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Foodborne pathogens in horticultural production systems: Ecology and mitigation

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ABSTRACT

Foodborne pathogen outbreaks have become an increasing problem in the horticultural industry due to changes in diets, production, processing and distribution practices, as well as greater awareness and detection. Once produce is infected, outbreaks can spread rapidly resulting in illness and even death among large groups of people. Strict new food safety laws have been implemented to reduce risks, but outbreaks are still occurring. Pathogens with the greatest threat in ready-to-eat horticultural crops include *Salmonella enterica*, *Escherichia coli* (STEC), and *Listeria monocytogenes*, with contamination introduced through animal manure, water, seeds and plant debris. While previously thought to be only transient inhabitants of horticultural production systems, it is now clear that enteric pathogens are adapted to survive for prolonged periods outside of their animal hosts, attaching tenaciously to plants via biofilm formation and internalization in plant tissues. Management practices including treating animal manure, water and seeds, increasing soil biological diversity and activity, and limiting damage to plants via pests and equipment can help reduce food safety risks in pre-harvest production systems. Further reducing food safety risks in these systems will require innovative, interdisciplinary research that integrate the fields of soil microbial ecology, plant pathology, plant breeding and engineering. Specifically, we advocate for additional research to: 1) better understand how soil and phyllosphere ecology affects pathogen residence time, 2) identify key traits and markers to integrate selection for enteric pathogens into crop breeding programs, and 3) develop new detection technologies that rapidly and accurately detect enteric pathogens on produce.

1. Introduction to the challenges of foodborne pathogens in the horticultural industry

The occurrence and severity of illnesses linked to foodborne pathogens has become a growing problem worldwide. In the United States alone, the Center for Disease Control (CDC) estimates that 48 million people, or 1 in 6 Americans, get sick from a foodborne illness each year (Painter et al., 2013). Approximately 48% of these outbreaks are linked to the consumption of fresh fruits and vegetables. Illnesses linked to foodborne pathogens occur in a diverse assortment of fruit and vegetable crops, and are caused by a wide variety of organisms including many genera and species of bacteria, viruses and parasitoids (reviewed in Köpke et al., 2007). For example, *Listeria* spp. have been found in cantaloupe (CDC, 2011); *Salmonella enterica* in tomatoes, seed sprouts, cantaloupe and mamey (Beuchat, 2002); *Escherichia coli* in lettuce, sprouts and carrots; *Shigella* spp. in lettuce, scallions and parsley; *Vibrio chloerae* in strawberry; parasites in raspberries and basil; and, hepatitis A virus in lettuce and raspberries (Buck et al., 2003). The number of microbial taxa implicated in foodborne pathogen outbreaks is expected to rise in coming decades as other lesser-known pathogens and new bacterial strains continue to emerge as causal agents (Berg et al., 2014).

Enteric pathogens that are capable of colonizing animal intestines are currently of the greatest concern for causing illness in fresh produce (Fernandez-Alvarez et al., 1991; Beuchat, 1996). In particular, *E. coli* O157:H7 and *S. enterica* are the most common etiologic agents of disease outbreaks linked to the consumption of fresh produce (Mootinan et al., 2009; Olaimat and Holley, 2012), because of their low infection doses (Chart, 2000; Darwin and Miller, 1999; Tilden Jr. et al. 1996) and

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ability to survive under refrigerated conditions (De Rover, 1998). *Listeria monocytogenes* is generally most problematic in processed ready-to-eat cold-stored meat and dairy products; though several recent outbreaks linked to contamination of fresh produce indicate that this pathogen is also becoming increasingly problematic in horticultural systems (Zhu et al., 2017). Crops consumed raw (ready-to-eat) rather than cooked prior to consumption pose the greatest food safety risk (Hoffmann et al., 2015). Crops most often implicated in foodborne illnesses are leafy greens, seed sprouts, melon, cantaloupe, berries, tomatoes, and green onions (Mandrell, 2009; Sivapalasingam et al., 2004; Fletcher et al., 2013).

1.1. Implications for human health

Outbreaks of enteric pathogens in fresh produce are generally rare, resulting in a low number of total cases per capita consumption of food items overall (0- < 10%) (Mandrell, 2009). However, when outbreaks do occur, they can have dramatic effects on human health. Of the Americans infected by a foodborne illness annually, 128,000 are hospitalized and 3000 die (Painter et al., 2013). Moreover, unlike other diseases, illnesses caused by enteric pathogens result from a single acute exposure to the microbial hazard. Consequently, once a food source becomes contaminated, outbreaks can spread rapidly infecting many people. In one of the largest outbreaks in recent history, over 6000 schoolchildren became ill as a result of eating white radish sprouts infected with *E. coli* O157:H7 grown at a single farm in Japan (Michino et al., 1999). In the U.S. state of Colorado, an outbreak of *Listeria* spp. in cantaloupe linked to a single farm killed 33 people (https://www.cdc.gov/listeria/outbreaks/cantaloupes-jensen-farms/index.html).

Factors that affect foodborne pathogen outbreaks include virulence of the pathogen, pathogen load, and immune response of the host with the children, elderly and those with compromised immune systems being most susceptible (reviewed in Mandrell, 2009).

1.2. Implications for the horticultural industry

Outbreaks of foodborne pathogens can cause serious damage to the horticultural industry. The U.S. Department of Agriculture Economic Research Service (USDA-ERS) estimates that in the U.S., foodborne illnesses impose over $15.5 billion in economic burden annually (Hoffmann et al., 2015). An 8-day recall of spinach in 2006 cost over $350 million to the U.S. economy alone (Hussain and Dawson, 2013). In some cases, farms are liable for their role in pathogen outbreaks. Owners of the Colorado farm linked to the *Listeria* spp. outbreak in cantaloupe were fined and sentenced to probation and home detention for their role in the deaths associated with this outbreak (https://www.usatoday.com/story/news/nation/2014/01/28/sentencing-of-colorado-cantaloupe-farmers/4958671/). After an outbreak of *Salmonella* spp. was linked to cantaloupes grown in the U.S. state of Indiana in 2012, many farms stopped producing this high-value crop rather than risk additional outbreaks and associated lawsuits (S. Monroe, Purdue Food Safety Specialist, personal communication), and acreage devoted to this crop declined by over 52% within just two years (USDA-NASS, 2015).

Table 1
USDA FSIS and FDA food safety guidelines for determining the bacteria quality of ready-to-eat foods and pasteurized egg products [8,9].

Pathogens[1]	Sample weight (g)	Types
E. coli O157	325	Raw product
Non-O157 Shiga toxin producing *E. coli*	325	"n60"[2] trim sample[15]
Listeria monocytogenes	25	Ready to eat product and pasteurized egg product
	Presence in food contact surface swab	
Salmonella spp	325	Ready to eat product
	100	pasteurized egg product

[1] Cell should not be detected in 325, 100 or 25 g of target food.
[2] N60 is considered the gold standard sampling procedure for beef trimmings applied for raw ground, which is used in the beef industry.

1.3. Legislation to prevent disease outbreaks in fresh or ready-to-eat food

In response to the increasing prevalence of foodborne pathogen outbreaks, new regulations have been put into place to try preventing food safety risks. Criteria for quality control are based on aspects of global food culture, eating habits, and food types consumed by vulnerable populations (e.g. pregnant, immunocompromised people and infants). For example, the FDA Food Safety Modernization Act (FSMA), the most sweeping reform of the U.S. food safety laws in more than 70 years, was signed into law by President Obama on January 4, 2011. FSMA aims to ensure that the U.S. food supply is safe by shifting the focus from responding to contamination to preventing it (https://www.fda.gov/food/guidanceregulation/fsma/ last updated on 06/21/2107).

The categories and corresponding regulations of ready-to-eat foods in the U.S. (CFS, 2007; FDA, 2001), Hong Kong (CFS, 2007), Australia (FDA, 2001), New Zealand (NSW, 2009), and the European Union (CR, 2005) are summarized in Tables 1–4. In the U.S., ready-to-eat foods

Table 2
Government of Hong Kong Special Administrative Region food safety guidelines for determining the bacteria quality of ready-to-eat foods[8].

Criterion	Class A*	Class B**	Class C***	Class D****
Pathogens	Unit (CFU/g)			
***E. coli* (total)**	< 20	20 to > 100	≥100	NA
***E. coli* O157**	ND in 25 g	NA	NA	Present in 25 g
***Salmonella* spp.**	ND in 25 g	NA	NA	Present in 25 g
***E. coli* (total)**	< 20	20 to < 100	≥100	NA
L. monocytogenes				
-For food under refrigeration (excluding frozen food) or food intended for infants	ND## in 25 g	NA	NA	Present in 25 g
-For other ready-to-eat food	< 20	20 to < 100	NA	≥100

* Class A means the microbiological status of the food sample is satisfactory.
** Class B means the microbiological status of the food sample is less than satisfactory, but still acceptable for consumption.
*** Class C means the microbiological status of the food sample is unsatisfactory. This may indicate sub-optimal hygienic conditions and microbiological safety levels. Licensees of food premises should be advised to investigate and find out the causes and to adopt measures to improve the hygienic conditions. Taking off follow-up samples to verify the improvement may be required.
**** Class D denotes the microbiological status of the food sample is unacceptable. The food sample contains unacceptable levels of specific pathogens that is potentially hazardous to the consumer. NA means not applicable/ND means not detected.