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Review Article

Holistic Approaches to Reducing *Salmonella* Contamination in Poultry Industry

Ummu Afiqah Abdul-Rahiman[1], Noordiana Nordin[1]*, Noor Azira Abdul-Mutalib[1,2] and Maimunah Sanny[1,3]

[1]*Laboratory of Food Safety and Food Integrity, Institute of Tropical Agriculture and Food Security, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[2]*Department of Food Service and Management, Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[3]*Department of Food Science, Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*

ABSTRACT

Salmonella are widely found in the poultry industry, which subsequently may pose a risk to animal and human health. The aim of this review is to highlight strategies for the prevention and control of *Salmonella* at each stage in the poultry production chain by monitoring risks from the farm to the retailer. Among the primary approaches for control of *Salmonella* at the farm level includes the administration of synthetic and natural compounds to live chickens (vaccination and antibiotic), litter management as well as fortification of feed and acidification of drinking water. In the poultry processing plant, multiple hurdle technology and different chilling conditions to reduce *Salmonella* were discussed. In the retail level, an effective monitoring program to control *Salmonella* contamination by good manufacturing practices and hazard analysis and critical control points has been reviewed. Overall, we conclude that these approaches play a role in reducing the dissemination of *Salmonella* in the poultry industry. However, there is no published data related to logistic scheduling of poultry processing.-

Keywords: Contamination, control, poultry industry, prevention, *Salmonella*

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E-mail addresses:
ummu.rahiman@gmail.com (Ummu Afiqah Abdul-Rahiman)
noordiana@upm.edu.my (Noordiana Nordin)
n_azira@upm.edu.my (Noor Azira Abdul-Mutalib)
s_maimunah@upm.edu.my (Maimunah Sanny)
*Corresponding author

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INTRODUCTION

Foodborne diseases can be caused by biological, physical, or chemical hazards. Biological hazards such as bacteria, especially from the genus *Salmonella*, have been reported in many cases of foodborne-related illness (Cummings et al., 2010). Poultry product consumption may be a leading cause of salmonellosis (Bryan, 1980; Painter et al., 2013; Scallan et al., 2011). Rouger et al. (2017) stated that the prevalence of *Salmonella* in live chickens and in many types of raw chicken products could indicate that the microbe had already established its route in the chicken industry.

Salmonella dissemination may result from not using best practices (cross-contamination from unhygienic personnel, polluted water, and dirty processing facility) during transporting, processing or packaging of poultry meat and poultry products. Numerous studies have found that these bacteria are now becoming resistant towards antibiotics, causing these microbes to increase in number even if the chickens have been administered orally with antibiotics (Bansal et al., 2006; Gebreyes et al., 2004; Li et al., 1993; Salomonsson et al., 2005; Seo & Lee, 2004). The high number of poultry-associated *Salmonella* outbreaks in humans (Gaffga et al., 2012) highlights the need for well-developed approaches for combatting *Salmonella* contamination throughout the poultry production chain. In the year 2015, a national outbreak investigation was carried out in Canada as *Salmonella* Enteritidis was identified in frozen raw breaded chicken products. There were a total of 51 cases reported over a 6-month period by which 45% of these cases were hospitalised (Public Health Notice, 2015). Therefore, regulators recommended that industry strengthen messaging to all the poultry handlers and consumers to handle raw poultry and poultry products at appropriate condition including storage temperature as well as cooking temperature to reduce contamination along the poultry supply chain.

In addition to public health concerns, *Salmonella*-contaminated poultry have negative impacts on the economic status of a country, as it will be rejected for international trading; consequently, the competitiveness of the industry is affected (Rodríguez & Suárez, 2014). The growing world population has triggered a rise in the consumer demand for a wide variety of foods, resulting in an increasingly complex global food chain (Wirsenius et al., 2010). These challenges have placed greater responsibility on food producers and handlers to ensure food safety. Therefore, the level of microbial contamination in poultry at each stage of the poultry production line must be monitored thoroughly, from the poultry-farming level to the retailer. A reduction in microbial contamination would not only reduce the prevalence of food-borne illnesses, but also ensure a high standard of quality and economic stability in the poultry industry.

Characteristics of *Salmonella* and its Pathogenicity

Salmonella (family: Enterobacteriaciae) is generally grouped into two major species:

Salmonella enterica and *Salmonella bongori*. According to Grimont and Weill (2007), *S. enterica* is further divided into six subspecies designated by Roman numerals as follows: *enterica* (I), *salamae* (II), *arizonae* (IIIa), *diarizonae* (IIIb), *houtenae* (IV), and *indica* (VI). When *Salmonella* is observed under the microscope, it appears as a flagellated, straight rod gram-negative bacterium. *Salmonella* could be motile or non-motile (variants like *Salmonella* Gallinarum and *Salmonella* Pullorum) (van Asten et al., 2004).

According to Botteldoorn et al. (2003), *Salmonella* can colonise a wide range of hosts such as poultry, cattle, and pigs. *Salmonella* can also persist in a wide variety of environmental conditions, where it can grow in foods stored at temperatures as low as 2 – 4°C and also at temperatures as high as 54°C (Juneja et al., 2007). They are sensitive to heat and usually killed at temperatures ≥ 70°C. *Salmonella* grow in the pH range of 4 – 9 with the optimum pH range of 6.5 – 7. 5. They require high water activity (a_w) between 0.99 and 0.94 (pure water a_w = 1.00), but they can survive at a_w < 0.2. Complete inhibition of growth occurs at temperatures < 7°C, pH < 3.8, or water activity < 0.94 (D'Aoust & Maurer, 2007).

The highly ubiquitous species of *Salmonella* serovars can be divided into typhoidal and non-typhoidal *Salmonella* (NTS) serovars (Gal-Mor et al., 2014). Despite their genetic similarity, these two groups elicit very different diseases and distinct immune responses in humans. An example of typhoidal *Salmonella* is *Salmonella* Typhimurium which causes typhoid fever through ingestion into intestinal tract. It will then multiply in the liver and spleen and may persist in gall bladder for years as it triggers ulceration of intestine and also causes delirium (Cooper et al., 1994). In contrast, non-typhoidal *Salmonella* causes gastroenteritis, bacteraemia, and focal infection. Foodborne illnesses in humans are commonly caused by non-typhoidal *Salmonella* such as *Salmonella* Enteritidis, which commonly found in chicken egg and meat. Graham (2002) reported that approximately 1% of immunocompromised individuals and children below five years of age risked death due to the consumption of poultry contaminated with non-typhoidal *Salmonella*.

The most common reason for the spread of *Salmonella* from the environment to a flock is unhygienic farming activities, overcrowding, and a lack of biosecurity measures in poultry houses (Frederick & Huda, 2011). The application of preventive and control measures in the poultry supply chain, from farm to retailer, are put into place to significantly minimize *Salmonella* contamination and its subsequent transmission to humans. *Salmonella* can reside in the gut of a chicken and be excreted in its faeces (Shivaprasad et al., 1990). However, when *Salmonella*-contaminated chicken is consumed by humans, it can result in serious systemic disease (Chappell et al., 2009). *Salmonella* has several attributes that enable it to multiply much faster and infect new cells. Among the features are long tails, which are called flagella because of their movement; they can inject protein by piercing cells using a complex needle which is present on their membrane (Schraidt & Marlovits, 2011). The action mechanism by which *Salmonella* infects humans is through the gastrointestinal tract, from where it gains access to the epithelium (Schikora et al., 2011). *Salmonella* activates its virulence mechanism once it reaches the submucosa of the stomach, which allows it to survive and replicate in the host (Reed et al., 2002).

Poultry Industry: From Farm to Retailer

Salmonella can enter the poultry production chain at many points. In general, there are many interlinked segments in the poultry industry which allows maximum control of produced products. This industry implements the ladder concept (as illustrated in Figure 1), in which chickens are produced based on demand. By this means, the poultry industry is able to produce a high-quality product efficiently. The structure of the poultry industry starts from the primary breeder, feed mill, breeders, hatchery, grow-out farms, processing plants, and further processing before the poultry is transported and marketed (Van der Vorst et al., 2007).

At the primary breeder level, poultry companies aim to produce chickens that have desirable characteristics, such as an abundance of white meat and efficient feed conversion (Raji, 2018). To achieve this, chickens are raised from a natural process

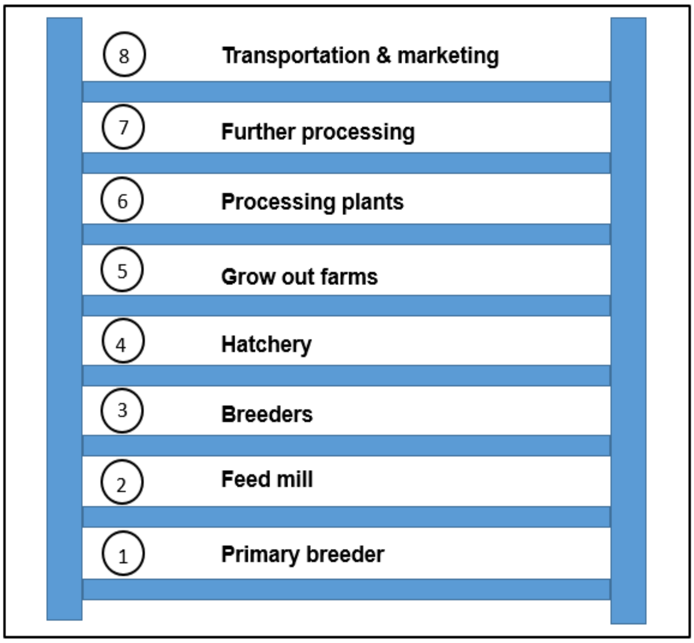

Figure 1. Ladder concept in the structure of poultry industry (modified from https://www.uspoultry.org)

of selecting and crossbreeding birds with the most desirable qualities. In nearly all cross-breeding programmes, the cross-breed birds exhibit considerably better egg production and growth rate. At the feed-mill level, companies produce different formulas to accommodate the different nutrition stages of chickens. Since 1996, farmers in poultry's industry have fed genetically modified corn and soybeans which are commercially available to the chickens. Next, the offspring of breeder parents will be raised to become larger and healthier broilers for markets. Modern advances in farming including advanced housing, climate controls, biosecurity, and good animal husbandry as well as cooperation between farmers and veterinarians helped in raising desirable broilers to meet the increasing demands of poultry meats. At the hatchery level, fertile eggs are placed in incubators under optimum incubation conditions until nearly the end of hatchery, when the eggs are transferred to trays; chicks hatch by pecking through the large end of the eggs. The newly hatched chicks are then transported to grow-out farms by independent farmers.

After approximately six to seven weeks, chickens at the grow-out farm are taken to the processing plant (Bailey et al., 2002). In a modern poultry processing plant, every step is taken to ensure that the chickens are processed quickly and painlessly (G. C. Mead, 2012). Ten stages are involved in poultry processing; the first stage, *stunning*, is performed to render chickens unconscious prior to slaughter. After slaughter, the chickens will be placed in a hot water bath to loosen their feathers, a procedure called *scalding* (Slavik et al., 1995). The next step in processing is *evisceration*, during which the internal organs of the poultry are removed. The carcasses are then washed and

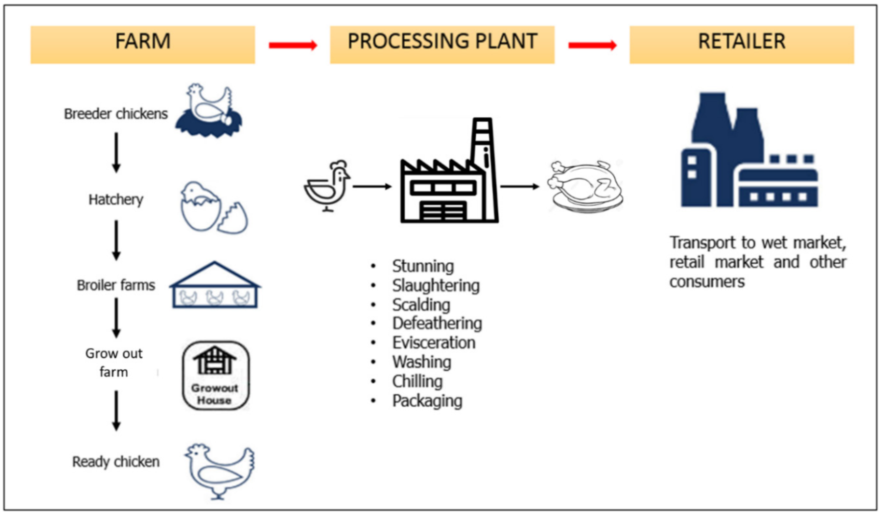

Figure 2. Poultry production chain from farm to retailer

chilled to limit the growth of bacteria. After chilling they are packaged for distribution or cut into parts (Thomas, 1977). After processing, the poultry is transported from the processing plant to grocery stores, wet markets, and other retail outlets via refrigerated trucks. Figure 2 shows the poultry production chain, beginning with the farm and ending with the retailer.

Route of *Salmonella* Contamination in the Poultry Industry

The first entry point for *Salmonella* in chickens begins as early at the hatchery stage in the farm (Foley et al., 2011). Hence, hens that appear to be healthy may be undiscernibly infected with *Salmonella* and could contaminate their eggs by sitting on them. These bacteria can be present on faeces and passed to other egg shells (Cox et al., 2000). Insects can also serve as a vehicle for *Salmonella* contamination in poultry farm. Chen et al. (2011) identified houseflies as a source of *Salmonella* contamination at a poultry farm in Selangor, Malaysia due to the close association of houseflies with faeces and garbage. A high prevalence of *Salmonella* at farms where chickens are raised eventually leads to high levels of bacterial contamination in slaughterhouses. During transportation from farm to processing plant, chickens experience stress, and excrete faeces that may contain *Salmonella*, thus bacterial infection easily occurred (Marin & Lainez, 2009). Earlier studies have shown that the longer the transportation time, the higher the incidence of bacterial infection in poultry (Mulder, 1995).

Salmonella can gain access and contaminate poultry at any processing step, for instance, when multiple chickens are placed in the same water bath during scalding, allowing cross-contamination between *Salmonella*-infected chickens and *Salmonella*-free chickens (Mulder et al., 1978; Rasschaert et al., 2008). Furthermore, *Salmonella*-infected chickens and its *Samonella*-contaminated faeces can easily disseminate through multiple movements during feather removal process (Nde et al., 2007). Evisceration (process of organ removal) may contribute to the contamination of chicken carcasses. For example, *Salmonella* can be easily transferred from the intestines of a contaminated chicken to other chickens which were initially free from *Salmonella* bacteria (Gast & Porter, 2020). A study by Carramiñana et al. (1997) revealed that poultry livers were heavily contaminated with *Salmonella* whereby, 55% of the samples were *Salmonella*-positive indicate cross contamination had possibly occurred. *Salmonella* contamination may also happen if processed chickens are being washed, chilled, and pre-packaged using insanitary machines (Jones et al., 1991). Moreover, contamination can occur via improper handling of poultry meat by poultry workers who do not follow proper sanitation procedures, such as using sanitized utensils and gloves (Mazengia et al., 2015).

During transportation from processing plants to retail markets, *Salmonella* contamination or populations may increase if the transport period is too long or if preservation conditions are neglected (Corry et al., 2002). Improper handling practices by wholesalers at retail markets are also considered to be a risk factor for *Salmonella* cross-contamination in poultry meat, for example when the same chopping board is used for raw and ready-to-eat food (e.g. vegetables) (El-Aziz, 2013). Table 1 presents a summary of the routes of *Salmonella* contamination in poultry.

Table 1

Summary of route for Salmonella *contamination in poultry at farm, processing plant and at the retailer*

Route	References
Farm	
Hatchery	Foley et al. (2011)
Transportation	Marin and Lainez (2009)
Processing plant	
Scalding	Mulder et al. (1978)
Defeathering	Nde et al. (2007)
Evisceration	Carramiñana et al. (1997)
Retailer	
Long transport period	Corry et al. (2002)
Handling	El-Aziz (2013)

Control Measures to Reduce *Salmonella* Contamination in Poultry Farm

The aim to reduce the prevalence of *Salmonella* in the poultry industry has always been a challenging issue, indicating that a proactive approach to control contamination levels is needed. As discussed earlier, *Salmonella* can begin its entry in the poultry production in the farm during hatchery (White et al., 1997). Thus, it is crucial for farms to implement promising preventive measures at this primary stage. Among the current strategies used to reduce contamination at the farm level is vaccination with both live and dead strains of *Salmonella*. Barrow (2007) reported that a live, attenuated *Salmonella* strain provided better protection than a dead strain in terms of antibody production by chickens. This is because the dead strain cannot induce cytotoxic T cells or secrete IgA antibodies, which are important for the protection of mucosal surfaces. At this point, vaccination with an attenuated *Salmonella* Typhimurium strain has proven to prevent *Salmonella* Typhimurium infection in layer chickens. Additionally, this vaccination also provides additional cross-protective immunity against infections with *Salmonella* Enteritidis, and *Salmonella* Gallinarum serovars (Lee, 2015).

Another immune strategy incorporated in recent years to reduce the pathogen is passive immunity, in which antibodies are fed to hatchlings. It is expected that this technique will enable the maternal antibodies to be transferred from the yolk to the chick and thus prevent *Salmonella* colonization (Chalghoumi et al., 2009). This hypothesis was confirmed by a study conducted by Rahimi et al. (2007), in which the authors observed that three-day old chicks with *S.* Enteritidis that received purified yolk IgY in drinking water showed lower levels of *S.* Enteritidis in caecum when twenty-eight days old. Antimicrobial activity may involve agglutination of the pathogen to the egg yolk, generating a competition for adhesion sites or stimulation of the immune system by the egg-yolk components (Vandeplas et al., 2010).

The use of antimicrobial compounds is also an option for combatting *Salmonella* in poultry. Gallinacins, cationic antimicrobial peptides that are naturally present in chickens, are effective against *Salmonella*, as they can facilitate interactions with negatively charged membrane pathogens (Milona et al., 2007). Colony-counting assay experiments conducted by van Dijk et al. (2007) showed a strong bactericidal and fungicidal activity against food-borne pathogens such as *Campylobacter jejuni*, *Salmonella* Typhimurium, *Clostridium perfringens*, and *Escherichia coli*. Studies have explored the incorporation of antimicrobial peptides into chicken feed to act as an antibiotic with which to limit *Salmonella* contamination (Bennoune et al., 2009; Joerger, 2003). However, issues regarding economy and ecology must be resolved before this idea can be applied into practice.

Salmonella normally does not survive at pH 3.0; thus, an approach using acidification of feed and drinking water with short chain fatty acids (SCFA) and medium chain fatty acids (MCFA) could result in bactericidal or bacteriostatic (Corrier et al., 1990). MCFA is much more effective than SCFA against *Salmonella*, as only 25mM could cause *Salmonella* to become bacteriostatic compared to SCFA, which would require 100mM (Van Immerseel et al., 2006). This is because MCFA has more carbon molecules (6 – 10), making it more effective. In short, acidification of the chicken environment can be an effective control measure at the farm level, as it can be applied for use with young chickens.

Farm litter modification with various acidification compounds, such as organic acids, formalin, sodium bisulfate, aluminium sulphate, and sulfuric acid has been reported to be a more practical and cost-effective strategy for reducing *Salmonella*-shedding in the litter. According to Vicente et al. (2007), when the pH of the litter is modified, ammonia emissions are reduced, resulting in a significantly lower *Salmonella* count. However, a meaningful control of *Salmonella* requires a careful removal of all litter and subsequent cleaning and disinfection between batches of chicken. Apart from litter modification, acidification of the poultry diet has also proved to be an efficient way to reduce the microbial load. In this approach, the poultry are fed with fermented liquid feed (FLF). In order to acidify the FLF, lactic acid bacteria are introduced to the liquid feed. Hence, when the poultry consume the FLF, the Enterobacteriaceae along the gastrointestinal tract are reduced (Heres et al., 2003). Usually, fermented feed will contain high lactic and acetic acid contents, which help to reduce *Salmonella* in the anterior part of the gastrointestinal tract (GIT).

Colonization of *Salmonella* in the avian GIT can also be controlled through dietary modification. Klasing (1998) claimed that the dietary characteristics of poultry directly impact the fowls' susceptibility to various pathogens. Hence, the dietary characteristics of poultry should be monitored thoroughly. There have been several studies of dietary modification for poultry, such as introducing high-fibre feed. It is assumed that poultry feeding on dietary fibre will likely prefer the utilization of normal microbial populations, such as *Lactobacillus* and *Bifidobacterium* species (Bedford, 1996). These bacteria can produce lactic acid and maintain a low pH in the GIT. For example, alfalfa is a high-fibre dietary source that helps to promote lactic acid production in the GIT, thus inhibiting *Salmonella* (Donalson et al., 2008).

Nutritional strategy is another approach to combatting the growth of *Salmonella* along the GIT. This is because a damaged GIT may increase the chance for an invasion of pathogens (McDevitt et al., 2006). Hence, to ensure gut health in poultry, the chickens' nutrition can be formulated with several amino acids, such as arginine, glutamine, serine, and threonine. These amino acids can limit the growth of *Salmonella* (Hume et al., 1997). Effective nutrient absorption is an important aspect of poultry diet intervention. It has been hypothesized that the remaining nutrients (i.e. those unabsorbed by the poultry) could possibly be utilized by pathogenic microbes to aid in their growth. Thus, to ensure an efficient absorption process of nutrients, exogenous enzymes, such as alpha-amylase, could be incorporated into corn-based products in the poultry diet (Santos, 2005). It has been shown that poultry growth performance increases significantly as *Salmonella* decreases (Mamber & Katz, 1985).

In addition, to prevent pathogen colonization, antibiotics have been incorporated into poultry feed. However, for the past few years, the emergence of antibiotic-resistant bacteria has become an issue of concern, which may be due to the practice of adding antibiotics to poultry feed (Singh et al., 2006) resulting in the use of antimicrobials in feed being prohibited by law in most parts of the world. Therefore, alternative options, such as the use of probiotics and prebiotics, have been used to promote the growth of microflora communities. The probiotic microbe that is commonly used in poultry feed is of the *Lactobacillus* genus. Jin et al. (1996) found that *Lactobacillus fermentum* and *Lactobacillus acidophilus* blocked the attachment of *Salmonella* Typhimurium and *Salmonella* Pullorum to the epithelial cells due to competition. As for prebiotics, the mechanism of action for eliminating pathogens is through the direct binding of fermentable carbohydrates and sugar alcohols (e.g. lactose, lactosucrose, and lactulose) to pathogens in intestinal lumen, which prevents bacteria from adhering to epithelial cells (Chambers et al., 1997; Tellez et al., 1993).

Byrd et al. (2008) found that when chlorate was added to poultry feed or drinking water, the incidence of *Salmonella* Typhimurium was low. The reason for this is that in the process of *Salmonella* respiration, nitrate reductase helps to convert nitrate into nitrite. However, nitrate reductase does not have the ability to distinguish between nitrate and chlorate (Rusmana & Nedwell, 2004); hence, in use, the chlorate is reduced to chlorite, which in turn creates a toxic environment and eventually kills the *Salmonella*.

In most developed countries, such as the United Kingdom, Sweden, and Denmark, the control programme for *Salmonella* has been effective, as these countries have adopted a few strategies for the frequent monitoring of poultry farms. For instance, Sweden has implemented an uncompromising strategy in the bacteriological examination of pooled faecal samples. If *Salmonella* is identified in the samples, the flock is destroyed (Wierup et al., 1995). In Japan, *Salmonella* control continues to be an important topic, as the country ranks as one of the highest consumers of eggs in the world. Japanese consumers eat a large portion of their eggs raw, making *Salmonella* control even more important whereby the use of vaccines at poultry farm is more common (Esaki et al., 2013).

Control Measures to Reduce *Salmonella* Contamination in Poultry Processing Plant

Poultry processing is a highly automated industry; therefore, if *Salmonella*-positive chickens from a farm enter the processing plant, a significant amount of cross-contamination is possible. Thus, the best practice for controlling the spread of *Salmonella* is to use multiple approaches at multiple points at which chickens may be contaminated (Stopforth et al., 2007). To address this, several chemicals are currently being applied as antimicrobial controls during reprocessing, poultry chilling and post-chilling (Yang et al., 1998). Antimicrobial chemicals are generally sprayed, but in this technique, the effectiveness is limited due to short contact times and inadequate coverage.

Previously, chlorine has been used in poultry chillers at a concentration of 20 – 50 ppm (G. G. Mead & Thomas, 1973). However, several other antimicrobial chemicals have been discovered that offer a more significant reduction of *Salmonella* in comparison with chlorine. Acidified sodium chlorite, bromine, chlorine dioxide, cetylpyridinium chloride, organic acids, peracetic acid, trisodium phosphate, sodium metasilicate, monochloramine, electrolyzed water, and hypochlorous acid (chlorine) are examples of approved antimicrobials for poultry (Nagel et al., 2013). Among these antimicrobials, organic acid and peracetic acid are considered environmentally friendly, but they could change the colour of the meat product (Mani-Lopez et al., 2012). Hence, a possible ideal application for poultry would be to combine a few antimicrobials. For example, a combination of peracetic acid and hydrogen peroxide achieves a synergistic effect in reducing *Salmonella* contamination (Bauermeister et al., 2008).

At the slaughterhouse, another approach to the reduction of *Salmonella* contamination that significantly impacts the safety of poultry is chilling. The main aim of chilling is to limit the growth of food-spoilage microbes and *Salmonella*. According to James et al. (2006), immersion chilling using an ice-water mixture causes a larger reduction in the number of microbes compared to the spray chilling method. When chlorine is added to ice water during chilling, the process kills the microbes more effectively. Another effective chilling method is air chilling by which the air-chilled chicken is cooled by passing the birds through several chambers where cold, purified air is circulated to cool the meat, resulting in no added moisture, stronger flavour and decrease chance for contamination (Kim et al., 2017). In the air chilling system, birds travel across the belt for almost three hours passing three different cooling chambers by which each chamber has controlled temperature and humidity. Air chilling is a significant contributor to the tenderness and flavour of the meat as compared to conventional water chilling system. The water chilling system operates differently whereby thousands of chickens are submerged into a cold-water bath mixed with chlorine (to control bacterial contamination), which consequently dilutes the natural juices of the bird (Micciche et al., 2018).

In order to improve the safety of poultry meat and poultry products, the poultry industries take on a process control system called "hazard analysis critical control point" (HACCP). In general, this system helps to ensure product safety by identifying possible health hazards before they occur. The concept of HACCP was developed over 60 years ago by the Pillsbury Company as they were trying to develop microbiologically safe food products for space (NASA) (Gehring & Kirkpatrick, 2020). Thereafter, the HACCP system was implemented and the United States Department of Agriculture Food Safety and Inspection Service (USDA-FSIS) had enforced rule whereby they required meat and poultry plants to incorporate HACCP in their safety operations.

HACCP is considered as an evaluation and control system of the whole food production chain solely for reducing potential health risks to consumers. Safety program in HACCP in poultry processing aims to maintain the safety of the poultry meat as hazards may occur during processing. Thus, possible hazards are defined, evaluated, controlled so that they can be prevented. 'Hazard' means any biological, physical or

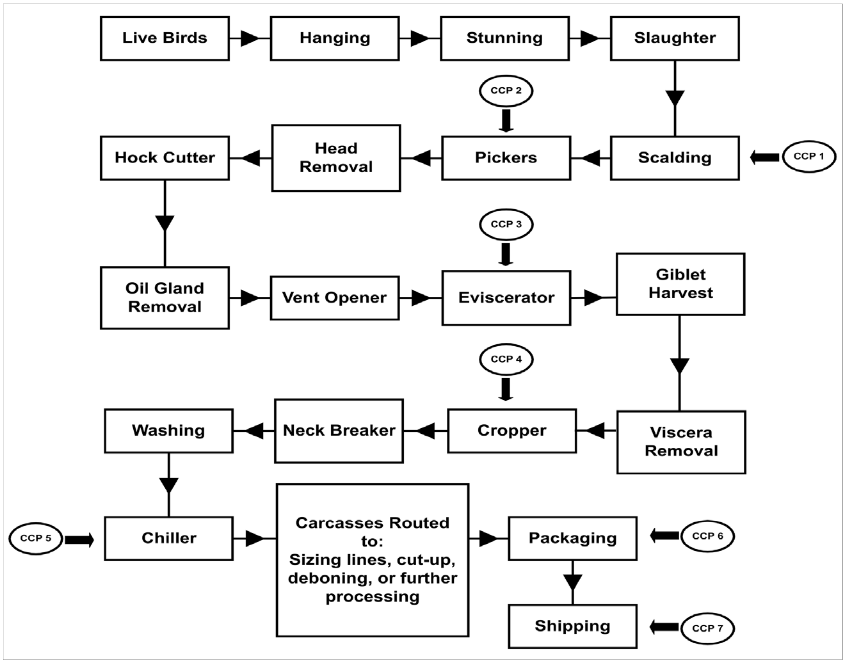

Figure 3. Example of poultry processing HACCP flow diagram (Northcutt and Russell, 2010)

chemical property that can cause adverse health effects for consumers (Park et al., 2014). Poultry processing plants are required to have a HACCP plan. Figure 3 shows the general poultry processing HACCP flow diagram in a poultry processing plant.

Control Measures to Reduce *Salmonella* Contamination in Poultry Retail Market

The final supply chain of poultry meat ends at retail levels. Here, as mentioned above, poultry meat is easily contaminated with *Salmonella* or other microbial pathogens via many routes, which include unhygienic conditions or practices by food handlers or improper storage temperatures of raw poultry meat (Donado-Godoy et al., 2012).

In the farm-to-table continuum, post-processing food handling is very important in the reduction of foodborne illnesses caused by *Salmonella*. Therefore, adequate training for the personnel is of a prime factor in the handling of meat that is safe and suitable for human consumption (Zanin et al., 2017). Poultry handlers who are engaged in meat hygiene activities should be well-trained to have an excellent level of knowledge and practice to carry out specified meat hygiene tasks, e.g., post-mortem inspection and HACCP. It is expected that from an appropriate training program, poultry handlers at retailing stage who come into direct contact with meat would maintain appropriate personal cleanliness while working. Besides, these workers would also have a positive attitude towards the importance of personal cleanliness like hand washing as well as adequate protective clothing appropriate to the circumstances. Good hygiene practices especially washing of hands properly before sales of meat or usage of proper clothing such as hand gloves, masks and head covers can reduce the spread of this microbe to the raw poultry meat.

Foodborne diseases usually arise when the causative organism, initially present in low numbers can multiply on the chicken carcass surface during transport and distribution of poultry to the retail stores. The potential risks may arise through poultry-handling mistakes, such as leaving meat at inappropriate temperature during transportation. It is important to note that *Salmonella* multiplies very slowly at 10 °C, and not at all at 6 °C to 7 °C (Ha et al., 2020). In light with this information, applicable precautionary measures could be done. FDA has prescribed the shippers, carriers, receivers and others who engage in food transport to monitor safe temperatures during poultry meat transport between distribution centres and retail stores as the growth of *Salmonella* on carcasses can be entirely prevented with attentive temperature control (Alfama et al., 2019). On that account, equipment for constant monitoring of temperatures should accompany transport vehicles and bulk containers wherever required. Additionally, the conditions of transport should cater for sufficient protection from any biological, physical or chemical contamination, and should reduce the growth of pathogenic bacteria. If meat is mistakenly exposed to unfavourable temperature conditions or sources of contamination that may affect the quality and safety of poultry meat, an inspection should be conducted by a qualified person before further transport or distribution is granted (Biswas et al., 2019).

When considering the storage of poultry meat, it is supposed that the chickens are already cleaned to be chilled or frozen, and ready for selling. Studies have shown that storage conditions of processed broilers at the retail outlet can affect the bacterial load on the meat (Masoumbeigi et al., 2017). If broiler chickens are not packaged separately, cross-contamination can happen, increasing the occurrence of *Salmonella* within a batch. Shafini et al. (2017) conducted a study to compare the prevalence of *Salmonella* in packed and unpacked chicken sampled from retail outlets. The results showed contamination of *Salmonella* spp. in unpacked chicken were higher (84.8%) compared to the packaged chicken (54.5%). *Salmonella* can also multiply if other storage conditions (including storage temperature, relative humidity and broiler moisture, pH, and storage density) are neglected (Trinetta et al., 2019). Fresh meat, poultry and seafood are considered as the most difficult items to store as these food items are rich in carbohydrate and protein suitable for the utilization of most microbes. Therefore, when keeping this item in the refrigerator, various food safety aspects need to be considered. First of all, these food items have to be kept in a safe temperature which is 4 °C or lower (Silva et al., 2018). Besides, all carcass meats should be unwrapped and hung so that air can circulate around them. It is important to put absorbent paper beneath the meats for quick clean-up of drips. Fresh meat must not be kept too long whereby maximum period to keep boned meat should be no longer than three days while chicken parts should be discarded within two days. Additionally, fresh meat should be covered with plastic or stainless-steel trays and should be packed in ice when they are stored in the lower shelves of the refrigerator (Masson et al., 2017).

Apart from favourable transport and storage condition, the weather is a key influence on salmonellosis. In Malaysia, the tropical weather temperature allows faster replication of *Salmonella*, increasing the contamination risk throughout the entire poultry supply chain. *Salmonella* is known to proliferate at a warmer climate with higher relative humidity (Ishihara et al., 2020). However, the influence of weather on salmonellosis is not always immediate but most often delayed for around 2 – 4 weeks which possibly because *Salmonella* colonisation takes place earlier during a hot day, however, the consequent human salmonellosis cases only occur when those infected chickens are consumed weeks later (Akil et al., 2014). To address climatic factor-driven *Salmonella*-contamination risk, quality control (QC) officer assure that temperature control schemes are adequate in tropical climate weather. Additionally, public health agencies should review food temperature control guidance for meats handled in retail establishments. Such preventive measures at retailing stage should aim to reduce bacterial transmission and improve food producer and consumer awareness.

Another strategy with which to control *Salmonella* contamination in poultry is through the implementation of hazard analysis and critical control points programs in the entire poultry marketing chain (González-Miret et al., 2006). It is important that the use of the HACCP (hazard analysis critical control point) approach, based on the use of multi-functional strategies (combining the innovative use of sanitizers and modern disinfection techniques) and supervised by professional food handlers and food regulators with a visionary commitment by management from the production, through the processing, preservation, handling, and final preparatory stages, be imposed to help eliminate or reduce significantly the prevalence of *Salmonella*, *Escherichia coli*, and other food-borne pathogens or contaminants and the consequent food poisoning in the society. HACCP is now helping to decrease health risks connected to the distribution of fresh food in wet markets across China. The improvements that HACCP promoted in China's wet markets can be achieved in other countries where local markets are prominent. Continued efforts to enhance food safety and hygiene in wet markets across the globe will also strengthen food security by generating greater access to local food (Zhu et al., 2017).

CONCLUSIONS

The continuation of the poultry supply chain, which begins at the farm and ends at the retailer, requires the monitoring of multiple risk factors in order to control the level of *Salmonella* contamination. Hence, it is important to determine those risk factors that contribute to the *Salmonella* contamination of raw poultry meat so that appropriate control measures can be taken. This review highlights the most recently developed strategies for use in the significant reduction of *Salmonella* in the poultry supply chain. To summarize, the strategies discussed in this review include preventive measures that start at the farm such as the modification of feed and drinking water, immune strategies and feed additives such as antibiotics, probiotics and prebiotics. These approaches have significantly impacted the reduction of *Salmonella* at the farm level. Prevention of bird flock contamination based on the good manufacturing practices and good agricultural practices are most useful ways to prevent contamination of bird flocks before slaughter. Approaches that have been practised at the slaughterhouse include a multiple hurdle strategy (combination of few technologies and approaches), the use of antimicrobial compounds during reprocessing and various poultry-chilling techniques. It has been shown that these strategies play a role in reducing the dissemination of *Salmonella* in poultry meat. However, there is no published data related to logistic scheduling of poultry processing. Therefore, further research on the optimization of logistic scheduling of poultry processing conditions is indicated to fill in the data gap on the effects of applying different logistic scheduling conditions to eliminate *Salmonella* in poultry meat.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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