn, M. C. Giurcanu, P. Adams, G. Vellidis, A. H. C. van Bruggen, M. D. Danyluk, and A. C. Wright. 2015. Distribution and characterization of *Salmonella enterica* isolates from irrigation ponds in the southeastern United States. *Appl. Environ. Microbiol.* 81:4376–4387.

73. Mahovic, M., G. Gu, and S. Rideout. 2013. Effects of pesticides on the reduction of plant and human pathogenic bacteria in application water. *J. Food Prot.* 76:719–722.

74. Malayil, L., S. Chattopadhyay, E. F. Mongodin, and A. R. Sapkota. 2021. Coupled DNA-labeling and sequencing approach enables the detection of viable-but-non-culturable *Vibrio* spp. in irrigation water sources in the Chesapeake Bay watershed. *Environ. Microbiomes* 16:13.

75. Malayil, L., P. Ramachandran, S. Chattopadhyay, R. Cagle, L. Hittle, A. Ottesen, E. F. Mongodin, and A. R. Sapkota. 2020. Metabolically-active bacteria in reclaimed water and ponds revealed using bromodeoxyuridine DNA labeling coupled with 16S rRNA and shotgun sequencing. *Water Res.* 184:116185.

76. Markland, S. M., D. Ingram, K. E. Kniel, and M. Sharma. 2017. Water for agriculture: the convergence of sustainability and safety. *Microbiol. Spectr.* 5.

77. Mathai, P. P., H. M. Dunn, P. Magnone, Q. Zhang, S. Ishii, C. L. Chun, and M. J. Sadowsky. 2019. Association between submerged aquatic vegetation and elevated levels of *Escherichia coli* and potential bacterial pathogens in freshwater lakes. *Sci. Total Environ.* 657:319–324.

78. McEgan, R., G. Mootian, L. D. Goodridge, D. W. Schaffner, and M. D. Danyluk. 2013. Predicting *Salmonella* populations from biological, chemical, and physical indicators in Florida surface waters. *Appl. Environ. Microbiol.* 79:4094–4105.

79. Miller, W. A., D. J. Lewis, M. Lennox, M. G. C. Pereira, K. W. Tate, P. A. Conrad, and E. R. Atwill. 2007. Climate and on-farm risk factors associated with *Giardia duodenalis* cysts in storm runoff from California coastal dairies. *Appl. Environ. Microbiol.* 73:6972–6979.

80. Moyne, A. L., M. R. Sudarshana, T. Blessington, S. T. Koike, M. D. Cahn, and L. J. Harris. 2011. Fate of *Escherichia coli* O157:H7 in field-inoculated lettuce. *Food Microbiol.* 28:1417–1425.

81. Murphy, C. M., D. L. Weller, M. S. Reiter, C. A. Bardsley, J. Eifert, M. Ponder, S. L. Rideout, and L. K. Strawn. 2022. Anaerobic soil disinfestation, amendment-type, and irrigation regimen influence *Salmonella* survival and die-off in agricultural soils. *J. Appl. Microbiol.* 132:2342–2354.

82. Murphy, C. M., D. L. Weller, and L. K. Strawn. 2023. *Salmonella* prevalence is strongly associated with spatial factors while *Listeria monocytogenes* prevalence is strongly associated with temporal factors on Virginia produce farms. *Appl. Environ. Microbiol.* 89:e0152922.

83. Ng, P. J., G. H. Fleet, and G. M. Heard. 2005. Pesticides as a source of microbial contamination of salad vegetables. *Int. J. Food Microbiol.* 101:237–250.

84. Nguyen, K. H., C. Senay, S. Young, B. Nayak, A. Lobos, J. Conrad, and V. J. Harwood. 2018. Determination of wild animal sources of fecal indicator bacteria by microbial source tracking (MST) influences regulatory decisions. *Water Res.* 144:424–434.

85. Oates, S. C., M. A. Miller, D. Hardin, P. A. Conrad, A. Melli, D. A. Jessup, C. Dominik, A. Roug, M. T. Tinker, and W. A. Miller. 2012. Prevalence, environmental loading, and molecular characterization of *Cryptosporidium* and *Giardia* isolates from domestic and wild animals along the Central California coast. *Appl. Environ. Microbiol.* 78:8762–8772.

86. Pachepsky, Y., J. Morrow, A. Guber, D. Shelton, R. Rowland, and G. Davies. 2012. Effect of biofilm in irrigation pipes on microbial quality of irrigation water. *Lett. Appl. Microbiol.* 54:217–224.

87. Pachepsky, Y. A., and D. R. Shelton. 2011. *Escherichia coli* and fecal coliforms in freshwater and estuarine sediments. *Crit. Rev. Environ. Sci. Technol.* 41:1067–1110.

88. Pagadala, S., S. C. Marine, S. A. Micallef, F. Wang, D. M. Pahl, M. V. Melendez, W. L. Kline, R. A. Oni, C. S. Walsh, K. L. Everts, and R. L. Buchanan. 2015. Assessment of region, farming system, irrigation source and sampling time as food safety risk factors for tomatoes. *Int. J. Food Microbiol.* 196:98–108.

89. Pandey, P., M. L. Soupir, Y. Wang, W. Cao, S. Biswas, V. Vaddella, R. Atwill, V. Merwade, and G. Pasternack. 2018. Water and sediment microbial quality of mountain and agricultural streams. *J. Environ. Qual.* 47:985–996.

90. Pandey, P. K., P. H. Kass, M. L. Soupir, S. Biswas, and V. P. Singh. 2014. Contamination of water resources by pathogenic bacteria. *AMB Express* 4:51.

91. Pandey, P. K., and M. L. Soupir. 2013. Assessing the impacts of *E. coli* laden streambed sediment on *E. coli* loads over a range of flows and sediment characteristics. *J. Am. Water Resour. Assoc.* 49:1261–1269.

92. Panoff, J. M., B. Thammavongs, M. Guéguen, and P. Boutibonnes. 1998. Cold stress responses in mesophilic bacteria. *Cryobiology* 36:75–83.

93. Partyka, M. L., R. F. Bond, J. A. Chase, and E. R. Atwill. 2018. Spatial and temporal variability of bacterial indicators and pathogens in six California reservoirs during extreme drought. *Water Res.* 129:436–446.

94. Partyka, M. L., R. F. Bond, J. A. Chase, and E. R. Atwill. 2018. Spatiotemporal variability in microbial quality of western U.S. agricultural water supplies: A multistate study. *J. Environ. Qual.* 47:939–948.

95. Partyka, M. L., R. F. Bond, J. A. Chase, L. Kiger, and E. R. Atwill. 2016. Multistate evaluation of microbial water and sediment quality from agricultural recovery basins. *J. Environ. Qual.* 45:657–665.

96. Perkins, T. L., K. Clements, J. H. Baas, C. F. Jago, D. L. Jones, S. K. Malham, and J. E. McDonald. 2014. Sediment composition influences spatial variation in the abundance of human pathogen indicator bacteria within an estuarine environment. *PLoS One* 9:e112951.

97. Pham, C. H., J. Min, and M. B. Gu. 2004. Pesticide induced toxicity and stress response in bacterial cells. *Bull. Environ. Contam. Toxicol.* 72:380–386.

98. Potter, N., A. Hrozencik, and S. Wallander. 2023. Irrigation organizations: Water inflows and outflows. Economic brief 36. U.S. Department of Agriculture, Economic Research Service, Washington, D.C.

99. Salam, S., R. McDaniel, B. Bleakley, L. Amegbletor, and S. Mardani. 2021. Variability of *E. coli* in streambed sediment and its implication for sediment sampling. J. *Contam. Hydrol.* 242:103859.

100. Sassi, H. P., F. van Ogtrop, C. M. Morrison, K. Zhou, J. G. Duan, and C. P. Gerba. 2020. Sediment re-suspension as a potential mechanism for viral and bacterial contaminants. *J. Environ. Sci. Health A* 55:1398–1405.

101. Sbodio, A., S. Maeda, G. Lopez-Velasco, and T. V. Suslow. 2013. Modified Moore swab optimization and validation in capturing *E. coli* O157:H7 and *Salmonella enterica* in large volume field samples of irrigation water. *Food Res. Int.* 51:654–662.

102. Shaheen, M. N. F., E. M. Elmahdy, and M. Chawla-Sarkar. 2019. Quantitative PCR–based identification of enteric viruses contaminating fresh produce and surface water used for irrigation in Egypt. *Environ. Sci. Pollut. Res. Int.* 26:21619–21628.

103. Sharma, M., E. T. Handy, C. L. East, S. Kim, C. Jiang, M. T. Callahan, S. M. Allard, S. Micallef, S. Craighead, B. Anderson-Coughlin, S. Gartley, A. Vanore, K. E. Kniel, J. Haymaker, R. Duncan, D. Foust, C. White, M. Taabodi, F. Hashem, S. Parveen, E. May, A. Bui, H. Craddock, P. Kulkarni, R. T. Murray, and A. R. Sapkota. 2020. Prevalence of *Salmonella* and *Listeria monocytogenes* in non-traditional irrigation waters in the mid-Atlantic United States is affected by water type, season, and recovery method. *PLoS One* 15:e0229365.

104. Smith, R., M. Cahn, O. Daugovish, S. Koike, E. Natwick, H. Smith, K. Subbarao, E. Takele, and T. Turini. 2011. Leaf lettuce production in California. Available at: Leaf Lettuce Production in California (ucanr.edu). Accessed 12 March 2023.

105. Staley, C., K. H. Reckhow, J. Lukasik, and V. J. Harwood. 2012. Assessment of sources of human pathogens and fecal contamination in a Florida freshwater lake. *Water Res.* 46:5799–5812.

106. Staley, Z. R., V. J. Harwood, and J. R. Rohr. 2015. A synthesis of the effects of pesticides on microbial persistence in aquatic ecosystems. *Crit. Rev. Toxicol.* 45:813–836

107. Staley, Z. R., J. R. Rohr, and V. J. Harwood. 2011. Test of direct and indirect effects of agrochemicals on the survival of fecal indicator bacteria. *Appl. Environ. Microbiol.* 77:8765–8774.

108. Staley, Z. R., J. R. Rohr, J. K. Senkbeil, and V. J. Harwood. 2014. Agrochemicals indirectly increase survival of *E. coli* O157:H7 and indicator bacteria by reducing ecosystem services. *Ecol. Appl.* 24:1945–1953.

109. Stea, E. C., L. M. Purdue, R. C. Jamieson, C. K. Yost, and L. T. Hansen. 2015. Comparison of the prevalences and diversities of *Listeria* species and *Listeria monocytogenes* in an urban and a rural agricultural watershed. *Appl. Environ. Microbiol.* 81:3812–3822.

110. Steele, M., and J. Odumeru. 2004. Irrigation water as source of foodborne pathogens on fruit and vegetables. *J. Food Prot.* 67:2839–2849.

111. Stine, S. W., I. Song, C. Y. Choi, and C. P. Gerba. 2005. Effect of relative humidity on preharvest survival of bacterial and viral pathogens on the surface of cantaloupe, lettuce, and bell peppers. *J. Food Prot.* 68:1352–1358.

112. Strawn, L. K., M. D. Danyluk, R. W. Worobo, and M. Wiedmann. 2014. Distributions of *Salmonella* subtypes differ between two U.S. produce-growing regions. *Appl. Environ. Microbiol.* 80:3982–3991.

113. Strawn, L. K., E. D. Fortes, E. A. Bihn, K. K. Nightingale, Y. T. Gröhn, R. W. Worobo, M. Wiedmann, and P. W. Bergholz. 2013. Landscape and meteorological factors affecting prevalence of three foodborne pathogens in fruit and vegetable farms. *Appl. Environ. Microbiol.* 79:588–600.

114. Strawn, L. K., Y. T. Gröhn, S. Warchocki, R. W. Worobo, E. A. Bihn, and M. Wiedmann. 2013. Risk factors associated with *Salmonella* and *Listeria monocytogenes* contamination of produce fields. *Appl. Environ. Microbiol.* 79:7618–7627.

115. Suslow, T. V. 2010. Produce Safety Project issue brief: Standards for irrigation and foliar contact water. Available at: Produce Safety Narrative 1 (pewtrusts.org). Accessed 12 March 2023.

116. Thatte, D. 2019. The Food Safety Modernization Act in a nutshell. National Institute of Standards and Technology, Gaithersburg, MD. Available at: https://www.nist.gov/blogs/manufacturing-innovation-blog/food-safety-modernization-act-nutshell. Accessed 2 May 2023.

117. Thomas, J. L., R. M. Slawson, and W. D. Taylor. 2013. *Salmonella* serotype diversity and seasonality in urban and rural streams. *J. Appl. Microbiol.* 114:907–922.

118. Tian, P., D. Yang, L. Shan, D. Wang, Q. Li, L. Gorski, B. G. Lee, B. Quiñones, and M. B. Cooley. 2017. Concurrent detection of human norovirus and bacterial pathogens in water samples from an agricultural region in Central California coast. *Front. Microbiol.* 8:1560.

119. Topalcengiz, Z., L. K. Strawn, and M. D. Danyluk. 2017. Microbial quality of agricultural water in central Florida. *PLoS One* 12:e0174889.

120. Totton, S. C., A. M. O'Connor, T. Naganathan, B. A. F. Martinez, E. R. Vriezen, M. E. Torrence, and J. M. Sargeant. 2021. A scoping review of the detection, epidemiology and control of *Cyclospora cayetanensis* with an emphasis on produce, water and soil. *Epidemiol. Infect.* 149:e49.

121. Tousi, E. G., J. G. Duan, P. M. Gundy, K. R. Bright, and C. P. Gerba. 2021. Evaluation of *E. coli* in sediment for assessing irrigation water quality using machine learning. *Sci. Total Environ.* 799:149286.

122. Truchado, P., A. Garre, M. I. Gil, P. J. Simón-Andreu, G. Sánchez, and A. Allende. 2021. Monitoring of human enteric virus and coliphages throughout water reuse system of wastewater treatment plants to irrigation endpoint of leafy greens. *Sci. Total Environ.* 782:146837.

123. Truitt, L. N., K. M. Vazquez, R. C. Pfuntner, S. L. Rideout, A. H. Havelaar, and L. K. Strawn. 2018. Microbial quality of agricultural water used in produce preharvest production on the eastern shore of Virginia. *J. Food Prot.* 81:1661–1672.

124. Turini, T., S. Koike, M. Cantwell, L. Jackson, S. Koike, E. Natwick, R. Smith, K. Subbarao, and E. Takele. 2011. Iceberg lettuce production in California. University of California Vegetable Research and Information Center, Davis. Available at: Iceberg Lettuce Production in California (ucanr.edu). Accessed 24 August 2023.

125. U.S. Department of Agriculture. 2022. Irrigation & water use. Available at: https://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use/. Accessed 21 May 2023.

126. U.S. Food and Drug Administration. 1998. Guidance for industry: Guide to minimize microbial food safety hazards for fresh fruits and vegetables. Available at: https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-guide-minimize-microbial-food-safety-hazards-fresh-fruits-and-vegetables. Accessed 3 May 2023.

127. U.S. Food and Drug Administration. 2009. Draft guidance for industry: Guide to minimize microbial food safety hazards of leafy greens. Available at: https://wayback.archive-it.org/7993/20190206182702/https://www.fda.gov/Food/GuidanceRegulation/GuidanceDocumentsRegulatoryInformation/ucm174200.htm. Accessed 3 December 2023.

128. U.S. Food and Drug Administration. 2009. Draft guidance for industry: Guide to minimize microbial food safety hazards of tomatoes. Available at: https://www.federalregister.gov/documents/2009/08/03/E9-18453/draft-guidance-for-industry-guide-to-minimize-microbial-food-safety-hazards-of-tomatoes-availability. Accessed 3 December 2023.

129. U.S. Food and Drug Administration. 2015. Standards for the growing, harvesting, packing, and holding of produce for human consumption. *Fed. Regist.* 80:74353–74672.

130. U.S. Food and Drug Administration. 2021. FDA proposes changes to agricultural water requirements in the Produce Safety Rule. Available at: https://www.fda.gov/food/cfsan-constituent-updates/fda-proposes-changes-agricultural-water-requirements-produce-safety-rule. Accessed 26 March 2023.

131. U.S. Food and Drug Administration. 2021. FSMA proposed rule on agricultural water. Available at: https://www.fda.gov/food/food-safety-modernization-act-fsma/fsma-proposed-rule-agricultural-water. Accessed 10 April 2023.

132. U.S. Food and Drug Administration. 2021. Standards for the growing, harvesting, packing, and holding of produce for human consumption relating to agricultural water. *Fed. Regist.* 86:69120–69155.

133. VanKempen-Fryling, R. J., and A. K. Camper. 2017. *Escherichia coli* O157:H7 attachment and persistence within root biofilm of common treatment wetlands plants. *Ecol. Eng.* 98:64–69.

134. Vereen, E., R. R. Lowrance, M. B. Jenkins, P. Adams, S. Rajeev, and E. K. Lipp. 2013. Landscape and seasonal factors influence *Salmonella* and *Campylobacter* prevalence in a rural mixed use watershed. *Water Res.* 47:6075–6085.

135. Verhaelen, K., M. Bouwknegt, S. A. Rutjes, and A. M. de Roda Husman. 2013. Persistence of human norovirus in reconstituted pesticides—Pesticide application as a possible source of viruses in fresh produce chains. *Int. J. Food Microbiol.* 160:323–328.

136. Wall, G. L., D. P. Clements, C. L. Fisk, D. M. Stoeckel, K. L. Woods, and E. A. Bihn. 2019. Meeting report: Key outcomes from a collaborative summit on agricultural water standards for fresh produce. *Compr. Rev. Food Sci. Food Saf.* 18:723–737.

137. Walters, S. P., A. L. Thebo, and A. B. Boehm. 2011. Impact of urbanization and agriculture on the occurrence of bacterial pathogens and *stx* genes in coastal waterbodies of central California. *Water Res.* 45:1752–1762.

138. Wanjugi, P., G. A. Fox, and V. J. Harwood. 2016. The interplay between predation, competition, and nutrient levels influences the survival of *Escherichia coli* in aquatic environments. *Microb. Ecol.* 72:526–537.

139. Weller, D., A. Belias, H. Green, S. Roof, and M. Wiedmann. 2020. Landscape, water quality, and weather factors associated with an increased likelihood of foodborne pathogen contamination of New York streams used to source water for produce production. *Front. Sustain. Food Syst.* 3:124.

140. Weller, D., N. Brassill, C. Rock, R. Ivanek, E. Mudrak, S. Roof, E. Ganda, and M. Wiedmann. 2020. Complex interactions between weather, and microbial and physicochemical water quality impact the likelihood of detecting foodborne pathogens in agricultural water. *Front. Microbiol.* 11:134.

141. Weller, D., M. Wiedmann, and L. K. Strawn. 2015. Irrigation is significantly associated with an increased prevalence of *Listeria monocytogenes* in produce production environments in New York State. *J. Food Prot.* 78:1132–1141.

142. Weller, D., M. Wiedmann, and L. K. Strawn. 2015. Spatial and temporal factors associated with an increased prevalence of *Listeria monocytogenes* in spinach fields in New York State. *Appl. Environ. Microbiol.* 81:6059–6069.

143. Wilkes, G., T. A. Edge, V. P. J. Gannon, C. Jokinen, E. Lyautey, N. F. Neumann, N. Ruecker, A. Scott, M. Sunohara, E. Topp, and D. R. Lapen. 2011. Associations among pathogenic bacteria, parasites, and environmental and land use factors in multiple mixed-use watersheds. *Water Res.* 45:5807–5825.

144. Williams, T. R., A. L. Moyne, L. J. Harris, and M. L. Marco. 2013. Season, irrigation, leaf age, and *Escherichia coli* inoculation influence the bacterial diversity in the lettuce phyllosphere. *PLoS One* 8(7):e68642.

145. Won, G., A. Gill, and J. T. LeJeune. 2013. Microbial quality and bacteria pathogens in private wells used for drinking water in northeastern Ohio. *J. Water Health* 11:555–562.

146. Wu, S., P. N. Carvalho, J. A. Müller, V. R. Manoj, and R. Dong. 2016. Sanitation in constructed wetlands: A review on the removal of human pathogens and fecal indicators. *Sci. Total Environ.* 541:8–22.

147. Yin, H. B., G. Gu, X. Nou, and J. Patel. 2019. Comparative evaluation of irrigation waters on microbiological safety of spinach in field. *J. Appl. Microbiol.* 127:1889–1900.

148. Yin, H. B., X. Nou, G. Gu, and J. Patel. 2018. Microbiological quality of spinach irrigated with reclaimed wastewater and roof-harvest water. *J. Appl. Microbiol.* 125:133–141.

149. Zhu, L., M. Torres, W. Q. Betancourt, M. Sharma, S. A. Micallef, C. Gerba, A. R. Sapkota, A. Sapkota, S. Parveen, F. Hashem, E. May, K. Kniel, M. Pop, and S. Ravishankar. 2019. Incidence of fecal indicator and pathogenic bacteria in reclaimed and return flow waters in Arizona, USA. *Environ. Res.* 170:122–127.