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A quantitative risk assessment model of *Salmonella* contamination for the yellow-feathered broiler chicken supply chain in China

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ABSTRACT

A quantitative microbial risk assessment (QMRA) model was developed to investigate the health risk associated with *Salmonella* contamination in yellow-feathered broiler chicken supply chain in China extending from the farm to home consumption. A baseline model was developed based on most common industrial practices for risk estimates. Critical control points along the supply chain were identified using sensitivity analysis. Scenario analysis was conducted to compare the effectiveness of applicable intervention strategies on risk reduction, including alternative processing strategies in slaughter house and different storage conditions. Input parameters for the model were determined by onsite investigation, laboratory experiments and literature studies. The final risk estimate was expressed as the probability of salmonellosis per serving and the intervention effectiveness was expressed as the relative change in salmonellosis risk if an intervention had been implemented compared with the baseline. The model estimated that the mean predicted probability of illness per serving was 1.1×10^{-8} for baseline. Full cooking, reducing farm contamination, chlorine concentrations in chilling and cross-contamination in wholesale were the most significant factors in reducing the health risk. Scenario analysis indicated that post-evisceration spraying with a combination of electrolyzed water and sodium hypochlorite could result in the greatest relative risk reduction (343.8-fold reduction). The developed QMRA model provided a framework for estimating the health risk of *Salmonella* contamination in yellow-feathered broiler in China, and was applicable in determining the strategies to control *Salmonella* contamination for poultry industry.

1. Introduction

Chicken meat is a high protein and low-fat food that is available at a relatively low cost. However, *Salmonella* accounts for 93.8 million cases of gastroenteritis and 155,000 deaths globally each year and many of these were linked to the consumption of chicken (Majowicz et al., 2010; Oscar, 2004; Voetsch et al., 2004). According to the data reported from National Foodborne Disease Outbreak Surveillance System during 2003–2017 in China, a total of 899 outbreaks have been reported to be associated with *Salmonella*, which resulted in 21,881 illnesses, 11,351 hospitalizations, and 4 deaths (Li et al., 2020). Although there were no reliable estimates on the diseases burden of salmonellosis linked to chicken meat in China, *Salmonella* accounts for 70–80% of foodborne pathogenic outbreaks and were most often linked to chicken products (Wang et al., 2018; Wu, Liu, & Chen, 2018). There is a high prevalence of *Salmonella* along the poultry supply chain in China (Wang et al., 2014; Yang et al., 2020; Zhu et al., 2014). Ren et al. (2016) performed a microbiological quality of chicken and found the prevalence of *Salmonella* was 7, 62.9 and 54.7% for farm, slaughter house and retail market, respectively. This poses a high risk for human *Salmonella* infection.

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Table 1
Summary of variables and parameters used in the QMRA model.

Symbol	Description	Distribution/Formula	Unit	Source
Farming				
P_{fa}	Prevalence in fraction contaminated	Beta (27, 595)	prevalence	This study
C_{fa}	Contamination level in fraction contaminated	Pert (−0.5, −0.3, 2.04)	log CFU/g	This study
Slaughtering				
Bleeding				
T_{we}	Temp, bleeding	Normal (24, 5)	°C	Investigation
t_{we}	Time, bleeding	Pert (0.5, 0.67, 1)	h	Investigation
D_{we}	Bacterial growth	$0.002 \times (T_{we}+273.2) \times \exp(-((2424.9)/(8.1\ (T_{we}+273.2)))^{(49.8)}) \times t_{we}$	log CFU/g	Pang (2018)
C_{we}	Concentration after bleeding	$C_{fa} + D_{we}$	log CFU/g	Calculated
Scalding				
T_{sc}	Temp, scalding	Normal (60, 5)	°C	Investigation
t_{sc}	Time, scalding	Pert (1, 1.3, 1.6)	min	Investigation
D_{sc}	Bacterial reduction	Logistic (0.95, 0.07)	log CFU/g	This study
C_{sc}	Concentration after scalding	C_{we}–D_{sc}	log CFU/g	Calculated
Evisceration				
P_{ce}	The change of prevalence in evisceration	Lognorm2 (1.6, 0.9)	prevalence	This study
P_{ev}	Prevalence after evisceration	$P_{fa} \times P_{ce}/(1\text{-}P_{fa} + P_{fa} \times P_{ce})$	prevalence	Calculated
Chilling				
T_{ch}	Temp, chilling	Normal (2, 0.5)	°C	Investigation
t_{ch}	Time, chilling	Pert (20, 30, 40)	min	Investigation
S	Chlorine concentration	Pert (20, 50, 100)	ppm	Investigation
D_{ch}	Bacterial reduction	Normal (0.75, 0.1)	log CFU/g	This study
P_{ch}	Prevalence after chilling	$18.28 + 15.75C_{sc}+0.757P_{ev}\text{-}0.636S + 0.0044S^2$	prevalence	This study
C_{ch}	Concentration after chilling	C_{sc}–D_{ch}	log CFU/g	Calculated
Cold storage				
T_{st}	Temp, storage at factory	Normal (5, 2)	°C	Investigation
t_{st}	Time, storage at factory	Pert (12, 72, 168)	h	Investigation
D_{st}	Bacterial reduction	Pert (0, 0.3, 0.7)	log CFU/g	This study
C_{st}	Concentration after storage at factory	C_{ch}–D_{st}	log CFU/g	Calculated
Post-processing				
Wholesale				
P_{cd}	The change of prevalence in wholesale	Lognorm2 (3.5, 2.5)	prevalence	Calculated
P_{di}	Prevalence after wholesale	$P_{ch} \times P_{cd}/(1\text{-}P_{ch} + P_{ch} \times P_{cd})$	prevalence	Calculated
Retail				
T_{re}	Temp, retail in the market	Normal (5, 2)	°C	Investigation
t_{re}	Time, retail in the market	Pert (12, 72, 168)	h	Investigation
D_{re}	Bacterial reduction	Pert (0, 0.3, 0.7)	log CFU/g	This study
C_{re}	Concentration after retail	C_{st}–D_{re}	log CFU/g	Calculated
Consumption				
T_{co}	Temp, cooking	Normal (80, 10)	°C	Assumption
t_{co}	Time, cooking	Pert (30, 45, 60)	min	Assumption
D	D-value at reference temperature (70 °C)	$10^{-1.07}$	min	Murphy et al. (2003)
z	z-value	11.7	°C	Calculated
D_K	D-value at cooking temperature	$D \times 10^{\frac{70 - Tco}{Z}}$	min	Dogan et al. (2019)
D_{co}	Bacterial reduction	t_{co}/D_K	log CFU/g	Calculated
P_{co}	Prevalence after cooking	P_{di}	prevalence	Calculated
C_{co}	Concentration after cooking	C_{re}–D_{co}	log CFU/g	Calculated
A	Serving size	52.2	g	Wu and Yuan (2014)
M	Annual chicken consumption in China	4050	g/yr	Yu and Yu (2017)
Dose-response				
α	Model parameter	0.2274		FAO/WHO (2002)
β	Model parameter	57.96		FAO/WHO (2002)
O	Population in China	1.34×10^9		NBSC (2018)
P_{inf}	Probability of infection per serving	$1\text{-}(1 + A \times C_{co}/\beta)^{-\alpha}$		Calculated
P_{ill}	Probability of illness per serving	$P_{inf} \times P_{co}$		Calculated
N_{cases}	Number of illness cases per year	$M/A \times P_{ill} \times O$		Calculated

The yellow-feathered broiler chicken has a distinctive flavor and is preferred over other commercial breeds such as Arbor Acres and Cobb500 (Wang et al., 2019; Zhang, Wang, Li, Wu, & Xu, 2016). Since the H7N9 influenza pandemic in 2013, producers have advocated for the meat to be chilled and packaged for distribution at the time of slaughter (Wang et al., 2017). However, the performance objectives of *Salmonella* for chilled chicken meat in retail, as well as for products in slaughtering, have not been developed in China. The need for preventing *Salmonella* contamination in yellow-feathered broiler chicken is evident. With the implementation of intervention strategies along poultry supply chain, the industry can effectively reduce *Salmonella* contamination in the final products, which can subsequently reduce the risk of public health. Traditionally, microbial decontamination at the processing level mostly

relies on antimicrobial acids, including citric acid, lactic acid, etc (Mani-López, García, & López-Malo, 2012). In the last decades, novel interventions such as steam, modified atmosphere packaging (MAP) packages have been continuously studied (Kudra et al., 2011; Kure et al., 2020). With the increasing of intervention measures, how to make decision on intervention adoption is challenging.

The quantitative microbial risk assessment (QMRA) model uses point estimates and probability distributions to examine variables such as *Salmonella* concentrations at the retail or at any given point in the processing chain to estimate the chance of illness due to *Salmonella* from ingestion of a food (Rajan, Shi, & Ricke, 2017). QMRA allows flexibility in the selection of intervention strategies along the food supply chain for microbial risk control (Dogan, Clarke, Mattos, & Wang, 2019). QMRA studies of the *Salmonella* risks for chicken have focused on retail to consumption rather than originating at the farm-to-fork continuum (Jeong, Chon, Kim, Song, & Seo, 2018; Oscar, 2004; Zhu et al., 2017). A risk model for *Salmonella* in broiler chickens from farm to table has been developed by the WHO/FAO but most of input parameters were determined by assumption, such as initial bacterial prevalence of broilers, cross-contamination in slaughtering and serving size. Moreover, the effects of scalding, evisceration, chilling processes and other decontamination treatments were not included (FAO/WHO, 2002). The analysis of these additional processes is needed to effectively model the benefits of control interventions at the processing level.

Therefore, the objectives of this study were: (i) to construct a QMRA model from farm to table for estimation the probability of illness due to yellow-feathered broiler chicken consumption in China, (ii) to identify critical control points for *Salmonella* risks throughout the broiler chicken supply chain and (iii) to compare efficiency of different interventions that can be implemented through the processing chain. This study will provide a QMRA framework to estimate health risk due to the consumption of broiler chicken products in China and demonstrate how to use a QMRA model as a system tool to prioritize microbial contamination interventions for food safety and public health protection.

2. Materials and methods

2.1. Model overview

The prevalence and concentration of *Salmonella* along the supply chain starting from initial bacterial contamination on farm to slaughter house and to home consumption were incorporated into the QMRA model. A baseline model based on most common industrial practices was developed for risk estimate (Table 1). The model was divided into three modules: (a) farming, (b) slaughtering, (c) post-processing and consumption and these were collectively considered when examining the exposure risk to *Salmonella* (Fig. 1).

In this study, contamination of *Salmonella* along the poultry supply chain were investigated in Guangdong province, where is the foremost yellow-feathered broiler production and consumption area in China (Zhang et al., 2018). Sample collections in farm and slaughter house were conducted in an integrated yellow-feathered broiler production enterprise. The chosen enterprise consists of two commercial broiler farms (~breeding of 40 million birds per year) and one slaughter house (~slaughter of 9 million birds per year), which could be regarded as a representative poultry production company in China. Four brands of grocery distributed in four different districts (Tianhe, Haizhu, Yuexiu, and Liwan) of Guangzhou were chosen to carry out the retail sampling. A total of 3100 samples were collected at five different stages of the broiler supply chain including farm (n = 620), scalding (n = 620), evisceration (n = 620), immersion chilling (n = 620) and retail stores (n = 620) from October 2016 to December 2019. Thirty-one independent sample collections were performed in 31 months distributed in four seasons. For each collection, samples were randomly collected from farm (n = 20), scalding (n = 20), evisceration (n = 20), immersion chilling (n = 20) and retail stores (n = 20). To determine the prevalence of *Salmonella* in chicken from farm to retail markets, and to estimate levels of *Salmonella* contamination on farm by most probable number (MPN) analysis, qualitative detection methods for the presence of *Salmonella* in each sample was performed as described in the National Food Safety Standard GB 4789.4–2016 for the microbiological examination of *Salmonella* (National Food Safety Standards of China). The *Salmonella* contamination level in swabs samples from farm was determined using the three-tube three-dilution MPN method as described by the Food Safety and Inspection Service of United States Department of Agriculture (USDA/FSIS, 2008). Other model parameters were collected from onsite investigations, laboratory experiments and literature studies.

The bleeding step is carried out at the environmental temperature of 15–33 °C and this temperature is conducive to bacteria. The temperature and time for bleeding were described by Normal and Pert distributions based on previous studies (Oscar, 2004; Pang, Lambertini, Buchanan, Schaffner, & Pradhan, 2017). The growth of *Salmonella* was modeled using a modified Gompertz primary model (Equation (1)) and Arrhenius secondary model (Equation (2)) (Pang, 2018).

$$Y_{(t)} = Y_0 + (Y_{\max} - Y_0)\exp\left\{ - \exp\left[\frac{\mu_{\max} e}{Y_{\max} - Y_0}(\lambda - t) + 1\right]\right\} \quad (1)$$

where $Y_{(t)}$ is the concentration at time t (log CFU/g), $\mu_{\max}$ is the maximum growth rate at a specific temperature (log CFU g^{-1} h^{-1}), and $Y_{(0)}$ is the concentration at time 0 (log CFU/g).

$$\mu_{\max} = a(T + 273.15)\exp\left\{ - \left[\frac{\Delta G'}{R(T + 273.15)}\right]^n\right\} \quad (2)$$

where R is gas constant (8.314 J/mol K), $\Delta G'$ is activation energy for bacterial growth (J/mol), T is absolute temperature (°C), a and n are coefficients.

Scalding is the step using hot water immersion to facilitate the removal of feathers and reduce the pathogenic bacteria on meat during slaughtering (Osiriphun, Tuitemwong, Koetsinchai, Tuitemwong, & Erickson, 2012). The scalding water temperatures vary from 50 to 70 °C and scalding times are from 60 to 100 s. Chemical additives are not allowed in the water used for scalding in China. Bacterial inactivation during scalding was expressed using a Logistic distribution with parameter values derived from our previous published work (Xiao, Wang, Zhang, Zhang, et al., 2019).

The evisceration step uses a series of interconnected machines to remove the intestinal tract from the body cavity. Fecal contamination of carcasses may increase at this step, especially if the gastrointestinal system of the bird is damaged, resulting in cross-contamination and the increase of bacterial prevalence in evisceration (Berrang, Buhr, Cason, & Dickens, 2001). Data for prevalence changes (P_{ce}) were calculated based on testing of *Salmonella* in chicken carcasses every month (Equation (3)) and P_{ce} values were described by Lognorm2 distributions to capture the uncertainty and variability inherent to the data.

$$P_{ce} = \frac{P_{i-after}}{P_{i-before}} \quad (3)$$

where P_{ce} is the changes in prevalence, $P_{i\text{-}after}$ is the sampling result of prevalence after a specific processing step, in this case of evisceration step, $P_{i\text{-}after}$ is sampling result after evisceration. $P_{i\text{-}before}$ is the prevalence before the processing step, in this case of evisceration step, $P_{i\text{-}before}$ is sampling result of scalding. $P_{ce} < 1$ indicates a reduction in prevalence and $P_{ce} > 1$ indicates an increase in prevalence. Therefore, the predicted prevalence after evisceration step could be calculated by Equation (4) (Dogan et al., 2019).

$$P'_{i-after} = \frac{P_{i-before} \times P_{ce}}{1 - P_{i-before} + P_{i-before} \times P_{ce}} \quad (4)$$

where $P'_{i\text{-}after}$ is the predicted prevalence after a specific processing step.

Immersion chilling is the step using chlorine in the water to reduce

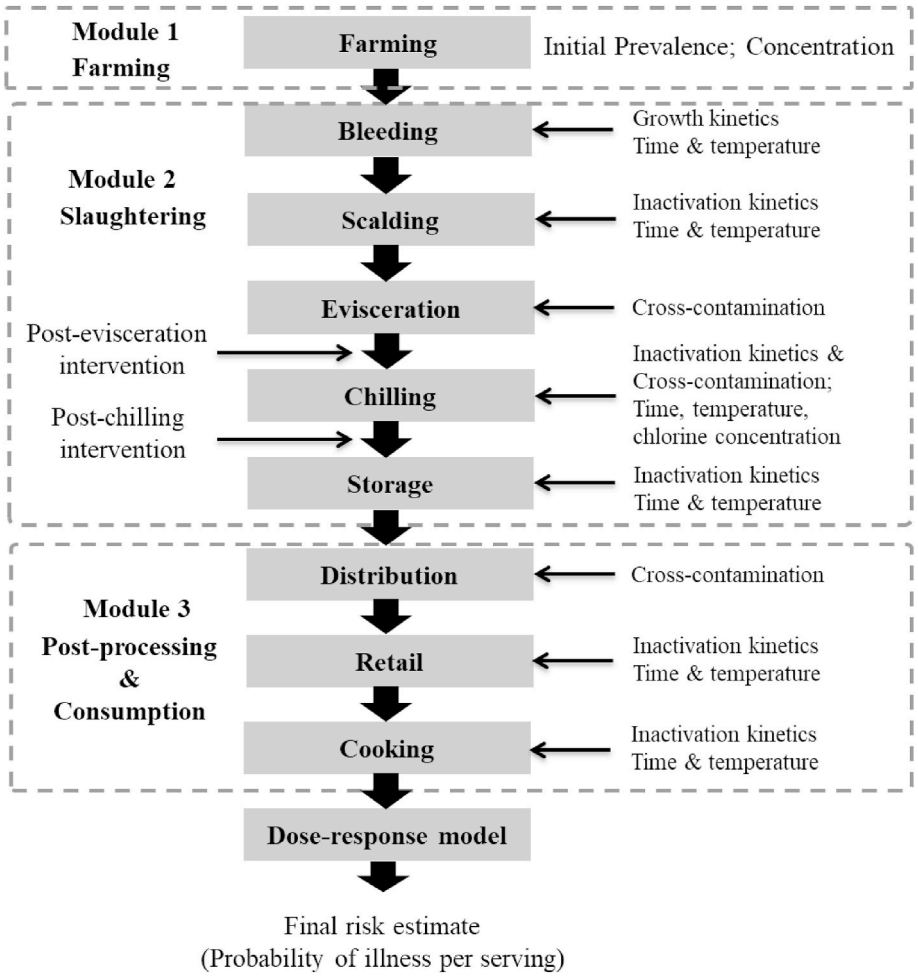

Fig. 1. Modular process risk model for *Salmonella* in yellow-feathered broiler chickens.

microbial contamination (James, Vincent, de Andrade Lima, & James, 2006; Northcutt, Smith, Musgrove, Ingram, & Hinton, 2005; Yang, Griffis, & Waldroup, 2002). In China, 50–100 mg/L chlorine is commonly used for poultry chilling (Jun, Guo, & Ning, 2013). Bacterial inactivation during immersion chilling was expressed using a Normal distribution with parameter values based on our previous published work (Xiao, Wang, Zhang, Liao, et al., 2019). Moreover, the chilling tank is a high-risk area where cross-contamination between contaminated and non-contaminated carcasses can occur via the wash water (Yang, Griffis, & Waldroup, 2002). The prediction of bacterial prevalence in chlorinated water during chilling was expressed using a nonlinear model derived from our previous published work (Xiao, Wang, Zhang, Liao, et al., 2019).

After immersion chilling, the slaughter house was assumed to store fresh chilled chicken meat in refrigerators at 2–8 °C and the chilled meat is assumed to be stored for a maximum of 7 days, a mean of 3 days and a minimum of half a day. *Salmonella* is not assumed to grow during refrigerator storage because properly working refrigerators keep the temperature <10 °C, the minimum growth temperature for *Salmonella* (FAO/WHO, 2002). Bacterial reduction during refrigerated storage was expressed using a Pert (0, 0.3, 0.7 log CFU/g) distribution based on our laboratory unpublished data.

2.2. Post-processing and consumption module

The post-processing and consumption module was composed of wholesale, retail and cooking points. Bacterial prevalence can increase due to cross-contamination that could also be calculated by Equations (3) and (4) (Jeong et al., 2018). In the retail market, chicken meat is sold at refrigerated temperatures so that the bacterial reduction could be described by a Pert (0, 0.3, 0.7 log CFU/g) distribution according to our unpublished data. In the household, the cooking temperatures varied from 60 to 100 °C and could be described by a Normal (80, 10) distribution that involved an undercooking event. Time of cooking assumed that chickens are cooked in a home oven and *Salmonella* are exposed to the final cooked temperature for a minimum of 30 min, a mean of 45 min, and a maximum of 60 min. Log reduction in cooking was calculated based on previous literatures (Dogan et al., 2019; Murphy, Duncan, Beard, & Driscoll, 2003).

2.3. Dose-response model

The chicken serving size was set at 52.2 g and annual chicken consumption in China was 4050 g as previously described (Wu & Yuan, 2014; Yu & Yu, 2017). The levels of *Salmonella* in chickens after cooking was multiplied by serving size to calculate the number of *Salmonella* cells ingested per contaminated serving. A Beta-Poisson model (Equation (5)) was used for the present study with α and β parameters of 0.2274 and 57.96 respectively (FAO/WHO, 2002). The probability of illness (P_{ill}) was calculated using Equation (6).

$$P_{\inf} = 1 - \left(1 + N/\beta\right)^{-\alpha} \quad (5)$$

where P_{inf} is the probability of infection per contaminated serving, N is the number of organisms ingested per contaminated serving, and α and β

are model parameters.

$$P_{ill} = P_{inf} \times P_{co} \quad (6)$$

where P_{ill} is the probability of illness per serving, P_{co} is the prevalence after cooking.

2.4. Risk characterization

2.4.1. Risk estimation

The QMRA model integrated relevant data, information, statistical distributions, and predictive models (Table 1). An Excel 2010 spreadsheet (Microsoft, Redmond, WA, USA) was employed to build the QMRA model. The @Risk package version 7.5 (Palisade, Ithaca, NY, USA) was used to fit statistical distributions and to run the scenarios and simulations. For each scenario, 10,000 iterations were run employing the Monte Carlo method. A Latin hypercube sampling method was used to sample different values for input parameters and variables.

2.4.2. Sensitivity analysis

Sensitivity analysis was performed using @Risk to provide a quantitative measure of the most important parameters affecting the probability of illness from *Salmonella* via the pathway explored in the baseline model. The value of this QMRA was that the general results can be used to prioritize risk mitigation strategies based on the parameters shown to have the strongest impact on risk (Zwietering & Van Gerwen, 2000). Sensitivity analysis was conducted using the approach called "change in the output mean" that was a greater reflection of the impact of the input variation on model outputs.

Table 2
Input distributions of interventions in broiler chicken slaughtering.

Intervention type	Log reduction	Distribution	Source
Scalding			
Soft scalding (sodium hydroxide)	1.6–1.8	Uniform (1.6, 1.8)	McKee et al. (2008)
Evisceration			
Post-evisceration (steam)	1.4–3.1	Uniform (1.4, 3.1)	Kure et al. (2020)
Post-evisceration spray (electrolyzed water and sodium hypochlorite)	1.9–3.1	Pert (1.9, 2.6, 3.1)	Northcutt, Smith, Ingram, Hinton, and Musgrove (2007)
Post-evisceration spray (Chicxide)	1.3–2.3	Uniform (1.3, 2.3)	Laury et al., 2009;
Post-evisceration spray (hypochlorite)	0.8–2.4	Uniform (0.8, 2.4)	Northcutt et al. (2007)
Post-evisceration spray (hot water)	0.7–1.2	Uniform (0.7, 1.2)	Northcutt et al. (2005)
Chilling			
Chilling (citric acid)	1.2–2.2	Uniform (1.2, 2.2)	Mani-López et al. (2012)
Chilling (trisodium phosphate)	0.3–1.5	Pert (0.3, 0.8, 1.5)	Sarjit and Dykes (2015)
Chilling (electrolyzed water)	0.2–0.9	Pert (0.2, 0.5, 0.9)	Shimamura, Shinke, Hiraishi, Tsuchiya, and Masuda (2016)
Air chilling	0.8–1.2	Normal (1.0, 0.2)	Huezo et al. (2007)
Storage			
Cold storage (vacuum packages)	1.1–3.2	Pert (1.1, 2.4, 3.2)	Kudra et al. (2011)
Cold storage (CO_2+CO MAP packages)	0.8–3.0	Pert (0.8, 1.9, 3.0)	Kudra et al. (2011)
Ambient storage (vacuum packages)	0.7–1.6	Pert (0.7, 1.0, 1.6)	Kudra et al. (2011)
Ambient storage (CO_2+CO MAP packages)	1.0–2.3	Pert (1.0, 2.0, 2.3)	Kudra et al. (2011)

2.4.3. Intervention scenarios

Fourteen intervention scenarios were evaluated in our model. Intervention involves the complete alteration of a processing step such as air chilling replacing immersion chilling. The efficacy data of the baseline processing step was replaced with the efficacy data of the alternative processing step. Besides, additional processing steps were added as interventions, such as adding extra processing aids at post-evisceration. Log reductions in *Salmonella* by intervention treatments in slaughtering were fitted to Pert, Uniform or Normal distributions. Data to estimate intervention efficacy were adopted from previous studies (see Table 2). Average risk estimates were determined from the average outputs of each model run for each intervention scenario and the intervention efficacy calculated as fold change.

3. Results and discussion

3.1. Baseline model risk estimates

The mean predicted probability of illness per serving was 1.1×10^{-8} for baseline, indicating that a mean of 693 salmonellosis cases per year would occur in China. The present study observed a much lower risk of salmonellosis following ingestion of a single chicken meal prepared at home when compared to previous estimates (FAO/WHO, 2002; Oscar, 2004; Zhu et al., 2014). The typical method of consumption of these chickens is to prepare a soup from the whole carcass by stewing (Pan, Li, Han, & Yang, 2013). This procedure achieves high internal meat temperatures and thermally inactivates *Salmonella* (Jeong et al., 2018). Therefore, the risk caused by the consumption of yellow-feathered broiler chicken in China was significantly low due to this characteristic cooking method.

Contamination changes over the steps of the broiler chicken supply chain can be visualized in Fig. 2 in terms of prevalence and concentration with their mean values, 5th and 95th percentiles. It was estimated that the prevalence of *Salmonella* increased from 4.3 to 21.5% during evisceration in the model. The evisceration step is a high-risk area where cross-contamination between contaminated and non-contaminated carcasses occurred via tools and hands, leading the increase of bacterial prevalence (Berrang et al., 2001). As previously described, the likelihood of *Salmonella* prevalence was estimated to increase by at least 44% if poor control measures were taken post evisceration (Parsons et al., 2005). Besides, increased in prevalence was previously observed for immersion chilling due to cross-contamination between chicken carcasses (Karolyi, Medić, Vidaček, Petrak, & Botka, 2003; Reiter, Fiorese, Moretto, López, & Jordano, 2007). However, immersion chilling with chlorination was modeled as baseline, which might explain the decreasing trend predicted from the model because of cross-contamination. The 95% confidence interval (CI) for prevalence of *Salmonella* in meat at retail was 0–54% in our study and was consistent with the previous studies conducted in China that ranged from 28 to 52.2% (Li et al., 2013; Wang et al., 2014; Yang et al., 2011; Yang et al., 2014; Yang et al., 2020; Zhu et al., 2014). There is a low prevalence of *Salmonella* reported in retail poultry meat from the European Union (7.1%) and the United States (4.4%) (Adzitey, Huda, & Ali, 2012; Gonçalves-Tenório, Silva, Rodrigues, Cadavez, & Gonzalesbarron, 2018). More effective strategies should be developed to reduce *Salmonella* contamination in the broiler chicken supply chain in China.

3.2. Sensitivity analysis

Sensitivity analysis can identify the critical control points and assess the importance of individual inputs on the overall outcome. The sensitivity of the baseline model revealed that the mean probability of illness per serving was most sensitive to consumer food safety practices and initial farm contamination. In this study, cooking temperature was the leading factor in preventing the occurrence of salmonellosis. The undercook of chicken meals would cause a 20-fold increase of the

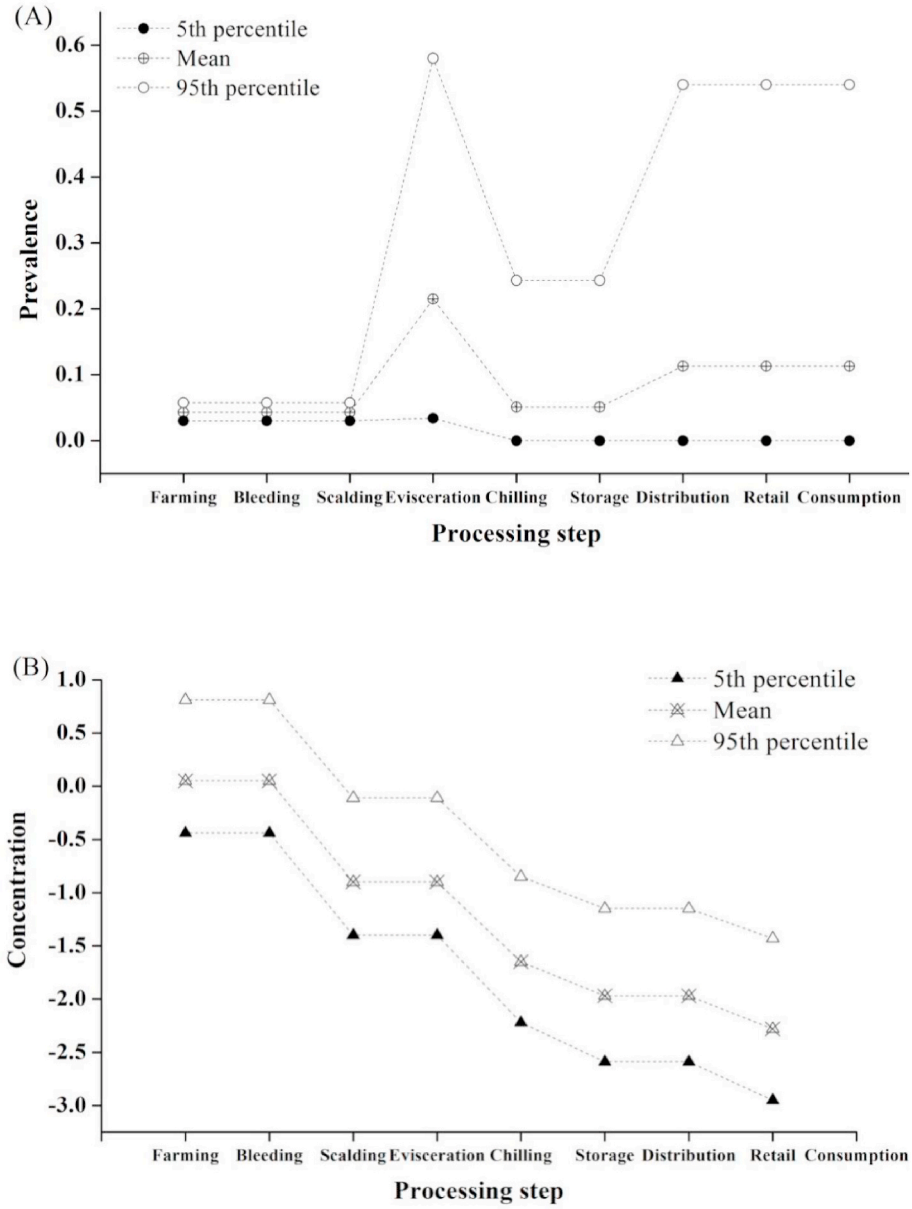

Fig. 2. Yellow-feathered broiler chicken supply chain and alterations in *Salmonella* (A) prevalence and (B) concentrations. Lines represent the point estimate (mean) and dotted lines represent the interval between 5th and 95th percentiles. *, concentration for consumption is not displayed because the value is very small and out of the scale of this plot.

infection risk (Fig. 3). In previous studies, cooking was also identified as the predominant factor to reduce the microbial risk associated with chicken consumption (Dogan et al., 2019; Jeong et al., 2018). For example, in the study of Dogan et al. (2019), if chicken consumed were cooked adequately, incidence of campylobacteriosis can be reduced to 0.12 cases per 100,000 person-years, while if all chicken meals were undercooked, the predicted incidence was increased to 8437 cases per 100,000 person-years. Thus, the education of full cooking is vital to improve consumers' safety. The bacterial contamination on the farm was addressed using intervention strategies including the establishment of stricter control measures such as vaccination programs in breeder flocks and removal of *Salmonella*-positive flocks from production (Alali et al., 2012; Gonçalves-Tenório et al., 2018).

Along the supply chain, slaughtering operations were also critical steps in controlling final risks (Fig. 3). The chlorine concentrations used for chilling had a profound effect on the reduction of bacterial concentration and prevalence. The processing stage accounted for a 0.8 log reduction in contamination levels from −0.9 to −1.7 log CFU/g in chilling (Fig. 2B). A similar trend was observed for prevalence changes that caused a decline from 21.5 to 5.1% during chilling (Fig. 2A). In addition, bleeding, scalding, evisceration, storage, wholesale all affected the final risk estimation. These steps were identified as critical control points where potential measures to mitigate chicken consumption-associated salmonellosis should be taken.

3.3. Scenario analysis

The effectiveness of intervention measures potentially used in slaughtering on reducing the occurrence of salmonellosis was quantitatively evaluated in scenario analysis, and the results could be the scientific basis in making decision of intervention adoption to improve the chicken safety. A scenario analysis indicated that all the evaluated intervention strategies evaluated could achieve 1.3- to 343.8-fold-reductions of mean probability of illness. Post-evisceration spraying with a

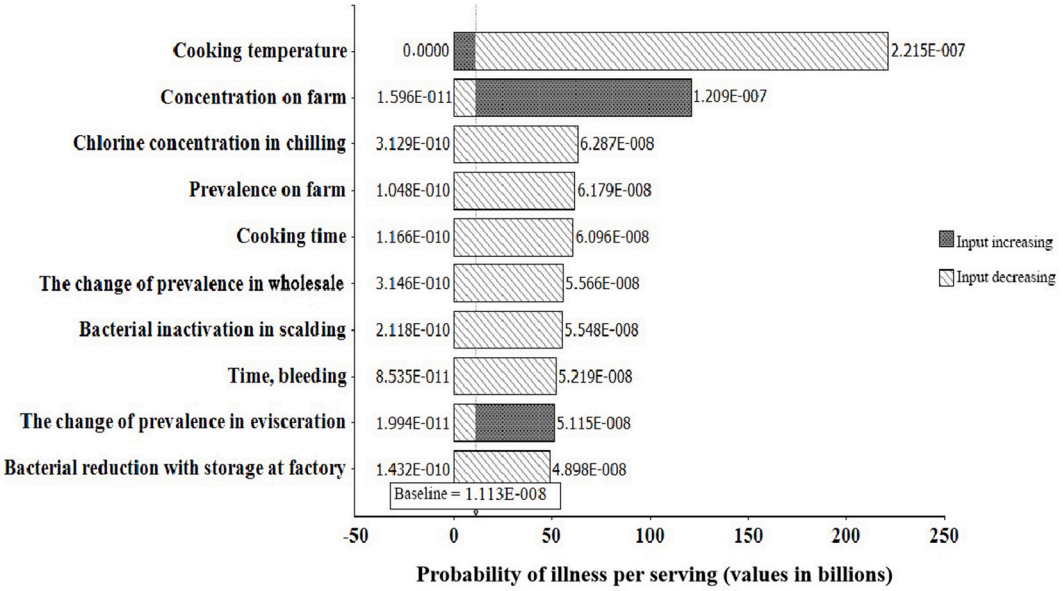

Fig. 3. Tornado plot for inputs ranked by absolute change in the output mean.

combination of electrolyzed water and sodium hypochlorite gave the greatest risk reduction (343.8-fold). Additionally, cold storage in vacuum packages (68.8-fold reduction) and immersion chilling with citric acid (4.1-fold reduction) were also effective measures (Table 3). In the baseline model, scalding without any additives was used as the reference processing operation. Soft scalding with sodium hydroxide reduced the estimated mean probability of illness 19.3-fold over the baseline prediction (Scenario 1). Scalding water at pH > 9.0 is bactericidal to *Salmonella*. The mechanism by which an alkaline environment is thought to destroy bacteria is by altering enzyme function and nutrient transport (McKee, Townsend, & Bilgili, 2008). Organic matter and uric acid derived from poultry feces in the tank reduce and maintain pH values near neutrality and favor *Salmonella* growth (Buncic & Sofos, 2012). Monitoring and controlling the pH of the scalding tank might remedy this issue.

After evisceration, additional processing steps such as spray washing offered great reductions in the final risk estimate from Scenarios 2 to 6 and the lowest risks were obtained in Scenario 3. Spray washing with chemical or physical interventions could help reduce bacterial contamination on chicken carcasses. In practice, carcass washing involves spraying or rinsing usually in a whole carcass inside-outside washer at pressures sufficient to remove visible contamination. Washing actually may involve multiple sprays from bleeding through chilling and may contribute to reduction of *Salmonella* prevalence on carcasses by 50–90% (Buncic & Sofos, 2012).

Immersion chilling treatment strategies also resulted in promising reduction in risk. As the most effective intervention in this group, citric acid applied in the chilling process led to a risk reduction to 2.7×10^{-9} (Scenario 7). Citric acid has demonstrated efficacy for pathogen control in both fresh and processed meat, but its usage is potentially limited by possible negative sensory impact and the need for low pH maintenance for optimum antimicrobial activity (Mani-López et al., 2012). Citric acid at 3% did not produce unacceptable odors and color acceptability was retained for longer periods compared to untreated controls (González-Fandos, Herrera, & Maya, 2009). Adding chlorine to the immersion chilling had a minor effect compared with citric acid. Chlorine use in immersion chilling is popular but its effectiveness is questioned due to high chlorine demand and remaining residue (Lee, Park, Kang, &

Table 3
Risk of salmonellosis with different scenarios in the broiler chicken supply chain.

Scenario	Mean	95% CI	Fold change[a]
Baseline	1.1×10^{-8}	0 [b]	–
1. Soft scalding (sodium hydroxide)	5.7×10^{-10}	0 [b]	19.3↓
2. Post-evisceration (steam)	1.4×10^{-10}	0[b]	78.6↓
3. Post-evisceration spray (electrolyzed water and sodium hypochlorite)	3.2×10^{-11}	0[b]	343.8↓
4. Post-evisceration spray (chicxide)[c]	8.1×10^{-10}	0[b]	13.6↓
5. Post-evisceration spray (hypochlorite)	6.2×10^{-10}	0[b]	17.7↓
6. Post-evisceration spray (hot water)	7.0×10^{-9}	0[b]	1.6↓
7. Chilling (citric acid)	2.7×10^{-9}	$(0–9.0 \times 10^{-8})$	4.1↓
8. Chilling (trisodium phosphate)	8.5×10^{-9}	$(0–1.0 \times 10^{-8})$	1.3↓
9. Chilling (electrolyzed water)	1.5×10^{-8}	$(0–1.6 \times 10^{-7})$	1.4↑
10. Air chilling	7.8×10^{-9}	$(0–1.0 \times 10^{-8})$	1.4↓
11. Cold storage (vacuum packages)	1.6×10^{-10}	$(0–8.0 \times 10^{-9})$	68.8↓
12. Cold storage (MAP packages)	3.0×10^{-10}	$(0–2.0 \times 10^{-9})$	36.7↓
13. Ambient storage (vacuum packages)	1.3×10^{-9}	$(0–1.0 \times 10^{-8})$	8.5↓
14. Ambient storage (MAP packages)	2.5×10^{-10}	$(0–2.0 \times 10^{-9})$	44↓

[a] Fold changes were calculated by comparing the mean probability of illness cases predicted by sixteen intervention scenarios with the mean. —, not applicable; ↑, risk increasing; ↓, risk reduction.

[b] Due to @Risk's method of calculating confidence intervals with Latin Hypercube sampling, lower bound values for some of the scenarios were <0. These values were truncated at 0 for the lower bound.

[c] Chicxide is a lactic acid- and citric acid-based antimicrobial intervention.

Ha, 2014; Yang, Li, & Johnson, 2001). In addition, the effectiveness of air chilling in terms of microbial inactivation was limited. The model in this study projected that air chilling would result in the reduction of *Salmonella* and ranged from 0.8 to 1.2 log CFU/g causing a 1.4-fold reduction in the final risk. This was equivalent to immersion chilling without any chemical intervention (Huezo, Northcutt, Smith, Fletcher, & Ingram, 2007).

Vacuum packages and MAP were incorporated into scenarios 11 to 14. Cold storage with vacuum packages resulted in a 68.8-fold relative risk reduction. No growth of several *Salmonella enterica* serotypes was observed in vacuum-packaged mechanically deboned chicken meat when the product was stored at 5 °C for 9 days (Kudra et al., 2011). Results from the microbiological assessments in this study indicated that MAP did not demonstrate any advantage over vacuum packaging for risk reduction. MAP appears to be effective under highly oxidative or strictly anaerobic conditions (Dogan et al., 2019).

3.4. Uncertainty and variability of the QMRA model

An intrinsic limit of the QMRA model is that insufficient data make risk estimates uncertain and false-negative detection was not considered (Nauta, 2000). When *Salmonella* was present in the chickens below the detection limit, this could still result in *Salmonella* growth (Jeong, Kim, & Seo, 2019). Variability and uncertainty in parameter distributions could be overcome by repeated sampling and randomized iterations during stochastic simulations (Rajan et al., 2017; Vásquez, Busschaert, Haberbeck, Uyttendaele, & Geeraerd, 2014).

4. Conclusions

This study provides a risk assessment of *Salmonella* in the yellow-feathered broiler chicken supply chain in China. The mean predicted probability of illness per serving was 1.1×10^{-8}. Consumer education was a critical factor in reducing the risk of foodborne illnesses since undercooking was the most important input parameter affecting the risk estimates. Initial contamination on farm and slaughtering operations were also crucial for the safety of the final product. All intervention strategies evaluated could achieve 1.3- to 343.8-fold reductions in the mean probability of illness. Although this QMRA contains limitations and assumptions as do all QMRA, it nevertheless provided a comprehensive modeling framework that could be adopted as future research discovers contamination routes and levels.

CRediT authorship contribution statement

Xingning Xiao: Conceptualization, Methodology, Software, Data curation, Writing - original draft. **Wen Wang:** Data curation, Writing - original draft, preparation. **Jianmin Zhang:** Visualization, Investigation. **Ming Liao:** Visualization, Investigation. **Chase Rainwater:** Writing - review & editing. **Hua Yang:** Supervision. **Yanbin Li:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodcont.2020.107612.

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