Mapping foodborne pathogen contamination throughout the conventional and alternative poultry supply chains

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ABSTRACT Recently, there has been a consumer push for natural and organic food products. This has caused alternative poultry production, such as organic, pasture, and free-range systems, to grow in popularity. Due to the stricter rearing practices of alternative poultry production systems, different types of levels of microbiological risks might be present for these systems when compared to conventional production systems. Both conventional and alternative production systems have complex supply chains that present many different opportunities for flocks of birds or poultry meat to be contaminated with foodborne pathogens. As such, it is important to understand the risks involved during each step of production. The purpose of this review is to detail the potential routes of foodborne pathogen transmission throughout the conventional and alternative supply chains, with a special emphasis on the differences in risk between the two management systems, and to identify gaps in knowledge that could assist, if addressed, in poultry risk-based decision making.

Key words: broilers, alternative broiler production, *Salmonella*, *Campylobacter*, organic

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INTRODUCTION

Foodborne pathogens such as *Salmonella* spp. and *Campylobacter* spp. present a major concern for the poultry industry on a yearly basis due to their association with poultry-related foodborne illnesses. Transport crates, poor environmental conditions, poor worker hygiene, and bird-to-bird pathogen transfer have all been identified as major preharvest contamination risk factors (Baggesen et al., 1992; Heyndrickx et al., 2002; Bull et al., 2006). During processing, poultry carcasses are primarily contaminated with pathogenic bacteria due to the leakage of fecal matter during major processing steps (Berrang et al., 2001). Cross-contamination has also been identified as a major risk factor during processing (Rasschaert et al., 2008). Intervention strategies are implemented at the preharvest and postharvest levels to mitigate the risk of contamination of the poultry product by these pathogenic bacteria.

In recent years, increased demand for antibiotic-free, "natural" products has pushed consumers towards the organic food market (Dimitri and Oberholtzer, 2009; Reisch et al., 2013). This has impacted the poultry industry, where broiler meat harvested from alternative poultry farming production facilities, such as organic and free-range, have increased in demand (van Loo et al., 2011; Rothrock Jr. et al., 2016). These types of operations are characterized by the lack of antibiotic use and the allowance of birds to access the outside environment. As such, birds are exposed to a less controlled environment, indicating an increased risk of microbial contamination of the birds.

The goal of this review is to map the potential routes of transmission of foodborne pathogens into poultry flocks and products throughout the poultry production and supply chain. An emphasis is included on the differences in management practices and risks associated between conventional and alternative (e.g., organic, pastured, free-range) poultry production systems, identifying gaps in knowledge that, if addressed, could benefit risk-based decision making in the industry.

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POULTRY PRODUCTION CHAIN

Overview

Conventional Poultry Production. Conventional poultry farms are the main source of poultry meat and eggs worldwide. In 2013, experts estimated that conventional poultry farms accounted for 90 to 95% of the broiler production in the European Union (van Horne and Bondt, 2013). Similarly, conventional livestock and poultry production accounted for approximately 88% of United States sales in 2015 (Greene et al., 2017).

Conventional poultry farms are characterized by large, enclosed houses that contain a high density of birds. Castellini et al. (2006) reported that an Italian conventional poultry farming system contained more birds per unit (15,600) than an organic farming system (1,000) and that, on average, the final broiler weight was higher in conventional systems, while mortality rate was lower. Part of this phenomenon is due to the use of antibiotics in conventional poultry production systems. Conventional poultry farms commonly use antibiotics for both therapeutic and prophylactic measures (Wegener, 2003; Sapkota et al., 2007). Traditionally, conventional farms incorporated antibiotics into broiler feed to help stimulate growth and improve feed efficiency (Threlfall et al., 2000; McEwen and Fedorka-Cray, 2002; Wegener, 2003). With recent advances on the study of antibiotic-resistant microorganisms, the United States has moved away from the prophylactic use of antibiotics, while the EU has banned their use as growth promoters in poultry feed (Castanon, 2007).

The conventional broiler production chain contains numerous opportunities for bacterial contamination from farm-to-fork (Heyndrickx et al., 2002). Typically, 1-day old broiler chicks are obtained from hatching facilities and transported to grow out facilities, where they are reared for 5 to 8 weeks before being slaughtered. Broilers are subsequently further processed and transported to retail facilities. Once reaching retail, broilers can be sold as whole carcasses, cut parts, or further processed chicken products. In 2015, it was forecasted that 11% of United States broilers were sold whole, 40% as cut-up parts, and 49% as further processed products (National Chicken Council, 2015).

Alternative Poultry Production Alternative types of poultry production operations include organic, pastured, and free-range systems. While the production chain is similar to conventional operations, alternative production systems are characterized by alternative rearing practices. Organic poultry farms are characterized by farms that rear birds without the use of antibiotics and allow the birds access to the outside (free-range), while pastured poultry operations require moveable pens/housing that are moved to fresh pasture on a daily basis (American Pastured Poultry Producers Association, 2017). Additionally, alternative poultry productions systems commonly use slow-growing bird breeds (Castellini et al., 2006; Fanatico et al., 2009). Because of these practices, alternative poultry operations are faced with higher bird mortality rates, with necrotic enteritis being a particular problem (Fanatico et al., 2009).

Organic farming has been traced back as far as the 1940s to writings of Sir Albert Howard and Lady Eve Balfour describing the practice (Klonsky and Tourte, 1998). Organic products became widely popular in the United States during the 2000s, when retail sales of organic foods increased from $3.6 billion in 1997 to $21.1 billion in 2008 (Dimitri and Oberholtzer, 2009). In 2016, organic broiler chickens accounted for approximately $750 million in sales in the United States (United States Department of Agriculture, 2017). This is characterized by consumers' desire for sustainable food consumption and products that are considered "natural" (Reisch et al., 2013). Consumers have also shown the belief that organic foods are safer and healthier than conventionally produced foods, but there has been no scientific evidence to prove this hypothesis (Hughner et al., 2007; Sofos, 2008; van Loo et al., 2011).

In 2002, the United States Department of Agriculture's **(USDA)** Agricultural Marketing Service (AMS) implemented the National Organic Program (NOP) to oversee the production of organic foods and implement uniform national regulations (Raab and Grobe, 2005). Currently, the USDA still oversees organic farming and provides mandates on labeling and production (United States Department of Agriculture, 2016). The USDA regulations for organic certification of poultry are contained in 7 CFR §205. The key points of these regulations are summarized in Table 1 (Electronic Code of Federal Regulations (2018)).

MICROBIOLOGICAL CONCERNS FACING THE POULTRY INDUSTRY

Foodborne Pathogens of Concern

Salmonella *spp* *Salmonella* spp. are Gram-negative, rod-shaped, motile, facultative anaerobic bacteria that are part of the *Enterobacteriaceae* family. The *Salmonella* genus contains 2 species, *Salmonella enterica* and *Salmonella bongori*. Each species contains several serotypes that are differentiated by surface and flagellar antigens (Brenner et al., 2000). Currently, there are more than 2,500 different serotypes in the *Salmonella* genus (Grimont and Weill, 2007). About 95% of all United States non-typhoidal salmonellosis cases are foodborne (Mead et al., 1999). *Salmonella enterica* remains one of the most common causes of foodborne illness worldwide. In 2010, it was estimated that there are approximately 93.8 million cases of gastroenteritis and approximately 155,000 deaths due to *Salmonella* spp. infection worldwide annually, with approximately 80.3 million of the cases being foodborne (Majowicz et al., 2010).

The burden of *Salmonella* on the United States broiler industry is high. From 1998 to 2017, there were 298 salmonellosis outbreaks due to consumption of chicken, resulting in 7,881 illnesses, 905 hospitalizations, and 4 deaths (Centers for Disease Control and Prevention,

Table 1. United States Department of Agriculture standards for organic poultry production according to 7 CFR §205.[1]

Factor	Key points	CFR section
Origin of livestock	All birds intended for slaughter/egg production must be under organic management by the second day of life	§205.236
Livestock feed	All feed, feed additives, and feed supplements must be 100% certified organic; water additives must be consistent with the regulations in §205.603	§205.237
Livestock health care	Animals must be kept in low stress environments; no hormones can be used to induce growth; no antibiotics can be used to treat birds that will be marketed as organic	§205.238
Livestock living conditions	Animals must have access to the outside, unless due to inclement weather; housing must provide room for exercise, direct sunlight, fresh air, shade, shelter, and adequate ventilation, supply of clean water, and sanitation	§205.239
Carcass washes	Carcass wash water can contain chlorine levels permitted by FDA[2] and EPA[3], but must be followed by a rinse with potable water that does not exceed 4 ppm chlorine	§205.102
Marketing and labeling	Products represented as "100% organic" or "organic" must include handler information and "Certified by ___" statements naming the appropriate certifying agency	§205.303
Record keeping	Accurate records must be kept on an ongoing basis; common records to be kept: feed receipts/certificates, sales records, production records, mortality/cull records	§205.103

Source: Electronic Code of Federal Regulations (2018).
[1]Source: Electronic Code of Federal Regulations (2018).
[2]Food and Drug Administration (FDA).
[3]Environmental Protection Agency (EPA).

2020). Realistically, the number of illnesses caused by *Salmonella*-contaminated broiler meat and products is likely much higher, due to sporadic illness events and unreported outbreak cases. A select number of recent United States multistate salmonellosis outbreaks due to consumption of chicken are described in Table 2. The high number of annual illnesses caused by *Salmonella* contamination of broiler meat underscores the importance of controlling for the organism.

Multiple serotypes of *Salmonella* were implicated in salmonellosis outbreaks in the United States from 2010 to 2019 (Table 2). A serotype of particular note is *Salmonella* I 4,[5],12:i:-, a monophasic variant of *Salmonella Typhimurium* (Garaizar et al., 2002). This *Salmonella* serotype has been identified as an emerging disease-causing serotype of *Salmonella* (Moreno Switt et al., 2009). Although sporadically isolated in the mid-1900s, the serotype did not receive much attention in the peer-reviewed literature until the late 1980s, when it was isolated from chicken carcasses in Portugal (Machado and Bernardo, 1990). Reported illness data support the emergence of this serotype as a disease causing agent in the United States, as it was the fifth most common salmonellosis-causing serotype in the nation in 2016, compared to the 18th in 2002 (Moreno Switt et al., 2009; Centers for Disease Control and Prevention, 2016). Some have suggested that the serotype is of primary concern for the pork industry (Bone et al., 2010), but its isolation from chicken carcasses, ground chicken, and live chickens and foodborne illness outbreaks attributed to chicken contaminated with *Salmonella* I 4,[5],12:i:- show its major implication for the poultry industry (Machado and Bernardo, 1990; Zamperini et al., 2007; Centers for Disease Control and Prevention, 2018b).

Campylobacter *spp* *Campylobacter* spp. are Gram-negative, spiral-shaped, microaerophilic bacteria that are part of the *Campylobacteraceae* family. The *Campylobacter* genus consists of 25 species and 8 subspecies (Man, 2011). Of particular interest to the food industry are *C. jejuni* and *C. coli*, which can be isolated from all types of domestic livestock and some wild animals (Humphrey et al., 2007). *Campylobacter* spp. have optimal growth ranges between 37° and 42°C, and rarely grow at <30°C. Some thermotolerant strains of *C. jejuni* and *C. coli* have optimal growth ranges between 42° and 45°C. These strains are thought to have adapted to the avian gastrointestinal tract, which is at a temperature of around 42°C (Park, 2002). Furthermore, the microaerophilic nature of *Campylobacter* spp. is potentially due to the lack of oxygen that exists in the avian gut (Park, 2002). *Campylobacter* spp. can remain viable in food products at temperatures as low as 4°C. While freezing reduces the viability of the cells, low levels of

Table 2. Chicken-associated salmonellosis outbreaks in the United States and Puerto Rico during 2011−2018.

Year	Food source	Serovar	Cases	Deaths	Reference
2011	Kosher broiled chicken livers	Heidelberg	190	0	(Centers for Disease Control and Prevention, 2012)
2012−2013	Chicken	Heidelberg	134	0	(Grinnell et al., 2013)
2013−2014	Chicken	Heidelberg	634	0	(Centers for Disease Control and Prevention, 2014)
2015	Raw, frozen, stuffed chicken	Enteritidis	15	0	(Centers for Disease Control and Prevention, 2015a)
2015	Raw, frozen, stuffed chicken	Enteritidis	5	0	(Centers for Disease Control and Prevention, 2015b)
2018	Chicken salad	Typhimurium	265	1	(Centers for Disease Control and Prevention, 2018a)
2018	Chicken	I 4,[5],12:i:-	25	1	(Centers for Disease Control and Prevention, 2018b)
2018	Chicken	Infantis	129	10	(Centers for Disease Control and Prevention, 2019)

Campylobacter have been recovered in food products stored at temperatures as low as −20°C after several weeks (Lee et al., 1998; Alter and Scherer, 2006)

Campylobacter spp. are one of the leading causes of gastroenteritis worldwide. Sporadic cases and underreporting of cases make the annual burden of *Campylobacter* spp. difficult to quantify, but according to Centers for Disease Control and Prevention (CDC) expert elicitation, there were 4,936 total outbreak cases as part of 120 foodborne-campylobacteriosis outbreaks in the United States from 1999 to 2008 (Batz et al., 2012; Wagenaar et al., 2013). Evidence suggests that there has been a rise in the incidence of *Campylobacter* worldwide over the past decade, including rising rates in North America, Europe, and Australia (Kaakoush et al., 2015). In 2012, it was estimated that the annual cost of all *Campylobacter*-associated illnesses was approximately $1.7 billion, illustrating the high economic burden of the microorganism (Hoffmann et al., 2012).

Due to its presence in the gut of animals that are commonly used for food, *Campylobacter* is most often associated with poultry meat and products, unpasteurized milk, beef, and other meat products. Untreated water has also been frequently implicated as the cause of sporadic campylobacteriosis cases (Hopkins et al., 1984; Domingues et al., 2012). Environmental samples, such as groundwater, can also harbor *Campylobacter* (Schaffter et al., 2004).

Other Pathogens. While most poultry safety-related research is focused on *Salmonella* spp. and *Campylobacter* spp., researchers have identified other organisms as potential concerns for the poultry industry. In 2000 and 2002, there were multistate listeriosis outbreaks in the United States linked to the contamination of turkey deli meat (Olsen et al., 2005; Gottlieb et al., 2006). Currently, there have been no chicken-associated listeriosis outbreaks in the United States, but the risk remains clear. In a survey of United States and United Kingdom foods, Gilbert et al. (1989) found 12% of ready-to-eat poultry product samples and 60% of raw chicken samples contaminated with *Listeria monocytogenes*. Conversely, Berrang et al. (2000b) did not consistently identify *L. monocytogenes* in raw, chilled broiler carcasses. Multiple studies have identified the organism in poultry processing and further processing plants (Berrang et al., 2005; Berrang et al., 2010). Loura et al. (2005) reported that raw broiler meat, worker hands, and processing equipment were sources of contamination of *L. monocytogenes* in poultry processing plants. Understanding the routes of contamination in these types of poultry processing environments is of high importance to lower the risk of cross-contamination to fully cooked product. Limiting birds' exposure to the organism before processing could help reduce the risk of the entry of the organism into processing environments. More data need to be collected on the presence of *Listeria* spp., and specifically *L. monocytogenes*, in the environment of poultry farms. Golden et al. (2019) found *Listeria* spp. and *L. monocytogenes* in 15.9 and 1.8%, respectively, of environmental (soil and feces) samples from pastured poultry farms. Due to the ubiquitous nature of *L. monocytogenes* in the environment and the rise in alternative poultry production methods, *L. monocytogenes* should be considered an emerging pathogen of concern for the poultry industry.

Arcobacter butzleri is another emerging foodborne pathogen in the food industry, characterized by its ability to cause gastroenteritis, bacteremia, and septicemia in humans and frequent isolation from animal-sourced foods (Atabay et al., 2003; Mor-Mur and Yuste, 2010). *Arcobacter* spp. are phylogenetically and phenotypically very similar to *Campylobacter* spp. (Vandamme and De Ley, 1991). Poultry is considered a main source of *A. butzleri*, with pork and beef being other major sources (Ho et al., 2006). *Arcobacter butzleri* has been commonly isolated from food processing environments, and particularly in slaughterhouses (Collado and Figueras, 2011; Ferreira et al., 2013; Giacometti et al., 2015). The organism has also shown the ability to form biofilms in food processing environments, which could act as a cross-contamination source to food products (Ferreira et al., 2013). Due to its association with poultry, *A. butzleri* is a potential pathogen of concern for the poultry industry. In 2008, *A. butzleri* was implicated as the likely cause of a foodborne illness outbreak related to chicken consumption at a wedding in Wisconsin, resulting in 51 illnesses (Lappi et al., 2013). Studies have found it highly prevalent on broiler carcasses and processing equipment at various points during processing (Houf et al., 2002; Son et al., 2007) and in retail meat (Atabay et al., 2003; Kabeya et al., 2004).

Preharvest Contamination Routes

Poultry as Reservoirs for Pathogenic Bacteria. The gastrointestinal tracts of poultry are significant reservoirs for *Salmonella* and *Campylobacter*, indicating why the two organisms have presented such a large public health risk for poultry-based food products. This is of major importance because organisms present in the gut of birds have the potential to spread to the outside of the bird during processing, posing a potential route of contamination for poultry meat. An understanding of the colonization properties of poultry-related foodborne pathogens is needed to help mitigate the risk of the organisms.

Campylobacter is a commensal microorganism in the gut of poultry and is mainly present in the cecum and colon (Berrang et al., 2001; Epps et al., 2013). Colonization of the gut normally occurs approximately three weeks after bird hatching, with the presence of maternal antibodies identified as a potential cause of the delay (Jacobs-Reitsma et al., 1995; Sahin et al., 2001; Hiett et al., 2002). The potential sources of *Campylobacter* that colonize the guts of birds have been examined in several studies. The external environment, previous poultry flocks, other domestic animals, contaminated water, and vertical transmission from parent birds have been suggested as potential major sources of

contamination (Pearson et al., 1993; Pearson et al., 1996; Petersen and Wedderkopp, 2001; Hiett et al., 2002). Bull et al. (2006) identified bird transport as a major contamination risk. Horizontal transfer of *Campylobacter* through bird feces has been identified as one of the major sources of flock contamination, and once a bird is contaminated, bird-to-bird transmission occurs rapidly (Humphery et al., 1993; Shreeve et al., 2000; Newell and Fearnley, 2003).

Unlike with *Campylobacter*, younger birds are more susceptible to *Salmonella* colonization than older birds (Milner and Shaffer, 1952; Bailey, 1988). Early studies of Milner and Shaffer (1952) showed that day-old chicks could be infected by as little as 5 *Salmonella* cells, while older birds were infected less frequently and required higher doses of *Salmonella* to be infected. Subsequently, *Salmonella* incidence in poultry decreases as the rearing time progresses (Lahellec and Colin, 1985). Nurmi and Rantala (1973) proposed that as birds grow in age, their intestinal microbiota develops and becomes more resistant to colonization by pathogens such as *Salmonella*, a phenomenon that has become known as competitive exclusion. Horizontal transmission of the organism has been identified as the major source for flock contamination (Heyndrickx et al., 2002). Poor hygiene, feed contamination, contamination by small animals including rodents and insects, size of farm, and carryover from the previous flock have all been identified as other significant risk factors (Lahellec and Colin, 1985; Baggesen et al., 1992; Skov et al., 1999; Heyndrickx et al., 2002). Interestingly, Heyndrickx et al. (2002) found no correlation between bird contamination during rearing and final product contamination, but instead identified fecal matter in transport crates as the major correlator of end product safety. Rasschaert et al. (2008) also identified that gastrointestinal colonization of birds with *Salmonella* was not correlated with final product food safety and identified cross-contamination from slaughter equipment as the main source of contamination. Despite this, poultry producers use *Salmonella* vaccines in young chicks to induce cell-mediated immunity and reduce the risk of further colonization of the gut by virulent *Salmonella* (Babu et al., 2003). The use of probiotics/prebiotics and various feed additives have also been shown to lower the probability of *Salmonella* gut colonization (Park and Kim, 2014; Carter et al., 2017; Vermeulen et al., 2017).

Studies have shown that poultry can serve as a potential reservoir for *Listeria* spp. Njagi et al. (2004) reported that the intestinal tracts of chickens and other types of poultry can act as reservoirs for *Listeria* in live operations. Dhama et al. (2013) further touched on this point and suggested that poultry can spread the organism into the litter and environment through fecal matter. This is important to note, because this marks a potential route of *Listeria* contamination into processing facilities and potentially the final poultry product. Due to the ubiquity of the organism, *Listeria* could pose a potentially increased risk to the organic poultry industry, where birds are allowed access to the natural environment (Bailey and Cosby, 2005; Miranda et al., 2008b). While the risk is noted, Milillo et al. (2012) found that only 7 of 399 (1.75%) of cecal samples from pasture-reared poultry were *Listeria*-positive, and showed that samples were positive for *L. monocytogenes* and hemolytic *L. innocua*. These researchers indicated that *Listeria* was more frequently isolated from younger birds, indicating that as the birds' intestinal microbiota matures, *Listeria* numbers decrease, but no follow up study was performed. Additionally, Locatelli et al. (2017) isolated a higher number of *L. innocua* isolates from feces and soil samples collected from pastured poultry farms when compared with *L. monocytogenes* isolates, similar to conventional poultry farms. Reports of the presence of *L. monocytogenes* in poultry processing plants further emphasize the need for a clear understanding of the relationship between poultry and *Listeria*.

Environmental Contamination. As mentioned previously, pathogen prevalence in cages during transport of birds has been linked to a higher prevalence of pathogen contamination in the final product (Heyndrickx et al., 2002; Bull et al., 2006). Additionally, contaminated poultry litter, feed, and drinking water have been identified as potential risk factors for increased pathogen risk in the final poultry product (Maciorowski et al., 2004; van Immerseel et al., 2009; Volkova et al., 2009). Contamination of these items can result from environmental factors, such as contaminated feces and soil, small animals, such as insects and rodents, and poor worker hygiene. Because of this, subsequent measures have been taken by poultry farmers to improve biosecurity measures and to implement proper worker hygiene (van Immerseel et al., 2009). Due to the nature of alternative poultry operations, these factors can be more difficult to account for. A clear understanding of the comparative risk of environmental contamination in conventional and alternative poultry farms is still needed, but recent studies have worked to address this knowledge gap. Table 3 contains pathogen prevalence data from preharvest samples across numerous studies.

While the prevalence of foodborne pathogens in the environment of conventional poultry farms is well established, recent studies have statistically compared the two types of farms (Siemon et al., 2007; Alali et al., 2010; Peng et al., 2016; Kassem et al., 2017). Petkar et al. (2011) reported that *Salmonella* survival in conventional and organic broiler feeds was not significantly different. Alali et al. (2010) found that *Salmonella* contamination of fecal matter and bird feed was significantly lower in samples collected from organic farms when compared to conventional farms. This notion is supported by the work done by Siemon et al. (2007). Peng et al. (2016) found various environmental samples from organic mixed-crop livestock farms were more contaminated with *Salmonella* than conventional poultry farms. Hoogenboom et al. (2008) found no significant difference in *Salmonella* prevalence in the feces of organically raised swine and conventionally-raised swine. Similarly, fecal samples collected from conventional and

Table 3. Foodborne pathogen prevalence in preharvest samples collected from conventional and organic poultry farms.

Farm type	Organism	Sample type	No. (%) positive samples	Reference
Conventional	*Salmonella*	Feces	93 (38.8)	(Alali et al., 2010)
		Feed	3 (5.0)	
		Water	0 (0.0)	
Conventional	*Salmonella*	Feces	168 (6.6)	(Bailey et al., 2001)
		Litter	84 (10.5)	
Conventional	*Salmonella*	Feces	11 (6.5)	(Peng et al., 2016)
		Feed, water	4 (7.0)	
		Litter, flies	6 (5.1)	
Conventional	*Salmonella*	Soil	6 (12.5)	(Rodriguez et al., 2006)
		Litter	5 (10.4)	
Conventional	*Salmonella*	Feces	35 (8.8)	(Thakur et al., 2013)
		Litter, grass, feed	42 (8.4)	
Conventional	*Salmonella*	Feces	125 (29.8)	(Siemon et al., 2007)
Organic	*Salmonella*	Feces	10 (5.6)	(Alali et al., 2010)
		Feed	3 (5.0)	
		Water	0 (0.0)	
Organic	*Salmonella*	Feces	27 (15.6)	(Peng et al., 2016)
		Feed, water	15 (15.0)	
		Litter, flies	31 (23.0)	
Organic	*Salmonella*	Feces	83 (16.2)	(Siemon et al., 2007)
Conventional	*Campylobacter*	Air	6 (15.0)	(Schroeder et al., 2014)
		Feces, litter	8 (20.0)	
		Feed pans, water lines	18 (45.0)	
Conventional	*Campylobacter*	Feces	118 (29.5)	(Thakur et al., 2013)
		Litter, grass, feed	4 (0.8)	
Organic	*Campylobacter*	Feces	86 (86.9)	(Luangtongkum et al., 2008)
		Feed	9 (37.5)	
		Litter	11 (42.3)	
		Grass	17 (53.1)	
		Water	29 (85.3)	

organic dairy farms were not significantly different in *Salmonella* prevalence (Fossler et al., 2004). A comprehensive, multistate survey of the environmental contamination of conventional and alternative poultry farms is still needed.

Processing Contamination Routes

Scalding. Scalding is used prior to defeathering of carcasses primarily to help loosen the feathers of the bird. This step has been identified as a potential source of microbial contamination of birds via cross-contamination. Mulder et al. (1978) found that cross-contamination occurred during scalding when external contamination was introduced via dust and feathers. Controlling for bacterial load in the scalding water is imperative in preventing cross-contamination of bird carcasses. The reduction of organic matter in scalding water has been identified as a measure to reduce *E. coli* and coliform numbers (Incili and Çalicioğlu, 2018).

Traditionally, one-tank scalding systems containing 50° to 60°C water were used for this step, but time has given rise to other types of scalding systems including steam-scalding and three-tank, countercurrent scalders. Numerous studies have been conducted on the effect of the type of scalding operation used on the microbiological quality of carcasses. Steam-scalded carcasses were found to present significantly less coliforms than conventionally scalded carcasses (Patrick et al., 1972). The three-tank, countercurrent system is characterized by the use of 3 successive scalding tanks where the flow of water and carcasses move in the opposite direction, so that carcasses move into progressively cleaner water (Cason et al., 1999). This system has been shown to improve the microbial quality of birds after scalding when compared to traditional systems (James et al., 1992). This is likely due to the countercurrent flow of water and use of multiple tanks, where studies have found that coliform, *E. coli*, *Campylobacter*, and *Salmonella* numbers were reduced in successive tanks (Veerkamp and Heemskerk, 1992; Cason and Hinton Jr, 2006). Furthermore, when compared with *Enterobacteriaceae* numbers in a conventional single-tank scalding system, Veerkamp and Heemskerk (1992) found lower numbers in the third tank of a countercurrent system.

The effect of pH on microbial quality of scalder water has also been widely investigated. Humphrey and Lanning (1987) concluded that 50°C water with a high pH (approximately 9) had no overall effect on *Salmonella* and *Campylobacter* numbers on bird carcasses but found reductions in the amount of these bacteria in the scalding water compared to tanks with a traditional pH (approximately 6.5−7). Conversely, Berrang et al. (2011) found that 50° to 55°C scalding water with a mean pH of 9.89 significantly reduced *Campylobacter* numbers on carcasses when compared to control water with mean pH 6.88, but did not significantly reduce *Salmonella* and *E. coli* when compared to the control. The introduction of 0.1% acetic acid in scald tank water reduced D_{52} values for *Salmonella* Newport, *Salmonella* Typhimurium and *C. jejuni* when compared to a control treatment, showing the effect of reducing pH in the scalding tank (Okrend et al., 1986). McCarthy et al.

(2018) corroborated these results with the introduction of a mechanistic model that identified pH and temperature as major factors in microbial quality of scalder water.

Various other antimicrobials have shown effectiveness in reducing bacterial numbers in scalding tanks as well. The use of a 200-ppm n-alkyl dimethyl benzyl ammonium chloride-40% solution in scalding water resulted in significantly less aerobic mesophilic bacteria when compared with an untreated control (Lansini et al., 2017). Scalder water at 54°C exposed to an acidic, copper, sulfate-based commercial sanitizer for 2 min resulted in complete elimination of *Salmonella Typhimurium*, *Listeria monocytogenes, Staphylococcus aureus, Pseudomonas fluorescens,* and *Shewanella putrefaciens* and a significant reduction of *E. coli* (Russell, 2008).

Defeathering. After scalding, poultry carcasses are defeathered using automated machines with finger-like plucking appendages. Defeathering has been identified as a major potential source of microbial contamination. Nde et al. (2006) found that *Salmonella* prevalence increased from 7% on freshly slaughtered turkeys to 16% on defeathered turkeys. Berrang et al. (2001) found that one of 120 carcasses were *Campylobacter*-positive predefeathering compared with 95 of 120 carcasses postdefeathering.

Multiple studies have been conducted on the effect of cross-contamination during this step (Allen et al., 2003ab; Nde et al., 2007; Projahn et al., 2019). Using an *E. coli* K12 marker, Allen et al. (2003a) determined that cross-contamination during broiler defeathering was mainly attributed to aerosols, large droplets, and feathers. Furthermore, it was noted that forward and backward contamination occurred when an inoculated broiler carcass was introduced to the process, but cross-contamination was highest when carcasses came from inoculated scalding water. Subsequent studies have identified feathers as a potential source of contamination, specifically of *Salmonella* (Allen et al., 2003b; Nde et al., 2007; Rasschaert et al., 2007). Allen et al. (2003b) identified that defeathering reduced overall bacterial numbers on broiler carcasses but caused dispersion of a marker organism which caused forward and backward carcass contamination. Results from Nde et al. (2007) support this, demonstrating through molecular subtyping that identical *Salmonella* isolates present on turkey feathers were found on defeathered turkey carcasses. Additionally, antibiotic-resistant strains of *Klebsiella pneumoniae* and *E. coli* isolated from defeathering machines before processing were isolated from broiler carcasses after processing (Projahn et al., 2019).

The type of defeathering operation used also appears to have an effect. Clouser et al. (1995) investigated the difference between conventional, kosher, and steam-spray defeathering systems. It was found that the prevalence of *Salmonella* on turkey carcasses post-defeathering process only significantly increased for the conventional system (increasing from 21% to 71%). Defeathering system type also has a profound effect on turkey carcass skin (Kim and Doores, 1993). Conventional defeathering induced less *Salmonella* attachment due to smooth skin surface after the process when compared with kosher and steam-spray systems. Kosher defeathering systems caused the roughest turkey skin (Kim and Doores, 1993). Additionally, Arnold and Silvers (2000) identified that picker finger material can affect bacterial adhesion and attachment. Bacterial attachment was lowest in rubber picker material as compared to stainless steel, polyethylene, and conveyer belting. A study evaluating the bacterial load of rubber picker fingers at 3 farms showed variable results, with overall bacterial load from the fingers ranging from 0 to 7.33 log CFU.

Berrang et al. (2001) identified that contaminated fecal leakage during the defeathering process was a significant source of carcass contamination. Studies have analyzed the effects of various methods to overcome this problem. When a tampon device was applied to the inside of 120 broiler carcasses with subsequent cloacae suturing predefeathering, only 13 of the carcasses were *Campylobacter*-positive post-defeathering, compared to 95 of 120 *Campylobacter*-positive carcasses when defeathered conventionally (Berrang et al., 2001). A 50-cc dry sterile sponge plug was also identified as an effective way to prevent fecal leakage and subsequent *Campylobacter* contamination (Berrang et al., 2018). Other types of control measures have been tested as well. Overall bacterial numbers were significantly lower in carcasses that were treated with 1% acetic acid after defeathering than a water control, with counts of 3.93 and 4.53 log CFU/carcass, respectively, but the effect of hydrogen peroxide (H_2O_2) was negligible (Dickens and Whittemore, 1997). An additional scalding step after defeathering had no significant reduction effect on *Campylobacter*, *E. coli*, and other coliforms (Berrang et al., 2000a).

Research on the post-defeathering bacterial load on carcasses for alternative poultry operations is still limited. A recent study found that organically processed carcasses contained significantly less average *Campylobacter* CFU/unit than conventionally processed carcasses, with 1.6 log CFU/unit and 2.5 log CFU/unit, respectively (Bailey et al., 2018).

Evisceration. During evisceration, birds' viscera are removed by manual or automated methods. This involves the removal of the cloaca and rectum and the scooping out of the birds' entrails (Fries, 2002). Cross-contamination during this processing step has been widely observed to occur by items such as contaminated evisceration equipment and poor worker hygiene. Contamination of equipment can occur when a bird's gastrointestinal tract is ruptured during evisceration, thus leading to leakage of fecal material. Leakage of fecal matter can also contaminate the skin of poultry during this step (Abu-Ruwaida et al., 1994). Lillard et al. (1984) reported that *Salmonella* incidence was significantly higher in eviscerated carcasses than in unprocessed control carcasses. Contrary to this finding, Nde et al. (2006) found that there was no significant difference in *Salmonella* prevalence in pre- and post-eviscerated carcasses. Feed withdrawal is a measure that is

taken where birds are not fed up to 12 h before slaughtering to try and reduce the amount of fecal matter present in the bird that could pose a potential contamination risk if leaked during evisceration (Buncic and Sofos, 2012). It is important that birds are not withheld feed for an extended period of time, as feed withdrawal lasting longer than 12 h can result in thinning of the intestinal wall, which presents a higher chance of rupturing during evisceration, increasing the likelihood of fecal leakage (Warriss et al., 2004). Control of the evisceration process through proper evisceration techniques, good worker hygiene, and feed withdrawal should result in carcasses with less fecal contamination, and a subsequent reduction in bacterial pathogen risk.

Washing. After evisceration, poultry carcasses are often subjected to wash cycles to remove fecal and other organic matter from the surface and gut cavity of the carcasses. Numerous studies have shown that this step often leads to an overall reduction in bacterial numbers on poultry carcasses (Sakhare et al., 1999; Stopforth et al., 2007), but another study showed that subsequent washes with untreated water were ineffective at reducing *Campylobacter* numbers on carcasses (Bashor et al., 2004). Furthermore, introduction of contaminated carcasses to wash water poses a potential threat of cross-contamination. Numerous washing intervention strategies have been investigated to mitigate the risk during this processing step, including the use of antimicrobial chemicals and high temperature water.

The primary wash systems used in the poultry industry are immersion and spray washers. Early studies showed that there was no statistical difference in the efficacy of traditional spray washers versus inside/outside washers at reducing *Enterobacteriaceae* numbers (Mulder and Bolder, 1981). Later studies have shown that spray washers are effective at reducing bacterial numbers on the surface of poultry carcasses but struggle to access the inside of carcasses (Wang et al., 2018).

The use of chlorine (sodium hypochlorite) during washing of poultry is widespread across the conventional poultry industry, but recent reports have suggested that sodium hypochlorite can interact with organic molecules on the surface of food products to produce harmful byproducts including haloquinones, halo-cyclopentene and cyclohexene derivatives (Hinton Jr et al., 2007; Bull et al., 2011). Although the use of chlorine is permitted in alternative poultry processing (Table 1), many processors have trended towards the use of other antimicrobials such as peracetic acid and organic acid washes (Micciche et al., 2018). When compared to a 25 to 35 ppm chlorine wash, trisodium phosphate and acidified sodium chlorite washes reduced *Campylobacter* levels on carcasses by an additional 1.03 and 1.26 log CFU/mL on average, respectively (Bashor et al., 2004). Chlorine dioxide (100 ppm) treatments provided up to 1.21 log CFU/g reductions of *Campylobacter* on poultry (Hong and Song, 2009). Various concentrations of oleic acid (2−10% wt/vol) applied to wash water had a significant effect in reducing aerobic bacteria, *Enterobacteriaceae*, and *Campylobacter* (Hinton Jr and Ingram, 2000). Other fatty acids have also been studied, and Hinton Jr and Ingram (2005) found that a mixture of tripotassium phosphate and lauric and myristic acids were highly effective towards gram negatives, gram positives, and yeasts, proving its potential use to improve the safety of poultry and cause reduction of potential spoilage organisms as well. Carcasses washed in potassium hydroxide and lauric acid solutions contained up to 1.55 log CFU/g less aerobic bacteria (based on total plate counts) than carcasses washed in distilled water (Hinton Jr et al., 2007).

Electrolyzed water has been characterized as another potential alternative to traditional chlorine washes (Park et al., 2002; Wang et al., 2018). Electrolyzed water (containing 25 mg/L of residual chlorine) reduced *Campylobacter* levels up to 3 log CFU/g on broilers compared to 1 log CFU/g after an untreated water was used (Park et al., 2002). Additionally, no viable *Campylobacter* cells were isolated from the wash water, as opposed to 4 log CFU/mL found in the untreated water after washing, showing its potential use in reducing cross-contamination risk during washing. More research needs to be conducted in this area to determine the large-scale applicability of this type of intervention.

Chilling. Before further processing or packaging, carcasses are subjected to a chilling process to lower the internal temperature of the bird. Primarily, 2 types of chilling processes are used in the industry: water-immersion chilling and air-chilling. Water immersion systems utilize a continuous flow of water to chill poultry carcasses, while air cooling systems utilize chill rooms or air blast tunnels for cooling (Allen et al., 2000). Some processors make use of a water spray during the beginning stages of air cooling. Water-immersion chilling is the primary chilling system used in the United States, while air-chill systems are mainly used in the European Union (Sanchez et al., 2002; Berrang et al., 2008). Several studies have found that both types of systems substantially reduce microbial load (Blank and Powell, 1995; Barbut et al., 2009; Svobodová et al., 2012), and a recently conducted meta-analysis found no significant difference in the microbial reduction efficacy of the two methods (Belluco et al., 2016).

Rapid-surface cooling has been investigated as a potential alternative system. A recent study showed that immersing carcasses in liquid nitrogen for 20 s reduced *Campylobacter* numbers by up to 1 log CFU/g (Burfoot et al., 2016). However, no control was included to compare to traditional systems, nor was there any mention on how the cooling process affected the meat quality.

Differences Between Conventional and Alternative Processing. Key differences in the prevalence of foodborne pathogen contamination of poultry at various points in the conventional and alternative poultry processing chain need to be noted for accurate assessments of risk of the various pertinent pathogens. Early results from Luangtongkum et al. (2006b) showed that *Campylobacter* prevalence was high in the gastrointestinal tract of both organic and conventionally raised, slaughter-age turkeys. The results were similar for broiler

flocks, as Heuer et al. (2001) found organic broiler flocks to have significantly higher *Campylobacter* prevalence compared to conventional flocks. *Salmonella* prevalence was also found to occur at a higher prevalence on organic, processed broiler carcasses when compared to conventional carcasses (Bailey and Cosby, 2005).

With the rise in popularity of alternative poultry production systems and the rise of antibiotic-resistant bacteria, updated data are necessary, but are rather sparse in the scientific literature. Bailey et al. (2018) found *Campylobacter* prevalence to decrease during broiler processing for both organic and conventional production systems. Fecal matter and post-water chill carcasses of conventionally processed broilers had significantly higher *Campylobacter* prevalence than organic birds, but otherwise, prevalence levels were similar throughout the processing chain (Bailey et al., 2018). While the risk of foodborne pathogen isolation from poultry appears to be similar for both management systems, the complex and evolving nature of alternative poultry processing makes the need for more comprehensive studies very high.

Postprocessing Foodborne Pathogen Contamination of Poultry and Poultry Products

After processing, poultry are portioned, packaged, and/or further processed into other products before they are delivered to retail establishments. Cross-contamination can occur during these steps, but proper hygiene control and cleaning and sanitizing of equipment are often effective at reducing the risk of cross-contamination of pathogenic bacteria (Mead et al., 1995). After processing, it is also very important to control for spoilage microorganisms to prevent off-flavors, odors, and spoilage of poultry meat due to growth of bacteria such as *Pseudomonas* spp. (Gill and Newton, 1978; Nychas et al., 2008). Technologies such as modified atmosphere and active packaging can be useful to control the growth of microorganisms already present on the surface of poultry meat (Skandamis and Nychas, 2002). Quantifying the growth of various microorganisms on the surface of poultry meat after packaging has been well characterized due to the generation of accurate predictive models presented in the literature. Researchers have used *Pseudomonas* spp. as an indicator organism to determine remaining shelf-life based on storage conditions and cold-supply chain management (Dominguez and Schaffner, 2007; Raab et al., 2008; Ghollasi−Mood et al., 2017). Various models have been generated to predict pathogen growth in raw poultry (Oscar, 2006; Juneja et al., 2007; Dominguez and Schaffner, 2008; Oscar, 2017) and cooked poultry (Wei et al., 2001; Castillejo-Rodriguez et al., 2002; Juneja et al., 2011).

Recent studies have provided the public with data on foodborne pathogen prevalence in retail poultry meat. A summary of these results is provided in Table 4. A meta-analysis performed by Golden and Mishra (2020) reported United States retail *Campylobacter* prevalence estimates of 59 and 55% for conventional and alternative broiler meat, respectively, and *Salmonella* prevalence estimates of 19 and 23%, respectively. Estimated prevalence was not significantly different between production system for either pathogen observed.

Antibiotic Resistance

For years, antibiotics have been used in the poultry industry in delivery systems such as feed additives for therapeutic, prophylactic, and growth stimulating properties (Threlfall et al., 2000; McEwen and Fedorka-Cray, 2002; Sapkota et al., 2007). Classically used antibiotics in the poultry industry are reviewed by Diaz-Sanchez et al. (2015). While antibiotic-resistant bacteria have always been present in nature, wide use of antibiotics has presented an opportunity for an increase in antibiotic-resistant pathogenic bacteria (D'Costa et al., 2011). Antimicrobial resistance occurs when bacteria obtain resistance to select antimicrobials by processes including: gene mutation, acquiring transposons, and plasmid-mediated gene transfer (Davies and Davies, 2010). Feed type has been shown to affect antimicrobial resistance, as Hegde et al. (2016) found that resistance genes in the gut microbiome were more highly expressed in chickens reared on conventional diet when compared to organic. With the rise of consumer concern over antimicrobial-resistant bacteria, many consumers have opted for the purchase and consumption of organic food products (Crandall et al., 2009). However, research has shown that even though organic poultry are raised without antibiotics, this does not eliminate the presence of antibiotic-resistant bacteria in organic poultry meat and farms (Cui et al., 2005; Miranda et al., 2008a; Rothrock Jr. et al., 2016). In a recent study by Rothrock Jr. et al. (2016), high prevalence of antibiotic-resistant isolates of *Listeria* (63.9%) and *Salmonella* (36.0%) were found in various sample types from pastured organic poultry farms in the southeastern United States.

Numerous studies have compared the prevalence of antibiotic-resistant bacteria on alternative and conventional retail broiler meat. Cui et al. (2005) found that all *Salmonella* Typhimurium isolates from conventional retail broiler meat were resistant to at least 5 of the tested antimicrobials, while 79% of *Salmonella* isolated from organic broiler meat were susceptible to the 17 tested antimicrobials. Lestari et al. (2009) also found that *Salmonella* isolates from organic retail broiler meat were susceptible to a larger number of antibiotics than isolates from conventional chicken, but all isolates were resistant to amikacin, ceftriaxone, and ciprofloxacin. Other reports have found that up to 68% of *Salmonella* from pasture-raised broiler meat contained class I integrons, nonmobile genetic elements that have been linked to antimicrobial resistance, and all isolates were resistant to sulfisoxazole and novobiocin (Barlow et al., 2004; Melendez et al., 2010). In a recent study, it was reported that there was a statistically significant lower amount of multidrug-resistant strains of *Salmonella* in

Table 4. Prevalence of pathogenic bacteria in alternative and conventional retail poultry meat samples.

Organism	Poultry type	Country	Production type	No. (%) positive samples	Reference
Arcobacter butzleri	Chicken	Turkey	Conventional	49 (65.3)	(Atabay et al., 2003)
	Chicken	Japan	Conventional	15 (15.0)	(Kabeya et al., 2004)
Campylobacter spp.	Chicken	Canada	Conventional	62 (62.0)	(Bohaychuk et al., 2006)
	Chicken	United States	Conventional	45 (72.1)	(Cui et al., 2005)
			Organic	150 (75.8)	
	Chicken	United States	Conventional	61 (43.3)	(Han et al., 2009)
			Organic	23 (43.4)	
	Chicken	United States	Antibiotic-free	11 (11.5)	(Mollenkopf et al., 2014)
			Conventional	12 (12.6)	
			Organic	2 (5.0)	
	Chicken	United States	Conventional	32 (38.0)	(Noormohamed and Fakhr, 2014)
			Organic	21 (29.6)	
	Turkey	United States	Conventional	11 (17.0)	(Noormohamed and Fakhr, 2014)
	Chicken	United States	Antibiotic-free	33 (73.3)	(Price et al., 2005)
			Conventional	43 (95.6)	
	Chicken	United States	Antibiotic-free	88 (74.6)	(Price et al., 2007)
			Conventional	64 (80.0)	
	Chicken	United States	Conventional	12 (33.3)	(Salaheen et al., 2016)
			Farmer's market	28 (87.5)	
			Organic	20 (71.4)	
	Chicken	United States	Conventional	26 (52.0)	(Scheinberg et al., 2013)
			Farmer's market	90 (90.0)	
			Organic	14 (28.0)	
ESBL bacteria[1]	Chicken	Benelux[2]	Conventional	60 (100.0)	(Stuart et al., 2012)
			Free-range	5 (62.5)	
			Organic	27 (90.0)	
L. monocytogenes	Chicken	Canada	Conventional	34 (34.0)	(Bohaychuk et al., 2006)
	Chicken	Spain	Conventional	25 (41.0)	(Miranda et al., 2008b)
			Organic	27 (49.1)	
Salmonella spp.	Chicken	Canada	Conventional	30 (30.0)	(Bohaychuk et al., 2006)
	Chicken	United States	Conventional	27 (44.3)	(Cui et al., 2005)
			Organic	121 (61.1)	
	Chicken	Colombia	Conventional	233 (26.0)	(Donado-Godoy et al., 2012)
			Free-range	37 (35.0)	
	Chicken	United States	Conventional	31 (22.0)	(Lestari et al., 2009)
			Organic	11 (20.8)	(Lestari et al., 2009)
	Chicken	United States	Pasture	18 (50.0)	(Melendez et al., 2010)
	Chicken	United States	Antibiotic-free	25 (26.0)	(Mollenkopf et al., 2014)
			Conventional	24 (25.3)	
			Organic	7 (17.5)	
	Chicken	United States	Conventional	4 (8.0)	(Scheinberg et al., 2013)
			Farmer's market	28 (28.0)	
			Organic	10 (20.0)	
	Chicken	United States	Conventional	18 (35.3)	(White et al., 2001)
	Turkey	United States	Conventional	12 (24.0)	(White et al., 2001)
	Chicken	United States	Antibiotic-free	10 (5.0)	(Zhang et al., 2011)
			Conventional	3 (1.5)	
S. aureus	Chicken	United States	Conventional	23 (43.4)	(Abdalrahman et al., 2015)
			Organic	25 (41.0)	
	Turkey	United States	Conventional	34 (64.2)	(Abdalrahman et al., 2015)
	Chicken	Spain	Conventional	35 (57.3)	(Miranda et al., 2008b)
			Organic	37 (67.3)	

[1]Extended spectrum beta-lactamase producing bacteria (ESBL).
[2]Belgium, Netherlands, and Luxembourg.

the environment of large-scale poultry farms that voluntarily withdrew antibiotics when compared to conventional large-scale poultry farms (Sapkota et al., 2014). In various reports, *Salmonella* Kentucky has been the most isolated antibiotic-resistant serotype from broiler meat and the environment of poultry farms, with Hadar, Orion, and Enteritidis as other commonly isolated serotypes (Lestari et al., 2009; Melendez et al., 2010; Sapkota et al., 2014).

The prevalence of other types of antibiotic-resistant bacteria has also been observed. Early reports by Luangtongkum et al. (2006a) found that less than 2% of *Campylobacter* strains isolated from organic broiler gastrointestinal tracts were resistant to fluoroquinolones compared to 46% of strains from conventional broilers, but a large number of the isolates from both conventional and organic broilers were resistant to tetracycline. Bailey et al. (2018) presented similar results, finding 81.6% of *Campylobacter* isolates from various organic broiler processing steps to be resistant to tetracycline, compared with 65.3% of isolated from conventional farms. Noormohamed and Fakhr (2014) isolated multidrug-resistant *Campylobacter* strains from both organic and conventional retail broiler meat. Both organic and conventional retail broiler meat have been found to contain antibiotic-resistant enterococci (Kilonzo-Nthenge et al., 2015). Similarly, 41.7% of *Enterobacteriaceae* isolated from organic broiler meat were multidrug-resistant

(Miranda et al., 2008a). Additionally, organic broiler meat was found to be statistically indistinguishable in the number of antibiotic-resistant *E. coli* isolates when compared with conventional broiler meat (Millman et al., 2013). These results show that although antibiotics are withheld from organically raised birds, this does not necessarily guarantee the absence of antibiotic-resistant pathogenic bacteria from processed organic broiler meat.

RISK ASSESSMENTS IN THE POULTRY INDUSTRY

Quantitative microbial risk assessments **(QMRA)** are widely used throughout the food industry as a tool to estimate the risk of foodborne biological hazards to human consumers. They allow for the mapping of foodborne pathogens throughout the complex supply chain of a food product. Numerous QMRAs estimating the risk of human campylobacteriosis and salmonellosis due to consumption of poultry meat are present in the scientific literature. *Campylobacter*-focused QMRAs are well reviewed by Nauta et al. (2009) and Chapman et al. (2016), and *Salmonella*-focused QMRAs are well reviewed by Rajan et al. (2017). The majority of poultry-related QMRAs focus on the risk of conventional poultry meat to the consumer, with the exception of the work presented by Rosenquist et al. (2013), who found that the risk of *Campylobacter* infection due to contaminated poultry meat was 1.7 times higher in Danish organically produced meat when compared with conventionally produced meat. At the current date, no QMRA has been performed on the risk of *Salmonella* infection to humans due to the consumption of alternatively-produced poultry meat.

There are many approaches to constructing a poultry-related QMRA model. Some models attempt to estimate the presence of pathogens throughout the entire farm-to-fork poultry continuum (Hartnett et al., 2001; Nauta et al., 2005), while others focus on the retail-to-consumption part of the supply chain (Pouillot et al., 2012; Smadi and Sargeant, 2013). Farm-to-fork type models require a comprehensive understanding of foodborne pathogen prevalence and behavior throughout the entire food chain. While this has been accomplished in QMRAs focused on conventionally produced poultry, there are still data gaps in our knowledge of prevalence in alternative systems. In a meta-analysis performed by Golden and Mishra (2020), sufficient data were available to provide estimates of *Salmonella* and *Campylobacter* prevalence in alternative poultry farming environment and retail meat samples in the United States, but data were lacking to provide these estimates for pathogen prevalence in broiler carcass at various points during processing (i.e., rehang, prechill, postchill). An understanding of how bacterial numbers change during processing of alternatively-grown poultry is pertinent to the production of an accurate QMRA model. Similar studies to the work presented by Bailey et al. (2018) should be adapted to track *Salmonella* throughout the alternative poultry processing supply chain. Additionally. a multi-state survey of the types of processing practices (e.g., type of washing system) that are utilized by the various types of alternative poultry production systems would be useful in QMRA construction. Similar surveys have been conducted for poultry processing facilities in the United States (Northcutt and Jones, 2004), but distinctions should be made between the type of production facility. This would give risk assessors a better idea of the practices that are prominently in use in the United States and incorporate those factors into the QMRA.

CONCLUSIONS

Salmonella spp. and *Campylobacter* spp. present a high risk for both conventional and organic poultry farmers. The emerging risk of pathogens such as *Listeria monocytogenes* also present the poultry industry with a different type of problem. The rise of organic, pastured, and free-range poultry farming, and production has provided the need to gain a better understanding of the risks associated with this alternative type of poultry farming. The antibiotic-free nature of these poultry management systems drives many consumers to purchase the product, but research has shown that antibiotic-resistant microorganisms are still present in abundance on retail poultry meat. Furthermore, alternative poultry farming allows for more points of introduction of the pathogens to poultry flocks through the natural environment. The need to formally quantify the differences in microbial risk between alternative and conventional poultry meat is high.

DISCLOSURES

The authors have no conflicts of interest to report

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